



**Tuning and
assessment of the
HYCOM-NORWECOM
V2.1 modeling
system**

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Tuning and assessment of the HYCOM-NORWECOM V2.1 modeling system

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Abstract

The HYCOM-NORWECOM modeling system is used both for basic research and as a part of the forecasting system for the Arctic Marine Forecasting Centre through the MyOcean project. Here we present a revised version of this model. The present model, as well as the sensitivity simulations leading up to this version, has been compared to a dataset of in-situ measurements of nutrient and chlorophyll from the Norwegian Sea and the Atlantic sector of the Arctic Ocean. The revisions having most impact included adding diatoms to the diet of micro-zooplankton, increasing micro-zooplankton grazing rate and decreased silicate-to-nitrate ratio in diatoms. Model runs are performed both with a coarse- (~ 50 km) and higher-resolution (~ 15 km) model configuration, both covering the North Atlantic and Arctic Ocean. While the new model formulation improves the results in both the coarse- and high-resolution model, the nutrient bias is smaller in the high-resolution model, probably as a result of the better resolution of the main processes and with that improved circulation. The final revised version delivers satisfactory results for all three nutrients as well as improved result for chlorophyll in terms of the annual cycle amplitude. However, for chlorophyll the correlation with in-situ data remains relatively low. Besides the large uncertainties associated with observational data this is possibly caused by the fact that constant C/N and Chl/N ratios are implemented in the model.

1 Introduction

Physical ocean forecasting systems are now operational in many ocean regions (Le Traon, 2013) and in several forecasting systems biogeochemical models have been included (Edwards et al., 2012; Wan et al., 2012). Biogeochemical models are less accurate both with respect to model formulations and parameterizations, and data for validation and model evaluation are scarce. At the same time, operational systems including biogeochemical variables can supply valuable information on environmental

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indicators such as oxygen concentration, N/P ratios, and algae concentrations. Over time, they may give information on accumulated quantities, such as annual primary production and inter-annual variability in phytoplankton production. Data assimilation is also being used for improving the model predictions (Sakov et al., 2012) and for estimating unknown parameters, the assimilation of ocean color data in operational models underway.

HYCOM-NORWECOM is used as a part of the operational system for the Arctic (the Arctic Marine Forecasting Centre) implemented through the EU-FP7 supported MyOcean project. The biogeochemical forecast has been operational since the fall of 2011. In connection to the setup of the biogeochemical part of the forecasting system, a series of sensitivity runs testing alternative model formulations were performed and a subsequent update of the HYCOM-NORWECOM system was implemented. The final model formulation chosen was uploaded to the forecasting system in October 2012 and is now the operational model used. Daily values of nutrient, phytoplankton, oxygen etc can be browsed at <http://www.myocean.eu/web/24-catalogue.php> and downloaded after registration. Focal areas for this study are the Nordic Seas and the Arctic. These areas contribute to a large fraction of the world ocean carbon sink (Takahashi et al., 2009). Aside from assessing the whole model area (Fig. 1) we focus the comparison on two smaller regions, one in the Norwegian Sea, important area for the heat transport into the Nordic Seas and one in the Barents Sea, which is the area where one of the branches of Atlantic Water enters the Arctic Ocean.

Here we present the previous and updated version together with the sensitivity simulations leading up to the revised version. The model results are evaluated against an in-situ dataset for the Norwegian Sea and the statistical results are presented. The HYCOM-NORWECOM model was tested against in-situ data, satellite data, and climatologically nutrients, however we found that the in-situ data was the most instructive and the tuning relied most heavily on these data when making the upgrade. Statistical measures of the models performance for each of the parameter sets were calculated in sub-regions as well for the entire area.

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2 Methods

2.1 Model description

HYCOM-NORWECOM is a coupled physical biological modelling system. HYCOM (V2.2.12), the HYbrid Coordinate Ocean Model (Bleck, 2002), is an ocean model using hybrid coordinates; isopycnal coordinates in the deep stratified waters, and z level coordinates in the upper mixed layer. A description of this setup of HYCOM can be found in Sakov et al. (2012) and user guides for the different versions of HYCOM are available online at <http://hycom.org/hycom/documentation>. HYCOM is routinely used for forecasting and the forecasts are compared to in-situ and remote-sensing observations of salinity temperature and sea ice on a regular basis (<http://myocean.met.no/ARC-MFC/V2Validation/index.html>). Comparisons between observations, free-runs (used in this study) and assimilative runs can be found in Sakov et al. (2012) and Samuelsen et al. (2009a). NORWECOM (Aksnes et al., 1995; Skogen and Søliland, 1998) is currently run with 11 variables: nitrate, phosphate, silicate, diatoms, flagellates, micro- and meso-zooplankton, nitrogen detritus, phosphorous detritus, biogenic silica and oxygen (Fig. 2). The micro- and meso-zooplankton were recently added and use the formulations and parameters defined in ECOHAM (Pätsch et al., 2009; Stegert et al., 2009). The coupling of NORWECOM towards HYCOM was first done in 2005 and has been used for several studies in the Norwegian Sea and North Atlantic (Hansen et al., 2010; Samuelsen et al., 2009b). River nutrients were derived from output from the GlobalNEWS model (Seitzinger et al., 2005). An overview of the different version can be found in Table 1.

The complete description of the NORWECOM as of 1998 can be found in the user guide (Skogen and Søliland, 1998), below we provide a description of the changes of the model presented here compared to that version. With regards to nutrient limitation the original version applied a multiplicative relationship for the total growth (μ_{phy}) of

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phytoplankton:

$$\mu_{\text{phy}} = \mu_{\text{max}} \times \text{Rad_lim} \times \prod_{i=1}^n \text{Nut_lim}_i \quad (1)$$

Where μ_{max} is the maximum growth rate, Rad_lim is the growth limitation due to light and Nut_lim_{*i*} is the growth limitation for nutrient *i*. In the current version it is the minimum of the limitation factors that determine the growth:

$$\mu_{\text{phy}} = \mu_{\text{max}} \times \min(\text{Rad_lim}, \text{Nut_lim}_{i,i=1,n}) \quad (2)$$

Except when growth is not limited, Eq. (1) will give a smaller growth rate than Eq. (2) since the value of the limitation of light and nutrients are always between 0 and 1.

As in the version from 1998 (Skogen and S¸oiland, 1998), the main distinction between diatoms and flagellates in NORWECOM is that diatoms consume and is limited by silicate in addition to phosphate and silicate. Diatoms have higher maximum growth rate than flagellates (Table 2), but the temperature-dependence for growth is the same. The half saturation constants for nitrate and phosphate are smaller for flagellates ($K_N = 1.5 \text{ mmol m}^{-3}$ and $K_P = 0.094 \text{ mmol m}^{-3}$) than for diatoms ($K_N = 2.0 \text{ mmol m}^{-3}$ and $K_P = 0.125 \text{ mmol m}^{-3}$).

In HYCOM-NORWECOM, the region of focus was moved from primary being used in the North Sea to the Norwegian Sea, therefore the extinction coefficient due to water and non-chlorophyll substances was reduced from 0.07 to 0.04 (Hansen and Samuelsen, 2009).

The original NORWECOM did not include zooplankton, but now there is an option of running the model with two zooplankton components, microzooplankton and mezo-zooplankton. The formulations for zooplankton are the same as ECOHAM v4 (P¸atsch et al., 2009), but modified to adjust for differences in the food-web structure. In HYCOM-NORWECOM, the mortality rate for phytoplankton independent of grazing is 0.035. When zooplankton is excluded, a quadratic relationship representing both grazing and

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other causes of mortality is used. Zooplankton grazing (G) by a size-class of zooplankton (Z) on a specific food source (fs) is described by:

$$G_{fs,Z} = \frac{T_{fac}g}{k + \sum P_{fs,Z}fs} fs \times Z \quad (3)$$

Here, T_{fac} is the temperature dependence $T_{fac} = 1.5^{\frac{T-T0}{10}}$, where T is the local temperature and $T0$ is set to 10°C , g is the maximum grazing rate (0.4 day^{-1} for mesozooplankton) and k is the half saturation constant for zooplankton grazing which is set to 1 mmol N m^{-3} for both size classes of zooplankton.

$$P_{fs,Z} = \frac{pi_{fs,Z}fs}{\sum pi_{fs_i,Z}fs_i} \quad (4)$$

where pi_{fs} are the grazing preferences for the different food sources, the grazing preferences for microzooplankton can be found in Table 2, while the preferences for mesozooplankton are 0.45 for diatoms and 0.275 for both microzooplankton and detritus.

The assimilation efficiency for both size-classes of zooplankton is set to 0.75 (Pätsch et al., 2009) and the mortality (M_Z) is also formulated as a half saturation relationship:

$$M_Z = \mu_Z \frac{Z}{k_m + Z} \quad (5)$$

where the half saturation constant k_m is $0.2 \text{ mmol N m}^{-3}$ for both size classes of zooplankton. For the loss terms of zooplankton 90 % of the material goes into the detritus pool and 10 % is returned to nitrate.

2.2 Experiment setup

The tuning was done on a coarser grid (30–50 km) than the 15 km grid (Fig. 1) used in the operational runs, this limited the computational costs for the sensitivity simulations

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considerably, as the 15 km model takes about 5 times as long to run. In all, 16 sensitivity simulations were performed with the coarse model (simulation names starting with N) and the parameter changes in each run are summarized in Table 2 and the location of the relevant code is given in Table 3. In order to assess the effect of the revised parameters on the model grid that are being used in the forecasting system, two simulations were also performed with the higher resolved grid (simulation names starting with TP); the original parameters and optimized parameters. The model was started from climatological nutrient values and constant low values for the other variables in 1993. In order to spin up the model, it was then run with the original parameters from 1993–1995. The sensitivity simulations were initiated in 1996 and run for a 6 year period. The impact of a single parameter or model formulation change was investigated in 11 sensitivity simulations. Subsequently the impact of five different combinations of these alterations was studied. Model-data comparisons were performed in the period 1998 to 2001 because of relatively good in-situ data coverage combined with availability of ocean color data in this period.

The data to be compared to in-situ data was extracted from the model from files containing daily averages. The modeled values from the grid box and model layer containing the observation point on the day of the observation were selected. The model data was not interpolated temporally or spatially. In the case that there were several observations within the same grid cell and layer, the mean of the observed values was used. One caveat should be mentioned in connection to the modeled chlorophyll: the model assumes constant N/Chl ratio ($11 \text{ g N g}^{-1} \text{ Chl}$ in the control run), and chlorophyll is therefore a diagnostic field from the model and not actually predicted by the model.

2.3 Description of data

A dataset collected as a part of the Norwegian Institute of Marine Research monitoring activities was used. In addition to comparing the simulations to the entire dataset, we also focused the comparison on two sub-regions; one in the Norwegian Sea and one the Barents Sea (Fig. 3). The available in-situ data relevant to the NORWECOM

model are nutrients (silicate, nitrate, nitrite and phosphate) and chlorophyll, obtained by analysis of discrete water samples. Because we only have one type of nitrogen nutrient source in the model, the modeled nitrate was compared to the sum of observed nitrate and nitrite. The Norwegian Sea sub-region includes Station M and thus data is available throughout the year for all of the variables, while in the Barents Sea data are collected primarily during August and September (Fig. 3).

2.4 Statistical method for model evaluation

In the paper by Allen et al. (2007), several metrics for evaluation of biogeochemical models were presented. In this study, a combination of two of these metrics was used for the comparison between the model simulations and data; the model efficiency (ME) and percentage model bias (Pbias). These statistical quantities are defined in the following way:

$$ME = 1 - \frac{\sum_{n=1}^N (D_n - M_n)^2}{\sum_{n=1}^N (D_n - \bar{D})^2} \quad (6)$$

where D_n are the observations, M_n are the model estimates and \bar{D} is the mean of the observations. The model efficiency is a measure of the model-data misfit in relation to the variability of the data.

$$Pbias = \frac{\sum_{n=1}^N (D_n - M_n)}{\sum_{n=1}^N D_n} \times 100 \quad (7)$$

Pbias gives an indication on whether the model consistently under- or overestimates compared to the data.

In addition, SD, correlation coefficient and the variance of chlorophyll and nutrients were evaluated in Taylor diagrams (Taylor, 2001) that show the overall quality of the runs.

2.5 Code availability

The full model code is available at https://svn.nersc.no/hycom/browser/HYCOM_2.2.12/CodeOnly/src_2.2.12/. The code is continually under development and version control is used when updating the code, so the version used for in the reference run, which were performed in October 2011 is revision number 186, while the updated version of the model after the tuning is revision number 224.

3 Results

3.1 Performance of control runs

The model efficiency showed that the results from the control runs with the original parameters (N00 and TP0) were in general good with respect to nutrients (Fig. 4). The model performance was better for nitrate and phosphate than for silicate. In terms of ME for the nutrients there is little difference between the coarse and the fine model. The percentage bias is also similar in the two control runs and again the estimates of nitrate and phosphate have higher skill compared to silicate (Fig. 5). The bias is positive, meaning that the modelled nutrients are consistently lower than the observed nutrients (Eq. 7). The nutrient bias is slightly better in the high-resolution model than the coarse model (not apparent in the figure). Below 500 m, the nutrients are excellent in terms of bias. However, since the observed nutrients have low variability below 500 m the ME shows no skill. Above 500 m, the biases are generally poorer, while the model shows some skill in terms of predicting the observed nutrients, as shown by the ME. Silicate has no skill in the years 1999 and 2000.

The prediction of the chlorophyll content is even more challenging than for the nutrients. Hereby the original model shows no skill for the ME for both runs (Fig. 4) and large negative percentage biases (Fig. 5), meaning that the model consistently overestimates the chlorophyll. Correlation between the observed and modelled chlorophyll is

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poor and the amplitude of the annual cycle is overestimated. We have also observed that the model runs are consistently late in the spring bloom, a persistent feature in this model system (Samuelsen et al., 2009b). In addition the model overestimates the chlorophyll during the summer on both model grids, which causes the large bias and negative model efficiency.

3.2 Parameter alterations

As seen in Sect. 3.1, the main challenge of the model lies in the overestimation of chlorophyll during the summer months. Many of parameter changes were thus aimed at reducing the error in the phytoplankton fields, but as seen in Figs. 4 and 5 many of the changes had a positive influence on the simulated nutrient values as well. The original and new model formulations and parameter values of all the sensitivity simulations are listed in Table 2.

The first run, N01, had quadratic rather than linear mortality rate of phytoplankton, this change was aimed at increasing the phytoplankton losses during periods with high phytoplankton biomass. This alteration had little effect on the results, nevertheless it was also tried in combination with other parameter changes, N07 and N13, but no improvement was observed, therefore this alteration was not included in the final model formulation.

In nature, a wide range of Si : N ratios are observed in diatoms (Sarhou et al., 2005), therefore the second and third run, N02 and N03, altered the fixed uptake ratio of Si : N for diatoms, by decreasing and increasing this value by 25 % respectively. In the control runs the model tended to consume all the silicate before nitrate in the spring, while this was not the case in the observations. A reduction in this ratio improved the modelled silicate in terms of model efficiency, while estimates of nitrate and phosphate gets reduced skill. This change however, reduced the summer chlorophyll concentrations, most likely because the spring diatom bloom consumed more nitrate, which is the limiting nutrient during the summer bloom. Increasing the ratio had the opposite effect.

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Because large flagellate summer concentration has been a recurring challenge in the model the reduced Si : N ratio was retained in some of the subsequent runs.

The next three sensitivity simulations explored alterations to the zooplankton mortality term; quadratic mortality (for both zooplankton size classes) – N04, increased and decreased mesozooplankton mortality – N05 and N06. These alterations had little effect on the error statistics and were not considered in any of the subsequent runs.

Three runs where the sensitivity to the choice of nitrate to chlorophyll ratio was investigated. The first (N08) was a simple increase by 25 %, while the values of 12.5 (N09) and 6.3 (N10) were found in the literature (Foulland et al., 2007; Yentsch and Vaccaro, 1958). The alteration had little effect on the overall results, even on chlorophyll. This was a bit surprising, but also reassuring that the model is not too sensitive to the choice of this parameter, as in the North Atlantic values varying from 1 to 12.5 was found in the literature (Foulland et al., 2007; Yentsch and Vaccaro, 1958).

Motivated by the observation that diatoms can be consumed by microzooplankton (Sarhou et al., 2005) we made an experiment where diatoms were included in the diet of microzooplankton (N11). The microzooplankton grazing rate was also increased (N12). These runs, especially N12, had a negative effect on the silicate results, but a positive effect in the nitrate and phosphate. These changes also contributed to better results for the chlorophyll. The increased microzooplankton grazing rate resulted in improved performance of the model and it was the first simulation where the biases in 1998 and 1999 were better than “Poor”.

From the above simulations we learned that reduction of the Si : N ratio and microzooplankton grazing were the changes having the most positive impact on the model performance. Since these changes to zooplankton grazing negatively affected the silicate results, this alteration was combined with the reduction of the Si : N ratio in simulations N14 and N15. The run including diatoms in the microzooplankton diet was combined with reduced Si : N ratio in run N14, this only improved the silicate results. When these changes were also combined with increased microzooplankton grazing (N15) the results for all nutrients improved. In the last experiment, N16, a reduction of

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the maximum growth rate for both types of phytoplankton were added to N15, this had an additional positive effect on the chlorophyll errors. The parameter set in N16 was decided upon and studied in the high-resolution model.

3.3 Assessment of revised model simulation

5 The original and revised run were compared in two sub regions; the Norwegian Sea and the Barents Sea. In these two regions the sampling was better than in other regions, in the Norwegian Sea there are data throughout the year, while in the Barents Sea, each season is sampled in addition to an extensive survey in August/September (Fig. 3). Overall the regional estimates were worse than the ones including all data.

10 The results show that in terms of Pbias, nutrients were more improved in the Barents Sea than in the Norwegian Sea (Fig. 6). The model efficiency shows improvement in the estimates of all three nutrients for both regions (Fig. 7). Chlorophyll remains below “no skill” in the Barents Sea, while it shows an improvement from “poor” to “very good” in some years in the Norwegian Sea (Fig. 7). The difference between the original and revised run in terms of chlorophyll is summarized in a Taylor diagram (Fig. 8). This Taylor diagram show that overall the new runs are in better agreement with the data, the improvement is mostly in terms of reduced standard error (green dashed curves). The amplitude is improved in the Norwegian Sea, but for all data it is now too low. There are only small differences in the correlation coefficients.

20 To assess the revised run at different depths, profiles in the upper 1000 m of the water column have been compared to in-situ data for nutrient and chlorophyll (Figs. 9 and 10). The winter nutrient profiles show a clear improvement, although they are consistently lower than the observed concentration. While the revised run is closer to the observed values for all three nutrients, especially silicate has a mean very close to the observed during the winter months. Phosphate and nitrate has a systematic deep bias during winter. In April there is a clear indication in the observations that nutrients are being consumed in the upper layers, this is not the case in either of the model runs, and consistent with the modeled surface chlorophyll values that are lower than observed

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in this period. The late onset of the spring bloom has been a persistent challenge in the model for several years (Samuelsen et al., 2009b) and seems to be related to delayed onset of stratification in the physical model fields, rather than the biological formulations. The comparison also show that the new set of parameters does not only influence the nutrients close to the surface, but also in the deeper water column where one may expect physical (advection) processes to control the nutrients on the time scale we are considering here $O(\sim 10 \text{ year})$.

4 Discussion

A total of 18 sensitivity runs including control runs were performed, on the higher-resolution and coarser model grid. First, the effect of tuning of single parameters, such as mortality for phytoplankton and zooplankton, Si : N ratio, N : Chl ratio and grazing preference for zooplankton was studied. Second, the tuning of combinations of parameters, for instance grazing preference and mortality rate, were tested in the coarse model. The conclusion was that the best results were obtained when a combination of grazing preference for microzooplankton, Si : N ratio in diatoms and reduced growth rate for phytoplankton was used. This combination of parameters was then changed in the higher-resolution model and the effects of changing parameters were investigated there as well. Also in the higher-resolution model grid the simulations with revised parameters show improvements for nutrients and chlorophyll.

4.1 Uncertainties connected to validation

In general, the quality of the measurements depends on how often it is measured – i.e. the uncertainty decreases when the number of observations increases. It is however different requirements for geographical coverage, number of stations and frequency depending on the different issues addressed, parameters measured and the area complexity (e.g. Ottersen et al., 1998). For example, for observing changes in the deep

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ocean, taking measurements one or a few times a year is enough, there are however large claims to the accuracy of these observations. In comparison, the coastal areas and surface waters needs to be measured substantially more often in order to capture the variability, but the requirements to accuracy can often be relaxed.

Actual programs on in situ monitoring of the biogeochemical environment are mainly carried out by manual sampling and subsequent analysis along with regularly monitoring cruises onboard Research Vessels or by stationary measuring systems like buoys. Monitoring cruises are very cost intensive, and therefore restricted in spatial and temporal coverage, hence limiting the availability of high quality observational data. In addition to the spatial and temporal limitation of the observations the measurement methodologies especially for the biogeochemical parameters is an issue in terms of uncertainty of the specific measurement (i.e. Proctor and Roesler, 2010).

Exemplary for the variety of biogeochemical measurements we outline here the challenges connected to the measurements of Chl *a* concentration, which are performed by analyzing filtered water samples by using e.g spectrophotometer or HPLC. By nature this method requires laboratory equipment and manual interaction and is therefore very costly. A range of autonomous sensors has been designed to overcome these limitations. The sensors measure the Chl *a* fluorescence, which is used to provide an estimate of the Chl *a* concentration (fluorometer Chl *a*, $\mu\text{g L}^{-1}$). When comparing the ratio between fluorometer Chl *a* and HPLC Chl *a* (w:w), we find that this is not constant and may vary with a factor 3–4 depending on the light regime, shading effects and the species composition of the samples. Similar challenges exist for the methodologies of the nutrient content of the water column.

On top of the uncertainties connected to the observed data themselves, when comparing to model results there is an added uncertainty in what the data represent. One measurement may represent the value in a few litres of water, while the model value represents the value in $\sim 10^9 \text{ m}^3$ of water, more or less depending on the model resolution.

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4.2 Parameter changes

Since the chlorophyll values in the control run were systematically too high, most of the parameter changes were included to reduce the phytoplankton biomass during summer. Parameter alterations were conducted to study the sensitivity of the results, including different Si : N ratios or the inclusion of diatoms in the diet of microzooplankton to display the variety of properties reported in the literature. Several of the parameter alterations investigated had very little impact on the results of the model. Quadratic, rather than linear, mortality in the phytoplankton was one of the changes that had little effect while a change in the grazing rates had a large effect indicating that the phytoplankton in this model system is largely controlled by zooplankton grazing rather than other sources of mortality.

Changes in the zooplankton mortality also had little effect on the results, this is the closure term in the model and it is a bit surprising that this term only had a small effect on the model results. Changes in the grazing term makes the large impact on the model results, this probably means that zooplankton is more controlled by food availability than other mortality sources. The sensitivity of this model to the diet compositions has also been shown in a more theoretical study on parameter estimation by data assimilation by Simon et al. (2012).

Altering the N : Chl ratio would on one hand decrease the amount of chlorophyll per phytoplankton biomass, but on the other hand light in the model is attenuated by chlorophyll rather than phytoplankton biomass, hence when this ratio is lower, light penetrates further down in the water column and thus increasing the light available to phytoplankton at greater depths. Perhaps the combination of positive and negative effects on the chlorophyll concentration is the reason why the model is not sensitive to this parameter. Nevertheless, the change of N : Chl (which is proportional to the C : Chl ratio in this model) with light availability is now well established (Geider, 1987) and implementing a variable N : Chl ratio is one of the future developments planned for this model.

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The changes in the uptake ratio of silicate to nitrate had a large influence on the progress of both the diatom bloom and the flagellate bloom. Silicate is the limiting nutrient for diatoms, hence when lowering this ratio, more nitrate can be consumed leaving less nitrate for the flagellates and hence limiting the size of this bloom. Observed uptake ratios of Si : N vary widely and probably also varies between species, regions and seasons. Ideally a flexible uptake ratio could be included, for example as in the ERSEM model (i.e. Blackford et al., 2004), but including variable stoichiometry also increases the number of variables that has to be advected in the model and hence the computations cost considerably.

Because of computational limitations only a small subset of the parameters was tested in this tuning exercise, the parameters were picked based upon passed experience with the model, but other parameters could also have been tested. As grazing seems to be an important control mechanism in the model, the zooplankton assimilation efficiency may be an important parameter. The temperature dependence of growth and respiration for both zooplankton and phytoplankton would probably influence the progress of the blooms, but passed experience with the model has shown that this model has very little sensitivity to parameters related to phytoplankton growth, hence these parameters have been mostly left unchanged in this study. Additionally the sinking rates for detritus influence the amount of regenerated nutrients during summer.

4.3 Regional differences in performance

Evaluating the final run (TP1) compared to all data (Figs. 4 and 5) and compared to data in the sub-regions (Figs. 6 and 7) it is clear that the model performed better when it is compared to all data. Especially the bias for nutrient in the Norwegian Sea (Fig. 6) is poor in the new run. The explanation for this may lie in the placement of water masses in the model combined with the locations of the measurements. In the Norwegian Sea the majority of measurements are taken at a single location (Station M). For the model to perform well there, it needs to simulate the correct water masses at this exact point. Station M is located close to a front between two water masses, and we have seen

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that the model is not always simulating the location of this front well. In the Barents Sea most of the data are collected in sections or over the whole area during early fall, therefore some of the dependency on simulating the correct location of fronts falls away in this region. At station M phosphate and nitrate has a systematic deep bias during winter. This is also probably connected to the location of different water masses in this region.

The location of the ice front would affect the results of the biogeochemical model (Samuelsen et al., 2009a). The observations used here have not been collected from ice-breakers, so the data are primarily from open-ocean regions. Still, large error could occur if the model places the ice edge too far south. The comparison of the model simulation (free-run) to observations show that the ice-edge follows the observed pattern (Sakov et al., 2012), but we cannot rule out that some model errors occur as a result of the placement of the ice-edge. In addition, the parameterization of light through ice and the fact that we don't include ice-algae in the model are also sources of errors.

The revised run shows a severe improvement compared to the original run, particularly in terms of nutrients but also in terms of chlorophyll, but while the previous run tended to overestimate the annual cycle of chlorophyll, the revised run tends to underestimate the amplitude (Fig. 8). We have showed that the model reproduces a reasonable annual cycle, but one persistent challenge to reproduce the correct initiation time of the spring bloom. The model is consistently late in its initiation time and none of the parameter alterations significantly affected the timing of the spring bloom, this indicates that the error in timing is an effect either of the physical model or a missing process, such as for example phyto-convection (Backhaus et al., 2003). Another challenge is to show that the model also produces realistic interannual variability. The model shows less variability than the observed data, but this is also expected as the observations include a spatial and temporal variability that cannot be resolved of a model of this resolution. Finally, these models can also be improved by data assimilation, both as a mean of improving the forecast fields as a method for optimizing model parameters (Simon et al., 2012).

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We used a coarse model of the North Atlantic and Arctic to do a sensitivity study of several of the parameters in a biogeochemical model. In the process we improved the overall model results and explored the parameter sensitivity of this particular model. During the sensitivity analysis the changes that were based in observations, for example that Si : N is highly variable and that microzooplankton are grazing on diatoms, had a positive influence on the model. This suggests that perhaps greater refinement of the models in general should be done in closer collaboration with ecologist and field oceanographers.

The model is part of an operational system for the Arctic and based on the sensitivity runs and the comparisons of these to available in situ observations a new set of parameters were decided on and implemented in the operational model.

A major difference between the model runs presented here and the operational system is that the operational system includes data assimilation in the physical model (Sakov et al., 2012), which may alter the physical model and in turn alter the performance of NORWECOM. A study of the impact of data assimilation on this model (Samuelsen et al., 2009a) showed that there were typically a difference of 5–10 % for the nutrients and chlorophyll between the free run and the run with assimilation, but with difference up to 20 % in the Arctic. As newer data becomes available more improvements can be included also taking into account the effect of assimilation on the system.

Acknowledgements. This work was done with the support of the EU FP7 Project MyOcean2 (project number 283367) and the NFR funded SEASERA project SEAMAN (project number 227779/E40). A grant for CPU time was given by the Norwegian Supercomputing Project (NO-TUR2).

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Table 1. Model versions and references.

HYCOM	NORWECOM	HYCOM-NORWECOM	References
V2.2.12	V2.0	V1.0	Description: Skogen and S�oiland (1998); Examples of application: Hansen and Samuelsen (2009); Hansen et al. (2010)
V2.2.12	V2.0 + zooplankton	V2.0	Application: Samuelsen and Bertino (2011)
V2.2.12	V2.0 + zooplankton + parameter tuning	V2.1	This paper

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Table 2. Overview of runs performed with the associated parameter values.

Parameter for tuning	Original value	New value
N00 Reference run		
TPO Reference run with high resolution		
N01 Quadratic mortality for phytoplankton	$cc(3), cc(3) = 4.0E - 7$	$cc(3)/15.0 + cc(3) \times P/15.0$
N02 Si : N ratio in diatoms	$1.75 \text{ mg Si mg}^{-1} \text{ N} = 0.875 \text{ mmol Si mmol}^{-1} \text{ N}$	$0.575 \text{ mmol Si mmol}^{-1} \text{ N} = 1.15 \text{ mg Si mg}^{-1} \text{ N}$
N03 Si : N ratio in diatoms	$1.75 \text{ mg Si mg}^{-1} \text{ N} = 0.875 \text{ mmol Si mmol}^{-1} \text{ N}$	$1.175 \text{ mmol Si mmol}^{-1} \text{ N} = 2.35 \text{ mg Si mg}^{-1} \text{ N}$
N04 Quadratic mortality in zooplankton	$mju \times (z/(z + cnit \times k6)), m] = 0.2,$ $z = \text{zooplankton-conc} [\text{mg N m}^{-3}],$ $cnit = 14.01 \text{ mg N mmol}^{-1} \text{ N}, k6 = 0.2$	$mju2/5.0 + mju2 \times \text{bio}/25.0$
N05 Mesozooplankton mortality (+25 %)	$mju1 = 0.2$	$mju1 = 0.25$
N06 Mesozooplankton mortality (-25 %)	$mju1 = 0.2$	$mju1 = 0.15$
N07 Combination of N01 and N02	$cc(3), cc(3) = 4.0E - 7,$ $1.75 \text{ mg Si mg}^{-1} \text{ N} = 0.875 \text{ mmol Si mmol}^{-1} \text{ N}$	$cc(3)/15.0 + cc(3) \times P/15.0, 0.575 \text{ mmol Si mmol}^{-1} \text{ N} = 1.15 \text{ mg Si mg}^{-1} \text{ N}$
N08 N : Chl ratio	11	13.75
N09 N : Chl ratio	11	12.5
N10 N : Chl ratio	11	6.3
N11 Grazing preferences for microzooplankton	$pi21 = 0.633\text{-flagellates},$ $pi24 = 0.367\text{-detritus}$	$pi21 = 0.333\text{-flagellates}, pi21 = 0.333\text{-diatoms}, pi24 = 0.333\text{-detritus}$
N12 Grazing preferences for microzooplankton	$g = 0.5$	$g = 1.0$
N13 Combination of N11 and N1	$pi21 = 0.633\text{-flagellates},$ $pi24 = 0.367\text{-detritus} cc(3),$ $cc(3) = 4.0E - 7$	$pi21 = 0.334\text{-flagellates}, pi21 = 0.333\text{-diatoms}, pi24 = 0.333\text{-detritus},$ $cc(3)/15.0 + cc(3) \times P/15.0$
N14 Combination of N11 and N2	$pi21 = 0.633\text{-flagellates},$ $pi24 = 0.367\text{-detritus},$ $1.75 \text{ mg Si mg}^{-1} \text{ N} = 0.875 \text{ mmol Si mmol}^{-1} \text{ N}$	$pi21 = 0.334\text{-flagellates}, pi21 = 0.333\text{-diatomer}, pi24 = 0.333\text{-detritus},$ $0.575 \text{ mmol Si mmol}^{-1} \text{ N} = 1.15 \text{ mg Si mg}^{-1} \text{ N}$
N15 Combination of N14 and N12	$pi21 = 0.633\text{-flagellates},$ $pi24 = 0.367\text{-detritus},$ $1.75 \text{ mg Si mg}^{-1} \text{ N} = 0.875 \text{ mmol Si mmol}^{-1} \text{ N},$ $g(\text{micro}) = 0.5$	$pi21 = 0.334\text{-flagellates}, pi23 = 0.333\text{-diatoms}, pi24 = 0.333\text{-detritus}$ $0.575 \text{ mmol Si mmol}^{-1} \text{ N} = 1.15 \text{ mg Si mg}^{-1} \text{ N}, g(\text{micro}) = 1.0$
N16 Combination of N14 and reduced growth rate for phytoplankton	$pi21 = 0.633\text{-flagellates},$ $pi24 = 0.367\text{-detritus},$ $1.75 \text{ mg Si mg}^{-1} \text{ N} = 0.875 \text{ mmol Si mmol}^{-1} \text{ N},$ $Vmax(\text{dia}) = 1.53E - 5, Vmax(\text{fla}) = 1.02E - 5$	$pi21 = 0.334\text{-flagellates}, pi23 = 0.333\text{-diatoms}, pi24 = 0.333\text{-detritus}$ $0.575 \text{ mmol Si mmol}^{-1} \text{ N} = 1.15 \text{ mg Si mg}^{-1} \text{ N}, Vmax(\text{dia}) = 1.15E - 5,$ $Vmax(\text{fla}) = 0.76E - 5$
TP1 High-resolution run with the parameter values of N16	$pi21 = 0.633\text{-flagellates},$ $pi24 = 0.367\text{-detritus},$ $1.75 \text{ mg Si mg}^{-1} \text{ N} = 0.875 \text{ mmol Si mmol}^{-1} \text{ N},$ $Vmax(\text{dia}) = 1.53E - 5, Vmax(\text{fla}) = 1.02E - 5$	$pi21 = 0.334\text{-flagellates}, pi21 = 0.333\text{-diatoms}, pi24 = 0.333\text{-detritus}$ $0.575 \text{ mmol Si mmol}^{-1} \text{ N} = 1.15 \text{ mg Si mg}^{-1} \text{ N}, Vmax(\text{dia}) = 1.15E - 5,$ $Vmax(\text{fla}) = 0.76E - 5$

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Table 3. Location of changes in the model code, all files are located in https://svn.nersc.no/hycom/browser/HYCOM_2.2.12/CodeOnly/src_2.2.12/nersc/NORWECOM/.

	Parameter for tuning	Relevant files	Remarks
N01	Quadratic mortality for phytoplankton	m_NOR05_detritus.F: line 77–89 mod_necessary_ecovars.F90: line 45–54	ZOOPL is "defined" in all runs in this paper
N02/N03 N04/N05/N06	Si : N ratio in diatoms Meso zooplankton mortality	mod_necessary_ecovars.F90: line 45–54 m_NOR05_zoo_growth.F: line 53	For quadratic mortality, the mortality was set inside the loop calculating mesozooplankton (this code was never submitted to the subversion control system).
N07 N08/N09/N10	Combination of N01 and N02 N : Chl ratio	See above for N01 and N02 biocom.h: line 107–108	
N11	Grazing preferences for microzooplankton	m_NOR05_zoo_growth.F: line 26, 100–132	
N12	Grazing preferences for microzooplankton	m_NOR05_zoo_growth.F: line 26, 101	
N13	Combination of N11 and N01	See above for N11 and N01	
N14	Combination of N11 and N2	See above for N11 and N02	
N15	Combination of N14 and N12	See above for N14 and N12	
N16	Combination of N14 and reduced growth rate for phytoplankton	See above for N14 and m_NOR05_affin.F: line 64 and 66	

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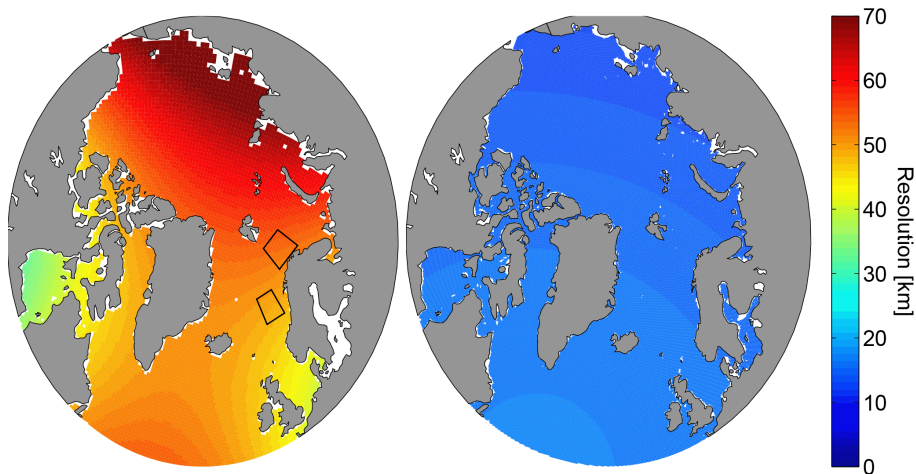


Figure 1. Resolution of the two model grids used in this study. The two areas indicated by black lines in the map to the left are the areas referred to as Norwegian Sea – southern area – and Barents Sea – northern area.

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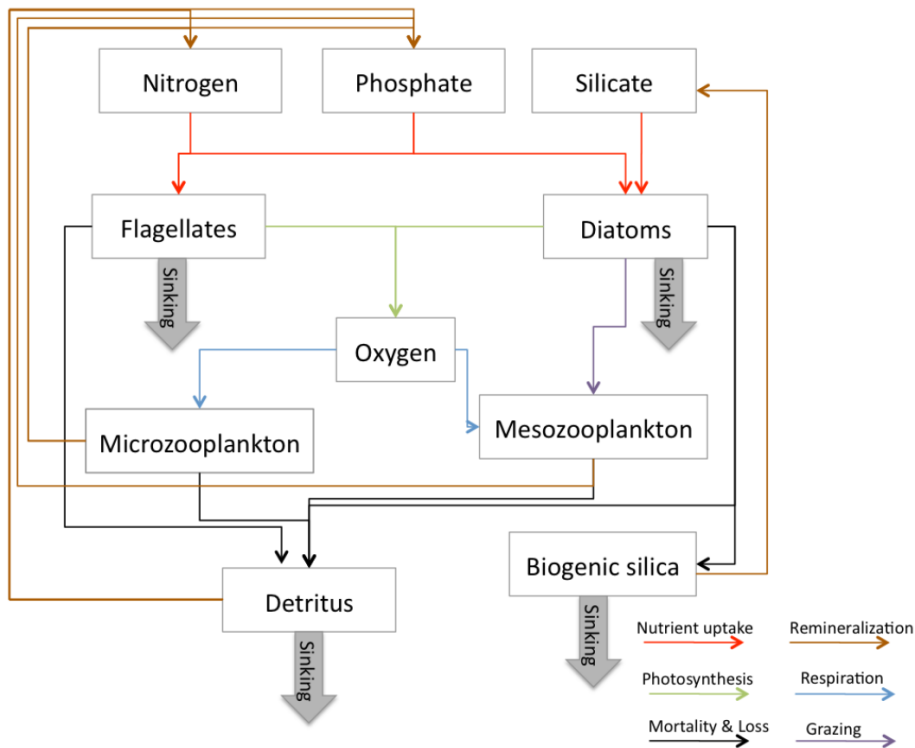


Figure 2. Flow chart of the interaction between the individual model components in NORWECOM.

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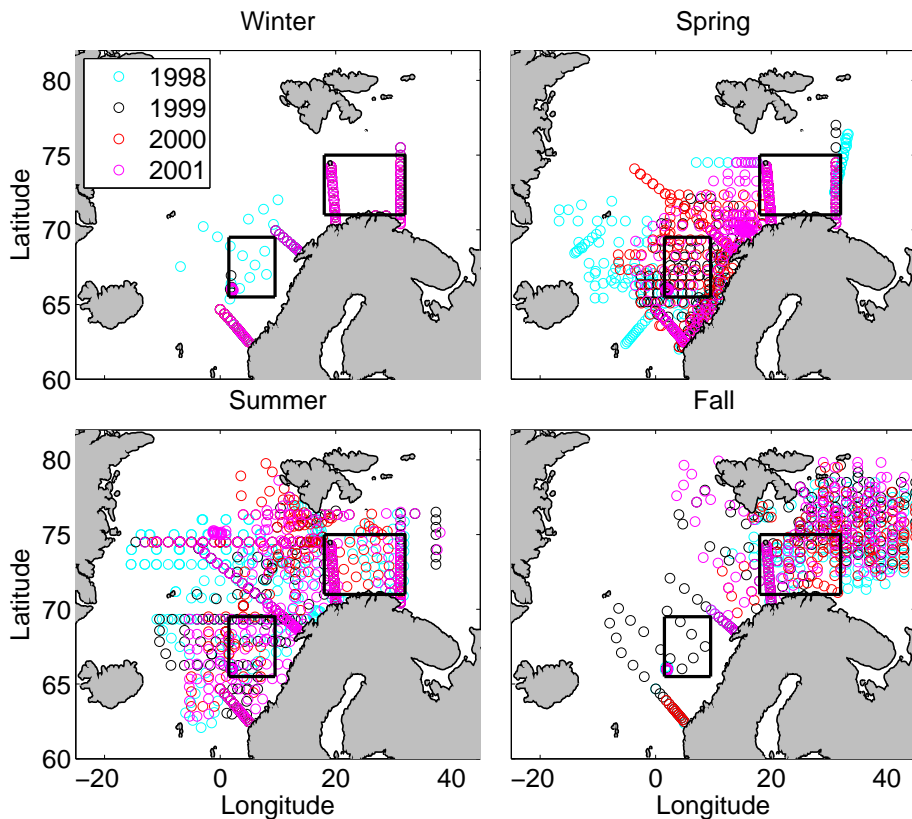


Figure 3. Spatial data coverage for nitrate in different years and seasons for the dataset used. The coverage for the other variables is similar. The southern areas are mostly sampled in summer and autumn, while the Arctic regions are more sampled in summer and fall. There are very few open-ocean measurements during winter, but in the sections visible in the winter-panel (upper, left) there are data for all years and seasons.

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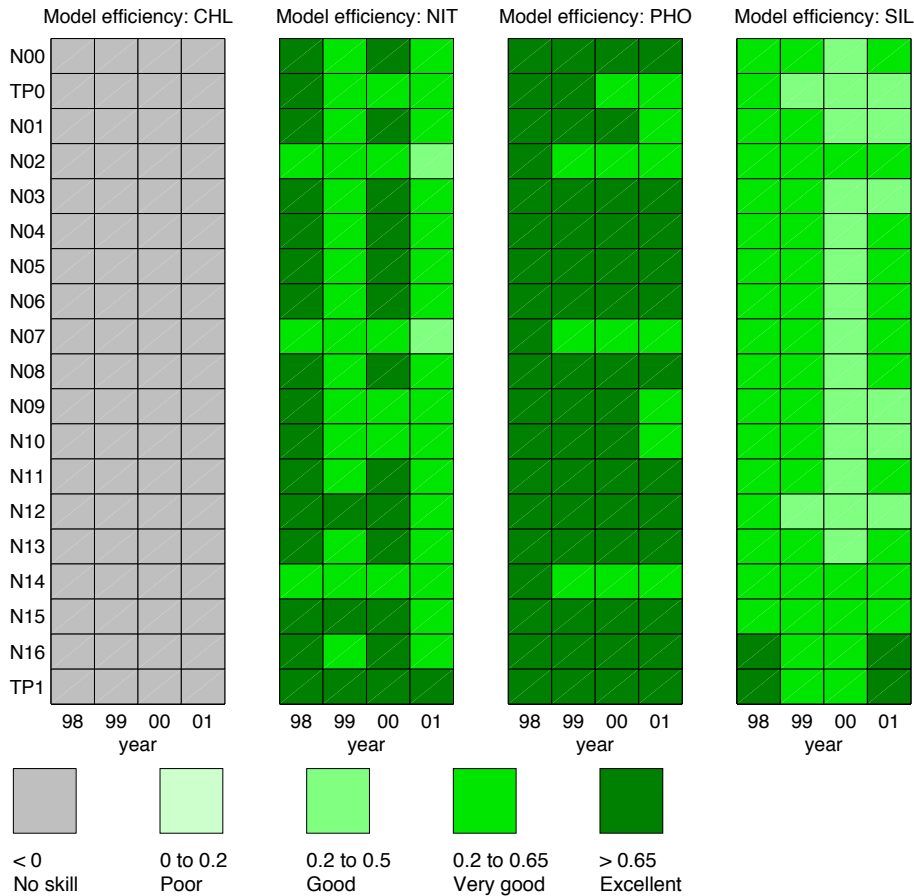


Figure 4. Model efficiency for the model compared to the entire dataset in all simulations.

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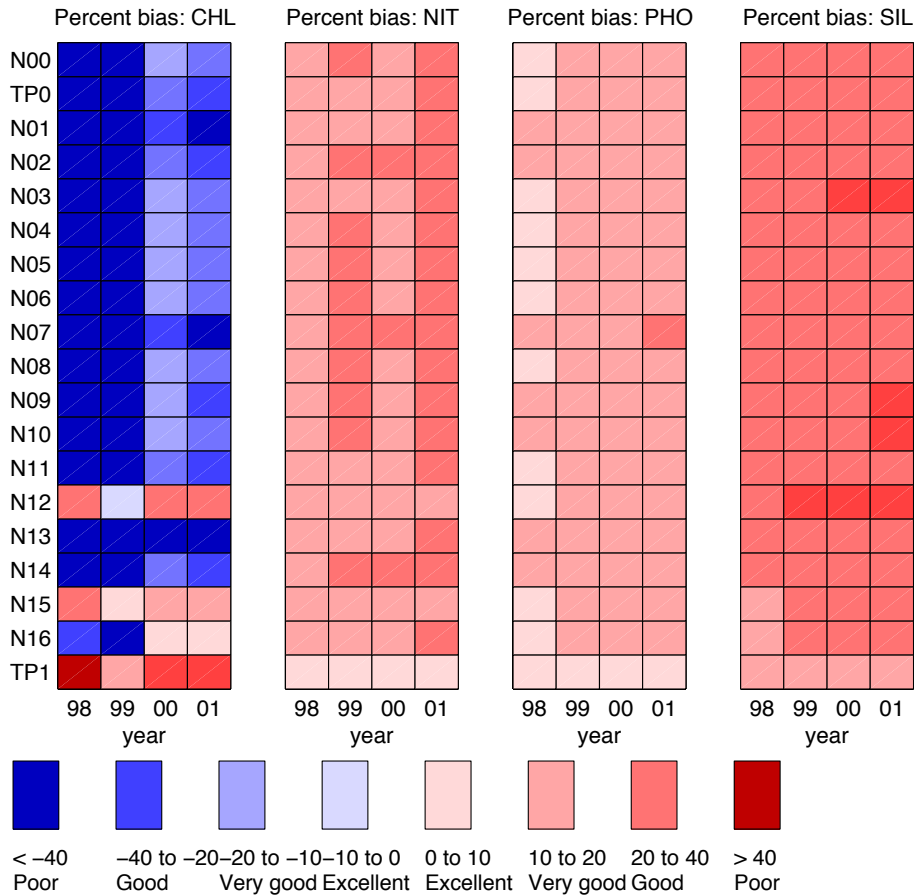


Figure 5. Percentage bias for the model compared to the entire dataset in all model simulations.

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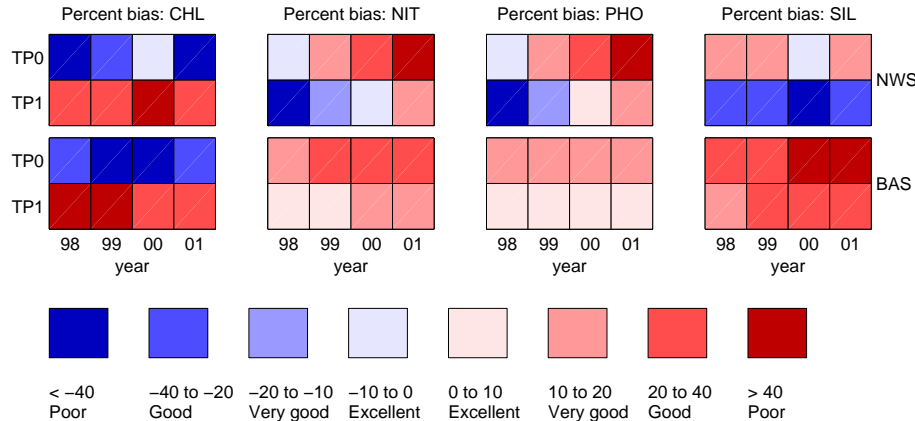


Figure 6. Percentage bias for the model compared to the dataset in the two subregions Barents Sea (BAS) and Norwegian Sea (NWS) the in different years of the simulations with the fine-scale model with the original (TP0) and final set of parameters (TP1).

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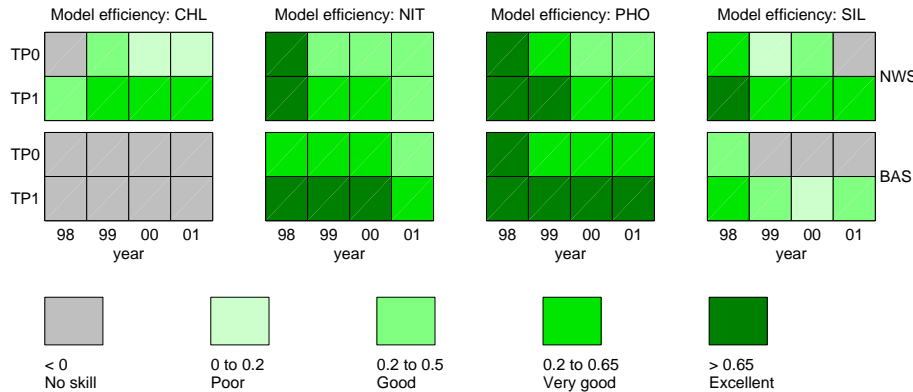


Figure 7. Model efficiency for the model compared to dataset in the two subregions Barents Sea (BAS) and Norwegian Sea (NWS) in different years of the runs with the fine-scale model with the original (TP0) and final set of parameters (TP1).

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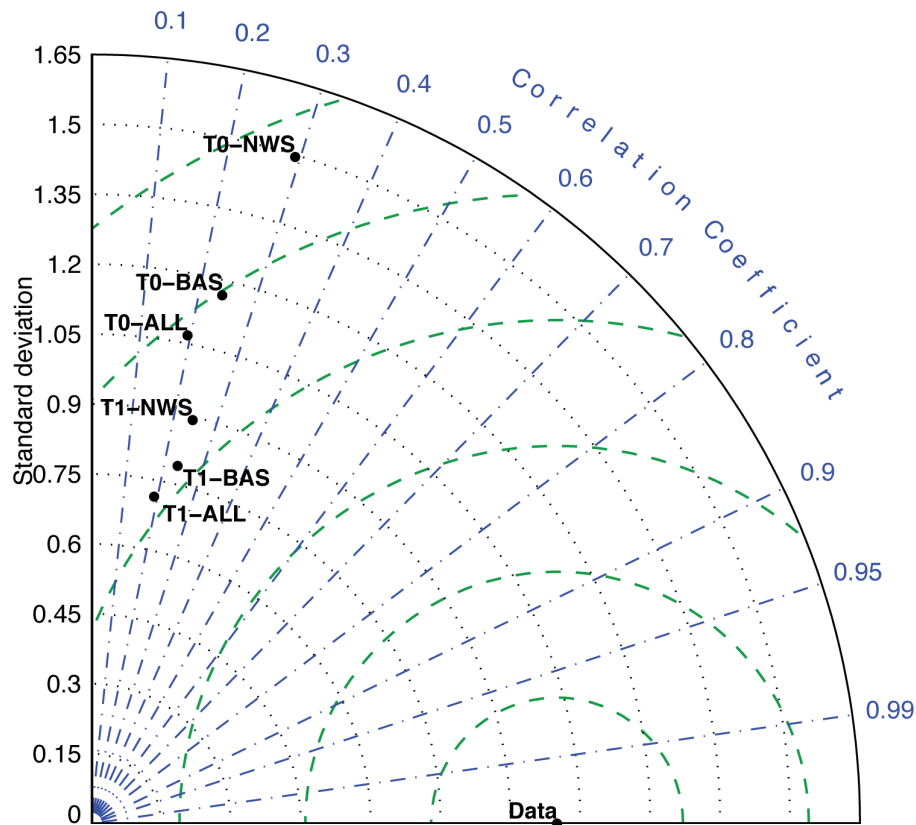


Figure 8. Taylor-diagram for comparison with in-situ chlorophyll for the entire area (ALL), the Barent Sea (BAS) and the Norwegian Sea including station M (NWS).

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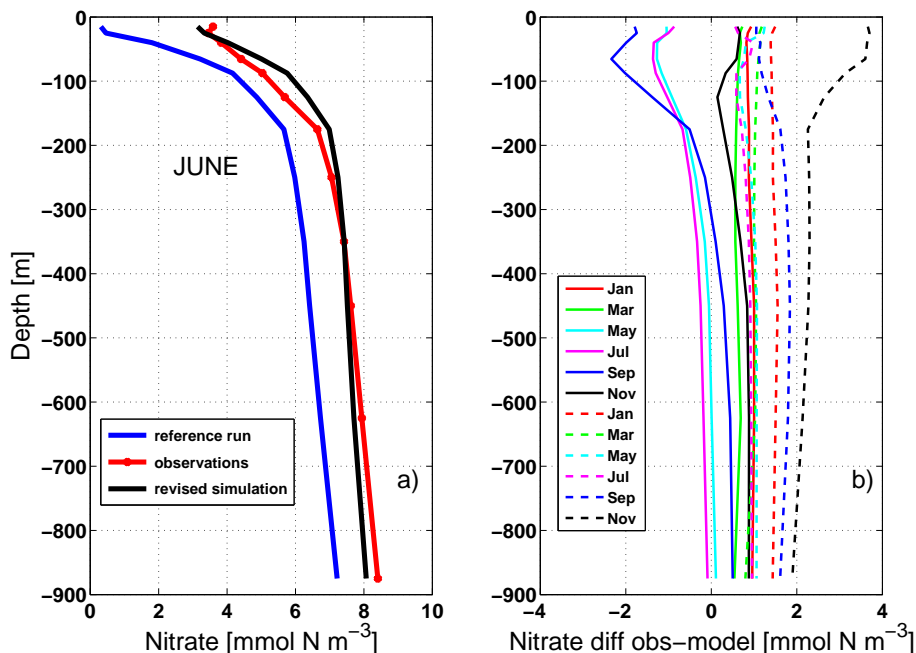


Figure 9. Nitrate profiles from the control and reference run using the higher resolution model in June (a) in the Norwegian Sea box as well the difference between observations and model in the other months (b) – solid lines are the revised simulation and dashed lines the control run. All data in the Norwegian Sea box between 1998 and 2001 have been used.

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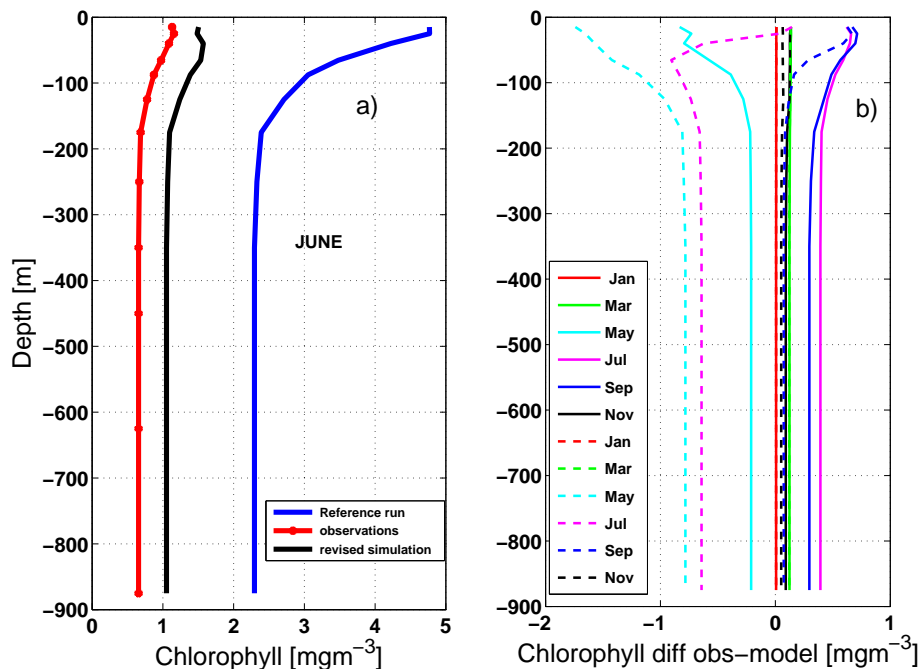


Figure 10. Chlorophyll profiles from the control and reference run using the higher resolution model in June (a) in the Norwegian Sea box as well the difference between observations and model in the other months (b) – solid lines are the revised simulation and dashed lines the control run. All data in the Norwegian Sea box between 1998 and 2001 have been used.

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