Editor (regarding including NORWECOM user guide as supplementary material): Thank you; this will be helpful; it might help if you edit the text so it's a little clearer that this is actually included - e.g. "this is included as supplementary material" on page 4 of the text.

Relpy: we followed your suggestion on line 26-29, page 3: “The complete description of the NORWECOM V2.0 can be found in the user guide (Skogen and Søiland, 1998), included as supplementary material. Below we provide a description of the differences in the biogeochemical formulations in HYCOM-NORWECOM here compared to that version. ”

Editor: Supplementary Figure 1 would be a good addition to the manuscript's main text; any chance it could be moved into the main body?

Reply: We moved this figure into the main body of the text as figure 3 and adjusted the text accordingly.

Editor (regarding figure showing zooplankton mortality): The figure quality is somewhat poor here; also, could you perhaps indicate the range of zooplankton abundance on the plot so that readers can more clearly see that the mortality functions are not significantly different at these abundances?; this could be done in the caption, but might be better on the plot itself

Reply: We improved the quality by using thicker lines, in addition we shaded in a range of common zooplankton values in the figure. We also included this text in the figure label: ’The gray shading indicates the range of common values for zooplankton concentration. This range was determined by computing the 10th and 90th percentile values for the monthly mean micro- and mesozooplankton fields of the reference run - NA0 - in the period 1998-2001. Then the minimum of the 10th percentile values and the maximum of the 90th percentile values were used as the range of common values.

Editor (regarding phyto-convection): The abstract of the Backhaus et al. (1999) paper says "In shelf seas and coastal areas, as well as in fjords, deep sinking is prohibited by the proximity of the sea bed"; I interpret this to support my rewording but a tweak to my proposed text could be to say "... by phytoplankton entrained typically from the shallow …"

Reply: While you are right in Backhaus et al, 1999 it was named the sentence you are referring to in the abstract, the 2003 paper extend the hypothesis to the open ocean and we are therefore hoping that you are accepting, to stay with the sentence as it is in the text including the 2003 reference.

Tuning and assessment of the HYCOM-NORWECOM V2.1 biogeochemical modeling system for the north Atlantic and Arctic Ocean

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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, have 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 model 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 (~15km) 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 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 processes in the ocean are less well understood than those of physics, and model formulations and parameterizations are correspondingly less well developed or constrained. Additionally, relative to ocean physics, there are fewer observational data for the validation and evaluation of modelled biogeochemistry. At the same time, operational systems including biogeochemical variables can supply valuable information on environmental 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 is 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 where one of the branches of Atlantic Water enters the Arctic Ocean.

Here we present HYCOM-NORWECOM V2.0 and V2.1 together with the sensitivity simulations leading up to the V2.1 (Table 1). 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 local in-situ observations and derived gridded climatology of nutrients, as well as satellite data. However, we found that the in-situ data was the most instructive and the tuning relied most heavily on this dataset 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.

2 Methods

2.1 Model description

HYCOM-NORWECOM is a coupled physical biological modeling 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 predictions are regularly evaluated using in-situ and remote-sensing observations of salinity, temperature and sea ice (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. (Samuelsen et al., 2009a). NORWECOM (Aksnes et al., 1995; Skogen and Søiland, 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 and Kühn, 2008; 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). An overview of the different version can be found in Table 1.

The complete description of the NORWECOM V2.0 can be found in the user guide (Skogen and Søiland, 1998), included as supplementary material. Below we provide a description of the differences in the biogeochemical formulations in HYCOM-NORWECOM here compared to that version. With regards to nutrient limitation the NORWECOM V2.0 applied a multiplicative relationship for the total growth (μ_{phy}) of phytoplankton:

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$$\mu_{phy} = \mu_{\max} \times \mathrm{Rad\_lim} \times \prod_{i=1}^{n} \mathrm{Nut\_lim}_i \quad (1)$$

Where μ_{max} is the maximum growth rate, Rad_lim is the growth limitation due to light and $\mathrm{Nut\_lim}_i$ is the growth limitation for nutrient *i.* In HYCOM-NORWECOM it is the minimum of the limitation factors that determines the growth:

$$\mu_{phy} = \mu_{\max} \times \min\left(\mathrm{Rad\_lim}, \mathrm{Nut\_lim}_{i,i=1,n}\right) \quad (2)$$

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

As in NORWECOM V2.0 (Skogen and Søiland, 1998), the main distinction between diatoms and flagellates in NORWECOM is that diatoms consume and is limited by silicate in addition to phosphate and nitrate. Diatoms have higher maximum growth rate than flagellates (Table 2), but the temperature-dependence for growth is the same, following Eppley (1972). The half saturation constants for nitrate and phosphate are smaller for flagellates (K_N=1.5 mmol/m^3 and K_P=0.094 mmol/m^3) than for diatoms (K_N=2.0 mmol/m^3 and K_P=0.125 mmol/m^3). The model assumes constant N/Chl-ratio (11 g N/g Chl in the control run).

NORWECOM V2.0 was primarily applied to the North Sea, while HYCOM-NORWECOM, focused the open ocean regions of the North Atlantic, therefore the extinction coefficient due to water and non-chlorophyll substances was reduced from 0.07 to 0.04 (Hansen and Samuelsen, 2009).

NORWECOM V2.0 (Skogen and Søiland, 1998 - supplementary material) did not include zooplankton, but now there is an option of running the model with two zooplankton components, microzooplankton and mezozooplankton. The formulations for zooplankton are the same as in ECOHAM (Pätsch and Kühn, 2008), 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 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:

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

Here, T_{fac} is the temperature dependence $T_{fac} = 1.5^{\frac{T-T0}{T0}}$, 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 0.5 day^{-1} for microzooplankton) and k is the half saturation constant for zooplankton grazing which is set to 1 mmolN/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 rate (M_Z) is also formulated as a half saturation relationship:

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

where m_z is the maximum mortality rate (0.2 day^{-1}) and the half saturation constant k_m is 0.2 mmolN/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 to limit the computational cost, as the 15-km model takes about 5 times as long to run. The model was forced by the ERA-Interim (Dee et al., 2011) from 1989 and ERA40 (Uppala et al., 2005) for the period prior to 1989 (only spinup). The physical model was initialized from rest with climatological temperatures and salinity from the GDEM (Carnes, 2009). The biogeochemical model was initialized from climatological nutrients and oxygen values from the Worlds Ocean Atlas (WOA2001: Conkright et al., 2002)and constant low values for the other variables in 1993. Throughout the run relaxation back to climatological temperature, salinity, nutrients and oxygen was applied at the lateral boundaries. A weak relaxation of salinity (relaxation timescale of 200 days) was also applied at the surface. River nutrients were derived from GlobalNEWS model output (Seitzinger et al., 2005). 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 A1. In order to assess the effect of the revised parameter set on the 15-km model, two simulations were performed; one with the with the higher resolved grid (simulation names starting with TP); the original set of parameters (TP0) and one with revised set of parameters (TP1). 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. During the spin-up there was an adjustment of basin-averaged silicate of about 0.2 mmol/m^3 during the first year, followed by a decreasing trend of about 0.2 mmol/m^3 per decade that continues throughout the model run. For the basin-averaged nitrate and phosphate there are no initial adjustments, but throughout the run there are decreasing trends of less than 0.1 mmol/m^3 and 0.004 mmol/m^3 per decade respectively. The drift in the North Atlantic and the Norwegian Sea and Barents Sea boxes (Fig. 1) are larger than for the entire domain (Fig. 3). The largest changes are at depths from 100 to 500 meters and the same reduction of nutrients is seen in the surface values during winter. There is a small reduction in maximum phytoplankton over time, but primary production shows no drift (Fig 3). The basin-scale drift of nutrients was investigated previously in a 50-year run with HYCOM-NORWECOM V1.0 on the coarse model grid also used in this study. There was a small drift for the concentration of all three nutrients of ~0.1 mmol/m^3 for nitrate (increase) and silicate (decrease) and a ~0.01 mmol/m^3 decrease of phosphate (Hansen, 2008), therefore we do not anticipate that this drift will subside with time and conclude that three years spin-up is sufficient for the system. 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-observation comparisons were performed in the period 1998 to 2001 because of relatively good in-situ data coverage combined with availability of ocean colour data in this period.

The model results 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 results were not interpolated temporally or spatially. In the case of several observations within the same grid cell and layer, the mean of the observed values was used.

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2.3 Description of observations

An observational 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. 4). 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 observational data are available throughout the year for all of the variables, while in the Barents Sea observations are collected primarily during August and September (Fig. 4).

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2.4 Statistical method for model evaluation

In the paper by Allen et al. (2007), several metrics for evaluation of biogeochemical models were presented. A combination of model efficiency (ME) and percentage model bias (Pbias) was used for the comparison between the model simulations and observations. These statistical quantities are defined as:

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

where D_n is observation from station n, M_n is the corresponding model estimate, $\overline{D}$ is the mean of the observations, and N is the total number of stations. The model efficiency is a measure of the model-observation misfit in relation to the variability of the observational data.

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

Pbias gives an indication on whether the model results are consistently under- or overestimated compared to the observations.

In addition, standard deviation, correlation coefficient and the centered root mean square error of chlorophyll and nutrients were evaluated in Taylor diagrams (Taylor, 2001) that show the overall quality of the runs.

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. 5). 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, but the results from the high-resolution model is slightly better. 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. 6). The bias is positive, meaning that the modeled 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. Below 500 meters (not shown), nitrate and phosphate are generally excellent in terms of bias, while silicate varies from excellent to good, except for a region in the central Norwegian Sea where it is poor. However, since the observed nutrients have low variability below 500 meters the ME shows no skill in most regions. Below 500 meters the model is probably quite influenced by both initial condition and the relaxation towards climatological nutrients at the boundary, as the residence time for the deep waters is estimated to be 2-10 years (Aagaard et al., 1985). Above 500 meters, the biases are generally poorer, while the model shows some skill in terms of predicting the observed nutrients. For the upper waters masses the residence time in this region it is about 3 month (Poulain et al., 1996), hence the initial and boundary condition have limited influence there.

The prediction of the chlorophyll content is even more challenging than for the nutrients. Here the runs with the original parameter set for both resolutions show no skill for the ME (Fig. 5) and large negative percentage biases (Fig. 6), meaning that the model consistently overestimates the chlorophyll. For chlorophyll there is no consistent improvement with resolution. Correlation between the observed and modeled chlorophyll is poor and the amplitude of the annual cycle is overestimated (Fig. 7). Analyses have shown that the model

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runs are consistently late in the spring bloom, a persistent feature in this model system (Figure 3: Samuelsen et al., 2009b).

3.2 Parameter modifications

As seen in section 3.1, the main challenge of the model lies in the overestimation of chlorophyll during the summer months. Many of the parameter changes were thus aimed at reducing the error in the phytoplankton fields, but as seen in figures 5 and 6 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.

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The first run, N01, had quadratic rather than linear mortality 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 (Sarthou 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 modeled 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. 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 (Fouilland et al., 2007; Yentsch and Vaccaro, 1958). In the North Atlantic values varying from 1 to 12.5 was found in the literature (Fouilland et al., 2007; Yentsch and Vaccaro, 1958). The alteration had little effect on the overall results for nutrient, but a rather large effect on chlorophyll. In general an increase of this ratio lead to an improvement in the chlorophyll comparison and a decrease to deterioration of the model results. We did not alter this value during the tuning, but think that a mechanistic model allowing for variable N:Chl ratio should be included in the model.

Motivated by the observation that diatoms can be consumed by microzooplanton (Sarthou 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 on 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 both 1998 and 1999 were better than 'Poor' for chlorophyll.

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 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

The observations in some regions such as Station M and in the repeated sections (visible in the winter panel of Fig. 4) are collected more systematically and are more numerous than in the other regions. In the Norwegian Sea at Station M observations are available throughout

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the year, in the repeated sections each season is sampled, and an extensive survey in of the Barents Sea is done annually in August/September (Fig. 4). This should be kept in mind when comparing the performance of the run with original and revised parameters in different regions (Figs. 8 and 9). Overall the regional estimates were worse than the one including all observational data, but there are also areas where there are significant improvements. The results show that in terms of Pbias, nitrate and phosphate were improved in the central Norwegian Sea and Eastern part of the Barents Sea (Fig. 8). In the northwest of the Norwegian Sea eastern part of the Barents Sea there is little improvement, but the two latter regions only have data in specific seasons (Fig. 4). For silicate the regions where there is improvement is more intermittent, but the bias in the original run was 'poor' over most of the region, this is no longer the case. The bias for chlorophyll changes sign, but not show any regional improvement. The model efficiency shows improvement in the estimates of all three nutrients, in particular in the central Norwegian Sea where the results were initially not so good (Fig. 9). Chlorophyll remains below 'no skill' in the most of the domain, except for a few places in east and north part of the domain, where it is 'good' (Fig. 9). Most of the differences between the two runs occur in the upper 100 meters. Processes in the deeper layers are slower and therefor we do not expect impacts by the parameter alterations in the biogeochemical model on the time scale of the model simulation period. The difference between the original and revised model run in the Norwegian and Barents Sea (boxes in Fig. 4) in terms of chlorophyll is summarized in a Taylor diagram (Fig. 7). This Taylor diagram shows that overall the new runs are in better agreement with the observations, the improvement is mostly in terms of reduced standard error (green dashed curves). The amplitude is improved in the Norwegian Sea, but for the comparison to all observations it is now too low. There are only small differences in the correlation coefficients, but they are overall slightly lower in the run with revised parameterizations.

To assess the revised run at different depths, profiles in the upper 1000 meters of the water column in the Norwegian Sea box have been compared to in-situ data for nitrate and chlorophyll (Figs. 10 and 11). Below 200 meters the differences from observations are similar for the two parameter sets. The same is the case for the upper 200 meters, during January and April when the water column is well mixed and the surface concentrations reflect the deep concentrations. During July the run with revised parameters is closer to the observation for nitrate, but further from the observations for silicate (Fig. S1), during October both of these nutrients are closer to the observation with the revised parameters. For

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phosphate (Fig. S2) the original run is close to the observations at the surface, but closer to the observations around 50 meters and also in the depth interval 400-800 meters. However, we have seen before that there is an overall improvement in the surface nutrients for the run with the revised model (Figs. 8 and 9). For chlorophyll (Fig. 11), it is clear that the overestimation of values that occurs with the original parameterization has now been reduced to give reasonable values. 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 in this period (not shown). The late onset of the spring bloom has been a persistent challenge in the model for several years and seems to be related to delayed onset of stratification in the physical model fields, rather than the biological formulations (Samuelsen et al., 2009b).

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4 Discussion

4.1 Uncertainties connected to observations

In general, the representativety of the measurements depends on how often it is measured – i.e. the uncertainty decreases with increasing number of observations. Depending on the issues addressed, there will be different requirements for geographical coverage, number of stations, frequency and parameters measured (Figure C1 - Ottersen et al., 1998).

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

Exemplary for the variety of biogeochemical measurements are the challenges connected to the measurements of Chl *a* concentration, which are performed by analysing filtered water samples with spectrophotometric or high-performance liquid chromatography (HPLC) methodologies which are cost intensive. In order to lower the costs, a range of autonomous sensors has been developed to overcome these limitations. These sensors measure the Chl *a* fluorescence, which is used to provide an estimate of the Chl *a* concentration.

In addition, when comparing to model results there is an added uncertainty in what the observations represent. One measurement may represent the value in a few litres of water, while the model value represents the value in ~10^9 m^3 of water, depending on the model resolution. Here, the same dataset was used for evaluation of the effect of the tuning, as was used to study the needs for tuning. To be fully validated, the model should be compared to independent observed data (Stow et al., 2009). However, due to scarce availability of observed data, it was decided to use all data for both activities.

4.2 Parameter changes

Most of the parameter changes were included to reduce the systematic overestimation of phytoplankton biomass during summer. Some parameter alterations were conducted to study the sensitivity of the model to the variety of ecosystem properties reported in the literature, this included different Si:N ratios and the inclusion of diatoms in the diet of microzooplankton. Several of the parameter alterations investigated had little impact on the results of the model as seen in the error statistic. Quadratic, rather than linear, mortality in the phytoplankton was one of the changes that had little effect on the error statistics, while a change in the grazing rates had a large effect. The sensitivity of this model to the diet compositions of zooplankton has also been shown in a more theoretical study on parameter estimation by data assimilation by Simon et al. (2012). It is a factor that the change to the grazing parameter was larger than the changes to the mortality parameters, However, the changes in N04 cause the mesozooplankton to increase by about 60% and (the other alteration of the mortality rate caused changes of the same order of magnitude) and this indicates that rather large changes in the zooplankton concentrations are needed to perturb the nutrients and phytoplankton concentrations. The zooplankton mortality is the closure term in the model, but contrary to some earlier studies (e.g Steele and Henderson, 1992) perturbations of the functional form of the mortality in N04 had little effect on the results. One possible explanation for the low sensitivity is that the zooplankton mortality resulting from the different functional forms is not very different over the range of common zooplankton concentrations (Fig. S3). A similar response of the model to the functional form of the zooplankton mortality was found in another modelling study (Yool et al., 2011).

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Increasing the N:Chl ratio would on one hand decrease the amount of chlorophyll per phytoplankton biomass, but also how quickly light is attenuated with depth. This alters the vertical distribution of phytoplankton, but it changes the concentrations only by a few percent, hence this effect is small compared to the effect on the chlorophyll concentration from altering the N:Chl ratio. 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.

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, and when lowering this ratio more nitrate can be consumed leaving less nitrate for the flagellates and limiting the size of the 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 past experience with the model. As grazing seems to be an important control mechanism in the model, the zooplankton assimilation efficiency may be an important parameter to test in the future. The temperature dependence of growth and respiration for both zooplankton and phytoplankton would probably influence the progress of the blooms across regions, but past experience with the model has shown that this model has 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 observational data (Figs. 5 and 6) and to observations in different regions (Figs, 8 and 9), it is clear that the model performed better overall than on a region-by-region basis. The explanation for this may lie partly 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

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point. Station M is located close to a front between two water masses, and the model is not always simulating the location of this front well (Fig. S4). In the Barents Sea most of the observations 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. In shallow areas, such as along the coast and in the Barents Sea, better representation of benthic processes as well as the lack of tides are probably sources of errors.

The location of the ice edge affect the results of the biogeochemical model (Samuelsen et al., 2009a). The observations used here are primarily from open-ocean regions, so we have limited knowledge of the model performance close to the ice edge. The comparison of the physical model simulation (free-run) to satellite observations shows that the ice-edge follows the observed pattern (Sakov et al. 2012), but of course it is not 100% accurate. In the model light does not propagate through ice, and the ice edges also influences mixing, therefore errors are expected in both chlorophyll and nutrients if the model places the ice edge incorrectly. In addition, the fact that we don't include ice-algae in the model also introduces sources of errors.

5 Conclusions

In total 18 sensitivity runs were performed on the higher- and coarser resolution model grid. First, the effect of tuning of single parameters was studied. Subsequently, the tuning of combinations of parameters were tested in the coarse model. The conclusion was that the best overall 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 differences in performance between the two sets of parameters were investigated in that configuration.

The revised run shows a clear improvement compared to the original run, particularly for nutrients but also for chlorophyll, but while the previous run tended to overestimate the annual cycle of chlorophyll, the revised run tends to underestimate the amplitude (Fig. 7). Based on these results, the revised parameter set presented here were also implemented as part of an operational system for the Arctic. 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

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(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. Data assimilation can also be applied to the biogeochemical model, both as a mean of improving the forecast fields and as a method for optimizing model parameters (Simon et al., 2012).

We have shown that the model reproduces a reasonable annual cycle, but the initiation time of the spring bloom is consistently later than the observations. None of the parameter alterations affecting the timing of the spring bloom by more than a few days, while the lag in bloom initiation compared to observations is 20-30 days, 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 (the early seeding of the spring bloom by phytoplankton that was mixed down during winter: Backhaus et al., 1999, 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.

During the tuning process the parameter sensitivity of the module was explored and the changes that were motivated by observation-based findings, 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 greater refinement of the models in general should be done in closer collaboration with ecologist and field oceanographers.

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 HYCOM-NORWECOM V2.0 used for in the reference run, which were performed in October 2011 is revision number 186, while HYCOM-NORWECOM V2.1 corresponds revision number 224.

Acknowledgements

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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 Søiland, 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

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

	Parameter for tuning	Original value	New value
N00	Reference run		
TP0	Reference run with high resolution		
N01	Quadratic mortality for phytoplankton	cc(3), cc(3)=4.0e-7	cc(3)/15.0+cc(3)*P/15.0
N02	Si:N-ratio in diatoms	1.75 mgSi/mgN=0.875 mmolSi/mmolN	0.575mmolSi/mmolN=1.15 mgSi/mgN
N03	Si:N-ratio in diatoms	1.75 mgSi/mgN=0.875 mmolSi/mmolN	1.175mmolSi/mmolN=2.35 mgSi/mgN
N04	Quadratic mortality in zooplankton	m_z*(z/(z+cnit*k6)), m_z=0.2, z=zooplankton-conc [mgN/m^3]., cnit=14.01mgN/mmolN, k6=0.2	m_z/5.0+m_z*z/25.0
N05	Mesozooplanton mortality (+25%)	$m_{z\text{-}meso}$=0.2	$m_{z\text{-}meso}$=0.25
N06	Mesozooplanton mortality (-25%)	$m_{z\text{-}meso}$=0.2	$m_{z\text{-}meso}$=0.15
N07	Combination of N01 and N02	cc(3), cc(3)=4.0e-7, 1.75 mgSi/mgN	cc(3)/15.0+cc(3)*P/15.0, 1.15 mgSi/mgN
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 microzooplanton	pi21=0.633-flagellates, pi24=0.367-detritus	pi21=0.333-flagellates, pi23=0.333-diatoms, pi24=0.333-detritus

N12	Maximum microzooplankton grazing rate	g=0.5	g=1.0
N13	Combination of N11 and N1	pi21=0.633-flagellates, pi24=0.367-detritus cc(3), cc(3)=4.0e-7	pi21=0.334-flagellates, pi23=0.333-diatoms, pi24=0.333-detritus, cc(3)/15.0+cc(3)*P/15.0
N14	Combination of N11 and N2	pi21=0.633-flagellates, pi24=0.367-detritus, 1.75 mgSi/mgN	pi21=0.334-flagellates, pi23=0.333-diatomes, pi24=0.333-detritus, 1.15 mgSi/mgN
N15	Combination of N14 and N12	pi21=0.633-flagellates, pi24=0.367-detritus, 1.75 mgSi/mgN, g(micro)=0.5	pi21=0.334-flagellates, pi23=0.333-diatoms, pi24=0.333-detritus, 1.15 mgSi/mgN, g(micro)=1.0
N16	Combination of N14 and reduced growth rate for phytoplankton	pi21=0.633-flagellates, pi24=0.367-detritus, 1.75 mgSi/mgN, Vmax(dia)=1.53E-5, Vmax(fla)=1.02E-5	pi21=0.334-flagellates, pi23=0.333-diatoms, pi24=0.333-detritus, 1.15 mgSi/mgN, Vmax(dia)=1.15E-5, Vmax(fla)=0.76E-5
TP1	High-resolution run with the parameter values of N16	pi21=0.633-flagellates, pi24=0.367-detritus, 1.75 mgSi/mgN, Vmax(dia)=1.53E-5, Vmax(fla)=1.02E-5	pi21=0.334-flagellates, pi21=0.333-diatoms, pi24=0.333-detritus, 1.15 mgSi/mgN, Vmax(dia)=1.15E-5, Vmax(fla)=0.76E-5

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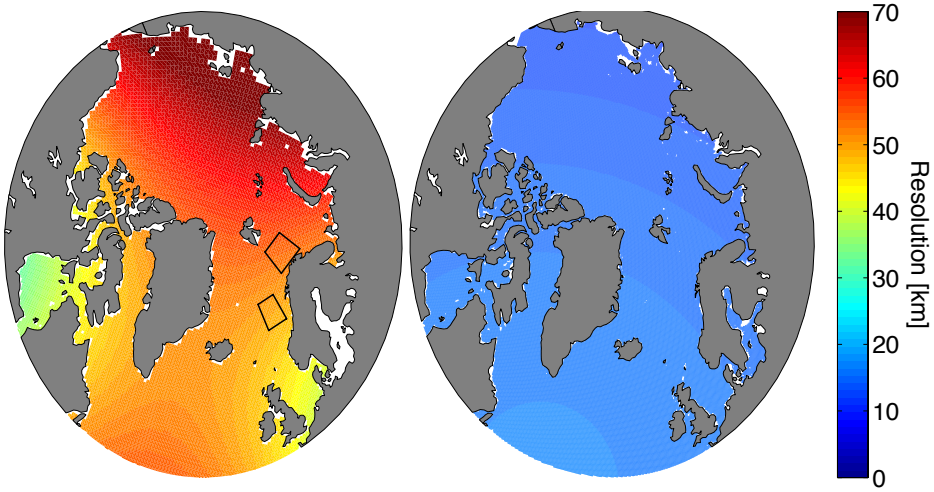
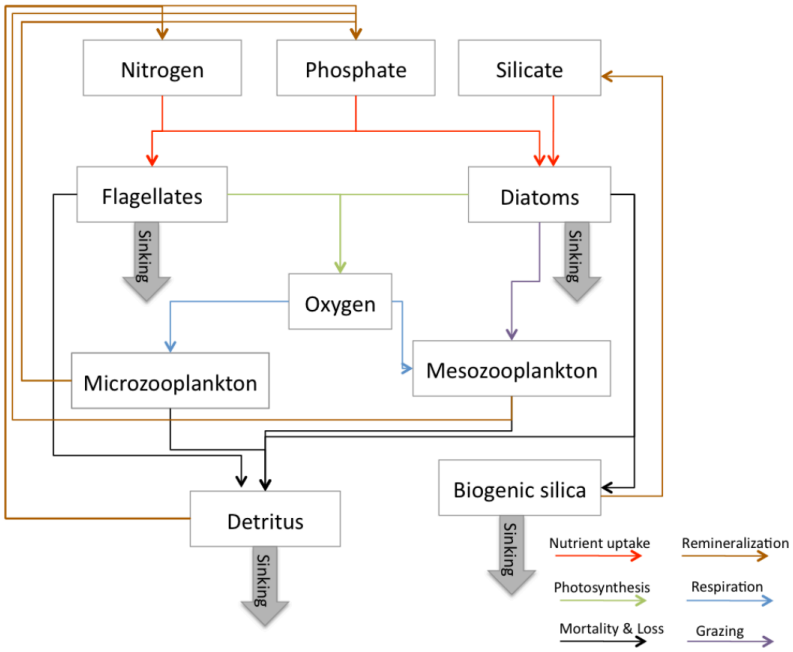


Figure 1. Resolution of the two model grids used in this study. The two areas indicated by black lines in the map to the left are the areas referred to as Norwegian Sea – southern area - and Barents Sea – northern area.



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

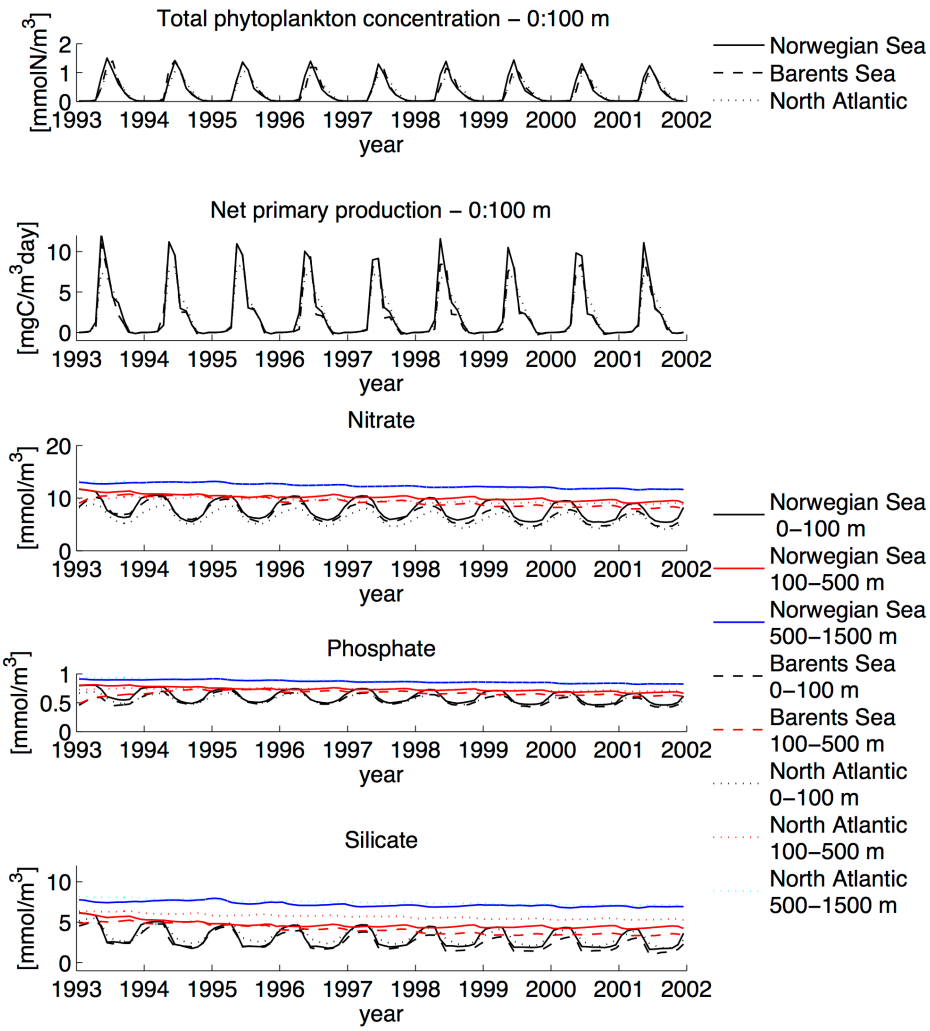

Figure 3. The temporal evolution of total phytoplankton, net primary production, and for the three nutrients in different depth intervals from initialization in 1993 to the end of 2001. Norwegian Sea and Barents Sea are here the boxes shown in Fig. 1. North Atlantic here refers to the area from 80° W to 80° E and 60° N to 80° N

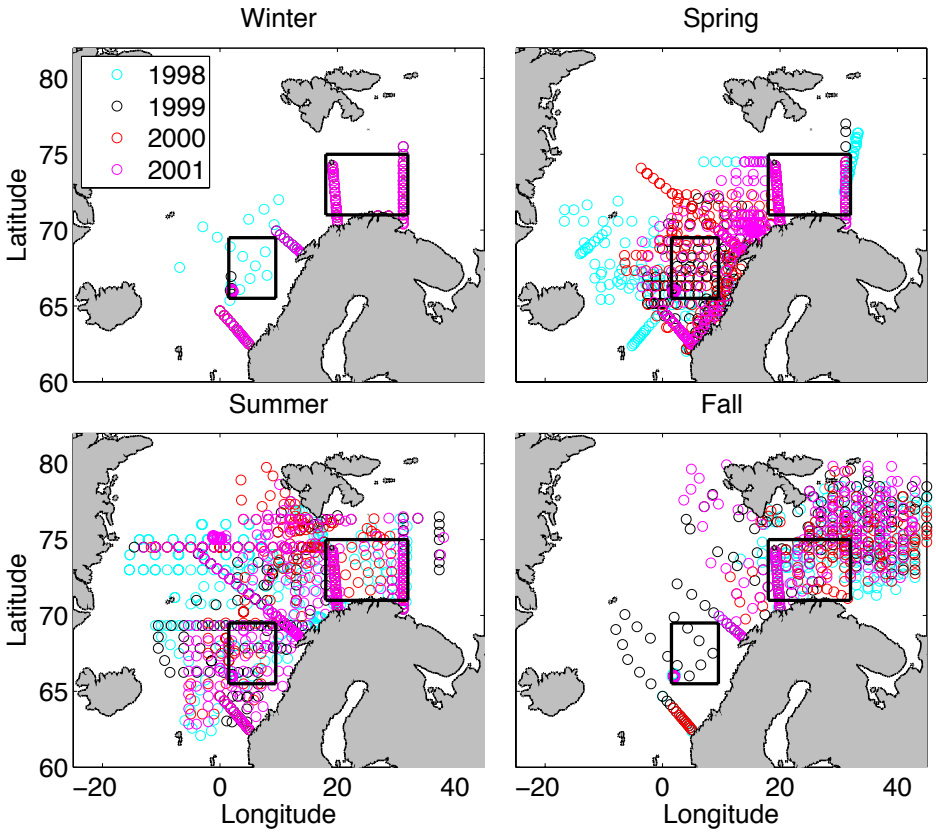

Figure 4. Spatial in-situ data coverage for nitrate in different years and seasons for the dataset used. The coverage for the other variables is similar. The southern areas are mostly sampled in spring and summer, while the Arctic regions are more sampled in summer and fall. There are very few open-ocean measurements during winter, but in the sections visible in the winter-panel (upper, left) there are observations for all years and seasons.

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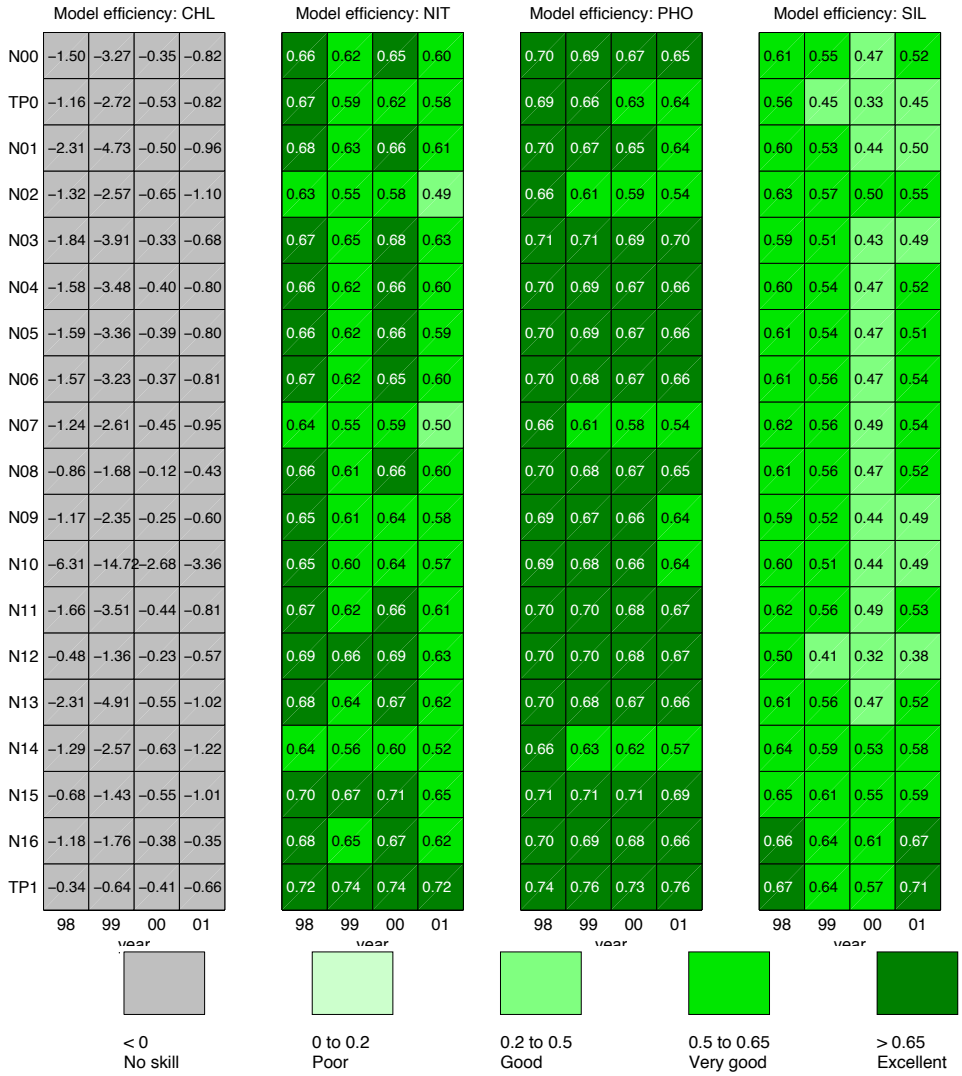

Figure 5. Model efficiency (ME, see text) for the model simulations compared to all available observations from the period 1998-2001.

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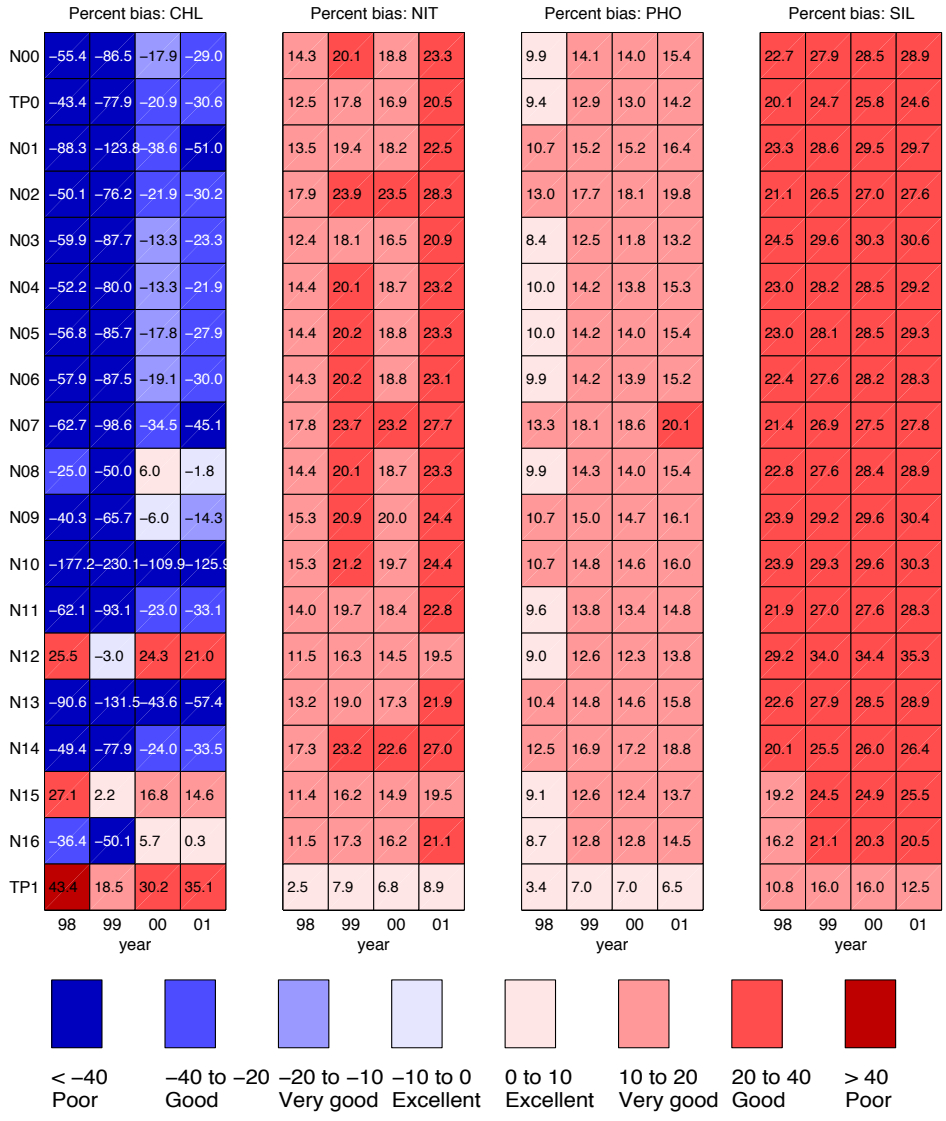

Figure 6. Percentage bias (Pbias, see text) for the model model simulations compared to all available observations from the period 1998-2001.

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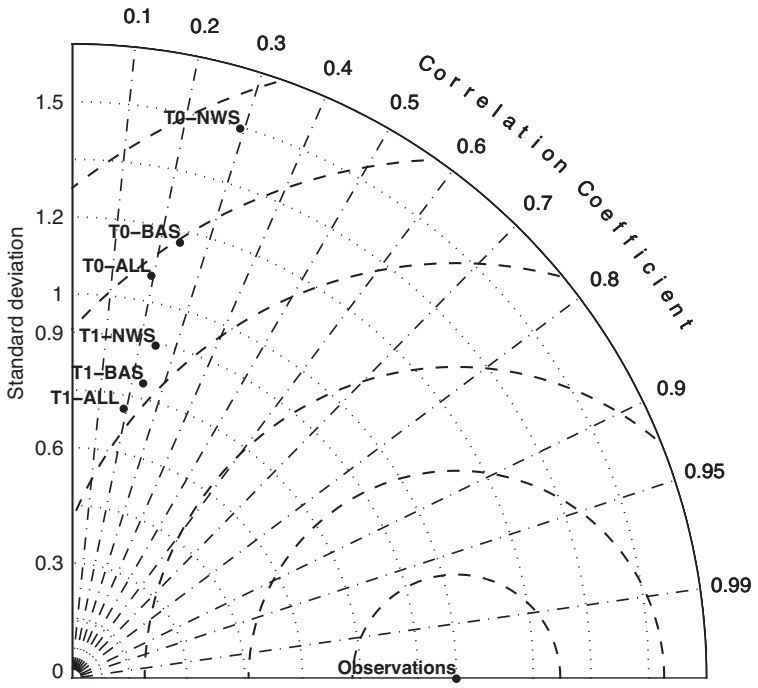

Figure 7. Taylor-diagram for comparison with in-situ chlorophyll for the entire area (ALL), the Barents Sea (BAS) and the Norwegian Sea including station M (NWS). The curved dotted lines show the standard deviation relative to the observations.

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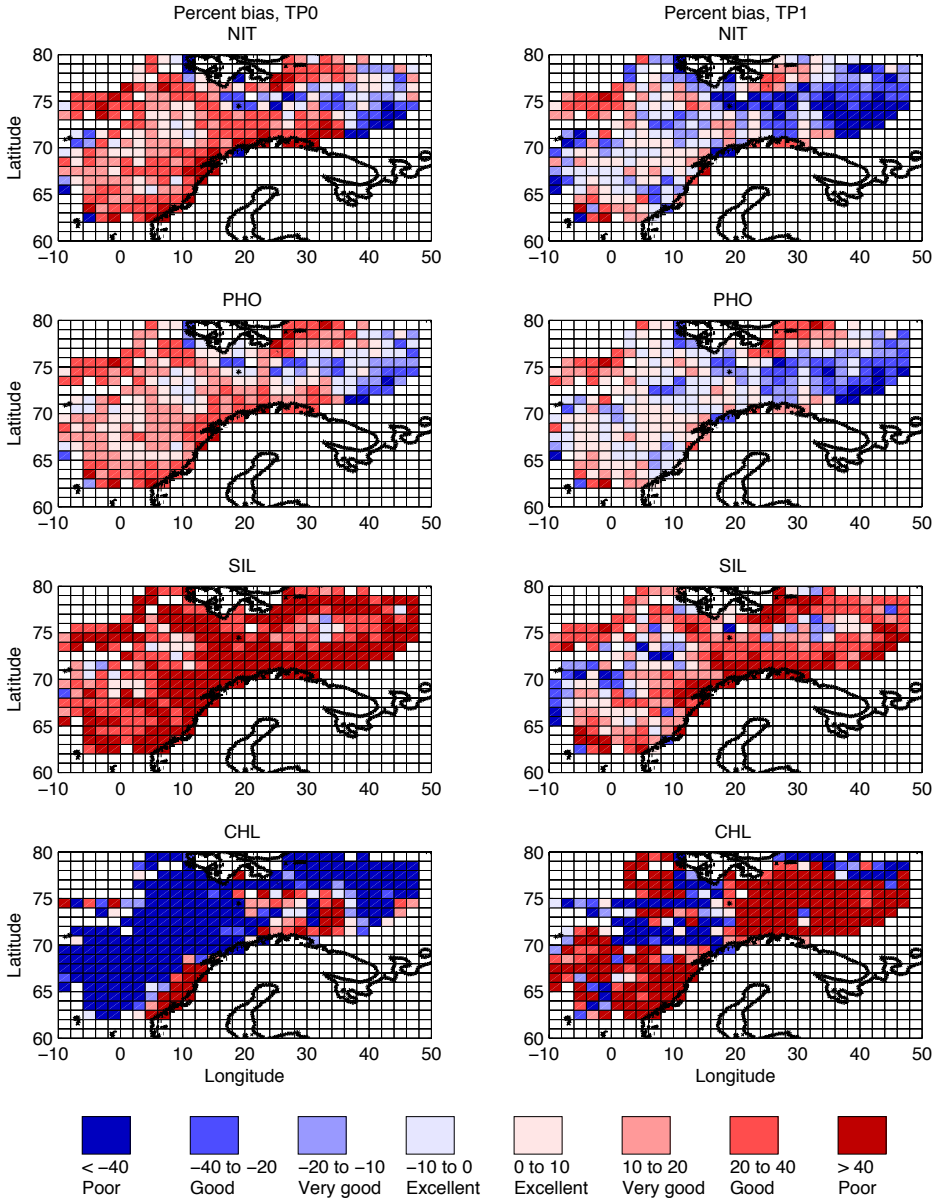

Figure 8. Percentage bias (Pbias, see text) in the upper 100 meters for the model simulations compared to all available observations from the period 1998-2001 in 2x1 degree boxes from the simulations with the fine-scale model with the original (TP0) and final set of parameters (TP1).

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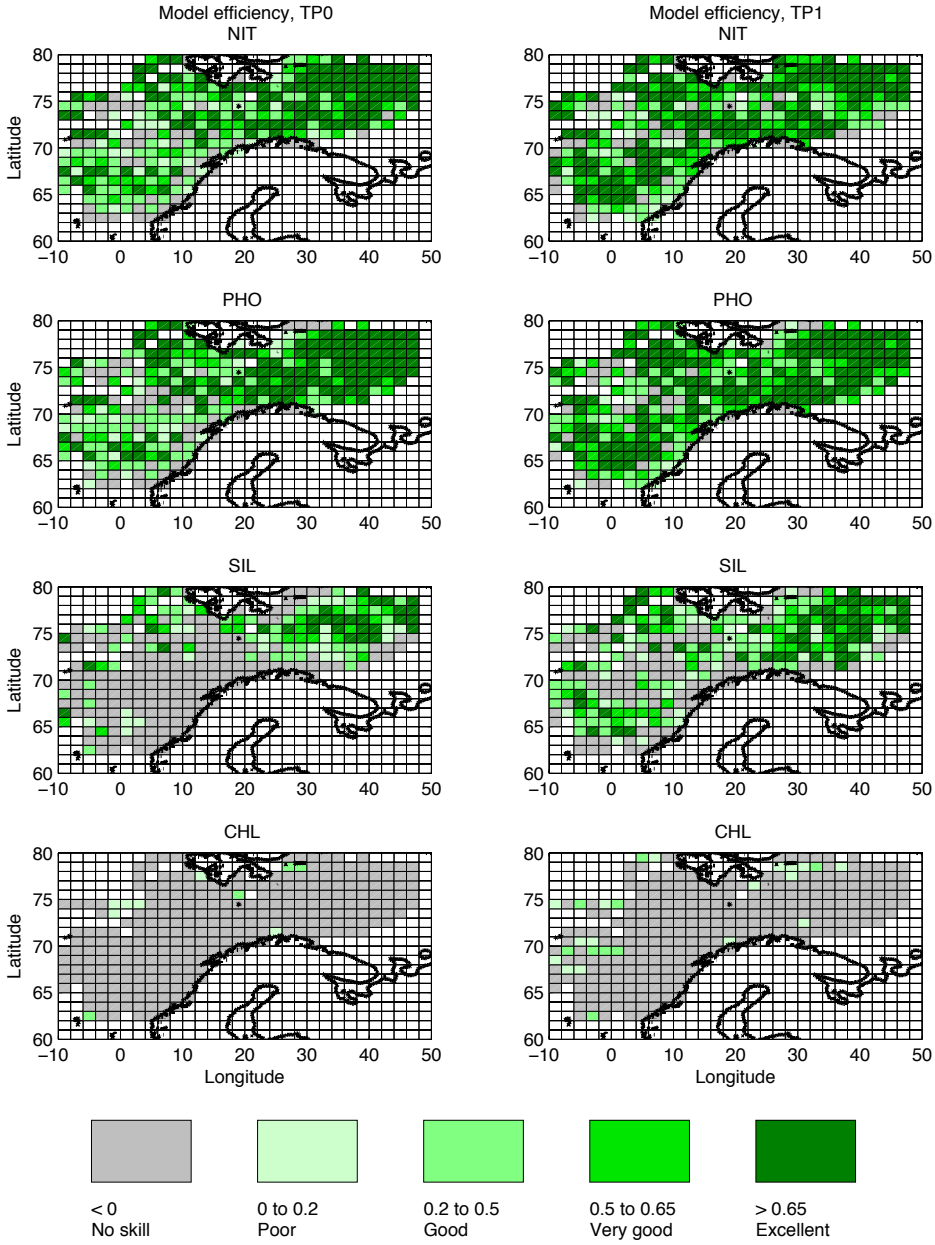

Figure 9. Model efficiency (ME, see text) in the upper 100 meters for the model simulations compared to all available observations from the period 1998-2001 in 2x1 degree boxes from the simulations with the fine-scale model with the original (TP0) and final set of parameters (TP1).

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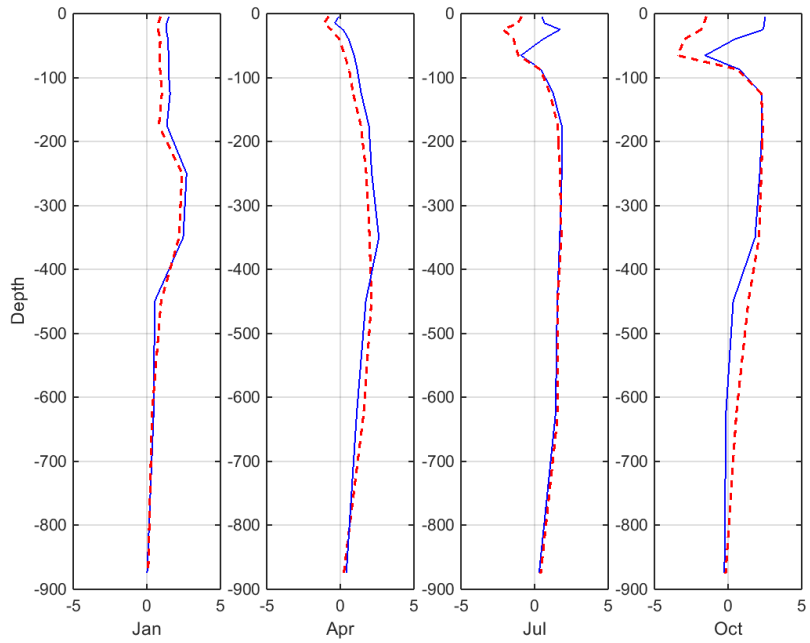

Figure 10. Profiles of difference between nitrate [mmol N/m^3] model and observations in different months in the Norwegian Sea box – solid lines (blue) are the revised simulation and dashed lines (red) the control run. All observations in the Norwegian Sea box between 1998 and 2001 have been used.

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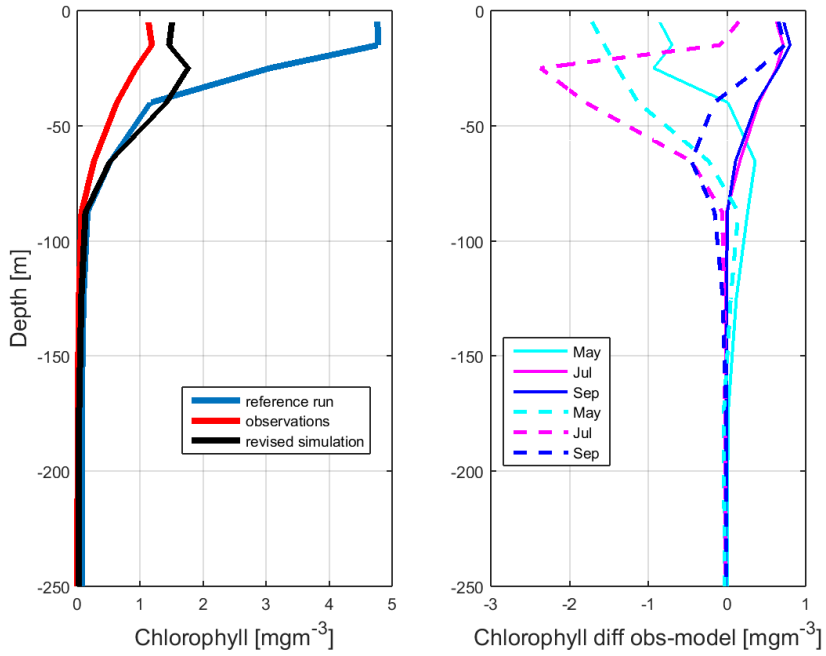

Figure 11. Chlorophyll profiles from the control and reference run using the higher resolution model in June (a) in the Norwegian Sea box as well the difference between observations and model in other months (b) – solid lines are the revised simulation and dashed lines the control run. All observations in the Norwegian Sea box between 1998 and 2001 have been used.

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Appendix

Table A1. 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/NO3	Si:N-ratio in diatoms	mod_necessary_ecovars.F90: line 45-54	
N04/NO5/NO6	Meso zooplankton mortality	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	Combination of N01 and N02	See above for N01 and NO2	
N08/N09/N10	N:Chl-ratio	biocom.h: line 107-108	
N11	Grazing preferences for microzooplanton	m_NOR05_zoo_growth.F: line 26, 100-132	
N12	Grazing preferences for	m_NOR05_zoo_growth.F: line 26, 101	

	microzooplankton		
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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