Dear Editor,

Please find our revised manuscript based on the referees' comments provided during the discussion phase of the submission process. You will find our point-by-point responses to every comment made by the referees. The revised manuscript, including the 'track changes', is included following our responses to the referees. We wish to thank the referees for their insightful comments that have contributed to improving the manuscript.

Our changes to the manuscript include:

- Revising manuscript to objectively analyse each of the experiment, and document the model performance for the users of each of these experiments (i.e. parameterization sets) as these experiments represent active use cases of ECOSMO. We have improved the clarity of the technical description and scientific messages of the manuscript.
- The text regarding sources and use of data for model evaluation has been revised to make it clear for the reader where the data comes from and for what purpose it was used. As can be seen in the revised manuscript, each dataset (climatology, in situ and satellite) has its own value especially with regard to spatial and temporal coverage and they complement each other well for model evaluation.
- The text has been improved in its scientific content with the following key points:
    - Comment on the added value of using explicit state variables for chlorophyll a in the model formulation
    - What do different parameter values mean in terms of model performance and internal dynamics.
    - Lessons learned with respect to future evolutions of the model

We have carefully considered all the technical points raised by the reviewers and made the necessary changes to the text. To improve the clarity of the manuscript and enhance its technical and scientific points, minor changes to the text were made. Any changes to the manuscript can be seen in detail with the 'track changes' enabled below following our responses to the referees.

Reply to comments from the reviewers

Reviewer #1
Referee's comments are provided in 'black italic', and our responses in 'blue'. Our proposed changes to the text appear in 'green'. We reference the manuscript provided below with its line numbers (e.g. L10-L19).

The paper presents and evaluates an updated version of the marine biogeochemical model ECOSMO II, that now also includes a parameterisation for a variable C:Chl ratio of phytoplankton. The biogeochemical is coupled to the HYCOM ocean model, configured for the Arctic Ocean. Model evaluation of a default setup is carried out against observed nutrients and Chl a from in situ measurements and remote sensing, and complemented by comparison to literature values of primary production. Model sensitivity to biogeochemical parameters is *evaluated in two further experiments. In general, all model configurations perform quite well with regard to the observations, and improvement in surface chlorophyll when parameters are adapted to the hydrodynamics of the Arctic.*

In general, the paper is well written and I very much appreciate the thorough comparison to observed tracers. One drawback is the - to my eyes - somewhat incomplete description of phytoplankton (see (1) below), and the slightly confusing description of how observations were used for comparison (2). I further encourage the authors to improve on the structure of the paper (3) and to extend a bit on the comparison of the three different experiments (see my comment no 4 below).

(1) For better understanding of how phytoplankton responds to nutrient and light limitation I suggest to present the equation(s) for phi (in Eqns 1 and 2). Without knowledge about this functional form it is difficult for the reader to understand its dynamics, in particular as DS2013 might not be accessible to everyone. Further, does the C:Chl ratio (or the amount of chlorophyll in phytoplankton) affect the light attenuation and P-I curve, i.e. the of phytoplankton growth rate?

We agree that the term 'phi' (growth limitation) is necessary to be present in a model description paper and understand the referee's concern that the DS2013 paper may not be accessible for everyone. For this reason, we include $\boldsymbol{\phi_{P_j} = \min(\alpha(I), \beta_N, \beta_P, \beta_{Si})}$ as the general equation for phi and expand this equation to include all of the necessary formulations for each individual term in the equation totalling to additional 6 equations. We believe these additions will address the request of the referee. The changes are as follows and each equation define a limitation respective to light or nutrient:

(L131-139)

$$\boldsymbol{\phi_{P_j} = \min(\alpha(I), \beta_N, \beta_P, \beta_{Si})} \quad \textbf{(3)}$$

$$\boldsymbol{\alpha(I) = \tanh(\varphi I(x, y, z, t))} \quad \textbf{(4)}$$

$$\boldsymbol{\beta_N = \beta_{NH_4} + \beta_{NO_3}} \quad \textbf{(5)}$$

$$\boldsymbol{\beta_{NH_4} = NH_4/(NH_4 + r_{NH_4})} \quad \textbf{(6)}$$

$$\boldsymbol{\beta_{NO_3} = (NO_3/(NO_3 + r_{NO_3}))\exp(-\gamma NH_4)} \quad \textbf{(7)}$$

$$\boldsymbol{\beta_{PO_4} = PO_4/(PO_4 + r_{PO_4})} \quad \textbf{(8)}$$

$$\boldsymbol{\beta_{Si} = Si/(Si + r_{Si})} \quad \textbf{(9)}$$

And the definition of these terms in the text:

(L146-148) DS2013 give σ_j, ϕ_{P_j}, φ, $r_{NH_4,NO_3,PO_4,Si}$, $\boldsymbol{\gamma}$**,** G_i and m_{P_j} as the phytoplankton maximum growth rate, growth limitation, photosynthesis efficiency parameter, nutrient-specific half saturation constant, NH_4 inhibition parameter, zooplankton grazing rates and mortality rates respectively.

For the reader to follow better, PAR was removed from the equations and was given as I(x, y, z, t) suggesting a point in 3D and time. PAR is dependent on surface radiation, I_S, water and chlorophyll specific attenuation constants and CHL concentration. C:Chl ratio indirectly affects the light attenuation as Chl is included there. We believe the equation in this form better relates the reader with CHL vs light attenuation. The changes to the text are as follows:

(L130) $\rho_{chl_j} = \frac{\theta_P^{max} \phi_{P_j} C_{P_j}}{\alpha_{P_j} I(x,y,z,t)\, Chl}$ **(1)**

(L146) Photosynthetically active radiation (PAR) is given as I(x,y,z,t).

(L154-155) In relation to the addition of a prognostic chlorophyll *a* state variable, photosynthetically active radiation I(x,y,z,t) at depth undergoing attenuation was modified to have chlorophyll *a* in the exponential term:

(L157) $I(x,y,z,t) = \frac{I_s(x,y)}{2} exp\left(-k_w z - k_{Chl} \int_z^0 \sum_{j=1}^{2} Chl_{P_j} \partial z\right)$ (12)

The model does not relate CHL to P-I curve at the moment in the context of growth, but it is a very valid point and will be including such relations in future iterations of ECOSMO. We have noted this in the discussion sections:

(L594-599) An important addition to explicit chlorophyll *a* variable is the inclusion of the initial slope of P-I curves to light-limitation on growth. In this study, light-limitation on growth was approached in a PFT and chlorophyll *a* independent fashion (Eq. 4). Future versions of ECOSMO should adopt ways (e.g. Evans and Parslow, 1985) to include the PFT specific P-I curve slopes to take full advantage of the explicit chlorophyll a variable. This would allow PFTs to differentiate their niche light conditions for production, and further allow better integration with the bio-optical modelling of the marine environment.

(2) The description of type of observations, and how these were used for model evaluation (section 4.1) is somewhat confusing (see also below, specific comments).

Also

Line 220-221: "Nitrate, silicate, phosphate and chlorophyll a in situ data from Institute of Marine Research (2018) were used for the statistical evaluation of the model results." Where were these data used and what is the difference to the comparison against WOA2013 data?

Reviewer-3 has also raised this issue. We explain the use of validation data better in Section 4.1 opening the section with the following:

(L257-259) The model simulations were evaluated using three different datasets as follows: (1) World Ocean Atlas 2013 (WOA13; Garcia et al., 2013), (2) Institute of Marine Research (2018) data (IMR18), (3) ESA Ocean Colour CCI v5.0 (OC CCI; Ocean Colour Climate Change Initiative; Sathyendranath et al., 2019).

That will inform the reader from the start what data is used. In the following paragraphs, we go through each of them in detail and explain how and for what purpose they were used. In summary, WOA13 is used for evaluating monthly and regional averages, whereas the IMR dataset is used to evaluate the model point-by-point collocating model against in situ data points. The extensive data from IMR18 allowed us to perform the statistical analysis whereas WOA13 was used for a visual comparison. OC CCCI data was used for an additional statistical analysis supporting IMR18 data.

The following sentences from the text should give the reader enough information on the type of data, and what it was used for:

(L261-262; WOA data) The model's consistency with the large-scale climatological inorganic nutrient distributions was quantified by comparing the regionally averaged monthly inorganic nutrient model data (nitrate, silicate and phosphate) to WOA13 data.

(L267-269; WOA data) These monthly time-series allowed a model evaluation for the regions ~~that~~, in which the in situ data was not optimal for the statistical analysis. Regional climatology data should be used with caution because WOA13 data are in some places based on very few observations and that may mislead the evaluation process.

(L274-278; IMR data) A separate evaluation for the model inorganic nutrients (nitrate, silicate and phosphate) and chlorophyll *a* was conducted using the IMR18 in situ data by performing a point-by-point (location and depth) co-location for the statistical analysis.

(L285-288; OC CCI data) A final model chlorophyll evaluation was conducted using OC CCI daily surface chlorophyll *a* and downwelling attenuation coefficient at 490 nm (kd490) at 4km x 4km spatial resolution.

(L294-296; OC CCI data) This separate analysis allows us to include chlorophyll *a* data for model evaluation in addition to IMR18 data.

To further assist the structure of the observed data, we added Figure A5 in the Appendix which includes the profile locations for the IMR data. (L698)

We would like to answer item 3, 4 and some of the minor comments in the following together.

(3) Some sentences of the model setup (section 3) already anticipate the results (e.g., lines 183-186: "Using lower ... column stabilizes." and 189-191: During the continuous ... will replace the parameterization set in EXP2."). I would suggest to reorganise the paper a bit (see also comment (4)), and draw conclusions only from the model evaluation.

Sentences anticipating the results were removed. Please see the crossed out sentences in L212-225. Please also refer to our extensive comments on the subject below.

(4) I enjoyed reading the analysis in section 4.3. I think this analysis could be complemented by constrasting it with the results obtained with EXP2 and EXP3. For example, Table 2 shows that EXP1 always performs best with regard to the correlation coefficient, in 7 (8) cases out of 12 with regard to the normalised StdDev (Bias%), and in half of the cases with regard to RMSE. Likewise, it performs always best (regardless of metric) for phosphate and nitrate, and in half of the cases with regard to chlorophyll. Even if some differences to EXP2 and EXP3 are only small, I think this could be discussed a bit more (so far, there seems only be a sentence in line 451), and contrasted with the outcome presented in Tables 4 and 5, which indicate that EXP3 performs best with

regard to surface Chl a. What is the reason for these differences? Is it because Table 4 and 5 only refer to surface values?

Line 278: "0.6-0.72" - Table 2 gives 0.79-0.83 for EXP1: confusion with EXP3?

Line 279ff: For the biases Table 2 gives the relative bias, but in the text you refer to absolute biases, which is somewhat confusing.

Line 280: "2.47-3.34" - this seems to be the bias of EXP3. Line 290: "0.74-0.78" - again, for EXP3?

Line 300: "0.81-0.89" - again EXP3?

Line 311: "0.97-1.2" - EXP3?

Line 451: "EXPeriment statistics for inorganic nutrients are very similar in all experiments (Table 2)." - Overall, to me it seems as if EXP1 performs better than EXP2 and EXP3 (see above my comment no. (4))

Referee #2 has also raised similar concerns. We agree that our review of the model results and discussions on the statistics of different experiments were misleading. Therefore, the text on Section 4.3 was extensively reviewed. Going through the comments and the manuscript, we understand how the text reads to be in favor of EXP3 which was not our intent. We value all the experiments as the parameter sets in these experiments are being actively used, and our intention in this manuscript was to document the model performance for each experiment. For this reason, along with many other revisions in the manuscript, we clearly state the use cases for each experiment in the introduction and the model setup, we reference what each experiment represents (i.e. EXP1 for the original ECOSMO, EXP2 for the operational model prior to July 2021 and EXP3 for the current operational model after July 2021).

To achieve an objective comparison among the experiments, the text regarding the statistics to which the referee refers now include results from all the experiments, not only EXP1, which also corrects the confusion stemming from EXP1 vs EXP3 as stated by the referee, as such each statistical range given in the text covers the min/max of all experiments (EXP1, 2, and 3). We have also noted that EXP1 better performs well in many aspects and each of these are documented in the text for both the statistical analysis and the monthly average comparison to WOA (as we also note in the text that EXP1 averages perform better for nitrate and phosphate) and discuss possible reasons. EXP2 is also included in these new additions.

The contrast between performances among EXP1 and EXP3 with reference to statistical analysis against IMR and satellite data are discussed better. Here are the changes, with their respective sections indicated:

Abstract:

(L16-17) We document the performance of each parameter set objectively analysing the experiments against in situ, satellite and climatology data.

The sentences favoring EXP3, which leads to confusion were removed **(L24-28)**.

Introduction:

(L78-81) We present the results from three experiments using ECOSMO II(CHL) adopting different parameter sets from DS2013 (the original parameter set tuned for the North and Baltic Seas), CMEMS Artic operational model prior to June 2021 and the current Arctic operational model parameterization.

The sentences which reads as the manuscript focuses only on EXP3 were removed **(L77-78 and L81-84)**.

(L85-88) To document the performance of each of these parameter sets for the users of ECOSMO, we present a detailed objective analysis of the lower trophic level dynamics for the North Atlantic and the Arctic Ocean against local in situ observations, gridded climatology of nutrients and satellite data in Sect. 4.

Model setup and evaluation framework:

(L207-209) Since these parameter sets represent active use cases, the objective analysis of these experiments in the following sections provide the users of ECOSMO a reference on how the model performs with different setups and longer time-scales.

Evaluation of the model experiments:

(L317-319) In this section, we analyse the model performance against climatology and in situ data using visual and statistical analysis. We include each experiment in the analysis as a reference for modelling studies that adopt ECOSMO II(CHL) and showcase the possible outcomes using various parameterization sets.

(L352-358) Experiments were generally comparable when the model results were regionally and monthly averaged (Fig. 3). Notable differences were found for the mid-summer nitrate and phosphate concentrations for the Barents, Norwegian and Greenland Seas, as the drawdown of these nutrients was better resolved by EXP1 compared to climatology as EXP1 summertime nutrients were lower than in EXP2 and 3. A possible reason why EXP1 has larger drawdown of nutrients during mid-summer is the higher photosynthesis efficiency applied in EXP1 resulting in higher uptake of nutrients and higher zooplankton grazing rate applied to EXP2 and 3 resulting in higher top-down pressure to phytoplankton preventing phytoplankton from consuming more nutrients.

(L414-420) Among the experiments, all perform very similar in terms of nutrient correlations, while for nitrate and phosphate, EXP1 performs slightly better in terms of nstds, EXP3 performs slightly better for silicate for the Barents Sea and EXP2 for the Norwegian Sea, though the differences among the experiments were almost negligible. Similarly, EXP1 perform better in terms of % bias and RMSE for nitrate and phosphate, and EXP3 perform better for silicate. The slightly better performance of EXP1 for nitrate and phosphate is also evident in summer averages when compared to climatology as mentioned before (Figs. 3a and 3c). The model performance for silicate when using monthly averages shows even less differences among the experiments, however, the EXP3 is slightly closer to WOA timeseries compared to EXP1 (Fig. 3b)

(L422-432) In situ chlorophyll *a* correlations for the upper 100 m (Table 2) are between 0.19 – 0.41, which are below those of inorganic nutrients. However, the model performs acceptable in terms of nstd's. For the Norwegian Sea, EXP3 has the better performance (0.97 and 1.2) and for the Barents Sea, EXP1 perform better (0.97). While EXP1 perform better for the Barents Sea and The NorwegianS (6.2 and 20.3 %) in terms of % bias, EXP3 perform better for NorwegianN (-25.1). Among all the experiments, EXP3 performed better in terms of RMSE for the three regions (0.9 – 1.4 mg m^{-3}). The concentration ranges (Fig. Fig. 4f) are similar (0 – 10 mg m^{-3}) for both the observed and modelled for the Norwegian Sea indicated by nstd's near 1.0, but the points are scattered away from the 1-to-1 line indicating the low correlations. Model chlorophyll *a* is always below 8 mg m^{-3} for the Barents Sea (Fig. Fig. 4e) where the observations show values above 10 mg m^{-3} indicating the lower nstd is underestimating the amplitude of variability.

Model chlorophyll *a* against satellite data and concluding remark on experiments:

(L572-581) The consistent higher bias of EXP1 compared EXP2 and EXP3 can be explained by its higher photosynthesis efficiency (Table 1). EXP1 show a very fast primary production response to light availability during the spring bloom period with notably higher chlorophyll *a* concentrations compared to the observations (results not shown) evident in the high %biases, whereas chlorophyll *a* concentrations in EXP2 and EXP3 are closer to observed values during spring bloom. Originally, the ECOSMO II parameterization was set for the North Sea and the Baltic Sea with different light conditions. In the open ocean such a high response curve leads to an overestimate of the bloom. However, winter convective mixing is very deep in the Nordic Seas, thus the light is a limiting factor on growth. To overcome deep mixing and prevent a late spring bloom, the phytoplankton were allowed to have very high growth rates for EXP2 and relatively less higher growth parameters were set for EXP3. Statistically and visually (Fig. 9), both EXP2 and EXP3 are very similar, with EXP3 performing statistically slightly better.

(L601 – 609) We note that the statistical analysis results against satellite chlorophyll *a* contradict the statistics against in situ data (Section 4.3) as EXP1 performed better in some cases such as % bias for the Barents Sea and south Norwegian Sea. However, in the analysis against satellite chlorophyll *a*, EXP1 was statistically outperformed by EXP2 and EXP3. First possible cause of this difference may be that the in situ data and satellite data are different datasets such that they cover different locations and seasons and use different size of datapoints. In situ data were restricted in both the overall number of data points, as well as the seasons where most of the data were from late spring and onwards whereas satellite data also cover earlier parts of the year under favourable weather conditions. As a results, model statistics may have a seasonal bias towards the timing of the in situ sampling. Second, satellite data cover only the surface of the water column where in situ chlorophyll *a* were well below the penetration depth of the satellites which might affect the statistics.

Conclusion:

(L629 – 635) We document ECOSMO II(CHL) model performance with objectively analysing the model inorganic nutrients and chlorophyll *a* against available data spanning from climatology to in situ and satellite chlorophyll *a*. We compare three experiments with different parameters representing the original implementation of ECOSMO II, CMEMS Arctic operational ECOSMO II(CHL) for the years 2016 – 2021, and the current (since June 2021) operational ECOSMO II(CHL). Through presenting the model description and its evaluation, we document the performance of ECOSMO for each of these use cases for the users of the model. While each setup perform better for some variables or datasets, the qualitative and quantitative evaluation of the model results of inorganic nutrients, chlorophyll *a* and primary production for each case demonstrated that the model is consistent with the large-scale climatological nutrient variability, and is capable of representing regional and seasonal changes.

The sentences favoring EXP3, which leads to confusion were removed **(L641-644)**.

Line 36: Here I would prefer a more specific link to a model application at copernicus (I had to search around a bit).

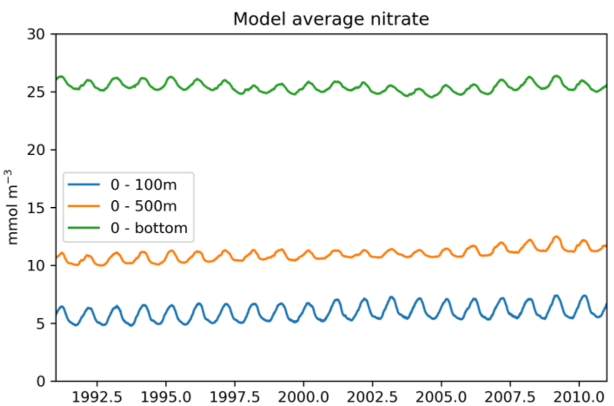
Added doi fort he ARC MFC model. **(L-39)**

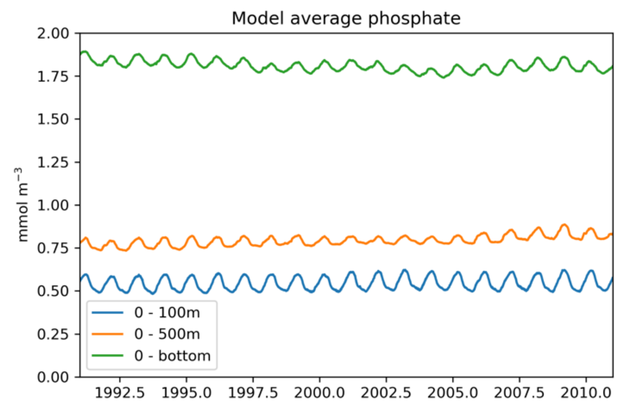
Line 89: 'use the time stepping' – What time step lenghts were applied?

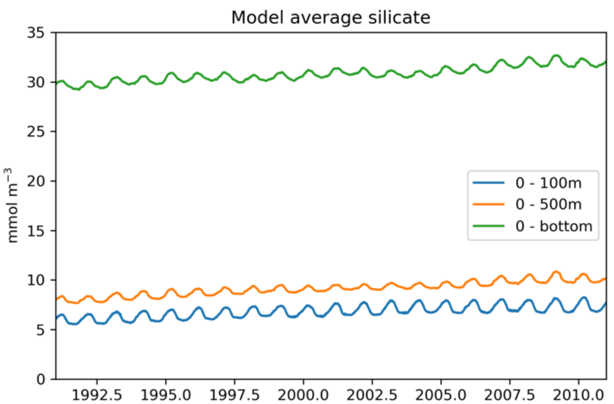
20 minutes. Added to the text. **(L97)**

Line 172: Evaluation after just two years of spinup seems to be quite soon - do you have any indication if the model drift (with regard to the BGC components) has decreased to some specific value?

Below we provide model average (spatial and vertical) evolution of nutrients between 1991 and end of 2010 during which the statistical analyses were performed. Inspecting the first years, the model does not have any abnormal drifts that could be interpreted as a the spinup prior to the analyses were sufficient. We note that, unless the referee or the editor have objections, we will not include the following figures in the manuscript.







Line 201-202: "The dynamics shown in Appendix A1 is expected to be valid for each model point." - How is this expectation justified?

The sentence will be changed with the following:

(L233-234) The dynamics shown in Appendix A1 is representative for regions with similar plankton dynamics (e.g. Norwegian Sea, Barents Sea), thus can be used as a showcase for the new chlorophyll *a* specific addition.

Line 229 "Processed model chlorophyll" - What does "processed" mean in this context?

We were aiming for the meaning 'post-processed', but the sentence is modified to:

(L289-291) We used this dataset for the years 1998-2010. Chlorophyll *a* and kd490 were remapped to the model grid and the model chlorophyll *a* was averaged within 1/kd490 (m) depth.

Figure 3 caption and elsewhere: "WOA18" - above you refer to WOA2013

The text is made consistent throughout and states WOA13 as the model evaluation is performed using the 2013 version. The one exception is the 'temperature' depicted in Figure 2 **(L175)** is WOA 2018. This was a recent addition based on Referee #3's comments.

Line 383-383: "silicate concentrations ... in the climatological data." - are discharge rates into the Arctic very different for different types of nutrients? (I.e., outside the assumed stoichometry)? Perhaps a note on this would be interesting ...

We added:

(L515-519) As the model is relaxed towards the climatology at the Bering Strait through a sponge layer in the model domain, the overall high nutrient concentrations near the Bering Strait and especially the high silicate concentrations at the Siberian coast due to higher Si/N ratio of Pacific origin water masses compared to the Atlantic water masses, and the addition of high Si/N ratio river discharge is reflected in the modelled annual averages.

Lines 443-446: It is not really clear to me what you want to say with this sentence - could it be rephrased?

The original text was:

EXP1 perform a very fast phytoplankton response to light availability during the spring bloom period where light availability is increased resulting in a steep curve where chlorophyll a concentrations are notably higher compared to the observations (results not shown) evident in the high %biases, whereas EXP2 and EXP3 have closer concentrations during spring bloom.

It was rephrased to:

(L572-575) The consistent higher bias of EXP1 compared EXP2 and EXP3 can be explained by its higher photosynthesis efficiency (Table 1). EXP1 show a very fast primary production response to light availability during the spring bloom period with notably higher chlorophyll *a* concentrations compared to the observations (results not shown) evident in the high %biases, whereas chlorophyll *a* concentrations in EXP2 and EXP3 are closer to observed values during spring bloom.

Lines 478-479: "using realistic ... spin-up period" - what are the realistic constant values? and: constant with respect to what - over time? over depth?

We agree that the sentence is misleading. The original text was:

We performed a 27-year run starting in 1990 using realistic constant values for the biogeochemical variables and considered the first 5 years as the spin-up period.

We corrected it with:

(L660-661) We performed a 27-year run starting in 1990 using WOA2013 profiles from January climatology for the biogeochemical variables and considered the first 5 years as the spin-up period.

Response to Reviewer #2:

Referee's comments are provided in 'black italic', and our responses in 'blue'. Our proposed changes to the text appear in 'green'. We reference the manuscript provided below with its line numbers (e.g. L10-L19).

The paper presents a description and evaluation of a new configuration of the biogeochemical model ECOSMO II (ECOSMO II(CHL)) in which they have included chl in the three functional phytoplankton types as prognostic variables. Furthermore, the paper presents a comparison of model experiments using three different parameter sets. In the appendix, the authors have also included a comparison between ECOSMO II and ECOSMO II(CHL) in a configuration where the models are coupled to the 1d physical model GOTM.

The paper is well written and the methodology ambitious. However, I would like to have seen a larger focus on the comparison between ECOSMO II and ECOSMO II(CHL). Furthermore, apart from two sentences (451-453) I find no discussion on why EXP1 seems to perform better

for nitrate and phosphate (Fig 3 and Table 2) than EXP 2 and 3. I find that the paper could be published in GMD after some minor revisions.

Lines 139-144. What limited the concentrations from becoming too small before you added this? Also, you state that: "The minimum concentration at which the loss terms are calculated are...". Should it say: " The minimum concentration at which the loss terms are switched off"?

There was no limit before the addition of the on/off switch, which quickly became a problem for a well-mixed open ocean. Hence we added this modification. It was a necessity for preventing a very late spring bloom, as the biomasses reached almost 0 after every winter. We agree with your suggestion and rephrased the sentence accordingly:

(L166-168) The minimum concentration at which the loss terms are switched off are 0.1, 0.005 and 0.01 mgC m^{-3} for phytoplankton, chlorophyll *a* and zooplankton respectively.

Fig.3: It is not obvious to me that EXP2 and 3 perform better than EXP1. It looks the opposite from this figure.

Referee #1 has also raised similar concerns. We would like to share the same comment here. For exact changes in the text, please refer to the comment we made to Referee #1's comments (3) and (4).

We agree that our review of the model results and discussions on the statistics of different experiments were misleading. Therefore, the text on Section 4.3 was extensively reviewed. Going through the comments and the manuscript, we understand how the text reads to be in favor of EXP3 which was not our intent. We value all the experiments as the parameter sets in these experiments are being actively used, and our intention in this manuscript was to document the model performance for each experiment. For this reason, along with many other revisions in the manuscript, we clearly state the use cases for each experiment in the introduction and the model setup, we reference what each experiment represents (i.e. EXP1 for the original ECOSMO, EXP2 for the operational model prior to July 2021 and EXP3 for the current operational model after July 2021).

To achieve an objective comparison among the experiments, the text regarding the statistics to which the referee refers now include results from all the experiments, not only EXP1, which also corrects the confusion stemming from EXP1 vs EXP3 as stated by the referee, as such each statistical range given in the text covers the min/max of all experiments (EXP1, 2, and 3). We have also noted the EXP1 better performs well in many aspects and each of these are documented in the text for both the statistical analysis and the monthly average comparison to WOA (as we also note in the text that EXP1 averages perform better for nitrate and phosphate) and discuss possible reasons. EXP2 is also included in these new additions.

The contrast between performances among EXP1 and EXP3 with reference to statistical analysis against IMR and satellite data are discussed better.

Line 320: Is it not the net primary production your extracting? You don't explicitly model respiration so what you model is gross primary production (photosynthesis) minus respiration i.e. the net?

We model gross primary production and do not include respiration as a loss term in the equations. Since respiration is not included in the equations, modifying the gross primary production with an arbitrary multiplier to include respiration (e.g. 0.9*GPP) when comparing to observations would add inaccuracy to our results. As the PP observations have a large range, removing 10% PP from the model GPP will still be within the observed PP ranges, thus we settled on providing GPP in the results and noted this in the section with the sentence **(L436-437)** "Because the model does not have an explicit term for respiration, we can only extract gross primary production from the model, which is then compared to observations. "

Lines 388-389: What is the reason for the difference in N/P ratios in the Barents sea between WOA and model, I guess mostly as a result of the difference in nitrate in this area?

The model uses Redfield stoichiometry for production and remineralization in the water column. This strict control on N:P ratios in the organic compartments of the model will restrict dynamical changes in the pelagic N:P ratios. The model's tendency to form a Redfield ratio will be counteracted by the relaxation to open boundary inorganic nutrient conditions of ocean climatology, the river nutrient climatology and the benthic nutrient dynamics.

Fig. A1: It would be interesting to see a plot comparing ECOSMOII and ECOSMOII(CHL) to observations so as to get a clearer view of the benefits of variable C:Chl ratios.

We understand that a visual element is necessary to support the statistics table that was included in the manuscript. For this reason, we added a figure (L698) in the revised manuscript which depicts the data points that were used to calculate the statistics. To distinguish depth layers easily, data points were averaged for each 10 meter depth interval and were depicted with larger markers with color coding for that depth interval.

We added the following text to support the figure:

(L677-685) While both simulations are statistically similar in general, especially in the deeper euphotic zone (40 – 80 m), ECOSMO II(CHL) statistically performs better at 0 - 20 m and 20-40 m range (Table A1) for almost all statistical quantities. The data that was used to calculate the statistics in Table A1 is visualised in Figure A2 using a scatter plot of the modelled and observed chlorophyll *a*, which confirms the values in Table A1 showing a slightly better performance of ECOSMO II(CHL) near the surface (0 - 20 m range). 30 m average point is visually slightly better for ECOSMO II, which probably reflects the better % bias performed for 20 – 40 m range (Table A1). While overall the model performance improves, further modifications to either model parameters or formulation should be done for the future iterations of ECOSMO as below 40 meters, the model has not gained a significant improvement suggesting that the chlorophyll *a* dynamics should be improved for low-light conditions.

Response to Reviewer #3:

Referee's comments are provided in 'black italic', and our responses in 'blue'. Our proposed changes to the text appear in 'green'. We reference the manuscript provided below with its line numbers (e.g. L10-L19).

The manuscript describes and evaluates the coupled HYCOM-biogeochemistry ECOSMO II model, configured for the Arctic Ocean. Its evaluation includes some suggestions for fine- tuning of the parameterization according to the geographical characteristics of the expanded domain. The technical description of the ECOSMO II model is well written and constitutes a good baseline for the modeling community. The evaluation of the model results, against observational values, is also of value for a quantitative validation of the model and it is well complemented by the commentary and the figures therein.

The paper is very well written, but it would benefit, in my opinion, by a better and more organized description of what observations were used in what experiments.

Reviewer #1 has also raised this issue. We would like to share the same comment here. For exact changes in the text, please refer to the comment we made to Referee #1's comments (2).

In summary, WOA13 is used for evaluating monthly and regional averages, whereas the IMR dataset is used to evaluate the model point-by-point collocating model against in situ data points. The extensive data from IMR18 allowed us to perform the statistical analysis whereas WOA13 was used for a visual comparison. OC CCCI data was used for an additional statistical analysis supporting IMR18 data.

The selection of the areas (and experiments) to show and compare seems ad-hoc. What is the justification for these selections?

The subregions were defined based on geographical definitions and environmental characteristics such that Barents Sea area defined in this manuscript cover the shelf area south and east of Svalbard, and following the opening to the west (roughly the line we defined, start the deeper ocean that the Norwegian Sea is located. Norwegian Sea is of high interest for our model development and this region in the manuscript extends 20^{o} of latitudes, and such a long latitude coverage can be significant in relation to the timing of the spring bloom, thus in our analyses we divided the region to north and south from halfway. We appreciate you raising concern for a need for a physical setting of the region and added annual temperature climatology to Figure 2 **(L175)**, and there the reader will see that the Norwegian Sea (N and S) is distinct from the Greenland region where the region borders roughly represent this distinction. Furthermore, the arctic regions (ARC-XXX) were separated from the rest as ARC regions are in general sea-ice covered. You will notice in the figures **(L708 and L715)** that ARC regions are distinctively free of observations, and ARC border separate the observed regions. BERING STR. region is defined to separate it from the rest as it is a nutrient relaxation to WAO13 region and LAPTEV and KARA are naturally divided with the surrounding islands. SPG region is a subregion within the subpolar gyre area. Necessary text for this information is added to the text.

(L248-255) The extent of the subdomains depicted in Figure 2 were defined by the geographical definitions of the regions and their environmental setting as such the BARENTS region covers the shelf area south and east of Svalbard and border NOR. N at the opening to the Norwegian Sea where it is deeper and is highly influenced by the Atlantic inflow. The Norwegian Sea is divided into north and south to take into account for the differences in daylength across the wide latitude range (20^{o}). The border between GREENLAND and NOR. N and S. roughly locates the temperature changes of the different water masses in the region (Fig. 2). ARC regions were set to cover sea-ice covered regions most of the year. BERING STR. Region was set to separate the boundary conditions from the rest of the domain. KARA and LAPTEV regions have naturally defined borders with the islands around them. SPG region is defined to represent the subpolar gyre region.

Why not compare all of the areas in all comparisons and statistics? Seems that it wouldn't add much more content and would be of better use in a comprehensive descriptive assessment of the model for this region at large. Perhaps a way to scope the comparative analysis would be to concentrate on one or two of the subregions of the model domain.

For the statistical analysis, the model comparison to IMR data were restricted by data availability, almost exclusive to the NOR.S, NOR.N and BARENTS regions, which are our main area of interest (Please see the figure that was added after the referees' comments for the location of the observations (Fig. A5; L715)). For this reason, the manuscript regarding statistics against in situ data can only focus on these 3 regions (Table 2, Fig.4).

For the regional and monthly averaged time-series plots (Fig.3; L359), we were less restricted as we have climatology to compare with. However, this should be done with caution, as in certain regions the climatology is based on very few observations. To show this, we added a figure (Fig A3; L708) that depicts the number of observed points for each region. After our inspection on the number of samples, we decided to include the regions of meaningful coverage in Figure 3, NOR.N, NOR.S, BARENTS, GREENLAND, SPG and KARA. We note that KARA is also limited in data outside summer period. BERING STR is not included in the figure as it is too close to the relaxation zone of the model. The text in the manuscript is extensively modified to account for these changes. Note that Figure 3 (L359) was updated after Referee #3's comments to extend the analysis coverage.

The performance comparison for the model would be well prescribed in a table of EXPT vs. AREA with some objectively-derived performance metric value (i.e. rmse/skill score).

As pointed out above, we can only do the statistical analysis for the regions where we have data and these regions were already covered in the text. Statistics (rmse, bias, correlation and standard deviations for nitrate, silicate, phosphate and chlorophyll a) for EXPT and AREA are given in Table 2. We tried to further extend the chlorophyll error statistics with the satellite data but for this region, satellite chlorophyll is hindered by clouds, ice cover and dark seasons. Therefore, we kept the statistical analysis in Table 4 and 5, Figure 9 consistent with the regions in Table 2 and Figure 3. But following the comments from the other referees, the text was extensively modified to include results for EXP1, EXP2 and EXP3 and comment on each of their strengths. Please refer to our comments to Referee #1 items (3) and (4).

In this regard, here are additions to the text:

(L268-272) Regional climatology data should be used with caution because WOA13 data are in some places based on very few observations and that may mislead the evaluation process. To detect the regions with low number of observations, WOA13 data points were extracted for each region and were summed up as monthly time-series (Fig. A3). As an example, the number of data points for the regions defined as ARC (Fig. 2) were almost negligible compared to the Norwegian Sea or the Barents Sea. Further discussion on this is given in Section 4.3.

(L325-330) We note that the number of samples for the monthly climatology vary between months and regions (Fig. A3). Especially for the cases of polar regions and eastern coastal Arctic, the number of data points that were used to construct the monthly climatology were negligible compared to the remaining southern regions (Fig. 2). We have also included KARA region in the discussion here as there are significant number of data points, though limited to only late-summer (months 7 – 11). Even in the case of the Norwegian and the Barents Seas, the number of samples for winter months are significantly lower than the rest of the year.

(L346-358) The Kara Sea is highly influenced by the coastal nutrient discharges as can be seen from the high standard deviations, especially for silicate including the late-summer where we have sufficient data for this analysis. Apart from surface silicate, the model performs generally well for the Kara Sea from month 7 and onwards. In addition to our comments about silicate above, the coastal discharge of nutrients should be improved in future studies, as in this study we used annual climatology for river nutrient discharge.

Experiments were generally comparable when the model results were regionally and monthly averaged (Fig. 3). Notable differences were found for the mid-summer nitrate and phosphate concentrations for the Barents, Norwegian and Greenland Seas, as the drawdown of these nutrients was better resolved by EXP1 compared to climatology as EXP1 summertime nutrients were lower than in EXP2 and 3. A possible reason why EXP1 has larger drawdown of nutrients during mid-summer is the higher photosynthesis efficiency applied in EXP1 resulting in higher uptake of nutrients and higher zooplankton grazing rate applied to EXP2 and 3 resulting in higher top-down pressure to phytoplankton preventing phytoplankton from consuming more nutrients.

This would allow for a good summary of the many combinations of experiments and areas covered. The many regions, very comprehensive, somewhat dilutes the detailed validation of the model itself, only providing a general descriptive validation with some statistical quantification for some of the areas.

We value the necessity of domain wide analysis as you also suggested here and above, and for this reason we originally included domain wide model output (Figs. 5 and 8) with region specific model variable quantities for the readers interest and reference for future studies.

While technically, this is a paper of excellent value, scientifically, it could have been further elaborated to elucidate what the model brings in terms of better understanding of the hydrodynamics and biogeochemistry of the Arctic region. It would also benefit from a more detailed description, via equations, diagrams, and text, of the plankton group dynamics and again, the scientific value of those results.

In summary, the paper is very well written and the technical topic is well covered, but the scientific value of the paper could be improved with more details on the model parameterization, inherent errors therein, and the "take home" message of what is learned scientifically.

As a model description paper, the main focus of this study is to provide the technical changes to ECOSMO, present the final state of the model, and evaluate the model performance using different parameterizations. While doing so, we have long-term model time-series spanning for 2 decades for the Nordic Seas and the Arctic. We included the general biogeochemistry of this region within a technical paper context. We plan for further scientific investigations of this data in future studies. However, considering the referee's comments, we will revised the manuscript towards strengthening its existing scientific messages in the abstract, conclusion and Section 6 has improved scientific emphasis. Specifically:

- Comment on the value added to the model by the including explicit chlorophyll a
- What do different parameter values mean in terms of model performance and internal dynamics.
- Lessons learned with respect to future evolutions of the model

Reviewer #1 also commented on expanding the equations in the manuscript and we followed both the suggestions of Reviewer #1 and #3 and detailed descriptions of phytoplankton growth dynamics were included. Please refer to our answer to Reviewer #1 on the subject.

Specific addditions to the text are:

(L16-21) We document the performance of each parameter set objectively analysing the experiments against in situ, satellite and climatology data. The model evaluations for each experiment demonstrated that the simulations are consistent with the large-scale climatological nutrient setting and are capable of representing regional and seasonal changes. Explicitly resolving chlorophyll *a* allows for more dynamic seasonal and vertical variations in phytoplankton biomass to chlorophyll *a* ratio and improves model chlorophyll *a* performance near the surface. Through experimenting the model performance, we document the general biogeochemisty of the Nordic Seas and the Arctic.

(L572-599) The consistent higher bias of EXP1 compared EXP2 and EXP3 can be explained by its higher photosynthesis efficiency (Table 1). EXP1 show a very fast primary production response to light availability during the spring bloom period with notably higher chlorophyll *a* concentrations compared to the observations (results not shown) evident in the high %biases, whereas chlorophyll *a* concentrations in EXP2 and EXP3 are closer to observed values during spring bloom. Originally, the ECOSMO II parameterization was set for the North Sea and the Baltic Sea with different light conditions. In the open ocean such a high response curve leads to an overestimate of the bloom. However, winter convective mixing is very deep in the Nordic Seas, thus the light is a limiting factor on growth. To overcome deep mixing and prevent a late spring bloom, the phytoplankton were allowed to have very high growth rates for EXP2 and relatively less higher growth parameters were set for EXP3. Statistically and visually (Fig. 9), both EXP2 and EXP3 are very similar, with EXP3 performing statistically slightly better.

The statistical analysis performed against satellite chlorophyll *a* highlights the use of satellite data as an independent dataset for model evaluation, and by its model domain-wide (though limited to surface) coverage, it allows for a more composite evaluation of the model as a whole. Satellite data is acquired in near-real time, thus presents a valuable opportunity for an operational model validation, whereas model validation with in situ data have significant delays (though very valuable for hindcast evaluation). Recent additions to satellite datasets such as the phytoplankton functional types (e.g. https://doi.org/10.48670/moi-00099) further details the use of satellite data for models. As an operational model, ECOSMO II(CHL) works well with satellite data with the inclusion of explicit chlorophyll *a* variables for each phytoplankton functional type (PFT). Not only ECOSMO II(CHL) better resolves surface chlorophyll *a* with its light-dependent dynamic carbon:chlorophyll *a* ratios (cf. Section A1), PFT specific parameters such as initial slope of P-I curves adds further details to model adaptability to varying environmental conditions (Fig. A1d) compared to an average constant ratio common to all PFTs. PFT specific model configurations further synergises with satellite PFT observations in the context of operational biogeochemical modelling. Future iterations of ECOSMO should also include such kind of evaluations. An important addition to explicit chlorophyll *a* variable is the inclusion of the initial slope of P-I curves to light-limitation on growth. In this study, light-limitation was approached in a PFT and chlorophyll *a* independent fashion (Eq. 4). Future versions of ECOSMO should adopt ways (e.g. Evans and Parslow, 1985) to include the PFT specific P-I curve slopes to take full advantage of the explicit chlorophyll a variable. This would allow PFTs to differentiate their niche light conditions for production, and further allow better integration with the bio-optical modelling of the marine environment.

(L645-649) ECOSMO II(CHL) benefits from the use of explicit definition of phytoplankton functional type chlorophyll *a* implementation, i.e. the use of phytoplankton-specific dynamic chlorophyll *a*-to-carbon ratios in reference to a fixed ratio in the original model, with improved surface estimations of chlorophyll *a*, and gains added value towards improving model evaluation opportunities using satellite observations and phytoplankton functional type specific additions to model structure.

ECOSMO II(CHL): a marine biogeochemical model for the North Atlantic and the Arctic

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Abstract. ECOSMO II is a fully coupled bio-physical model of 3d-hydrodynamics with an intermediate complexity N(utrient) P(hytoplankton) Z(ooplankton) D(etritus) type biology including sediment-water column exchange processes originally formulated for the North Sea and Baltic Sea. Here we present an updated version of the model incorporating chlorophyll *a* as a prognostic state variable: ECOSMO II(CHL). The version presented here is online coupled to the HYCOM ocean model. The model is intended to be used for regional configurations for the North Atlantic and the Arctic incorporating coarse to high spatial resolutions for hind-casting and operational purposes. We provide the full descriptions of the changes in ECOSMO II(CHL) from ECOSMO II and provide the evaluation for the inorganic nutrients and chlorophyll *a* variables, present the ~~modeled~~modelled biogeochemistry of the Nordic Seas and the Artic and experiment~~s~~ on various parameterization sets as use cases targeting chlorophyll *a* dynamics. We document the performance of each parameter set objectively analysing the experiments against in situ, satellite and climatology data. The model evaluation~~s~~s for each experiment demonstrated that the simulations are consistent with the large-scale climatological nutrient ~~settings, and~~setting and are capable of representing regional and seasonal changes. Explicitly resolving chlorophyll *a* allows for more dynamic seasonal and vertical variations in phytoplankton biomass to chlorophyll *a* ratio and improves model chlorophyll *a* performance near the surface. Through experimenting the model performance, we document the general biogeochemisty of the Nordic Seas and the Arctic. The Norwegian and Barents Seas primary production show distinct seasonal patterns with a pronounced spring bloom dominated by diatoms and low biomass during winter months. The Norwegian Sea annual primary production is around double that of the Barents Sea while also having an earlier spring bloom~~.~~ . ~~The parameterization experiments showed that the representation of open ocean chlorophyll a benefits from using higher phytoplankton growth and zooplankton grazing rates with less photosynthesis efficiency compared to the original implementation of ECOSMO II, which was valid for the North Sea and the Baltic Sea representing coastal domains. Thus, for open ocean modeling studies, we suggest the use of the parameterization sets presented in this study.~~

1 Introduction

Operational ocean forecasting and reanalysis systems that integrate in situ measurements, remote sensing observations, modelling and data-assimilation are fundamental tools for understanding the variability and dynamics of the physical and biogeochemical ocean state. Such systems are also essential for a better and more sustainable management of the oceans and marine ecosystems, supporting the development and understanding of human activities and the blue economy (von Schuckmann et al., 2016). In this context, the presentation of the underlying science, continuous evaluation and development of the forecast systems are required to provide the best possible forecast and reanalysis.

The presented model version, ECOSMO II(CHL), is adapted from the biogeochemical model ECOSMO (Schrum et al., 2006~~; S2006~~), later ECOSMO II (Daewel and Schrum, 2013; DS2013), and is currently used as the marine biogeochemical model for operational forecasts (https://doi.org/10.48670/moi-00003) of the Arctic Ocean (ARC MFC – Arctic Marine Forecasting Centre) under the umbrella of CMEMS (The European Copernicus Marine Environment Monitoring Service; marine.copernicus.eu). The biogeochemical forecast ECOSMO II(CHL) has been operational since April 2017 and the daily values of the selected variables can be retrieved from the CMEMS database. While based on the ECOSMO II version presented in DS2013, the transfer of the model to a different circulation model, region, and model resolution necessitated an adjustment of model parameterizations and additional functionalities, which in turn required a series of new sensitivity tests.

ECOSMO II is an intermediate complexity nutrient-phytoplankton-zooplankton-detritus (NPZD) type model describing the trophic interactions between three phytoplankton and two zooplankton components. It was shown to successfully simulate the seasonal and inter-annual ecosystem variability of primary and secondary production in the North- and Baltic Sea (Daewel and Schrum, 2013). In the framework of the ARC MFC forecasting system which covers the northern part of the Atlantic Ocean and the Arctic, its application and scientific scope was shifted to be used for the open ocean and sea-ice covered domains. Furthermore, when moving from one circulation model to another, biogeochemical models will behave differently as a result of differences in the physical model (Skogen and Moll, 2005). Both these changes require adjustments to the model formulation and parameters to give good result in the focus regions. ECOSMO II(CHL) most notably introduces chlorophyll *a* as a prognostic variable. Allowing ~~for~~ a flexible chlorophyll-to-carbon ratio is more realistic and has been shown to be more stable when chlorophyll is assimilated (Ciavatta et al., 2011). This addition allows the direct assimilation of ocean color observations into the forecasting and reanalysis systems. The description of the model changes, added components and the evaluation of the ECOSMO II(CHL) results within the North Atlantic and Arctic form the main content of this paper.

The North Atlantic above 60°N, the focus in this paper, is a typical spring-bloom system (Longhurst, 1998; Rey, 2004). During winter, strong winds and cooling mix the water column several hundred meters and brings up nutrients-rich waters (Nilsen and Falck, 2006). Once the water column stratifies enough for the bloom to start, the diatoms dominate the system. When silicate is depleted, the smaller flagellates and dinoflagellates dominate the phytoplankton community (Rey, 2004). Sporadically there are also extensive coccolithophores blooms covering large areas (Baumann et al., 2000). The main species of mesozooplankton in this area, *Calanus finmarchicus*, overwinters at depth (Melle et al., 2004) and ascend to the surface at the onset of spring, therefore there is already some zooplankton biomass present at the time of the start of the spring~~. and ascend to the surface at the onset of spring~~. There is also a fall bloom present as seen from satellite observations. The areas closer to the Arctic, being covered by sea ice, have different dynamics. In sea ice covered regions, small blooms can occur in leads and under thin ice but the main bloom commences as the ice retracts (Dalpadado et al., 2020; Dong et al., 2020; Polyakov et al., 2020). Here, sea ice algae will make up some of the primary production (Gradinger, 2009) and other mesozooplankton, such as *Calanus* g~~G~~*lacialis*, specialized to the sea ice environment (Melle and Skjoldal, 1998), are also important. Close to sea ice and in coastal regions, early stratification can occur when sea or land ice melts resulting in a seasonal halocline. Water masses in the eastern part of the basin are relatively warm, saline water characterizing the North Atlantic Current (Orvik et al., 2001), while ~~in~~ the western part of the basin has colder and fresher water masses with an Arctic or mixed origin (Fröb et al., 2018 Yashayaev et al., 2007).

Our main objective with this paper is to provide the description~~s~~ of the latest updates in ECOSMO II(CHL) and its coupling to HYCOM. We will particularly focus on the description of the prognostic chlorophyll *a* formulation. ~~We aim to justify the use of the model formulation and the parameterization set as a model tool for open ocean simulations for various cases.~~ We present the results from three experiments ~~from~~using ECOSMO II(CHL) ~~with~~adopting ~~the~~different parameter sets ~~that was adopted~~ from DS2013 (the original parameter set tuned for the North and Baltic Seas), CMEMS Artic operational model prior to June 2021 and the current Arctic operational model parameterization. ~~as the reference simulation. However, as the North Atlantic and Artic Oceans have different physical and biogeochemical dynamics compared to the North and Baltic Seas (e.g. light availability, deep mixing), the current operational model in the Arctic and the next phase operational model which will replace the current one in mid 2021 use different parameter sets.~~ We applied these 3 parameter sets on a model setup with a coarser grid than used for the operational simulations in order to allow for 2-decade long simulations for each case. To document the performance of each of these parameter sets for the users of ECOSMO, ~~W~~we ~~compare these cases and~~ present a detailed objective analysis of ~~the evaluation of t~~the lower trophic level dynamics for the North Atlantic and the Arctic Ocean against local in situ observations, gridded climatology of nutrients and satellite data in Sect. 4. ~~-~~Following the evaluation we provide information on integrated quantities, such as annual primary production, inter-annual variability in phytoplankton production and seasonal succession of plankton functional types as a reference for the Nordic Seas and the Arctic. We will finalize by commenting on the future updates and implementations of ECOSMO II(CHL).

2 The HYCOM-ECOSMO II(CHL) model

HYCOM-ECOSMO II(CHL) is a coupled physical-biological model (Fig. 1) where ocean physics are represented by the Hybrid Coordinate Ocean Model (HYCOM: Bleck, 2002) and the lower trophic marine biogeochemistry is resolved by ECOSMO II (Daewel and Schrum, 2013). The models are coupled online and the transport (advection and mixing) of biological state variables is handled as part of HYCOM's own native tracer-transport routines, thus both the physical and biological components use the same time stepping (20 minutes). The model is one-way coupled and biology does not affect model physics. HYCOM, as a hybrid vertical coordinate model, can optionally combine the depth-level (z-level), topography following and density-following (isopycnal) coordinates. In this study, we set vertical levels as the combination of z-level for the upper ocean and the mixed layer and isopycnal layers below. The upper 5 layers are always kept in z-levels ensuring a minimum vertical resolution which is important to resolve the light gradient in the upper ocean and thus representing the vertical variation in phytoplankton growth in a realistic manner. Isopycnal layers in the deep facilitates a good conservation of water-masses and tracer distributions.

ECOSMO II(CHL) is an intermediate-complexity lower trophic level biogeochemical model which distinguishes four inorganic nutrients (nitrate, ammonium, phosphate and silicate) utilized by three types of phytoplankton (diatoms, flagellates and cyanobacteria). In this study, cyanobacteria are turned off, as they were parameterized to grow below a certain salinity threshold which was intended to represent the cyanobacteria in the Baltic Sea (Daewel and Schrum, 2013). Our area of concern is the high latitudes, specifically the area north of 60ºN, thus the use of cyanobacteria falls short as a significant phytoplankton community for the region. Two types of zooplankton (micro- and meso-size classes) are parameterized based on their feeding preferences as herbivorous and omnivorous zooplankton and, as additional organic components~~matters~~, dissolved (DOM) and particulate (detritus) organic matter are included in the model. The model uses the molar Redfield ratio between C:N:Si:P components (106 : 6.625 : 6.625 : 1), and ~~discrete~~ nutrients are tracked both in the water column and in the ~~a~~ single sediment layer.

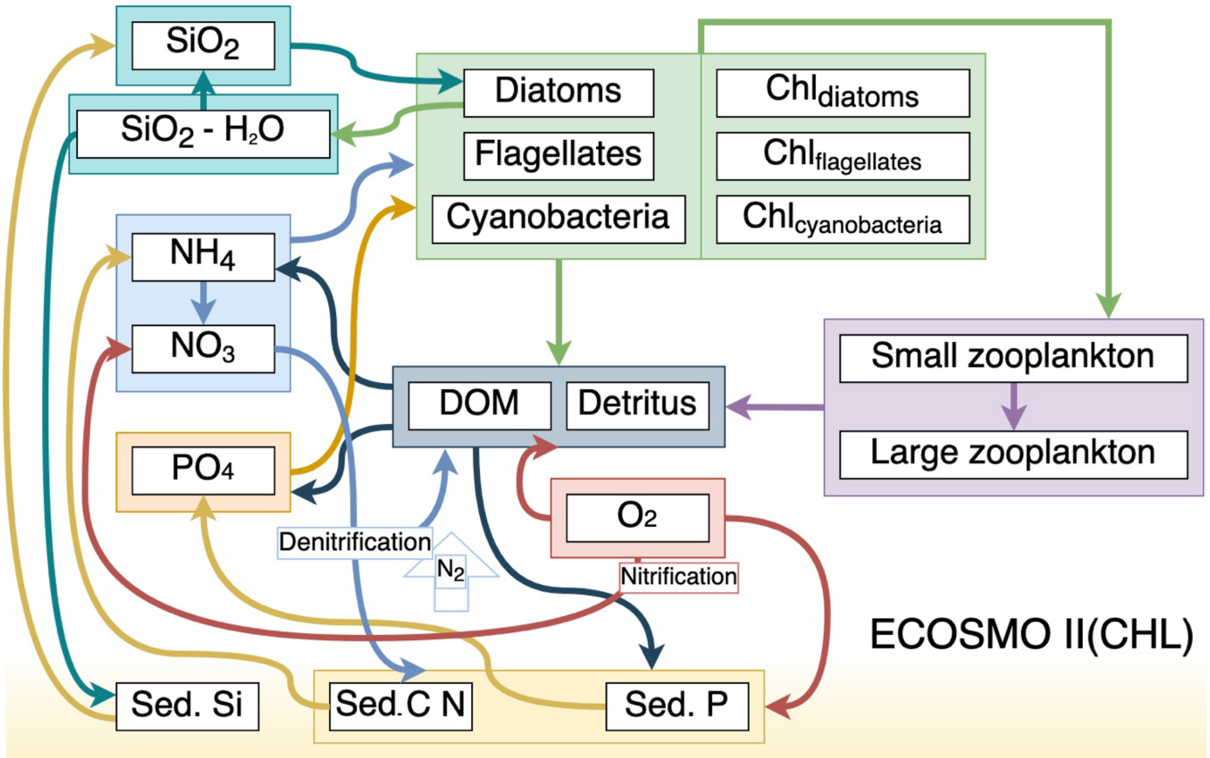


Fig. 1: Schematic diagram of biochemical interactions in ECOSMO II. (DOM: dissolved organic matter; Chl- prefixes stand for phytoplankton type specific chlorophyll *a* content; Sed. denote sediment pool with silicate, phosphorus and nitrate content.)

The full description of ECOSMO II is given in Daewel and Schrum (2013) (DS2013). In the following we provide a description of differences in the biogeochemical formulations in ECOSMO II(CHL) compared to DS2013. The most notable addition ~~on~~to DS2013 is the prognostic chlorophyll *a* for each phytoplankton type. The biological interaction (R_{chl_j}) term of the introduced chlorophyll *a* for P_1 and P_2 (diatoms and flagellates respectively) is in similar fashion to that of R_{P_j} in DS2013, ~~as such~~and the source terms are modified by the photoacclimation factor (ρ_{chl_j}) which accounts for the variation in chlorophyll-to-biomass ratio resulting in increased chlorophyll production under low light conditions (Geider et al., 1997), hence:

$$R_{chl_j} = \rho_{chl_j}\sigma_j\phi_{P_j}C_{P_j} - \sum_{i=1}^{2} G_i(P_j)C_{Z_i}\frac{Chl_{P_j}}{C_{P_j}} - m_{P_j}Chl_{P_j} \quad (2)$$

where,

$$\rho_{chl_j} = \frac{\theta_P^{max}\phi_{P_j}C_{P_j}}{\alpha_{P_j} I(x,y,z,t)\, \text{~~PAR~~}\, Chl} \quad (3)$$

$$\phi_{P_j} = \min\left(\alpha(I), \beta_N, \beta_P, \beta_{Si}\right) \quad (3)$$

$$\alpha(I) = \tanh\left(\varphi I(x,y,z,t)\right) \text{~~tanh~~} \quad (4)$$

$$\beta_N = \beta_{NH_4} + \beta_{NO_3} \quad (5)$$

$$\beta_{NH_4} = NH_4/(NH_4 + r_{NH_4}) \quad (6)$$

$$\beta_{NO_3} = (NO_3/(NO_3 + r_{NO_3}))\exp(-\gamma NH_4) \quad (7)$$

$$\beta_{PO_4} = PO_4/(PO_4 + r_{PO_4}) \quad (8)$$

$$\beta_{Si} = Si/(Si + r_{Si}) \quad (9)$$

$$G_i(P_j) = \sigma_{i,P_j}\frac{a_{i,P_j}C_{P_j}}{r_i + F_i} \quad (~~3~~10)$$

$$F_i = \sum_{j=1}^{2} a_{i,P_j}C_{P_j} \text{ ~~}\sum a_{i,P_j}C_{P_j}\text{~~} \quad (~~4~~11)$$

with j = 1,2 denote the specific phytoplankton types and i = 1,2 the specific zooplankton types. C denote carbon concentration specific to P (phytoplankton) and Z (zooplankton) in mg m^{-3}, while Chl denote chlorophyll *a* concentration in mg m^{-3}. Photosynthetically active radiation (PAR) is given as I(x,y,z,t). DS2013 give σ_j, ϕ_{P_j}, φ, $r_{NH_4,NO_3,PO_4,Si}$, γ, G_i and m_{P_j} as the phytoplankton maximum growth rate, growth limitation, photosynthesis efficiency parameter, nutrient-specific half saturation constant, NH_4 inhibition parameter, zooplankton grazing rates and mortality rates respectively. σ_{i,P_j} denotes zooplankton specific grazing rate with a_{i,P_j} and r_i representing food preference coefficient and half saturation constant respectively where F_i denote the total available food for the individual zooplankton. Silicate is not included in flagellate equations. Maximum Chl-to-C ratio (θ_P^{max}) is taken from Bagniewski et al. (2011), where they have tuned those parameters for the region south of Iceland. We note that their parameterization is N-based, while ECOSMO II(CHL) uses C-based parameters, thus we applied the conversion following the C:N Redfield ratio of 6.625 resulting in flagellates and diatoms to have 0.048 and 0.037 mgChl mgC^{-1} respectively. In relation to the addition of a prognostic chlorophyll *a* state variable, photosynthetically active radiation I(x,y,z,t) at depth undergoing attenuation was modified to have chlorophyll *a* in the exponential term:

$$I(x,y,z,t) = \sout{I_s(x,y)}\, \frac{I_s(x,y)}{2}\, exp\left(-k_w z - k_{Chl} \int_z^0 \sum_{j=1}^{2} Chl_{P_j} \partial z\right) \qquad (\sout{5}12)$$

where $I_s(x,y)$ is the surface net solar radiation (W m^{-2}) converted to PAR, and x, y identifies the models horizontal grid points, with z the water depth in meters. k_w and k_{Chl} are light extinction due to water (m^{-1}) and chlorophyll *a* concentration (m^2 $mgChl^{-1}$) respectively.

In addition to prognostic chlorophyll *a* state variables, phytoplankton and zooplankton loss terms now have an on/off switch regulated by a minimum concentration criterion preventing them from decreasing to very low concentrations. This allows them to recover and quickly respond to suitable growth conditions experienced in spring. The switch is applied to mortality and grazing terms for phytoplankton and chlorophyll *a*, and to mortality terms for zooplankton. The minimum concentration at which the loss terms are ~~calculated~~ switched off are 0.1, 0.005 and 0.01 mgC m^{-3} for phytoplankton, chlorophyll *a* and zooplankton respectively.

3 Model setup and evaluation framework

Model simulations are configured on a relatively coarse grid that varies between 30 and 70 km where the highest resolutions are located in the mid-North Atlantic (Fig. 2). Although, having finer resolution was previously shown to better represent nutrient dynamics for our domain (Samuelsen et al., 2015), the main purpose of our study is to introduce the required model structure for the North Atlantic/Arctic region and the experiments, which requires numerous tests and simulations in parallel. Therefore, we concluded that having a relatively coarse grid size fits better for our purposes.

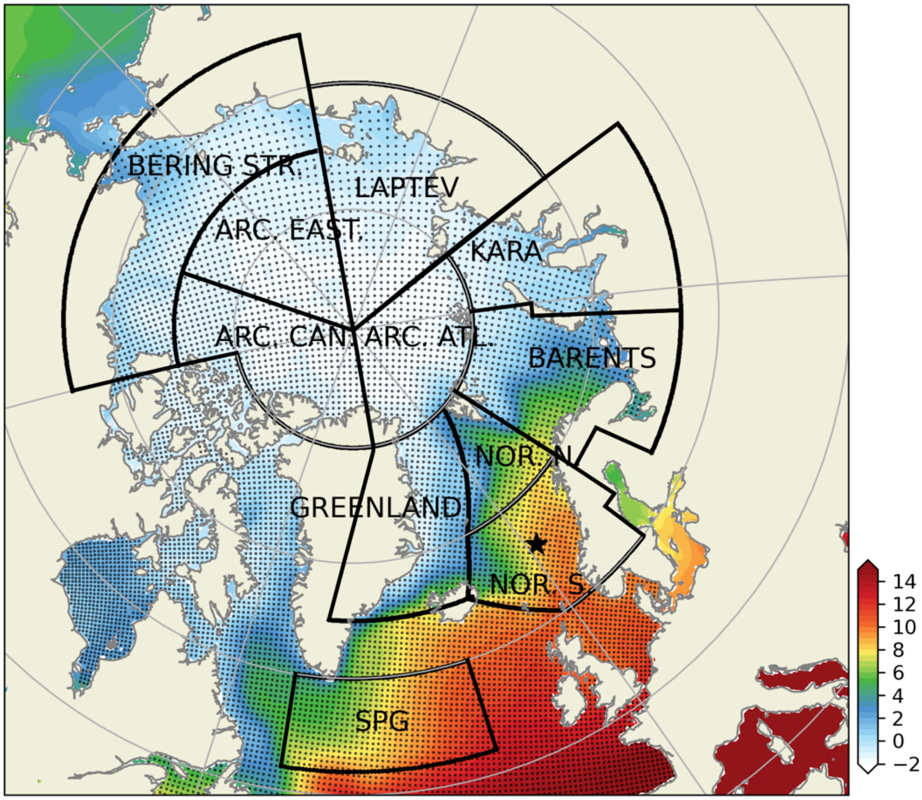


Fig. 2: Subdivision of model domain in prescribed geographical subdomains used for model quality assessments. The subdomains are as follows: Norwegian Sea South (NOR. S.), Norwegian Sea North (NOR. N.), Barents Sea (BARENTS), Kara Sea (KARA), Laptev Sea (LAPTEV), Bering Straitea (BERING STR.), Arctic-Canada (ARC. CAN.), Arctic-East (ARC. EAST), Arctic-Atlantic (ARC. ATL.), Greenland Sea (GREENLAND) and the Subpolar Gyre (SPG). The black points in the oceanic regions denote the model grid coordinates. The coordinates for the Station-M time-series station location is depicted with the star. While the model domain extends down to the equatorial regions, the figure focuses on the area of interest. Note that the BERING STR. subdomain is within the effective area of the open boundary conditions thus is relaxed to climatology. WOA18 1981 – 2010 annual surface temperature climatology (Boyer *et al.*, 2018) is depicted with the coloured shades.

Data for atmospheric forcing is retrieved from ECMWF ERA-Interim reanalysis with 6-hour resolution (Dee et al., 2011). The variables used to force the ocean model are 10m winds, air temperature at 2 meters, dew-point temperature at 2 meters, cloud coverage and total precipitation for the physical model and surface net solar radiation for the biogeochemical model. River runoff is modelled using a hydrological model, TRIP (Oki et al., 2009), resulting in a monthly climatology dataset, so the river runoff does not include any interannual variability. River runoff affects only salinity. Nutrient loads from the rivers are derived from the modelled dataset, GlobalNEWS (Mayorga et al., 2010; Seitzinger et al., 2010), which include nitrate, phosphate and silicate. Nutrient loads were scaled by the TRIP runoff volume resulting in monthly climatology loads.

The model physics was initialized in 1989 from a spin-up simulation that started in 1948 forced by the ECHAM6 atmospheric simulation (Schubert-Frisius and Feser, 2015). The biogeochemical model used inorganic nutrients (nitrate, phosphate and silicate) from the World Ocean Atlas 2013 (Garcia et al., 2013) monthly climatology as the initial conditions; the biomass concentrations were initialized with uniform, low values. The same climatology was used for the relaxation of temperature, salinity, nitrate, silicate, phosphate and oxygen at the open boundaries. The simulation was conducted until the end of 2010. The results are evaluated starting with the year 1991.

Table 1: Parameters that were modified between different experiments

	Model experiments		
	EXP1	EXP2	EXP3
Diatom maximum growth rate (σ_{P_1}) (1 day^{-1})	1.3	1.95	1.75
Flagellate maximum growth rate (σ_{P_2}) (1 day^{-1})	1.1	1.65	1.45
Photosynthesis efficiency (φ ~~$\propto$~~) (m^2 W^{-1})	0.03	0.01	0.012
Mesozooplankton grazing rate on phytoplankton ($\sigma_{i,P_j,}$) (1 day^{-1})	0.8	1.2	1.2
Mesozooplankton grazing rate on microzooplankton ($\sigma_{i,Z_{micro},}$) (1 day^{-1})	0.5	0.75	0.75
Microzooplankton grazing rate on phytoplankton ($\sigma_{i,P_j,}$) (1 day^{-1})	1.0	1.5	1.5

In this study, we employ 3 set of simulations (EXP1, EXP2 and EXP3) that use different phytoplankton growth rates, photosynthesis efficiency, and zooplankton mortality rates (Table 1). EXP1 uses the DS2013 parameter set which was used for ~~shallow and coastal seas such as~~ the North Sea and the Baltic Sea. Additionally, ~~For the open ocean, which is the focus of this study, w~~we introduce EXP2 (uses the parameter set for the operational forecast model for ARC MFC prior to July 2021) and EXP3 (uses the parameter set for the ~~next phase~~ operational forecast model for ARC MFC currently online following July 2021~~currently in development~~). Since these parameter sets represent active use cases, the objective analysis of these experiments in the following sections provide the users of ECOSMO a reference on how the model performs with different setups and longer time-scales. For the purpose of comparing these parameters, EXP2 and EXP3 can be considered as part of the same group against EXP1 such that in both EXP2 and EXP3, phytoplankton growth rates are set higher compared to EXP1. Th~~is~~e reasoning behind this increase is a response to deep winter convective mixing and resulting light limitation on growth in the open ocean. ~~Using lower growth rates (e.g. EXP1) result in a late response to light availability and recovering from high mixing in winter and delayed spring blooms. With higher growth rates, model spring bloom timing improves. However, later in summer these higher growth rates results in too much growth as the water column stabilizes.~~ To control excessive growth of phytoplankton in the following seasons, zooplankton grazing rates were increased. ECOSMO II has been used as an operational model for the Arctic since 2017 and its parameterization has been tested and improved various times, more than we can document here. Thus the parameter~~ization~~ sets for EXP2 ~~(current operational model)~~ and EXP3 ~~(next-generation~~

~~operational model)~~ are provided here as milestones for ECOSMO II development. ~~During the continuous development of HYCOM-ECOSMO II(CHL), the parameter set for EXP3 performed better in our prior analyses and will replace the parameterization set in EXP2.~~ To document the development process of the ECOSMO, we present all the experiments representing DS2013 (EXP1), operational model prior to July 2021 (EXP2) and next-phase operational model (EXP3). ~~The different parameters used in these simulations are given in Table 1. EXP1 is defined as the reference simulation and unless stated otherwise, results and discussions in the following sections refer to EXP1.~~ The model evaluation is followed by an overview of the notable aspects of the simulated biogeochemistry of the North Atlantic and the Arctic Oceans.

In addition to the 3D-HYCOM-ECOSMO II(CHL) simulations, we have also performed a 1D simulation using General Ocean Turbulence Model (GOTM; Burchard et al., 2006) using Framework for Aquatic Biogeochemical Models (FABM; Bruggeman and Bolding, 2014) as the online coupler ~~GOTM-ECOSMO simulation~~ at Station-M (66ºN 2ºE) in the Norwegian Sea to present the differences of ECOSMO II and ECOSMO II(CHL) both visually and statistically comparing with and without explicit chlorophyll *a* versions of ECOSMO. ~~This version of the model employs GOTM (General Ocean Turbulence Model; Burchard et al., 2006).~~ The details of this setup is provided in Appendix A1. Station-M ~~is~~is a long-term time-series station and is representative of the Norwegian Sea dynamics and data from Station-M is often used for the development of ECOSMO. The dynamics shown in Appendix A1 is ~~expected~~representative ~~to be valid~~ for regions with similar plankton dynamics (e.g. Norwegian Sea, Barents Sea)~~each model point~~, thus can be used as a showcase for the new chlorophyll *a* specific addition. Apart from the improvement of model chlorophyll *a* results, the addition of dynamic chlorophyll *a* establishes a higher level of functionality of ECOSMO such that phytoplankton functional types now have their unique carbon:chlorophyll *a* ratios, initial slope of P-I curves which enables better adaptability to different environments, and the model now has better integration with observation systems (e.g. remote sensing) and future improvements toward bio-optical modelling.

4 Model evaluation

In this section, we present a selection of model results to provide an overview of the performance of ECOSMO II(CHL). While the model domain extends to the equatorial regions, our focus is on the Nordic Seas and the Arctic. We present the evaluation of the observable model output against in situ data with the relevant statistics. The focus of this assessment is on the key parameters of the chemical and biological fields on a regional scale where the subdomains defined for model assessment ~~is~~are given in Fig. 2. This approach allows for assessment of the local biogeochemical characteristics of the model. The purpose of this assessment is twofold: (1) to assess the model formulation and its parameterization as a regional hindcasting and forecasting tool, as a component of CMEMS and (2) to introduce the model~~'s use~~ as a tool for scientific studies.

The extent of the subdomains depicted in Figure 2 were defined by the geographical definitions of the regions and their environmental setting as such the BARENTS region covers the shelf area south and east of Svalbard and border NOR. N at the opening to the Norwegian Sea where it is deeper and is highly influenced by the Atlantic inflow. The Norwegian Sea is divided to thinto e north and south to take into account for the differences in daylength across the wide latitude range (20º). The border between GREENLAND and NOR. N and S. roughly locates the temperature changes of the different water masses in the region (Fig. 2). ARC regions were set to cover sea-ice covered regions most of the year. BERING STR. Region was set to separate the boundary conditions from the rest of the domain. KARA and LAPTEV regions have naturally defined borders with the islands around them. SPG region is defined to represent the subpolar gyre region.

4.1 Observations

The model simulations were evaluated using three different datasets as follows: (1) World Ocean Atlas 2013 (WOA13; Garcia et al., 2013), (2) Institute of Marine Research (2018) data (IMR18), (3) ESA Ocean Colour CCI v5.0 (OC CCI; Ocean Colour Climate Change Initiative; Sathyendranath et al., 2019).

The model's consistency with the large-scale climatological inorganic nutrient distributions was quantified by comparing the regionally averaged Mmonthly inorganic nutrient model data (nitrate, silicate and phosphate) to WOA13 data from World Ocean Atlas 2013 (WOA13; Garcia et al., 2013) were used to quantify the model's consistency with the large-scale climatological nutrient distributions. The WOA13 data were horizontally averaged in the model subdomains presented in Fig. 2. Modelled inorganic nutrients were vertically interpolated to 5 and 100 meters matching the WOA13 depth levels, spatially averaged within the subdomains and monthly averaged in time to construct corresponding regional time-series (cf. Section 4.3; Fig. 3). These monthly time-series allowed a model evaluation for the regions that , in which the in situin -situ data was not optimal for the statistical analysis. Regional climatology data should be used with caution because WOA13 data are in some places based on may include very few observations and that may mislead the evaluation process. To detect the regions with low number of observations, WOA13 data points were extracted for each region and were summed up as monthly time-series (Fig. A3). As an example, the number of data points for the regions where we definedefined as ARC (Fig. 2) were almost negligible compared to the Norwegian Sea or the Barents Sea. Further discussion on this is given in Section 4.3.

A separate evaluation for the model inorganic nutrients (nitrate, silicate and phosphate) and chlorophyll *a* was conducted using the IMR18 in situ data While WOA18 data was used to evaluate model monthly averages, model Nnitrate, silicate, phosphate and chlorophyll a was compared by performing a point-by-point (location and depth) to in situ data from Institute of Marine Research (2018)co-locationomparison were used for the statistical evaluation of the model resultsanalysis (cf. Section 4.3; Table 2). For each in situ data point, the closest model grid was selected and the vertical profile was interpolated to the observed depth. Data with only 'good' flags were used totalling to more than 120000 data points for each nutrient and chlorophyll *a*. While the size of the observed dataset is unique, the regional coverage is limited to mainly the Norwegian Sea and the Barents Sea (Fig. A5). For this reason, the analysis using WOA13 and IMR18 complement each other well with one covering wider regions and the other providing a large dataset respectively.

Very few direct observations of primary production are available in our focus region. We have therefore used reported values from the literature for evaluating the estimated magnitude of primary production (cf. Sect. 5 for the references). A final model chlorophyll evaluation was conducted using OC CCI ESA Ocean Colour CCI v5.0 (Ocean Colour Climate Change Initiative; Sathyendranath et al., 2019) daily surface chlorophyll *a* and downwelling attenuation coefficient at 490 nm (kd490) at 4km x 4km spatial resolution were used for evaluation of simulated chlorophyll a. This dataset is derived from multiple sensors: SeaWIFS, MODIS Aqua, MERIS, SeaWIFS LAC and VIIR. We used this dataset for the years 1998-2010. Chlorophyll *a* and kd490 were remapped to the model grid and the model chlorophyll *a* was processed by averaginged within thetowithin 1/kd490 (m) depth. In the cases that kd490 data were missing, 1/kd490 valuethe model chlorophyll *a* was set toaveraged within 10 meters. Processed mModel chlorophyll *a* was then statistically analyzedanalysed using the OC- CCI chlorophyll *a*, and from this point on, OC -CCI chlorophyll *a* is referred to as the satellite chlorophyll *a*. Satellite and model data covering the ocean topography shallower than 100 meters were masked out. This separate analysis allows us to include chlorophyll *a* data for model evaluation in addition to IMR18 data. We should note that, for the North Atlantic and the Arctic, satellite data was oftenhighly hindered by cloud, sea-ice coverage and winter darkness seasons.

The analyses described above were appliedperformed to all of the experiments, EXP1, 2 and 3. Very few direct observations of primary production are available in our focus region. We have therefore used reported values from the literature for evaluating the estimated magnitude of primary production (cf. Sect. 5 for the references).

4.2 Statistical methods

We used the Institute of Marine Research (2018) dataset for inorganic nutrients and chlorophyll *a* to construct the statistical analyses. The statistical analyses cover 1991-2010 period and only the quality-controlled data were considered. For each in situ data point, the date and the corresponding horizontal model coordinate were identified and modeledmodelled nutrient and chlorophyll *a* were vertically interpolated to the depth of the in situ data point-. We computed percent bias (% bias), root mean square error (rmse), correlation (corr) and normalized standard deviations (nstd) for the co-located data:

$$\%\,bias = \left(\sum(M - O) * 100\right) / \sum O \qquad (613)$$

$$rmse = \sqrt{\sum(M - O)^2 / N} \qquad (714)$$

$$corr = \left(\sum_{i=1}^{N}(M_i - \bar{M})(O_i - \bar{O}) \sum(M_i - \bar{M})(O_i - \bar{O})\right) / \left(\sqrt{\sum_{i=1}^{N}(M_i - \bar{M})^2 \sum_{i=1}^{N}(O_i - \bar{O})^2 \sum(M_i - \bar{M})^2 \sum(O_i - \bar{O})^2}\right) \qquad (815)$$

$$nstd = \left(\sqrt{\left(\sum_{i=1}^{N}(M_i - \bar{M})^2 \sum(M_i - \bar{M})^2\right)/N}\right) / \left(\sqrt{\sum_{i=1}^{N}(O_i - \bar{O})^2 \left(\sum(O_i - \bar{O})^2\right)/N}\right) \qquad (916)$$

where M = estimated, O = observed, N = number of data points and ii the individual sample. These statistics were applied to the whole simulated period but are specific to each subdomain for regional evaluations.

4.3 Evaluation of the reference simulation (EXP1) against in situ datamodel experiments

In this section, we analyse the model performance against climatology and in situ data using visual and statistical analysis. We include each experiment in the analysis as a reference for modelling studies that adopt ECOSMO II(CHL) and showcase the possible outcomes using various parameterization sets.

FFig. 3 ig. 3 and 4 depictsshow ECOSMO II(CHL)'s performance in representing the upper 100 m concentrations of the macronutrients nitrate, silicate and phosphate against monthly climatology and co-located in situ data respectively. In the case ofFor these climatological comparisons using WOA138 data, model and observed time series are represented at the surface (5 m) and at 100 m. We Nnote that the number of samples for the monthly climatology vary between months and regions (Fig. A3). Especially for the cases of polar regions and eastern coastal Arctic, the number of data points that were used to construct the monthly climatology were negligible compared to the remaining southern regions (Fig. 2). We have also included KARA region in the discussion here as there are significant number of data points, though limited to only late-summer (months 7 – 11). Even in the case of the Norwegian and the Barents Seas, herethe number of samples for winter months are significantly lower than the rest of the year.

The model is generally in good agreement with the seasonality in climatology representing the high concentrations in winter and the drawdown of nutrients in summer, but with noticeably higher winter nutrients in the Barents Sea both at the surface and at 100 m. Note that the number of samples for the monthly climatology vary between months and regions (Fig. A2) here number of samples for winter months are significantly lower than the rest of the year. The modeledmodelled Norwegian Sea silicate concentrations are notably higher in winter at the surface and throughout the year at 100 m. Considering the consistent agreement of ~~modeled~~modelled and observed nitrate and phosphate for the Norwegian Sea, Greenland Sea, late-summer Kara Sea and the subpolar gyre region, the simulated high silicate suggests that further tuning may be required for silicate uptake by diatoms, diatom and opal silicate sinking rates or the remineralization rates of opal. The adopted 1:1 ratio of nitrate to silicate cellular structure of phytoplankton may not be as applicable for the region. We note that although on average ~~modeled~~modelled silicate is higher than observed, occasionally diatom productivity (silicate uptake) was limited by the model formulation ~~by~~as silicate ~~as~~ values approached 1 mmol m^{-3}~~L^{-1} (Fig. 4c and d)~~ (Fig. 3).~~.~~ The standard deviations of both the observed and ~~modeled~~modelled nutrients are large in the case of the Barents and Norwegian Seas. The monthly ~~modeled~~modelled nutrients correspond very well with the climatological values for the surface waters in the southern regions (Norwegian Sea, Greenland Sea and SPG regions) indicating satisfactory model performance on large scale productivity and its seasonal variability in these regions. The Kara Sea is highly influenced by the coastal nutrient discharges as can be seen from the high standard deviations, especially for silicate including the late-summer where we have sufficient data for this analysis. Apart from surface silicate, the model performs generally well for the ~~Kara sea~~Kara Sea from month 7 and onwards. In addition to our comments about~~to~~ silicate above, the coastal discharge of nutrients should be improved in future studies, as in this study we used annual climatology for river nutrient discharge.

Experiments were generally comparable when the model results were regionally and monthly averaged (Fig. 3). Notable differences were found for the mid-summer nitrate and phosphate concentrations for the Barents, Norwegian and Greenland Seas, as the drawdown of these nutrients was better resolved by EXP1 compared to climatology as EXP1 summertime nutrients were lower than in EXP2 and 3. A possible reason why EXP1 has larger drawdown of nutrients during mid-summer is the higher photosynthesis efficiency applied in EXP1 resulting in higher uptake of nutrients and higher zooplankton grazing rate applied to EXP2 and 3 resulting in higher top-down pressure to phytoplankton preventing phytoplankton from consuming ~~biomass to~~ ~~uptake~~ more nutrients.

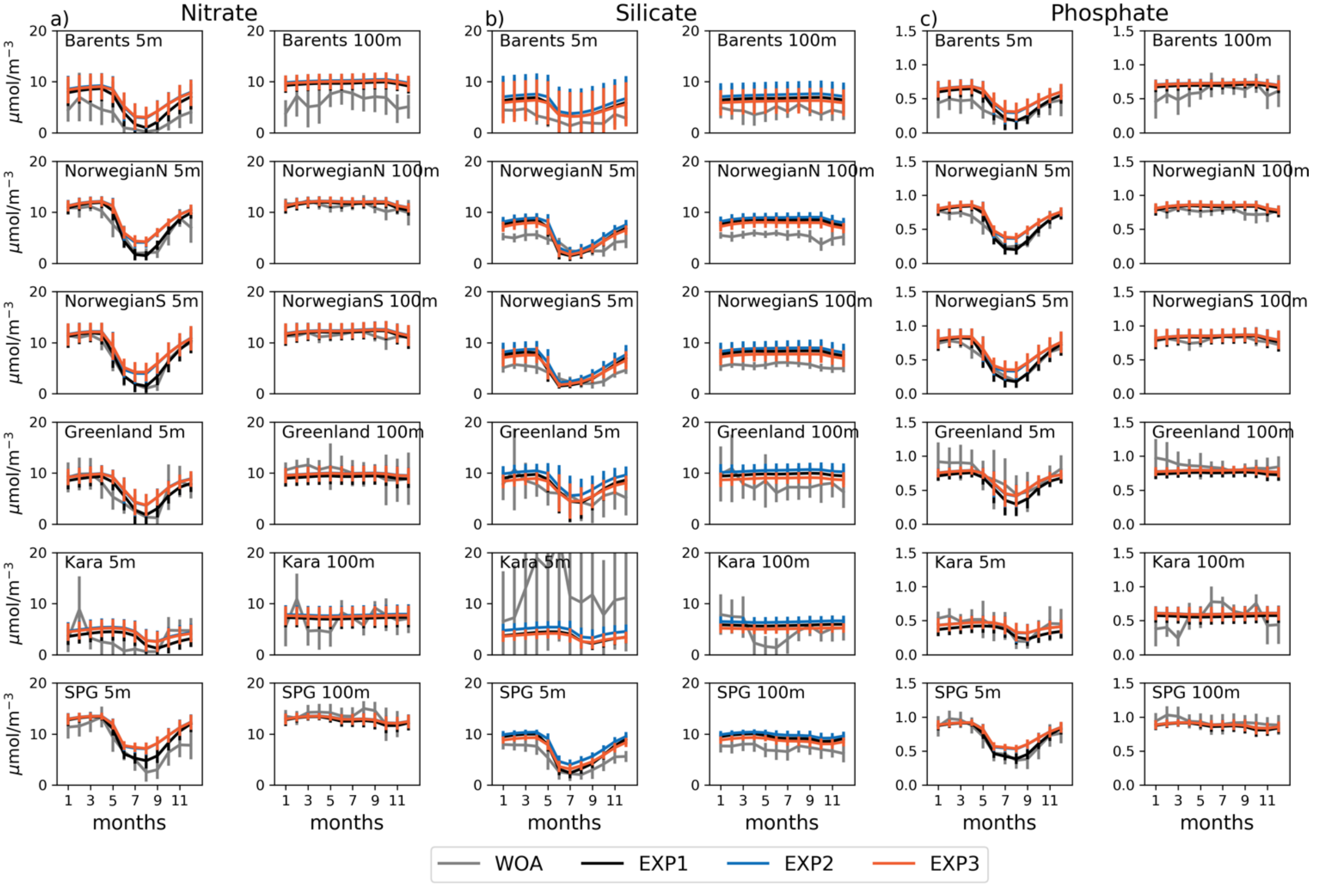


Fig. 3: Evaluation of seasonal cycle of nutrients at 5 m and 100 m ~~nutrients~~ for the model (black lines) vs WOA1~~8~~3~~8~~ (grey lines) regional monthly averages in the selected areas Barents, NorwegianS and SPG of the model domain for (a) nitrate, (b) silicate, and (c) phosphate. Model experiment (EXP1: ~~solid~~black, EXP2: ~~dashed~~blue, EXP3: ~~dotted~~orange) and WOA1~~88~~3 spatial standard deviations are plotted for each month as vertical lines). The number of observations for the WOA1~~88~~3 time-series is given in Figures A~~2~~3, A4, A5 and A6.

With point-by-point comparison, ~~F~~for nitrate, model and in situ data correlations are higher than 0.8~~3~~ for the three regions, with higher correlations at the higher latitudes (Table 2). One possible reason for the slight differences in correlations between lower and higher latitudes is the timing of the sampling. The majority of the sampling in the southern subdomains are held earlier in the year compared to the northern subdomains. As the model consistently initiates the spring bloom later than what is observed, a consequence of the physical model mixing scheme, it results in a later drawdown of nutrients, thus weaker correlations. The consistently occurring late spring bloom was also noted in previous Nordic Seas ~~modeling~~modelling studies using HYCOM as the physics model (Samuelsen et al., 2009 and 2015). ~~and t~~They related the bloom-timing issue to the physics model or the missing phytoplankton convection process of early seeding of the spring bloom by phytoplankton that was convected in winter. However, apart from the bloom timing, correlations higher than 0.~~72~~ 67 for silicate and 0.~~83~~ 8 for nitrate and phosphate in general represent a good agreement on the te~~i~~mporal~~ ing~~ and vertical~~depth~~ ~~of~~ nutrient variability.

Normalized standard deviations (nstd) for nitrate are within 0.6 7963 - 0.7284 indicating that the model underrepresents the amplitude of the observed variability. The model has % biases between 0.7 – 1.9 % 0.65 – 0.8 mmolN m^{-3} ffor the Norwegian Sea, whereas the bias is 2 mmolN m^{-3}13.5 – 31.3 % for the Barents Sea. For the case of root mean square error (rmse), modeled nitrate has errors between 2.471.94 – 3.3423.4334 mmolN m^{-3}. The simulated regional inorganic nutrients (EXP1) against in situ data are depicted in Fig. Fig. 4 where we make a point-by-point comparison of the modeledmodelled and observed inorganic nutrients. While the statistics includecover every data point, Fig. Fig. 4 depicts the upper 100 m. The observed upper 100 m nitrate maximum reach 14 mmolN m^{-3} while the modeledmodelled nitrate maximum is ~11 mmolN m^{-3} in the Barents Sea (Fig. Fig. 4a), whereas the nitrate maxima are similar (Fig. Fig. 4b) for the Norwegian Sea. The source of the lower bias and rmse for the Norwegian Sea is also evident in Fig. Fig. 4b where the model to observed data points are more scattered around the 1-to-1 line compared to Fig. Fig. 4a.

Table 2: Simulation statistics (model vs in situ) specific to each region

Variable	Region	CorrCoef			Norm. StdDev			Bias (%)			RMSE (mmol m^{-3})		
		Exp1	Exp2	Exp3	Exp1	Exp2	Exp3	Exp1	Exp2	Exp3	Exp1	Exp2	Exp3
nitrate	Barents	0.88	0.86	0.86	0.79	0.63	0.60	13.5	31.3	30.5	2.43	3.34	3.34
	NorwegianN	0.89	0.87	0.87	0.84	0.66	0.64	0.7	9.0	8.6	1.94	2.39	2.39
	NorwegianS	0.83	0.80	0.80	0.83	0.73	0.72	1.9	7.8	6.7	2.25	2.51	2.47
silicate	Barents	0.78	0.74	0.78	1.16	1.18	0.98	71.8	98.8	59.5	2.62	3.41	2.23
	NorwegianN	0.72	0.67	0.74	1.07	1.02	0.94	46.8	61.7	37.9	2.89	3.49	2.46
	NorwegianS	0.73	0.67	0.74	1.02	1.00	0.91	39.9	53.0	31.0	2.63	3.19	2.26
phosphate	Barents	0.90	0.88	0.88	0.80	0.63	0.61	0.7	13.9	14.7	0.13	0.17	0.17
	NorwegianN	0.90	0.88	0.89	0.94	0.75	0.72	0.0	7.1	7.4	0.11	0.13	0.13
	NorwegianS	0.83	0.81	0.81	0.95	0.84	0.82	-1.4	3.8	3.8	0.13	0.14	0.14
chlorophyll *a*	Barents	0.38	0.29	0.3	0.97	0.61	0.57	6.2	-62.1	-61.7	0.95	0.92	0.90
	NorwegianN	0.41	0.33	0.34	2.06	1.25	1.22	68.0	-26.7	-25.1	1.49	1.03	1.00
	NorwegianS	0.23	0.19	0.20	1.50	1.06	0.97	20.3	-36.4	-39.0	1.76	1.46	1.40

For silicate, model and in situ data correlations (Table 2) range between 0.74 7267 – 0.78, and, similar to nitrate, correlations are slightly higher at the higher latitudes. However, silicate variability due to uptake is only dependent on diatom productivity thus a direct relation to nitrate dynamics should not be expected. Both, the Barents and Norwegian Sea modeledmodelled maximum silicate for the upper 100 m maximum are higher than the observations with model % biases between 1.47 – 1.82 mmolSi m^{-3}319.9 – 71.98.8 and rmse between 2.26 6223 – 23.46 8949 mmolSi m^{-3}. The model performs well for the silicate nstd with values very close to 1 (0.911.020.91 – 0.981.161.18) indicating the model represents the amplitude in silicate seasonal variability well. TIn the model is formulated to limit the -uptake of silicate is limited towith concentrations abovebelowThe model code limits the uptake of silicate below 1.0 mmolSi m^{-3} concentration where the effect is visible in Fig. Fig. 4c,d. The sources of high model biases and rmse’s are also evident in these figures where the scattered data points are mostly below the 1-to-1 line.

The phosphate statistics are similar to those of nitrate, an expected result as all phytoplankton consume phosphate with a fixed Redfield N:P ratio. Correlations are between 0.81 – 0.~~89~~ 9 with higher values at the higher latitudes. The nstd’~~’~~s (Table 2) are slightly better than those of nitrate with values between 0.61 – 0.~~82~~ 95 indicating that the model underestimates the amplitude in phosphate variability. In agreement with the underestimated amplitude in variability, observed phosphate maximum for the upper 100m (not shown) reach 1.25 mmolP m^{-3}, where model maximum for all regions are ~1.0 mmolP m^{-3}. In terms of % biases (-1.4~~0.026~~ – 14.7 ~~0.08 mmolP m^-3~~) and RMSE~~’~~s (0.1~~3~~1 – 0.17 mmolP m^{-3}), the model simulates phosphate better than nitrate and ~~sil~~silicate.

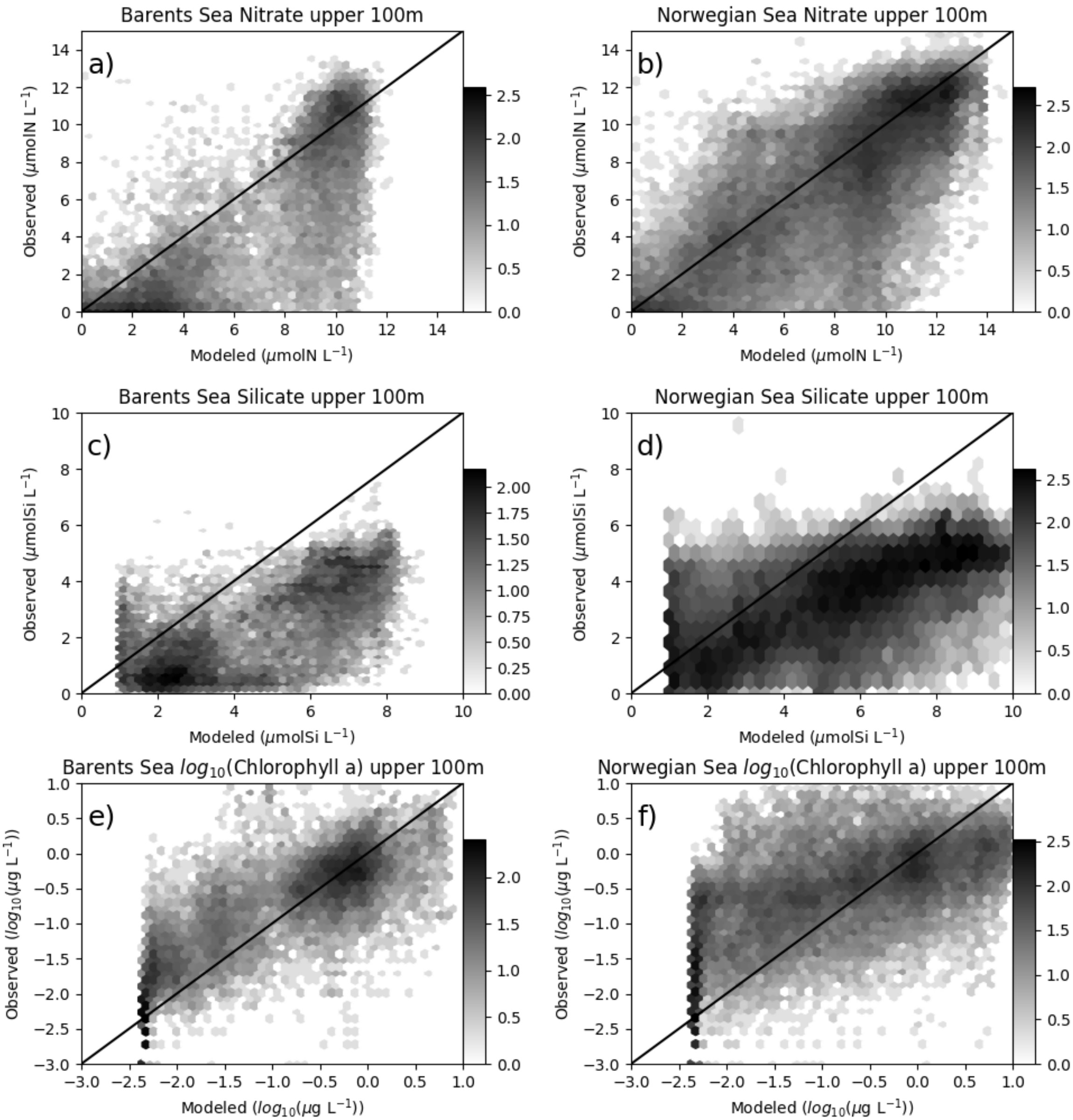


Fig. 4: Co-located modeled (EXP1) and in situ upper 100m nitrate (a) Barents Sea, (b) Norwegian Sea, silicate (c) Barents Sea, (d) Norwegian Sea and chlorophyll (e) Barents Sea, (f) Norwegian Sea comparisons. Log10 number of points are represented in hexagonal local clusters with shades of grey. Only the upper 100 m points are plotted.

Among the experiments, all perform very similar in terms of nutrient correlations, while for nitrate and phosphate, EXP1 performs slightly better in terms of nstds, EXP3 performs slightly better for silicate for the Barents Sea and EXP2 for the Norwegian Sea, though the differences among the experiments were almost negligible. Similarly, EXP1 perform better in terms of % bias and RMSE for nitrate and phosphate, and EXP3 perform better for silicate. The slightly better performance of

EXP1 for nitrate and phosphate is also evident in summer averages when compared to climatology as mentioned before (Figs. 3a and 3c). The model performance for silicate when using monthly averages shows even less differences among the experiments, however, the EXP3 is slightly closer to WOA timeseries compared to EXP1 (Fig. 3b)

In situ chlorophyll *a* correlations for the upper 100 m (Table 2) are between 0.23 19 – 0.41, which are below those of inorganic nutrients. However, the model performs well acceptable (EXP2 and 3 perform much better) in terms of nstd's. especially fFor the Norwegian Sea, EXP3 has the better performance (01.9750.97 and 1.21.062) and for the Barents Sea, EXP1 acceptable wellperform better (0.5797). for the Barents Sea. While EXP1 perform better for the Barents Sea and The NorwegianS (6.2 and 20.3 %) in terms of % bias, EXP3 perform better for NorwegianN (-25.1). Among all the experiments, EXP3 performed better in terms of RMSE for the three regions (0.9 – 1.4 mg m^{-3}).The model has minor negative biases (0.12 – 0.27 mg m^{-3}) and rmse's between 0.95 – 1.76 mg m^{-3}. The concentration ranges (Fig. Fig. 4f) are similar (0 – 10 mg m^{-3}) for both the observed and modeledmodelled for the Norwegian Sea indicated by nstd's near 1.0, but the points are scattered away from the 1-to-1 line indicating the low correlations. Model chlorophyll *a* maximum is limited tois always below 8 mg m^{-3} for the Barents Sea (Fig. Fig. 4e) where the observations show values above 10 mg m^{-3} indicating the lower nstd is's underestimating the amplitude of variability.

5 Simulated biogeochemistry of the North Atlantic and the Arctic

Primary production (PP) is the foundation for all marine biological production and the most frequently observed rate in BGC models. Still, there are only few observations of primary production available in the ocean as a whole, but the high Arctic is particularly poorly sampled (Matrai et al., 2013). Because the model does not have an explicit term for respiration, we can only extract gross primary production from the model, which is then compared to observations. The modelled gross annual primary production ranges from above 200 gC m^{-2} y^{-1} in the southern part of the model domain to almost zero in the central Arctic and features a gradual decrease from 144.26 gC m^{-2} y^{-1} to 41.48 gC m^{-2} y^{-1} from lower latitudes (SPG) towards the higher latitudes (Barents) respectively, with a sharp decrease to very low values (<6 gC m^{-2} y^{-1}) in the sea ice covered areas Fig. 5: Simulation averaged (EXP1) model results; (a) vertically integrated (0–200 m) annual primary production (gC m^{-2} y^{-1}), (b) annually averaged surface chlorophyll *a* (mg m^{-3}), and simulation averaged vertically integrated (0–200 m) plankton functional type biomass (gC m^{-2}) (c) diatoms, (d) microzooplankton, (e) flagellates, (f) mesozooplankton. The colorbar to FigureTable 3: Regional vertically integrated (0–200 m) annual gross primary production (gC m^{-2} y^{-1}) and simulation averaged vertically integrated (0–200 m) plankton functional type biomass (gC m^{-2}; DIA: diatoms, FLA: flagellates, MIC: microzooplankton, MES: mesozooplankton) in EXP1. See Sect. 3 for the definition of the regions. Note that the BERING STR. subdomain is within the effective area of the open boundary conditions thus is relaxed to climatology.(Fig. 5) as a consequence of light limitation. Rey (1981) estimated the primary production in the Norwegian Coastal Current to range from 90 - 120 gC m^{-2} y^{-1}, which agrees well with the values from this model (Fig. 5Fig. 5: Simulation averaged (EXP1) model results; (a) vertically integrated (0–200 m) annual primary production (gC m^{-2} y^{-1}), (b) annually averaged surface chlorophyll *a* (mg m^{-3}), and simulation averaged vertically integrated (0–200 m) plankton functional type biomass (gC m^{-2}) (c) diatoms, (d) microzooplankton, (e) flagellates, (f) mesozooplankton. The colorbar to Figure), although the used coarse resolution model does not represent a very distinct coastal current. Previous studies have estimated the primary production in the Fram Strait from 50 - 80 gC m^{-2} y^{-1} (Hop et al., 2006), while our model show values of 90-100 gC m^{-2} y^{-1} in the Atlantic waters and up to 30-60 gC m^{-2} y^{-1} on its western side. Lee et al. (2015) compared multiple Arctic models against in situ observations. Only a few of these observations were in the central Arctic while the majority were located in the Chukchi Sea, which is very close to the zone where the model is relaxed to climatology. They found a median value of all Arctic observations of 246 mgC m^{-2} d^{-1} which corresponds to about 90 gC m^{-2} y^{-1}. The regional estimates of primary production were similar, but the shelf regions were the most productive. The model results for the regions surrounding the central ~~Arctic ocean~~Arctic Ocean fall in the range of this estimate, but observation base estimates for the central Arctic, although only few are available, are higher than the model results. From Lee et al. (2015) the primary production estimates from the central Arctic varied between 10 and 100 mgC m^{-2} d^{-1} (~4 - 40 gC m^{-2} y^{-1}) while the model is below 1 gC m^{-2} y^{-1}. In the model formulation, the ice is blocking more light than what is realistic and ice leads cannot be resolved, so our estimate is expected to be low in ice covered regions. It is known that both melt ponds and leads can act as windows into the ocean, facilitating blooms (Assmy et al., 2017). The light below the ice will be improved in future versions of the model system. In situ observations in the Arctic range up to more than 5000 mgC m^{-2} d^{-1}~~,~~. ~~t~~The model does not reproduce the extremes in primary production, but the mean values are overall consistent with available observations.

For the Norwegian and Barents Seas, the modeled primary production show distinct seasonal patterns with almost negligible productivity between November – April due to low light availability (Fig. 6). During the onset of the spring bloom, production is notably at its highest during May – June followed by a gradual decrease towards late fall. Regional differences in primary production are also evident in year-round time-series, where the Norwegian Sea primary productivity is significantly higher than the Barents Sea productivity. The ~~S~~southern part of the Norwegian Sea (NorwegianS) has a notably earlier (~2 weeks) bloom compared to the northern counterpart.

Table 3: Regional vertically integrated (0–200 m) annual gross primary production (gC m^{-2} y^{-1}) and simulation averaged vertically integrated (0–200 m) plankton functional type biomass (gC m^{-2}; DIA: diatoms, FLA: flagellates, MIC: microzooplankton, MES: mesozooplankton) in EXP1. See Sect. 3 for the definition of the regions. Note that the BERING STR. subdomain is within the effective area of the open boundary conditions thus is relaxed to climatology.

Region	PP gC m^{-2} y^{-1}	DIA gC m^{-2}	FLA gC m^{-2}	MIC gC m^{-2}	MES gC m^{-2}
Barents	41.48	0.311	0.243	0.061	0.847
NorwegianN	98.2	1.191	0.442	0.12	1.673
NorwegianS	89.26	0.82	0.441	0.108	1.551

ArcAtl	2.6	0.051	0.027	0.007	0.044
Laptev	2.31	0.063	0.013	0.004	0.031
ArcEast	0.22	0.024	0.019	0.002	0.009
ArcCan	0.17	0.019	0.016	0.002	0.002
Bering STR	6.3	0.117	0.021	0.01	0.091
Kara	5.28	0.094	0.026	0.009	0.067
Greenland	34.95	0.399	0.153	0.046	0.595
SPG	144.26	1.56	0.647	0.214	2.128

The simulated seasonal evolution of primary production reflects the growth of plankton functional types, with diatoms (compared to flagellates) being the dominant type in the Nordic Seas spring bloom (Fig. 7). A relatively minor flagellate bloom follows a few weeks after that of diatoms. Zooplankton biomass increase from May – June in response to phytoplankton growth and is maintained till the end of the year. Note that ECOSMO II(CHL) allows zooplankton to feed on detritus, which contribute to zooplankton sustaining growth beyond the seasons of phytoplankton activity. Towards the lower latitudes, south of 45 °N, flagellates maintain a similar annually integrated productivity (~1.5 vs ~1.0 (gC m^{-2})) to that of diatoms (Fig. 5Fig. 5: Simulation averaged (EXP1) model results; (a) vertically integrated (0–200 m) annual primary production (gC m^{-2} y^{-1}), (b) annually averaged surface chlorophyll *a* (mg m^{-3}), and simulation averaged vertically integrated (0–200 m) plankton functional type biomass (gC m^{-2}) (c) diatoms, (d) microzooplankton, (e) flagellates, (f) mesozooplankton. The colorbar to Figurec-e). Mesozooplankton are the dominant grazer in all regions (Fig. 5Fig. 5: Simulation averaged (EXP1) model results; (a) vertically integrated (0–200 m) annual primary production (gC m^{-2} y^{-1}), (b) annually averaged surface chlorophyll *a* (mg m^{-3}), and simulation averaged vertically integrated (0–200 m) plankton functional type biomass (gC m^{-2}) (c) diatoms, (d) microzooplankton, (e) flagellates, (f) mesozooplankton. The colorbar to Figured-f). Similar to primary production, the NorwegianN and NorwegianS functional type biomasses are higher compared to Barents functional type biomasses with daily 200m averaged biomasses reaching 75 – 100 mgC m^{-3} for diatoms and mesozooplankton in the Norwegian Sea, and ~50 mgC m^{-3} for the Barents Sea respectively. For both Barents and Norwegian Sea, flagellate and microzooplankton biomasses do not exceed ~25 mgC m^{-3} during their highest productive seasons (Fig. 7).

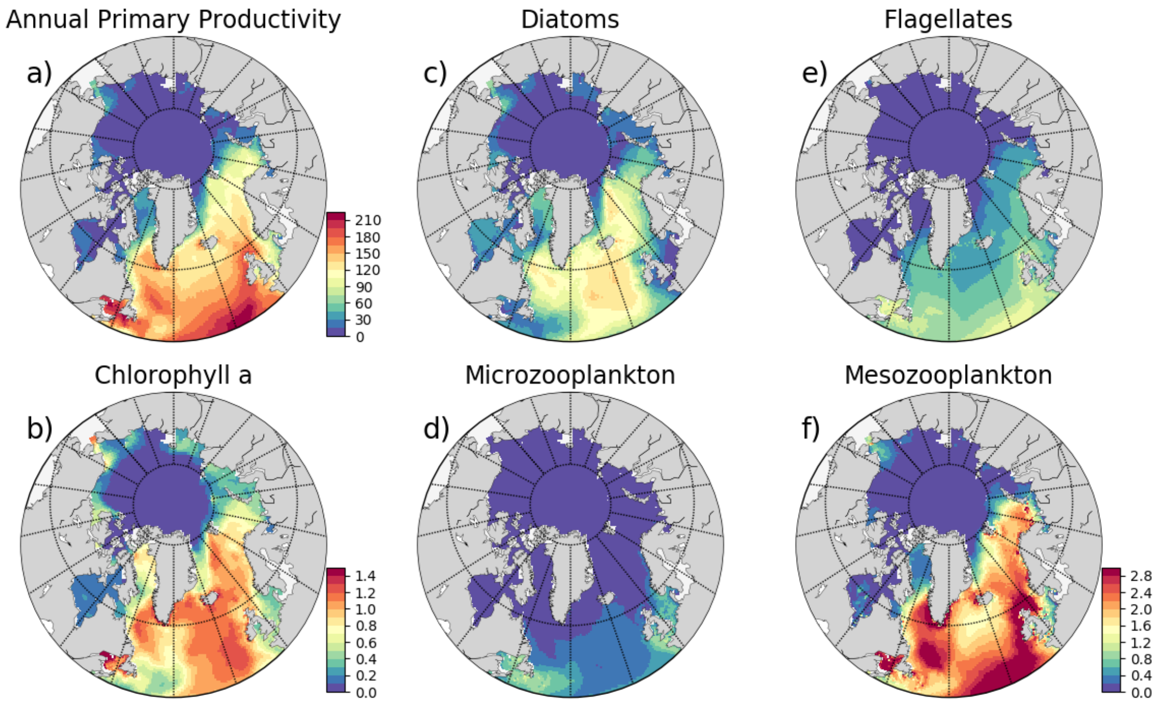


Fig. 5: Simulation averaged (EXP1) model results; (a) vertically integrated (0–200 m) annual primary production (gC m^{-2} y^{-1}), (b) annually averaged surface chlorophyll *a* (mg m^{-3}), and simulation averaged vertically integrated (0–200 m) plankton functional type biomass (gC m^{-2}) (c) diatoms, (d) microzooplankton, (e) flagellates, (f) mesozooplankton. The colorbar to Figure f applies to Figures c, d, e and f.

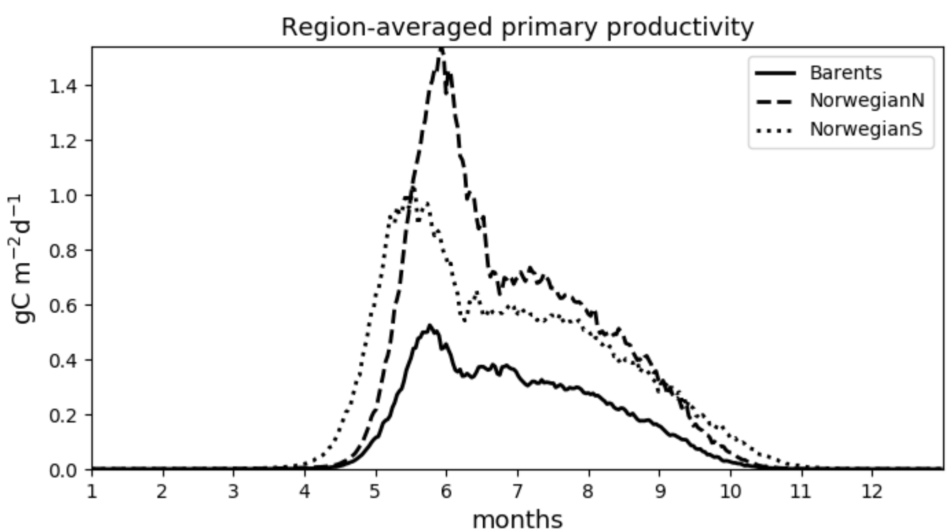


Fig. 6: Simulated (EXP1) time-series of 0-200 m integrated primary productivity (gC m^{-2} d^{-1}) for different regions: (a) Barents, (b) NorwegianN and (c) NorwegianS. See Table 3 for annually averaged primary productivities.

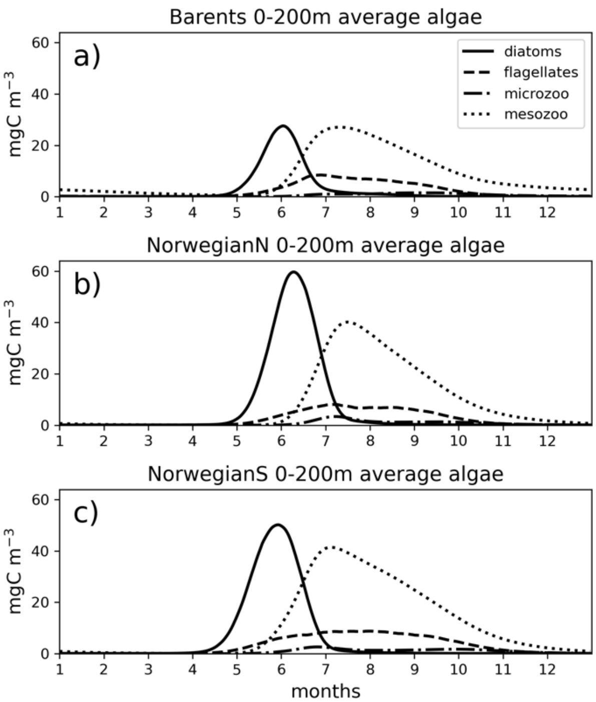


Fig. 7: Simulated (EXP1) daily averaged time-series of each plankton functional type (average of 0-200 m depth range).

The model predicts regionally high annually averaged inorganic nutrient concentrations for the subpolar gyre compared to the Norwegian and Barents Seas which is also reflected in monthly and regionally averaged concentrations (Fig. 8) with relatively lower concentrations in the coastal regions of the Nordic Seas compared to their offshore regions. The model also predicts a contrast between nutrient specific regions of high concentrations. Nitrate concentrations are higher at the lower latitudes, whereas phosphate and silicate are higher towards the higher latitudes. These features generally agree with the features of WOA2013 data (Fig. 8). As the model is relaxed towards the climatology at the Bering Strait through a sponge layer in the model domain, ~~T~~the ~~high~~ overall high nutrient concentrations near the Bering ~~Sea~~ Strait and especially the high silicate concentrations at the Siberian coast due to higher Si/N ratio of ~~river discharge~~ Pacific origin water masses compared to the Atlantic water masses, and the addition of high Si/N ratio river discharge is ~~more pronounced in the climatology data~~reflected in the modelled annual averages. As mentioned earlier, the model does not allow light to penetrate sea-ice. For this reason, the model overestimates surface inorganic nutrients compared to climatology below the sea-ice as these nutrients are not consumed by primary production, but are only affected by transport and remineralization. Overall, the model performs well in terms of N/P molar ratios (NO_3/PO_4; Fig. A4). Both model and climatology suggest a higher N/P ratio for the Nordic Seas and lower latitudes (~12-16). At the northern and southern Barents Sea~~coast~~, the climatology has a lower N/P ratio (<7) but has a high ratio at the ice-edge region (>17). In contrast, the model predicts a more regular N/P distribution with a gradual decrease from 16 to 12 from lower to higher latitudes at the Barents Sea.

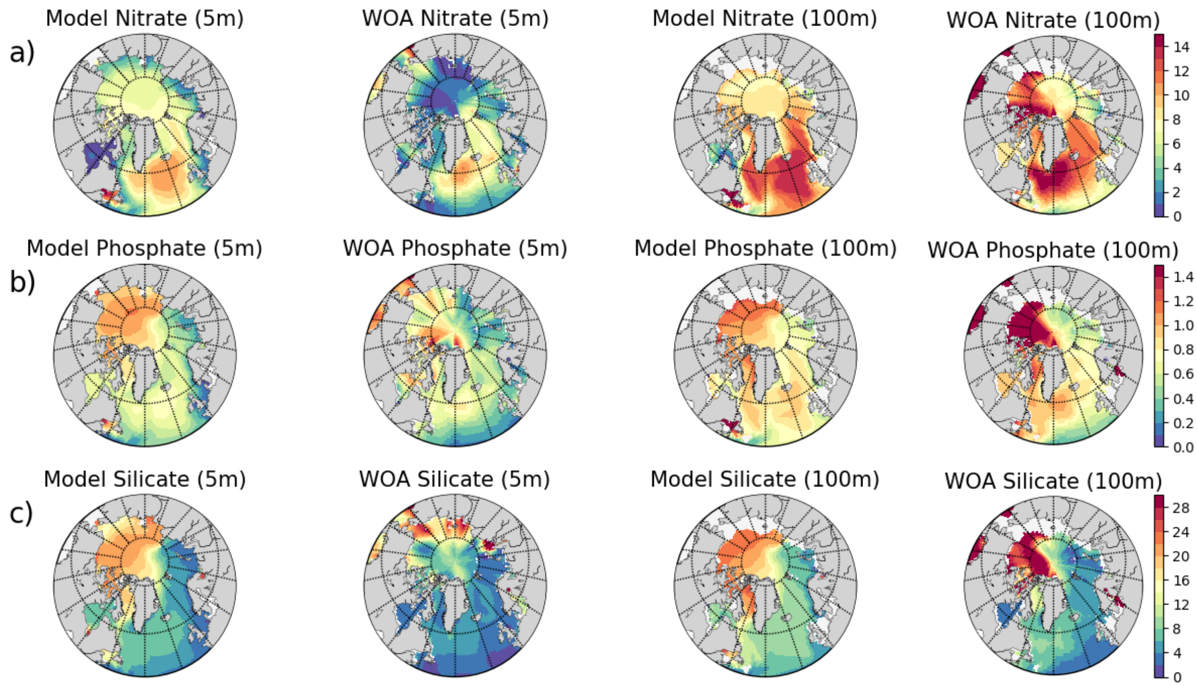


Fig. 8: Simulation averaged (EXP1; mmol m^{-3}) (a) nitrate, (b) phosphate and (c) silicate for 5 and 100 meters ~~iso~~depth and corresponding WOA201~~88~~3 annual climatologies.

6 Model ~~experiments~~chlorophyll *a* against satellite data and concluding remark on experiments

Here we present the evaluation of each model experiment against satellite chlorophyll *a*. ~~While this evaluation is a supplement to the evaluation performed in Sect. 4 against in situ data for the reference simulation (EXP1), the evaluation for EXP2 and EXP3 are provided here for the assessment of the model parameterization described in Sect. 3, and how they perform in relation to EXP1.~~ Since the parameters in EXP2 and EXP3 are used in open-ocean operational models, their performance in representing satellite chlorophyll *a* is vital for the assimilation of chlorophyll *a* in the operational model. The comparison of co-located surface in situ, model and satellite data are given in Figure 9 and their statistics are summarized in Table 4. The purpose of comparing the satellite data to both in situ and the model is to evaluate the satellite product itself for the region, as satellite products are prone to uncertainties based on the used algorithms and ~~is~~ are related to differences in absorption and backscattering properties of phytoplankton and concentrations of colored-dissolved organic matter (CDOM) and minerals (Dierssen, 2010). Thus, in the absence of in situ data, we have a better understanding when model and satellite data are compared. Table 5 summarizes model statistics against satellite data, which is both independent of the in situ samples and, due to the volume of satellite data, the statistics here are based on a much more extensive dataset compared to the statistics in Table 4.

For the three regions of interest, the satellite data have a negative bias against the in situ data (Table 4). The %bias is minor for the Barents region (-5.32%), but for the Norwegian Sea, the biases are -21.34% and -16.11% for the north and south respectively. The nstd's range between 0.51 – 0.65 mg m^{-3} suggesting that satellite chlorophyll *a* underrepresents the amplitude of the in situ observed variability of chlorophyll *a*. Satellite chlorophyll *a* rmse's range between 0.6 – 0.8 mg m^{-3}.

Table 4: Estimated chlorophyll *a* statistics against in situ surface chlorophyll *a*. Data points that are co-located with in situ data locations only are used. Co-located satellite data is also compared against in situ data for reference. See Sect. 3 for the calculation of statistics.

	Barents			NorwegianN			NorwegianS		
	Bias (%)	**RMSE** (mg m^{-3})	**Norm. StdDev**	**Bias (%)**	**RMSE** (mg m^{-3})	**Norm. StdDev**	**Bias (%)**	**RMSE** (mg m^{-3})	**Norm. StdDev**
Satellite	-5.32	0.60	0.65	-21.34	0.66	0.51	-16.11	0.80	0.53
EXP1	39.75	1.21	1.52	178.25	2.85	3.50	140.56	2.74	2.54
EXP2	-55.69	1.08	1.15	50.76	1.87	2.68	39.59	1.89	1.85
EXP3	-51.21	1.03	1.02	43.32	1.67	2.43	23.50	1.66	1.59

Table 5: Model chlorophyll *a* statistics against satellite data. See Sect. 3 for the calculation of statistics.

	Barents				NorwegianN				NorwegianS				SPG			
	Bias (%)	**RMSE** (mg m^{-3})	**Norm. StdDev**	**Corr Coef**	**Bias (%)**	**RMSE** (mg m^{-3})	**Norm. StdDev**	**Corr Coef**	**Bias (%)**	**RMSE** (mg m^{-3})	**Norm. StdDev**	**Corr Coef**	**Bias (%)**	**RMSE** (mg m^{-3})	**Norm. StdDev**	**Corr Coef**
EXP1	56.23	2.21	1.45	0.0	203.51	2.95	4.52	0.0	130.72	2.45	4.03	0.0	140.33	2.28	5.60	0.01
EXP2	-15.73	1.78	1.05	0.05	59.69	1.88	3.16	0.28	26.84	1.69	2.97	0.25	10.34	1.29	3.33	0.27
EXP3	-22.83	1.67	0.91	0.05	52.12	1.75	2.95	0.28	17.70	1.51	2.67	0.26	8.12	1.25	3.23	0.26

EXP1 has higher chlorophyll *a* concentration compared to EXP2 and EXP3. This is visually evident when model and satellite data are plotted against in situ data (Fig. 9) where EXP2 and EXP3 generally form clusters distinct from EXP1. EXP1 chlorophyll *a* are mainly located at the right side of the 1-to-1 line suggesting a positive bias against the in situ data evident in Table 4 with 39.75% for the Barents Sea and 178.25% and 140.56% for north and south Norwegian Sea respectively. The rmse's and nstd's are also higher compared to EXP2 and EXP3. Relatively, EXP1 is the least representative of the in situ chlorophyll *a* data among the experiments. EXP2 and EXP3 overestimate chlorophyll *a* for the Norwegian Sea with %biases ranging between 23.5% - 50.76%, and overrepresenting the amplitude of variability with nstd's ranging between 1.59 – 2.68 mg m^{-3}. For the Barents Sea, while EXP2 and EXP3 have negative biases and rmse's around ~1 mg m^{-3}, their nstd's show that they correctly estimateing the amplitude of variability. With a much larger number of data points, the model error statistics computed from satellite data are similar (Table 5) with EXP1 resulting in the highest chlorophyll *a* values statistically performing the worst compared to EXP2 and EXP3. Notably, EXP2 and EXP3 biases are much lower better compared to the statistics against in situ with the exception of NorwegianN, with lessas well as performing less errors overall. We note that the in situ data are restricted in both, the overall amount amount as well as the season, as most of the data are from late spring and onwards whereas satellite data also cover earlier parts of the year under favourable weather conditions. Satellite data also increase the regional coverage of the statistical analyses where SPG region statistics show that EXP2 and EXP3 outperform the EXP1 statistics (Table 5). The consistent higher bias of EXP1 compared EXP2 and EXP3 can be explained by its higher photosynthesis efficiency (Table 1). EXP1 show a very fast primary production response to light availability during the spring bloom period with notably higher chlorophyll *a* concentrations compared to the observations (results not shown) evident in the high %biases, whereas chlorophyll *a* concentrations in EXP2 and EXP3 are closer to observed values during spring bloom. Originally, the ECOSMO II parameterization was set for the North Sea and the Baltic Sea with different light conditions. In the open ocean such a high response curve leads to an overestimate of the bloom. However, winter convective mixing is very deep in the Nordic Seas, thus the light is a limiting factor on growth. To overcome deep mixing and prevent a late spring bloom, the phytoplankton were allowed to have very high growth rates for EXP2 and relatively less higher growth parameters were set for EXP3. Statistically and visually (Fig. 9), both EXP2 and EXP3 are very similar, with EXP3 performing statistically slightly better.

The statistical analysis performed against satellite chlorophyll *a* highlights the use of satellite data as an independent dataset for model evaluation, and by its model domain-wide (though limited to surface) coverage, it allows for a more composite evaluation of the model as a whole. Satellite data is acquired in near-real time, thus presents a valuable opportunity for an operational model validation, whereas model validation with in situ data have significant delays (though very valuable for hindcast evaluation). Recent additions to satellite datasets such as the phytoplankton functional types (e.g. https://doi.org/10.48670/moi-00099) further details the use of satellite data for models. As an operational model, ECOSMO II(CHL) works well with satellite data with the inclusion of explicit chlorophyll *a* variables for each phytoplankton functional type (PFT). Not only ECOSMO II(CHL) better resolves surface chlorophyll *a* with its light-dependent dynamic carbon:chlorophyll *a* ratios (cf. Section A1), PFT specific parameters such as initial slope of P-I curves adds further details to model adaptability to varying environmental conditions (Fig. A1d) compared to an average constant ratio common to all PFTs. PFT specific model configurations further synergises with satellite PFT observations in the context of operational biogeochemical modelling. Future iterations of ECOSMO should also include such kind of evaluations. An important addition to explicit chlorophyll *a* variable is the inclusion of the initial slope of P-I curves to light-limitation on growth. In this study, light-limitation was approached in a PFT and chlorophyll *a* independent fashion (Eq. 4). Future versions of ECOSMO should adopt ways (e.g. Evans and Parslow, 1985) to include the PFT specific P-I curve slopes to take full advantage of the explicit chlorophyll a variable. This would allow PFTs to differentiate their niche light conditions for production, and further allow better integration with the bio-optical modelling of the marine environment.

We note that the statistical analysis results against satellite chlorophyll *a* contradict the statistics against in situ data (Section 4.3) as EXP1 performed better in some cases such as % bias for the Barents Sea and south Norwegian Sea. However, in the analysis against satellite chlorophyll *a*, EXP1 was statistically outperformed by EXP2 and EXP3. First possible cause of this difference may be that the in situ data and satellite data are different datasets such that they cover different locations and seasons and use different size of datapoints. In situ data were restricted in both the overall number of data points, as well as the seasons where most of the data were from late spring and onwards whereas satellite data also cover earlier parts of the year under favourable weather conditions. As a results, model statistics may have a seasonal bias towards the timing of the in situ sampling. Second, satellite data cover only the surface of the water column where in situ chlorophyll *a* were well below the penetration depth of the satellites which might affect the statistics.

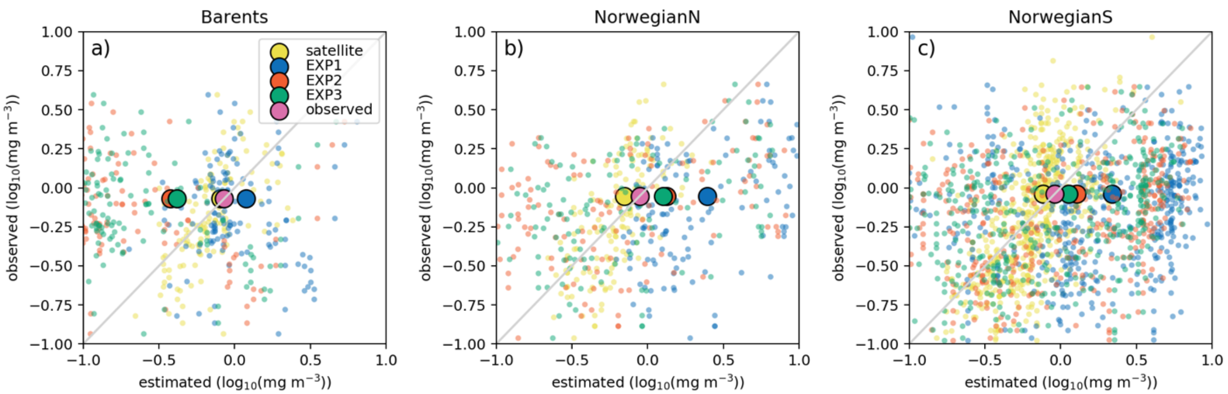


Fig. 9: Estimated surface chlorophyll *a* data against in situ observations (log10(mg m^{-3})). Region-wide averages are depicted with the large markers representative of the individual points depicted with the same colors in the background with smaller-sized markers.

~~The consistent higher bias of EXP1 compared EXP2 and EXP3 can be explained by its higher photosynthesis efficiency (Table 1). EXP1 perform a very fast phytoplankton response to light availability during the spring bloom period where light availability is increased resulting in a steep curve where chlorophyll a concentrations are notably higher compared to the observations (results not shown) evident in the high %biases, whereas EXP2 and EXP3 have closer concentrations during spring bloom. Originally, ECOSMO II parameterization was set for the North Sea and the Baltic Sea with different light conditions. In the open ocean such a high response curve overestimate the bloom. However, winter convective mixing is very deep in the Nordic Seas, thus the light is a limiting factor on growth. To overcome deep mixing and prevent a late spring bloom, the phytoplankton were allowed to have very high growth rates for EXP2 and relatively less higher growth parameters were set for EXP3. Statistically and visually (Fig. 9), both EXP2 and EXP3 are very similar, with EXP3 performing statistically slightly better. Experiment statistics for inorganic nutrients are very similar in all experiments (Table 2). Taking into account the model performance overall, EXP1 parameterization perform better for the coastal regional seas as it was originally designed for (DS2013), but for the case of open ocean, EXP3 parameterization has the better performance.~~

7 Conclusions

In this paper we ~~provided~~ present the mathematical description of ~~an updated version of~~ ECOSMO II(CHL) which is used as the biogeochemical model for the operational forecasting of the Arctic Ocean~~,~~. We document ECOSMO II(CHL) model performance with objectively analysing the model inorganic nutrients and chlorophyll *a* against available data spanning from climatology to in situ and satellite chlorophyll *a*. We compare three experiments with different parameters representing the original implementation of ECOSMO II, CMEMS Arctic operational ECOSMO II(CHL) for the years 2016 – 2021, and the current (since June 2021) operational ECOSMO II(CHL). Through presenting the model description and its evaluation, we document the performance of ECOSMO for each of these use cases for the users of the model. While each setup perform better for some variables or datasets, ~~its evaluation against in situ and remote sensing data, and analyses on different parameterizations targeting chlorophyll *a* dynamics.~~

~~T~~the qualitative and quantitative evaluation of the model results of inorganic nutrients, chlorophyll *a* and primary production for each case ~~has~~~~v~~ demonstrated that the model is consistent with the large-scale climatological nutrient variability~~settings~~, and is capable of representing regional and seasonal changes. The model primary production agrees with previous measurements. ~~Our parameterization experiments showed that for the open ocean domains, model chlorophyll a benefits from using higher phytoplankton growth and zooplankton grazing rates with less photosynthesis efficiency compared to the original implementation of ECOSMO II for the North Sea and the Baltic Sea which represent coastal domains. We related the improved effect on chlorophyll a to better timing of the spring bloom in the North Atlantic and Nordic Seas due to higher growth rates.~~ ECOSMO II(CHL) benefits from the use of explicit definition of phytoplankton functional type

~~With improved chl~~chlorophyll *a* implementation, i.e. the use of phytoplankton-specific dynamic chlorophyll *a*-to-carbon ratios in reference to a fixed ratio in the original model, with improved surface estimations of chlorophyll *a*, and gains added value towards improving model evaluation opportunities using satellite observations and phytoplankton functional type specific additions to model structure. In its current state, ECOSMO II(CHL) with its intermediate complexity definition of the North Atlantic and Arctic Ocean ecosystem structure including a sediment layer is a capable ~~modeling~~modelling tool for both scientific and operational use. The ~~modeling~~modelling structure presented in this study, ECOSMO II(CHL), including the physical model, HYCOM, forms the basis of the ~~modeling~~modelling framework that the future updates will build on~~ and ECOSMO II(CHL).~~ ~~is thus currently being developed to include migratory fish and a dynamic particle sinking scheme that will broaden the scope of the model.~~

Appendices

A.1 Comparison of ECOSMO II and ECOSMO II(CHL) chlorophyll *a* dynamics at Station-M

In this section we present a 1D model setup at Station-M (66ºN 2ºE) in the Norwegian Sea using GOTM as the physics model using 1-hour interval atmospheric forcing. The location of the station resides in the Norwegian Sea South region depicted in Figure 2. We performed a 27-year run starting in 1990 using ~~realistic~~ WOA201~~8~~3 profiles from January climatology ~~constant values~~ for the biogeochemical variables and considered the first 5 years as the spin-up period. Model results and statistics provided in Figure A1 and Table A1 are calculated from the last 22 years. Statistical analysis was performed using the Station-M time-series data which is included in the Institute of Marine Research (2018) dataset described in 4.2. We assumed a carbon:chlorophyll *a* ratio of 60 for ECOSMO II to perform the analyses using the total phytoplankton biomass. The chlorophyll *a* depiction from ECOSMO II therefore indicate only the phytoplankton biomass and does not affect the model in any way, whereas in the case of ECOSMO II(CHL), chlorophyll *a* is explicitly represented for each phytoplankton type and the results are real model chlorophyll *a* outputs. EXP3 parameters are used for these simulations.

The major difference between the 2 variants of ECOSMO II is that in the case of CHL variant, the model carbon:chlorophyll *a* ratio adapts to the light availability, where abundant light results in a higher ratio (days 140 – 250; Fig. A1d) at the surface, lower ratio in case of lower light availability either due to seasons or high attenuation due to high chlorophyll *a* at the surface. The latter case can be observed around day 150 (Fig. A1d).

A significant difference in the results is that the non-CHL variant simulates higher chlorophyll *a* concentrations (Figs A1a~~-~~,b, and c) assuming a 60 carbon:chlorophyll *a* ratio which is a representative average ratio for most of the productive period for ECOSMO II(CHL) (Fig. A1d). The difference is more pronounced in the upper 10 meters due to higher carbon:chlorophyll *a* ratio (~100) under abundant light. While both simulations are statistically similar in general, especially in the deeper euphotic zone (40 – 80 m), ECOSMO II(CHL) statistically performs better at 0 - 20 m and 20-40 m range (Table A1) for almost all statistical quantities. The data that was used to calculate the statistics in Table A1 is visualised in Figure A2 using a scatter plot of the modelled and observed chlorophyll *a*, which confirms the values in Table A1 showing a slightly better performance of ECOSMO II(CHL) near the surface (0 - 20 m range). 30 m average point is visually slightly better for ECOSMO II, which probably reflects the better % bias performed for 20 – 40 m range (Table A1). While overall the model performance improves, further modifications to either model parameters or formulation should be done for the future iterations of ECOSMO as below 40 meters, the model has not gained a significant improvement suggesting that the chlorophyll *a* dynamics should be improved for low-light conditions.~~While both simulations are statistically similar in general, especially the deeper euphotic zone (40 – 80 m), ECOSMO II(CHL) statistically performs better at 0 - 20 m range (Table A1).~~

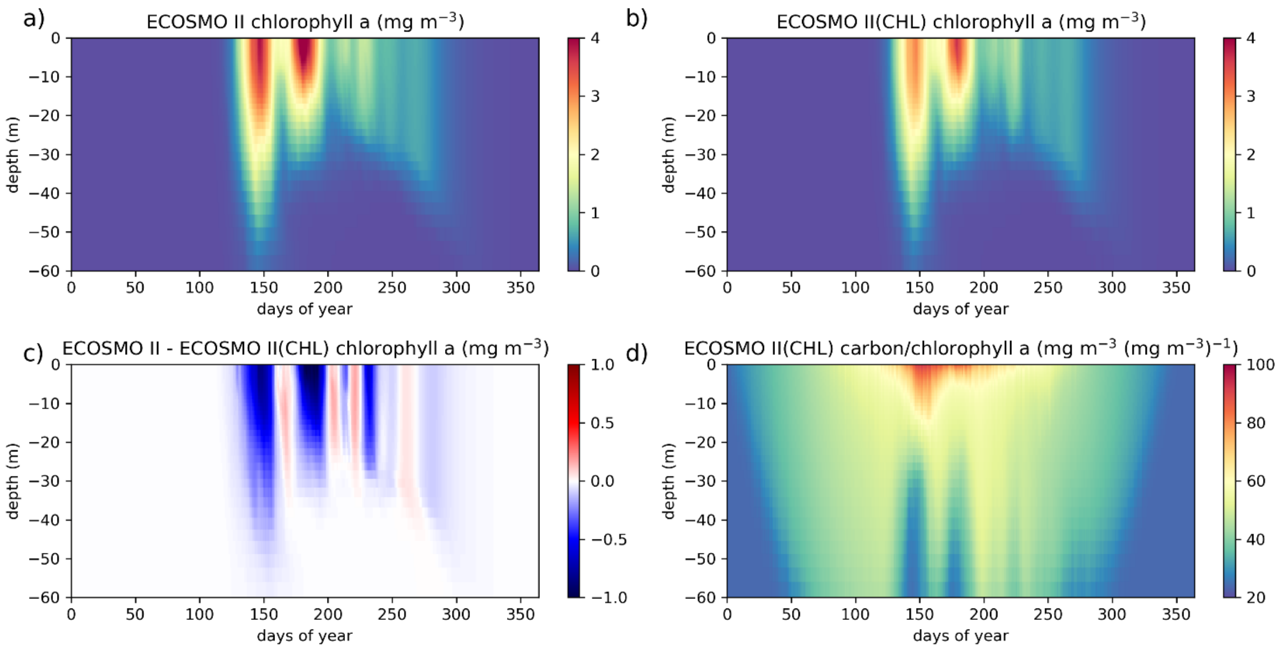


Fig. A1: ECOSMO II chlorophyll *a* seasonal evolution~~dynamics~~ is compared to ECOSMO II(CHL) using a 27-year (1990 – 2016) 1D simulation at Station-M (66ºN 2ºE) in the Norwegian Sea. Results provided here are the averages of the last 22 years (1995 – 2016) of the simulations given as annual climatologies. Figures a and b depict chlorophyll *a* concentrations of ECOSMO II and ECOSMO II(CHL) respectively, c depicts the chlorophyll *a* difference of the 2 simulations, and d depict the diatom and flagellate averages of carbon:chlorophyll *a* ratios.

Table A1-: Comparison of ECOSMO II and ECOSMO II(CHL) chlorophyll *a* statistics against in situ data depicting 20 m sections of the upper 80 m water column using an output from a 1D model simulated at Station-M (66ºN 2ºE) in the Norwegian Sea.

	ECOSMO II				ECOSMO II(CHL)			
	Bias (%)	RMSE (mg m^{-3})	Norm. StdDev	CorrCoef	Bias (%)	RMSE (mg m^{-3})	Norm. StdDev	CorrCoef
0 – 20 m	42.76	1.27	2.14	0.38	21.97	1.05	1.78	0.39
20 – 40 m	-23.96	0.68	1.25	0.40	-33.37	0.62	1.06	0.42
40 – 60 m	-62.99	0.49	0.72	0.26	-68.35	0.48	0.61	0.28
60 – 80 m	-89.75	0.18	0.15	0.44	-91.73	0.19	0.12	0.45

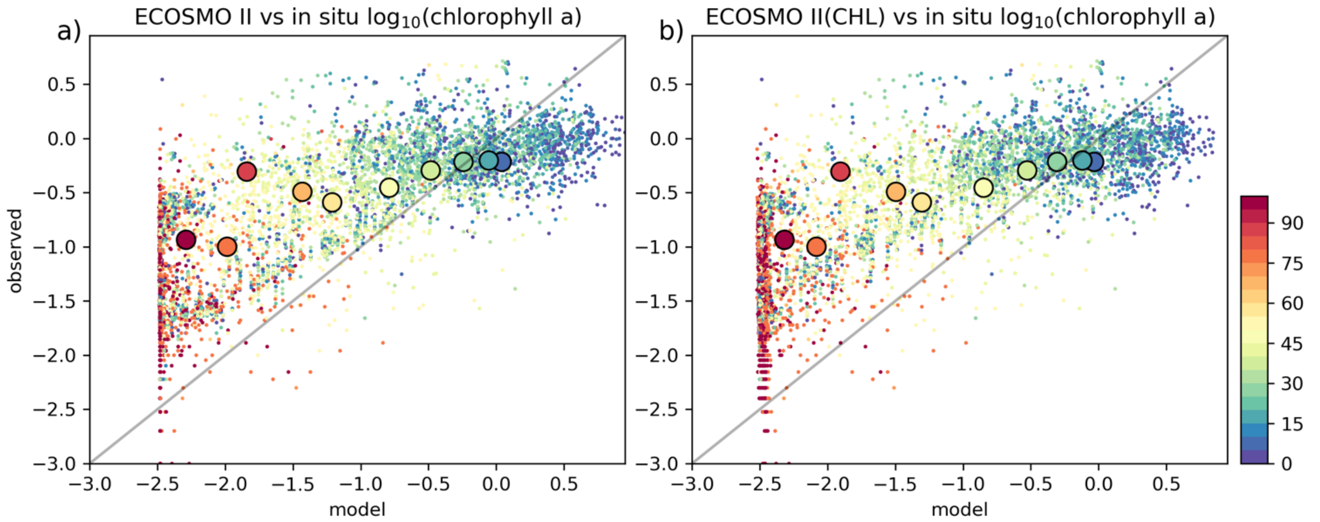
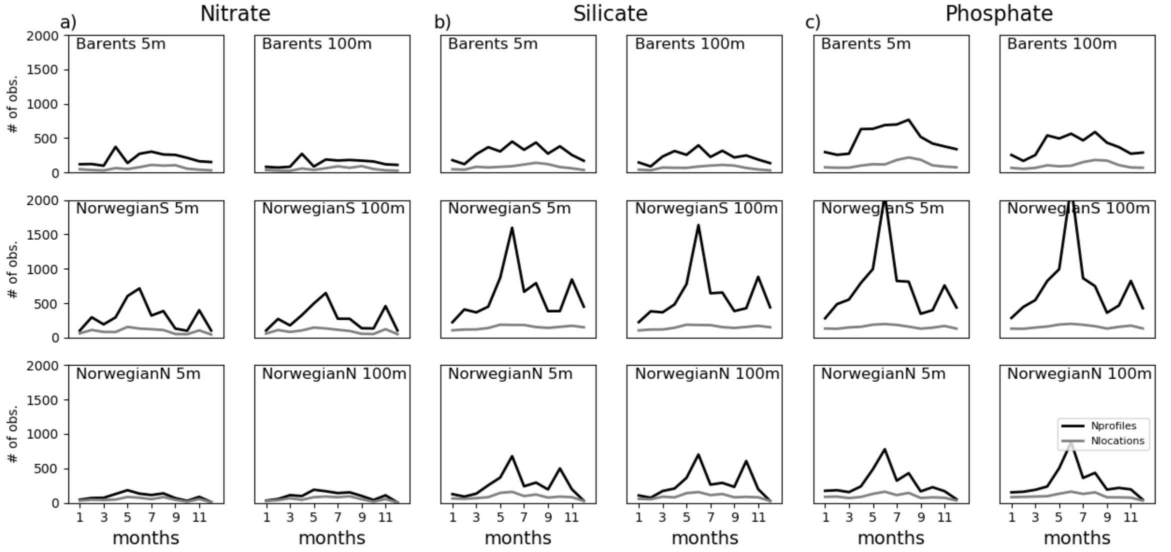


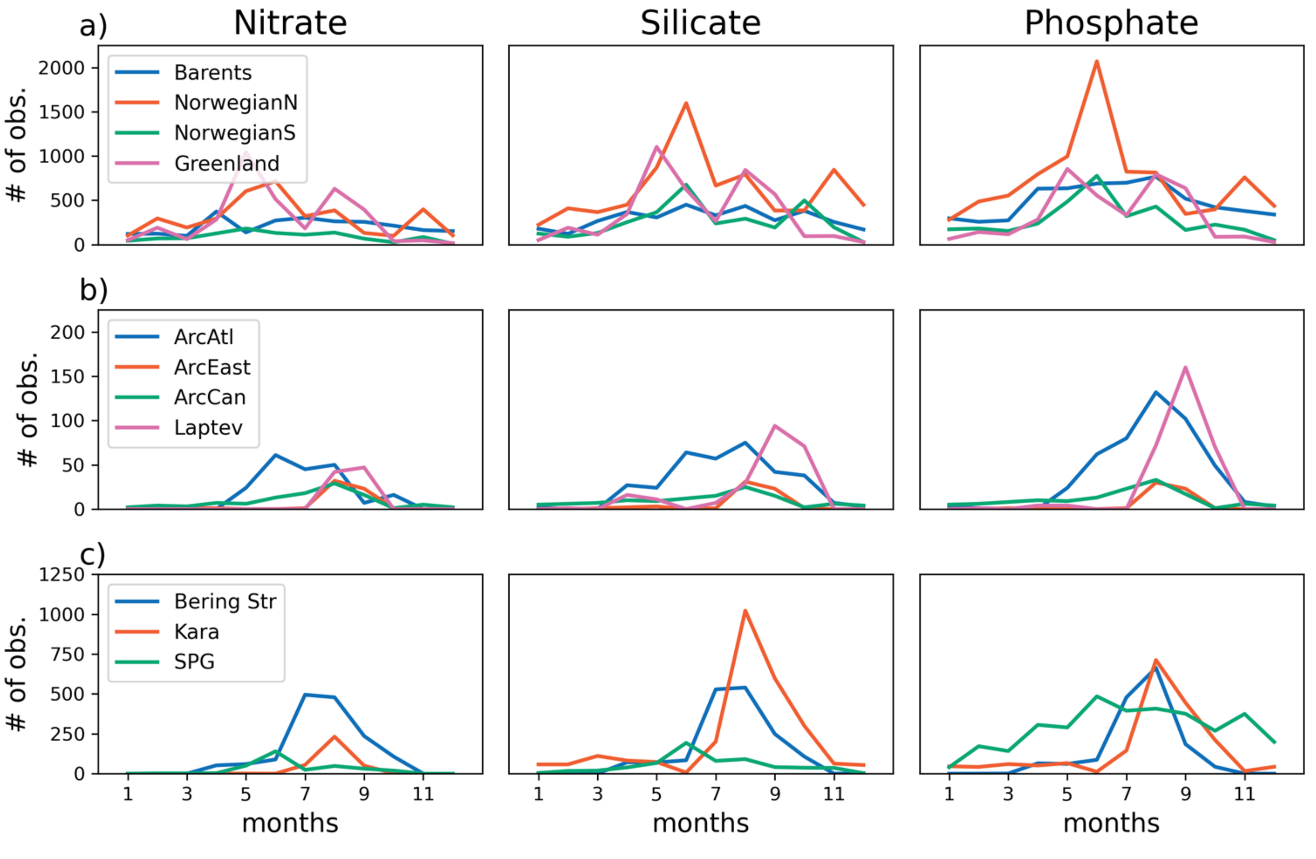
Fig. A2: (a) ECOSMO II and (b) ECOSMO II(CHL) 1D model chlorophyll *a* (log10(mg m^{-3})) is evaluated against in situ data at Station-M. Model data was interpolated to co-locate with the in situ data. Small markers depict the individual points and the large markers depict 10 meter interval averages. The observation depth is given in color coding.

A.2 World Ocean Atlas 2013~~8~~ and Institute of Marine Research (2018) data supplementary figures

In this section we provide the supplementary figures for Section 4.3 and 5 by presenting the number of observations used for the statistical analyses in WOA2018 dataset for each region and inorganic nutrient (Fig. ~~A2~~A3) and annual averages of NO_3/PO_4 molar ratios (Fig. A4~~3~~), and profile locations for the IMR18 dataset (Fig. A5).~~.~~



a) Nitrate
b) Silicate
c) Phosphate
Barents 5m
Barents 100m
NorwegianS 5m
NorwegianS 100m
NorwegianN 5m
NorwegianN 100m
# of obs.
months
Nprofiles
Nlocations



a) Nitrate
Silicate
Phosphate
Barents
NorwegianN
NorwegianS
Greenland
b)
ArcAtl
ArcEast
ArcCan
Laptev
c)
Bering Str
Kara
SPG
# of obs.
months

Fig. A32: Number of observations for the WOA138 inorganic nutrient time-series for the model regionsgiven in Figure 4. Multiple profiles exist for some of the locations, thus the black lines denote the total number of profiles and grey lines denote the number of different locations for those profiles.

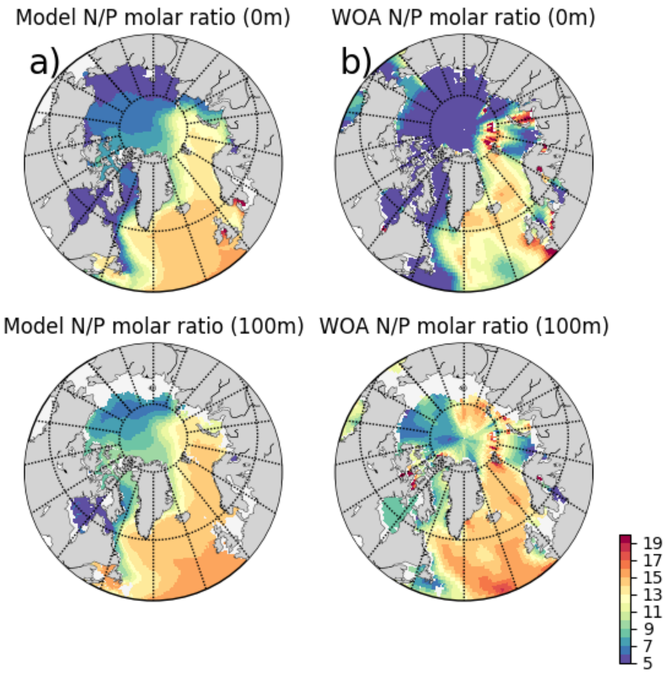


Fig. A34: Simulated and WOA2018 WOA2013 inorganic nutrients annual averages NO_3/PO_4 molar ratios, a) model, b) WOA2018 WOA2013 for 5 and 100 meters isodepth.

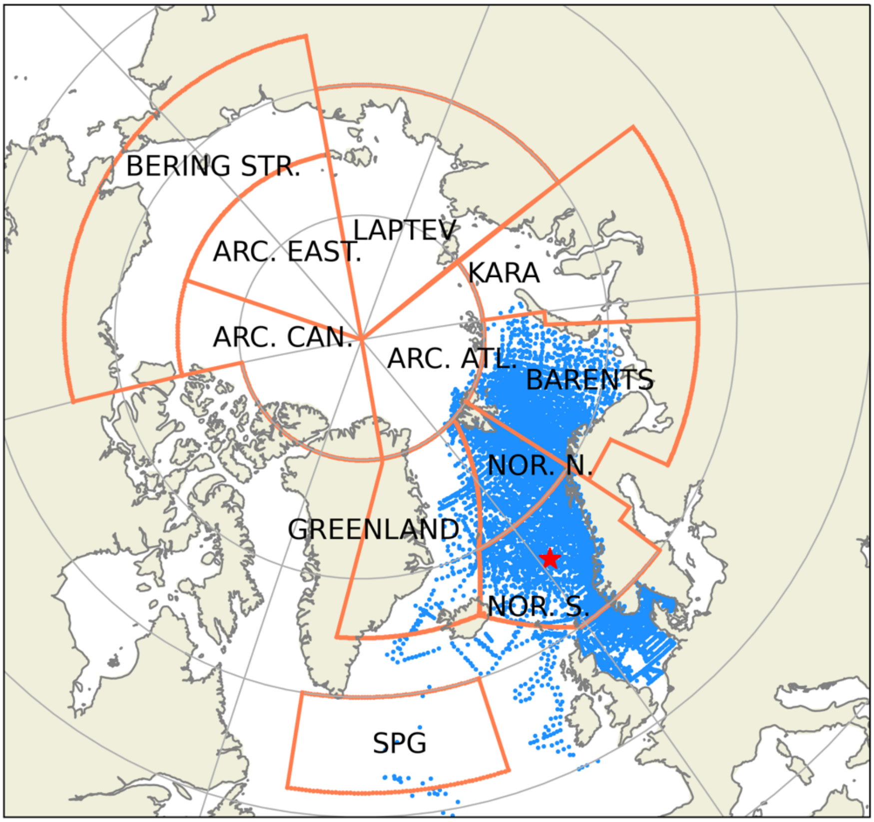


Fig. A5: Subdivision of model domain in prescribed geographical subdomains used for model quality assessments. The subdomains are as follows: Norwegian Sea South (NOR. S.), Norwegian Sea North (NOR. N.), Barents Sea (BARENTS), Kara Sea (KARA), Laptev Sea (LAPTEV), Bering Strait (BERING STR.), Arctic-Canada (ARC. CAN.), Arctic-East (ARC. EAST), Arctic-Atlantic (ARC. ATL.), Greenland Sea (GREENLAND) and the Subpolar Gyre (SPG). The points in the oceanic regions denote the profile locations for the observed biogeochemical variables that were used for the statistical analyses. The star depicts the coordinates of the Station-M time-series location. While the model domain extends down to the equatorial regions, the figure focuses on the area of interest. Note that the BERING STR. subdomain is within the effective area of the open boundary conditions thus is relaxed to climatology.

Code availability

The model code is openly available under Creative Commons Attribution 4.0 International license. The presented model of this publication is available in Lisæter et al. (2021). HYCOM version used is 2.2.37 and the ECOSMO II(CHL) code is available in HYCOM_2.2.37/CodeOnly/src_2.2.37/nersc/ECOSMO where m_ECOSM_biochm.F is the master biogeochemical code. The model setup used here is located under “model_setup/expt_09.0/SCRATCH/” directory. After the compilation following the procedure documented in “Doc” folder, the executable copied to the SCRATCH folder should be able to replicate the model presented here. Further instructions are provided in the README file. The different parameters given for each experiment in the manuscript can be applied to "HYCOM_2.2.37/CodeOnly/src_2.2.37/nersc/ECOSMO/ECOSMparam1.h". The model is set to produce daily averaged binary files, but scripts to convert the binary files to netcdf files are included in "MSCPROGS/src". The model code is written in FORTRAN. Model results provided in the manuscript are located under "model_output" directory.

Author contribution

VCY and AS designed the experiments and VCY carried them out. UD is the developer of ECOSMO II and together with AS, they coupled ECOSMO II to HYCOM physics model. VCY has built the ECOSMO II(CHL) version on ECOSMO II. The physics model setup for this study was mainly prepared by AS, and the preparation of the biogeochemical setup, sensitivity analyses and model evaluation were carried out by VCY. VCY prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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