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The 2007 North Atlantic spring bloom in operational analysis from the TOPAZ system

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Abstract

A reanalysis of the North Atlantic spring bloom in 2007 was produced using the real-time analyses from the TOPAZ (Towards an Operational Prediction system for the North Atlantic European coastal Zones) North Atlantic and Arctic forecasting system. The TOPAZ system uses a hybrid coordinate general circulation ocean model and assimilates physical observations: sea surface anomalies, sea surface temperatures, and sea-ice concentrations using the Ensemble Kalman Filter. This ocean model was coupled to an ecosystem model, NORWECOM (Norwegian Ecological Model System), and the TOPAZ-NORWECOM coupled model was run throughout the spring and summer of 2007. The ecosystem model was run online, restarting from analyzed physical fields (result after data assimilation) every 7 days. Biological variables were not assimilated in the model. The forecast was compared to remotely sensed chlorophyll and in-situ data. The impact of physical data assimilation on the ecosystem model was determined by comparing the results to those from a model without assimilation of physical data. The regions of focus are the North Atlantic and the Arctic Ocean. The results show that the model reproduces a realistic annual cycle, but the chlorophyll concentrations tend to be too low during winter and spring and too high during summer. Surface nutrients on the other hand are generally too low throughout the year. Assimilation of physical variables does not affect the results from the ecosystem model significantly. The differences between the weekly mean values of chlorophyll are normally within 5–10% during the summer months, and the maximum difference of ~20% occurs in the Arctic, also during summer. Special attention was paid to the nutrient input from the North Atlantic to the Nordic Seas and the impact of ice-assimilation on the ecosystem. The ice-assimilation increased the phytoplankton concentration: because there was less ice in the assimilation run, this increased both the mixing of nutrients during winter and the area where production could occur during summer.

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1 Introduction

Marine phytoplankton are important because they make up the base of the food chain that supports the majority of life in the ocean. They also play a key role in the absorption and redistribution of CO_2 in the ocean. But algae blooms are not always beneficial; in large quantities they can be harmful to marine life as well as unpleasant to humans. Much of the algae growth in the ocean is controlled by physical variables such as temperature, mixed layer depth, and light. This makes it, in principle, possible to forecast algae concentrations and other water quality parameters (nutrients, oxygen, etc.) on the time-scales from about a week to a month forward in time using a coupled physical-biological model.

In recent years forecasts of physical ocean variables have been improving and operational systems have been established by several partners of the Global Ocean Data Assimilation Experiment (GODAE) (e.g. Johannessen et al., 2006; Drévillon et al., 2008; Hurlburt et al., 2008). Operational systems typically consist of remote and in-situ monitoring in addition to ocean general circulation models (OGCM), providing input to nested coastal forecasting systems, oil-drift models, and biogeochemical models. The establishment of such operational models have largely been made possible thanks to the recent large increase in computing resources. However the capacity of these models to support physical-ecosystem models is not fully demonstrated: Berline (2007) showed improvements of ecosystem simulations obtained by assimilation of physical data but also recognized the need for a post-processing step to reduce the vertical adjustments of data assimilation. It is however not straightforward to generalize these findings to all data assimilation methods. At the time of writing none of the GODAE forecast systems are run coupled to an ecosystem, but many of them, including the TOPAZ system, are planning its inclusion in the near future in order to feed realistic lateral boundary conditions to coastal ecosystem forecast models. This goal justifies a careful examination of the effects of physical data assimilation in a coupled model. Since the TOPAZ system is the Arctic component of the MERSEA system, this study focuses on the nutrient inflow into the Nordic Seas and the impact of assimilating sea-ice parameters.

The biogeochemical models face an additional challenge compared to the physical models, not only because their numerous biological tracers make them computationally more costly, but also because of the large number of empirical parameters and the scarcity of data available for validation and tuning. A large number of models exists with complexities ranging from simple three-compartment (nutrient, phytoplankton, zooplankton) models that are now mostly used for process studies (e.g. Pasquero et al., 2005) to models with 100 or more state variables (e.g. Allen et al., 2001). There are however practical limits to how many parameters that can be tuned using a sparse biological observation network, and models of intermediate complexity are so far preferable for large-scale simulations.

Here we have performed and evaluated a test forecast for the spring and summer of 2007, the last operational period for the TOPAZ2 system (Towards an Operational Prediction system for. the North Atlantic European coastal Zones: Bertino and Lisæter, 2008). The primary production model is the Norwegian Ecological Model System (NORWECOM: Skogen and Søiland, 1998) which is coupled online to the TOPAZ forecasting system. In one run the physical system is run with assimilation, this means that the physical model fields are updated every seven days with operational analyzed fields and run one week forward in time as a coupled model, thus providing similar results as if the coupled system had been run in near real-time. We refer to the resulting coupled simulation as a "forecast" although it was produced a posteriori and forced by analyzed atmospheric fields. For reference, a free run without assimilation of physical variables was performed. The two main purposes of the study were (1) to evaluate the forecast quality and (2) to evaluate the impact of assimilation of physical variables on the coupled system.

The evaluation of the forecast itself showed that the seasonal cycle was reasonably well reproduced, however the chlorophyll was systematically underestimated in the winter/spring and over-estimated in the open ocean during summer. Comparison with in-situ data shows that the nutrients in the Faeroe-Shetland channel were realistically reproduced, while the model performance in the North Sea was not good. Elsewhere in the focus region there were no in-situ data available. The assimilation of ice caused both higher nutrient concentration during winter and more phytoplankton during summer. This was caused by a larger ice-free area in the assimilation run.

2 Methods

2.1 Physical model

The physical model used is the Hybrid Coordinate Ocean Model (HYCOM: Bleck, 2002). In our configuration this model uses isopycnal coordinates in the deep and stratified ocean and z-level coordinates in the upper mixed layer. In the isopycnal space, the vertical velocities are the vertical movements of the isopycnal layers, but not a component of the velocity vector. The KPP (K-Profile Parameterization) mixing scheme is used for the mixed layer (Large et al., 1994). The model is coupled to a sea-ice module consisting of two components; a thermodynamic model (Drange and Simonsen, 1996) and an elastic-viscous-plastic rheology (Hunke and Dukowicz, 1997). Freshwater fluxes from rivers are included as climatological monthly values. The TOPAZ large-scale model does not include tides.

For an effective spin-up of the ecosystem model we run the model on a coarse domain (∼50 km resolution) in the North Atlantic, hereafter called COARSE. COARSE has 23 layers in the vertical and because this model was intended for coupling to biogeochemical models, the upper 5 layers were defined as z-levels to ensure good resolution in the upper part of the water column. The technical details of the spin-up of this model and the model drift are summarized in Hansen and Samuelsen (2009). The model was initialized with the Generalized Digital Environmental Model Data Base climatology (GDEM: Teague et al., 1990) and run from 1957 to the end of 2005. From January 2006 the runs were switched to the data assimilative model TOPAZ2, which has a resolution of ~20 km in the area of the Norwegian Sea and the Arctic (Bertino and Lisæter, 2008) and therefore does not resolve eddies in high latitudes. The TOPAZ2 model was initialized from GDEM and spun up for eight years before switching to forecast mode in January 2005. The output from the operational forecast run have been used for the present experiment. TOPAZ2 has 22 layers, which are all hybrid; this means that the vertical resolution close to the surface is not fixed as in COARSE. This should however have little consequence in the weakly stratified high-latitude regions studied here.

The atmospheric forcing used was the 6-hourly ERA40 atmospheric fluxes (Uppala et al., 2005) from 1957 to 2002. In 2002 the forcing was switched to operational analysis from the European Centre for Medium-Range Weather Forecasts (ECMWF) until the end of the experiment.

2.2 Data assimilation

The data assimilation technique is the Ensemble Kalman Filter (EnKF: Evensen, 2006) with a dynamic ensemble of 100 members. The initial ensemble is set up with differences in the distribution of vertical layers and the ensemble is forced with random perturbations of the surface heat and momentum fluxes. One particular aspect of the EnKF is the possibility to rewrite the analysis step as a matrix multiplication to the right of the forecast ensemble (Evensen, 2003). In other terms the analyzed state vectors are combinations of the forecast ensemble members. This has consequences in terms of vertical stability of the water column, in particular in the HYCOM vertical coordinate system: when updating a state variable in the isopycnal domain, the analyzed variable is a combination of ensemble forecasts in the same density layer, thus at the same reference density. In this sense we expect no inversion of the vertical density gradient with the EnKF analysis and use the standard EnKF analysis without any post-processing.

The data assimilated in TOPAZ2 are merged sea level anomalies from Collecte Localisation Satellites (CLS) (Ducet et al., 2000), sea surface temperature (Reynolds data from the National Oceanic and Atmospheric Administration (NOAA)) and remotely sensed ice concentration from the SPECTRAL Sensor Microwave Imager (SSM/I), de-

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rived using the NORSEX algorithm (Svendsen et al., 1983). In-situ profiles are not yet assimilated in this version of the TOPAZ system. The result of these forecasts as well as error statistics are updated regularly on the web-page http://topaz.nersc.no.

2.3 Biological model

The biological model used is NORWECOM (Skogen et al., 1995; Skogen and Søiland, 1998). This model has been used for several studies both in the North Sea (Skogen and Moll, 2000; Skogen et al., 2004) and has also been applied to the Nordic Seas (Skogen et al., 2007). The original version of NORWECOM was coupled to the Princeton Ocean Model, here it has been coupled to HYCOM. The model includes three nutrients; nitrate, phosphate, and silicate and two phytoplankton functional groups; diatoms and flagellates. The model also includes detritus, biogenic silica, and oxygen.

Originally, the model also includes yellow matter and suspended particulates matters, but these two variables are omitted because the focus here is on open ocean waters. Most of the parameters from the original model were kept unchanged. We have however set the sinking rate for diatoms, which is variable in the original model, to a constant 1 m/d. The grazing mortality rate was constant in the original model, here it has been made a linear function of the phytoplankton concentration so that grazing mortality increases with increasing phytoplankton concentrations. This formulation improved the model performance when compared to satellite data (not shown).

The nutrients in the biological model were initiated from Levitus climatology (Conkright et al., 1998). The other variables were initialized with constant low values (0.1 mg N/m^3 for diatoms, flagellates and detritus and 0.1 mg Si/m^3 for biogenic silicate), except for oxygen which was initiated at 4300 mg O/m^3 in the entire domain. The biological variables in COARSE were initialized in 1987 and the coupled model was spun-up until the beginning of 2006. The spin-up was run with monthly climatological nutrients in the rivers, but for simplicity this was omitted in the TOPAZ2 model runs.

The ecosystem variables from COARSE were regridded by bilinear interpolation to the TOPAZ2 model grid and used as initial conditions. Because TOPAZ2 stretches further south than COARSE the values south of 11° S are initialized by climatology, while the region between 1° S and 11° S were initialized with a linear blend of results from COARSE and climatology. The coupled version of TOPAZ2 was then run from January 2006 to January 2007, coupled to the data assimilative operational system. The last model field from this run was used as initial condition for the comparison runs described below. The sequence of steps in the spin-up is summarized in Table 1.

2.4 Experiment setup

Two experiments were performed, both were initiated on the 2 January 2007 and run until the end of August 2007. In the first experiment the restart files were updated every seven days with the analysis fields from the TOPAZ2 forecast. The second experiment was a free run.

3 Results

The model was divided into five regions for assessment (Fig. 1). Region I is the region from 70° W to 20° W and 50° N to 60° N, it contains mostly polar water-masses south of Greenland, but there is also some warm Atlantic water masses present in the eastern part. Region II stretches from 20° W to 20° E and 50° N to 60° N, it includes the waters surrounding the British Isles and the North Sea and is dominated by warm Atlantic water masses. Region III is from 50° W and 10° W and 60° N and 70° N and covers the Iceland Sea, while region IV represents the Norwegian Sea and stretches from 10° W and 20° E and 60° N and 70° N. Region V is from 25° W and 60° E and 70° N and 80° N and contains the Barents Sea and the Greenland Sea. In Sect. 3.1 the general results from the model is described, this is based on the model run with assimilation. In Sect. 3.2 the forecast of chlorophyll is evaluated based on a comparison of the run with assimilation and observations from the Moderate Resolution Imaging Spectroradiometer (MODIS), while in Sect. 3.3 the two runs with and without assimilation are compared to study the effect of assimilation of physical variables on the ecosystem model.

3.1 General performance

The general performance of the model was evaluated by comparing the model nutrients to monthly climatologies (Conkright et al., 1998). This is unfortunately not an independent data set since the model was initiated with the climatological nutrient. In addition, the model is expected to deviate from climatology as it resolves interannual variability, but large discrepancies can be indications of model errors. We have defined "large" discrepancy as 2.5 µM for nitrate, 2.0 µM for silicate, and 0.15 µM for phosphate. The monthly chlorophyll concentrations were compared to monthly chlorophyll values from MODIS. For comparison with satellite-derived chlorophyll we consider a relative bias of less than 30% as good.

The model reproduced the annual cycle in all five regions (Fig. 2), but particularly in regions I, III, and IV there are rather large errors. In general the chlorophyll values are realistic prior to the spring bloom, the exception is Region II, the North Sea, where it is underestimated (Fig. 3). During summer, the bias is low in region II and IV, but large in the other regions. The results also show that compared to climatology most nutrients are underestimated in all five regions. The phosphate bias is generally low, the same is the case for the silicate concentrations during summer. Nitrate is also too low, especially during summer in region I and during winter in region III and IV.

3.2 Forecast evaluation

The forecast was evaluated using 8-day composite images from MODIS, in addition, nutrients and chlorophyll were compared to available in-situ data from ICES. The data were compared to weekly averages from the model in overlapping periods. Because the model is not designed for coastal areas, all data from waters with depth less than 100 m have been removed, but the ICES data were still much more frequent in coastal regions. There were no in-situ data in regions I, III, and V between January and August of 2007, but there was good data coverage in the North Sea – where only the Skagerrak and the Norwegian Trench are deep enough to be considered in this comparison. In the Faroe-Shetland channel data were available from May only.

The comparisons between weekly satellite data and model results are frequently obstructed by clouds and during the winter months the areas farthest north are unavailable from the satellite because the sun is too low. Figure 4 shows some relatively cloud-free examples from different regions and times of the year. The model frequently overestimates the open-ocean chlorophyll values as was previously indicated by the comparison with monthly data. In region II the chlorophyll concentrations east of the British Islands are usually underestimated, while west of the British Islands they are frequently overestimated. In general, for all regions, the chlorophyll concentrations in May and June are overestimated, while in July and August they are good. The coastal chlorophyll concentrations were often underestimated in all seasons. The satellite data are patchier than the model results which are quite smooth due to the lack of grid resolution. The model has a well-defined bloom along the ice-edge. Unfortunately this bloom was not visible in the satellite data because of the cloud cover, but it is a well-known phenomena (Sakshaug et al., 1992; Engelsen et al., 2002).

Comparison with the ICES data from the North Sea shows that nutrients are generally too low in the Skagerrak, particularly in the surface waters. The spring bloom starts later than what is observed and both nutrient and chlorophyll profiles indicate that the modelled water column has a deeper mixed layer than the observed. The observed data around the Norwegian trench were too sparse to make any conclusion about the model performance. The North Sea is heavily influenced by nutrient input from large rivers such as Elbe, and we do not expect this model to perform well here because river nutrients are excluded here. The model performs rather well in the Faroe-Shetland channel (Fig. 5), the general distribution of nutrients is reproduced even if the model tends to overestimate the concentration in the deep western part of the channel while it is too low at the surface. In the Faroe-Shetland Channel the vertical nutrient profiles indicate that the modelled water-column is less mixed than in observations, contrary to the Skagerrak.

3.3 Effect of assimilation

Of particular interest was the effect of the assimilation of ice on the ecosystem model results. To our knowledge, this is the first coupled physical-ecosystem model that is run with sea-ice assimilation. Region V is the only region where there are large amounts of ice – although small amounts of ice occur in region I and III – therefore we will focus on region V. The primary effect of assimilation was a reduction in the ice area of roughly 10% compared to the free run (Fig. 6a). This had a double effect on the ecosystem. First, during winter a larger open ocean area was exposed to the wind, therefore allowing for more nutrients to be mixed up during winter and causing higher surface concentrations (Fig. 6c). Second, it leaves a larger area to be exposed to sunlight during spring and summer, this combined with higher nutrient concentration at the surface causes a larger phytoplankton concentration in the assimilation run (Fig. 6b). The ice-edge bloom was more diffuse in the assimilation run than the free run, this is probably caused by the ice-edge "moving" abruptly during the restart with the analyzed files. Regionally, the assimilation of ice moves the ice-edge northward in the Greenland Sea and southward in the Barents Sea, this means that the Barents Sea becomes less productive, while the primary production in the Greenland Sea increases with assimilation.

The overall effect of assimilation was generally small. For chlorophyll there was a 5–10% difference during summer, usually with the assimilation run having the highest concentrations. The maximum difference (~20%) occurred in region V in May. Compared to the satellite and climatological data the performance of the model runs was roughly equal (Fig. 3), there are small differences in space and time, but no clear indication of one being better than the other.

The mixed layer was on average deeper in the assimilation run in region III, VI, and V, while it is shallower in region I. In region II, which is relatively shallow on average, the mixed layer depth is roughly unchanged. It is expected that the winter nutrient concentrations are higher in regions with a deeper winter-mixed-layer, however, the winter nutrient concentrations in the assimilation run are higher in all five areas. The nutrient concentrations are between 2 and 8% higher than the free run (Fig. 7). The assimilation run therefore brings up more nutrients during winter than the free run and this may be a different effect of assimilation, either by vertical or horizontal advection. The differences are largest in frontal areas, probably due to vertical movement of the isopycnals. During summer the concentrations are generally lower in the assimilation run, this is a result of higher primary production.

As an effect of the increased nutrient availability, the spring bloom, which consists mainly of diatoms, and the later flagellate bloom both have higher maxima (Fig. 8) in the assimilation run. The timing of bloom remains unchanged, except for the flagellate bloom in region I, which is later in the assimilation run. This is probably because the mixed layer shoals earlier in the free run in region I during the onset of this bloom (not shown).

4 Discussion

We have performed a simili-forecast of the spring and summer of 2007 using a coupled physical biological model for the North Atlantic and Arctic. The forecast was compared to climatology, satellite-derived chlorophyll, and in-situ data. The comparison showed that the general annual cycle was reproduced (Fig. 2), however the model underestimated chlorophyll during winter while it overestimated chlorophyll during summer (Fig. 3). The negative bias in the nutrients throughout the simulation period (Fig. 3) excluded excess nutrients as a cause for the high summer chlorophyll concentration. There are two other likely possibilities: The first is a too high phytoplankton production that make the phytoplankton consume too much nutrients. The second possibility is that the lack of grazers in the model (grazing mortality is parameterized) causes the mortality to be underestimated during summer. This will in turn cause surface nutrients to be more depleted. The summer overestimation is most likely caused by too low mortality as the summer nutrient concentrations are substantially lower than the climatology. The model is not expected to reproduce the climatology exactly, but, considering that the results were averaged over large areas (Fig. 1), the differences are both large and consistent between regions (Fig. 3). This indicates that the differences are not caused by interannual variability.

When compared to satellite images from MODIS, the model chlorophyll was frequently under-estimated in coastal and shallow regions even if it was over-estimated in the open ocean. The current model is not optimized for coastal regions and one of the aims of this forecast system is that it should provide nesting conditions (both physical and biological) to a coastal model. Therefore this models performance in the coastal regions is not a priority. The model results are also much smoother than the satellite data (Fig. 4), this is largely caused by the lack of eddy resolution (Hansen and Samuelsen, 2009). In addition the satellite images are not weekly averages, but a composite of incomplete satellite passes obtained that week.

The in-situ data were only available in the North Sea and the Faroe-Shetland channel. In the North Sea the model performs poorly because river nutrient inputs are missing and the model is not configured for this area. The nutrient and chlorophyll profiles indicated that the modelled water column is mixed deeper than in the observations. Excess mixing was also noticed by Winther and Evensen (2006). Comparison to a section across the Faeroe-Shetland channel showed that the model results were realistic there. The upper profile indicated that the water column here was on the contrary less mixed in the model than the observations (Fig. 5). This could be because the model does not include tides, which would increase the mixing in areas with steep bathymetry such as in the channel between these two island groups. About half of the inflow to the Norwegian Sea occurs in the Faroe-Shetland channel (Hansen and Østerhus, 2000) and realistic concentrations here indicate that the nutrient concentrations in the water masses entering the Norwegian Sea are reasonable.

The assimilative run was also compared to a free-run in the same period in order to investigate the effect of the assimilation of physical variables on the results from the ecosystem model. Assimilation did not have a dramatic influence on the ecosystem model, but the run with assimilation consistently had higher nutrient concentration than the free-run. This could not be connected to differences in the winter mixed layer depth and because the largest differences occur in frontal areas it is likely connected to vertical advection. Differences in horizontal advection may become more important if the comparison is run over a longer period than the current 8 months. The largest differences in chlorophyll concentration were in Region V where assimilation of ice caused the ice-covered area to be smaller both during summer and winter. In the other areas the difference was between 5 and 10%, but no consistent bias could be noticed. In this experiment it is not possible to differentiate between the effect of sea-ice assimilation and that of other physical variables. However, spatial plots of region V (not shown) show that the largest increase in both nutrients and phytoplankton occur in the regions where the assimilation has removed the ice cover. Compared to climatological data and MODIS chlorophyll (Fig. 3) there was no difference between the performance of the free-run and the assimilation run. These results are generally in contradiction with those of Berline et al. (2007) which indicates that the choice of physical model, assimilation scheme and ecosystem model are all critical in the assessment of the future ocean ecosystem forecasting systems.

This model will be set up for operational forecasting in the Atlantic and Arctic Ocean. The primary weakness of the ecosystem model seems to be the grazing formulation and not the physical framework. That there is no significant improvement in the error statistics of COARSE compared to TOPAZ2 (not shown) supports this conclusion. Therefore the first efforts will be towards finding alternative formulations that improves the model performance. Models without a zooplankton compartments do not necessarily perform worse than those with (Friedrichs et al., 2007) therefore efforts will be aimed at finding an alternative parameterization rather than adding compartments. The performance in the tropics has not been evaluated here and will be investigated later, but poor performance in the tropics may influence nutrient holding in northern region.

Having an ensemble of physical states in the TOPAZ system opens perspectives for running an EnKF also for the ecosystem model with assimilation of satellite ocean colour data. A preliminary demonstration has used the MICOM model (Natvik and Evensen, 2003a, b) and is now being updated with the HYCOM model (Simon and Bertino, 2009). A practical advantage is that the same physical ensemble can be used as input to the ecosystem data assimilation, allowing a consistent assessment of the model errors for their impact both on physical and on biological variables. A reanalysis is also planned with a higher resolution prototype of the TOPAZ system (TOPAZ3, 11 km to 16 km resolution, about 1/8th of a degree), which is the real-time system operating at time of writing. This would provide an eddy permitting physical system in the Nordic Seas as input for coupled physical-ecosystem analysis and forecasts.

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Table 1. The timeline of the model run.

Month, Year	Event
Jan 1957	The physical part COARSE is initialized with climatological values.
Jan 1987	The physical part of TOPAZ2 initialized from climatological values.
Jan 1987	The ecosystem module is initialized in the COARSE.
Jan 2005	The assimilation of physical data is initiated in TOPAZ2.
Jan 2006	The TOPAZ2 model is initialized with interpolated ecosystem fields from the COARSE.
Jan 2007	Start of the free versus assimilation comparison study.

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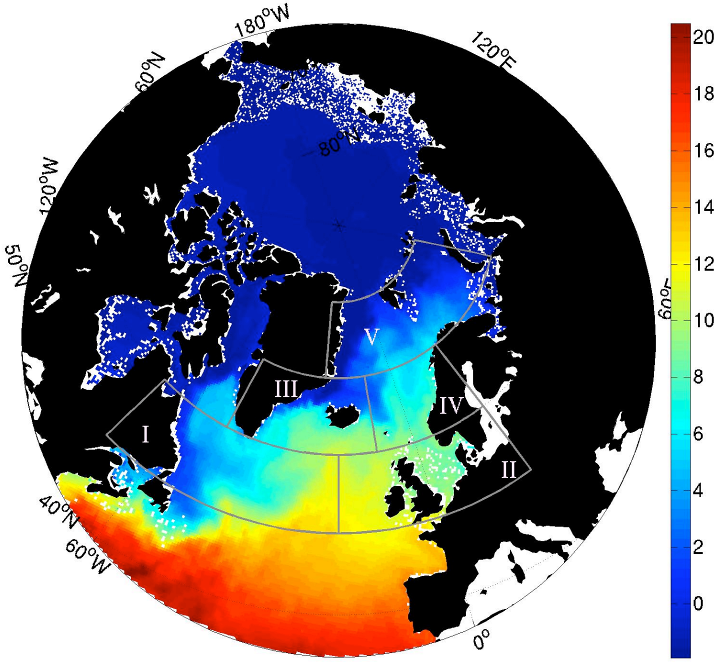
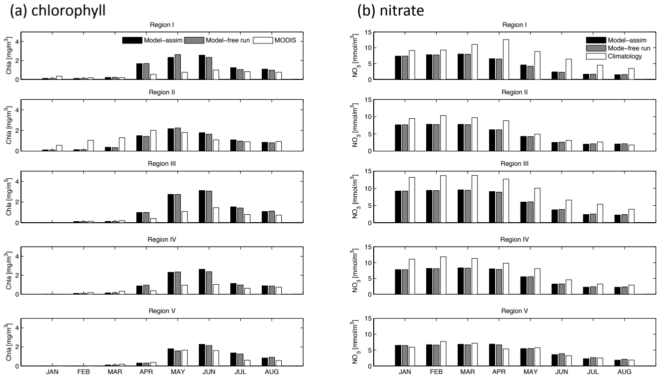


Fig. 1. The five areas that were selected as focus areas superimposed on the temperature averaged over the upper 100 m in January 2007 in the model run with assimilation.



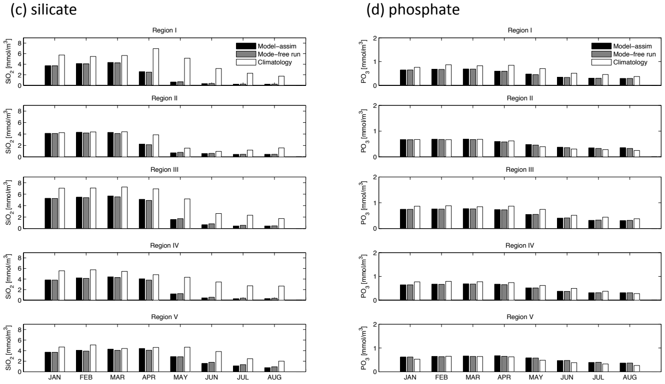
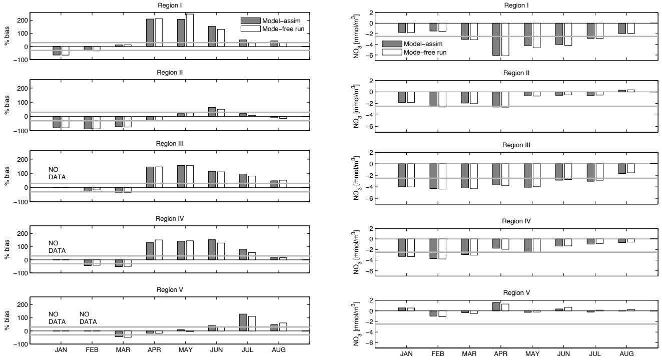


Fig. 2. Monthly mean values for **(a)** chlorophyll from the assimilation run (black), the free run (gray), and MODIS (white). Monthly mean values for **(b)** nitrate, **(c)** silicate, and **(d)** phosphate for the assimilation run (black), free run (gray), and climatology (white). The modelled chlorophyll concentrations are averaged over the upper 30 m, while the nutrients, both modelled and climatological are averaged over the upper 50 m.

(a) chlorophyll (b) nitrate



(c) silicate (d) phosphate

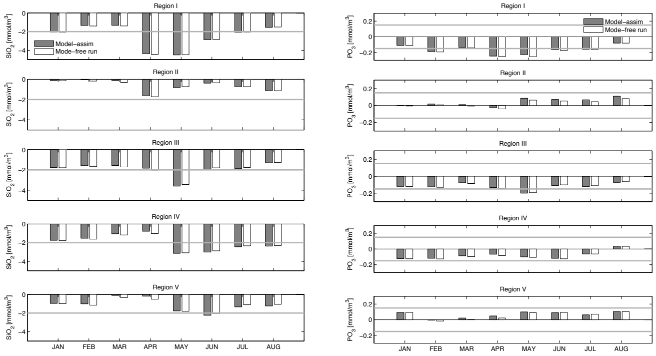


Fig. 3. Monthly error statistic for the model in each of the 5 regions for the assimilation run (gray) and free run (white). **(a)** Monthly modelled chlorophyll values are compared to monthly composits from MODIS. The gray line indicates a percent bias of 30. The nutrients have been compared to monthly climatologies and the bias between the monthly values have been computed. The values here were integrated over the upper 50 m: the gray lines indicate **(b)** 2.5 µM nitrate, **(c)** 2.0 µM silicate, and **(d)** 0.15 µM phosphate.

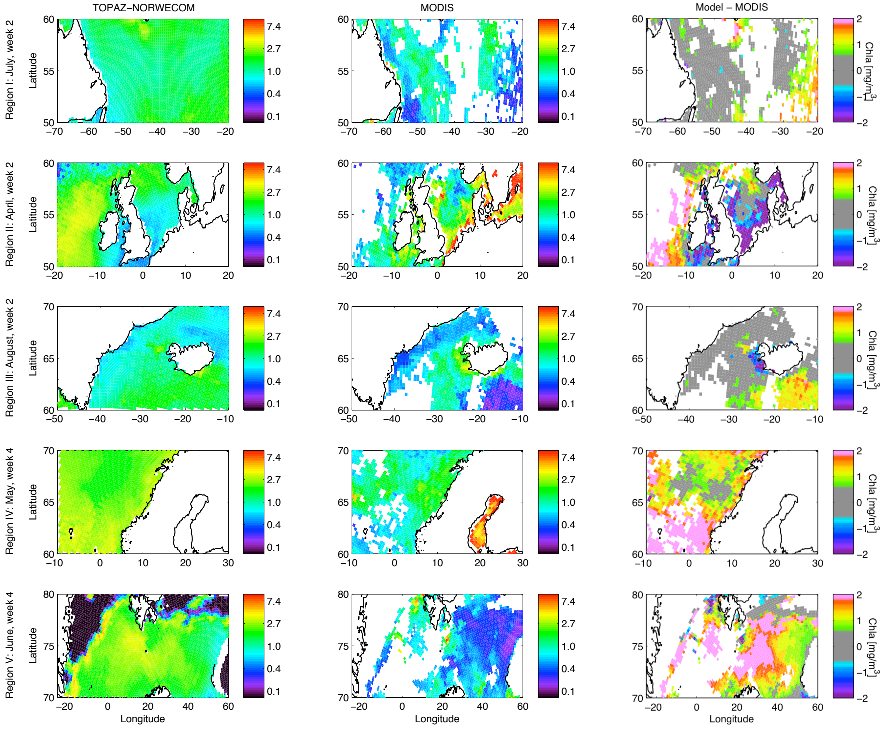


Fig. 4. Comparison between weekly model estimated and MODIS chlorophyll in the five regions. The regions were selected according to times when there was little cloud cover (Region I: July, week 2, Region II: April, week 2, Region III: August, week 2, Region IV: May, week 4, and Region V: June, week 4). The first column shows the model results, the second column shows the MODIS data, and the third column shows the difference between the two. The gray regions in the third column are areas where the difference is less that 0.6 mg Chl/m^3.

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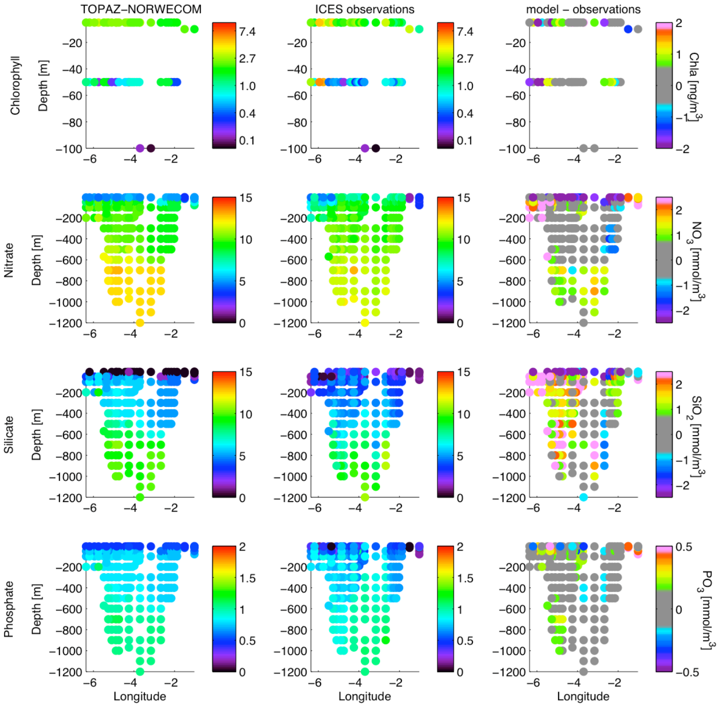

Fig. 5. Comparison between the model results and the in-situ data in the Faroe-Shetland channel in May 2007. The fist column shows the model results, the second shows the in situ data, and the third shows the difference between the two. The gray dots in the third column indicated that the differnce is less then 0.6 mg Chl/m^3 for chlorophyll, less than 0.75 mmol N/m^3 for nitrate and silicate, and less than 0.15 mmol N/m^3 for phosphate.

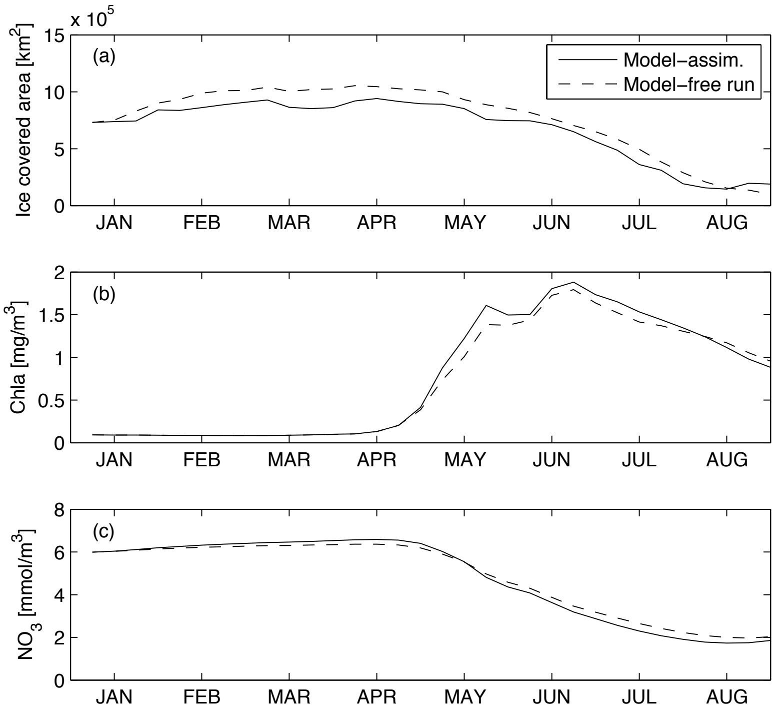

Fig. 6. The effect of assimilation of ice in region V, the assimilation run is plotted as a solid line and the free run as a dashed line. **(a)** Ice area, **(b)** mean chlorophyll concentration, and **(c)** mean nitrate concentration in region V from weekly averages. The chlorophyll concentration is depth-averaged over the upper 30 m, while the nitrate concentration is depth-averaged over the upper 50 m.

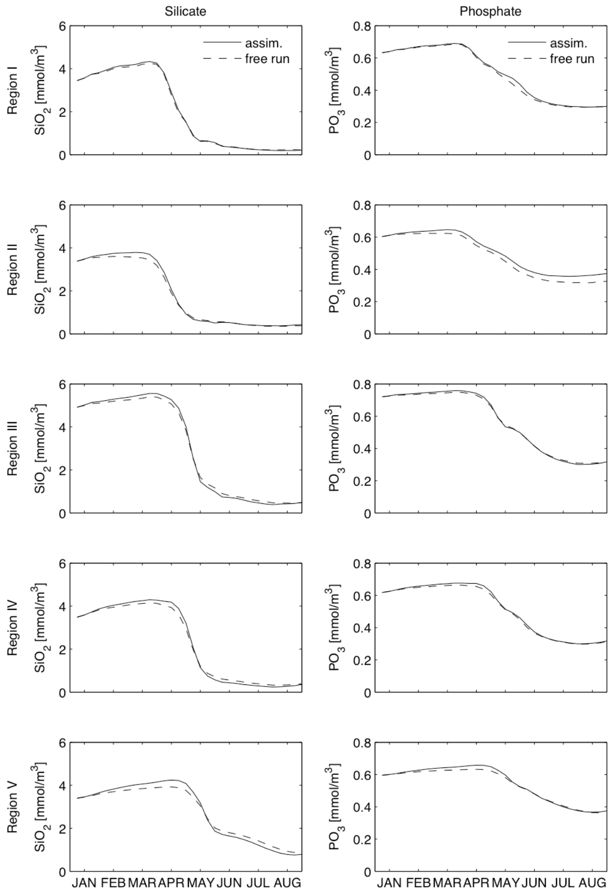

Fig. 7. Comparison between weekly averaged nutrients in the assimilation run (solid line) and the free run (dashed line): silicate (first column) and phosphate (second column) in the five regions. The nutrients have been depth–averaged over the upper 50 m.

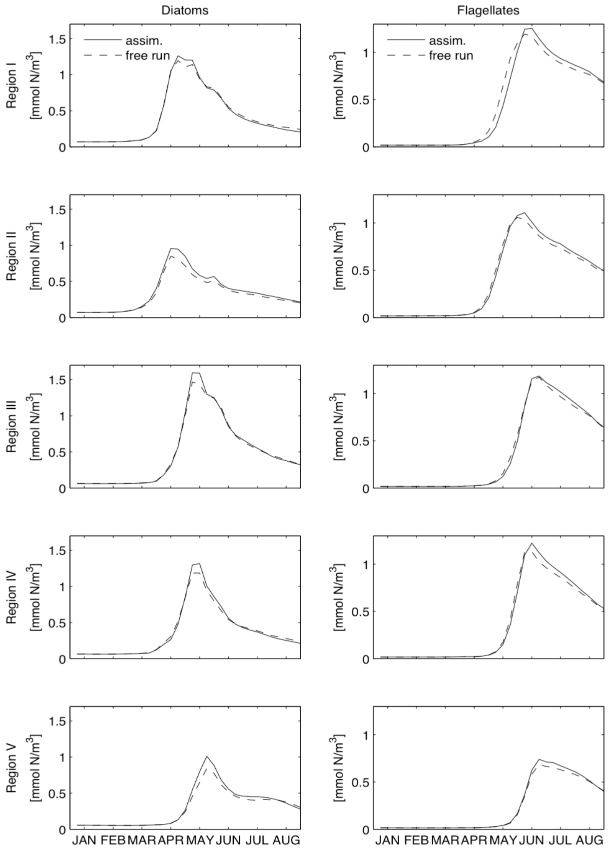

Fig. 8. Comparison between phytoplankton in the assimilation run (solid line) and the free run (dashed line): diatoms (first column) and flagellates (second column) in the five regions. The phytoplankton have been depth–averaged over the upper 50 m.

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