



# Influence of horizontal model grid resolution on the simulated primary production in an embedded primary production model in the Norwegian Sea

C. Hansen\*, A. Samuelson

Nansen Environmental and Remote Sensing Center/Mohn-Sverdup Center, Thormøhlensgate 47, N-5006 Bergen, Norway

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## ABSTRACT

The purpose of this paper is to investigate the influence of horizontal grid resolution in a physical model on an embedded primary production model. The area for the experiment was along the west coast of Norway, from 60° N to 70° N, an area of high mesoscale activity. The HYbrid Coordinate Ocean Model was coupled with the NORwegian ECOlogical Model system, and run in a nested system, consisting of three model grids with horizontal resolution of 50 km, 16 km and 4.5 km (hereafter: COARSE, MEDIUM and FINE) in the focus area. Two main results were obtained, first, the composition of the phytoplankton functional groups changed with increasing model grid resolution. In FINE, the diatoms produced a larger part (60%) of the total annual primary production than the flagellates, whereas in COARSE and MEDIUM, the primary production from the two phytoplankton groups was the same. This was explained by a higher transport of silicate into the euphotic layer in FINE compared to the other two. Second, the differences in the primary production first became large when the resolution of the model grid reached the Rossby radius of deformation. Whereas the total net primary production in MEDIUM only was 5% larger than in COARSE, the total net primary production in FINE was 20% higher than in COARSE. This was explained by the models ability to resolve mesoscale activity.

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## 1. Introduction

Along the coast of Norway, where the warm, saline (>35) Atlantic water in the North Atlantic Current (NAC) meets the fresher (<35) coastal water in the Norwegian Coastal Current (NCC), there is high mesoscale activity. Here, mesoscale activity is processes on a scale of 2–30 km. There have been a number of studies of the physical processes in the area, see e.g. Johannessen et al. (1989), Ikeda et al. (1989), Oey and Chen (1992), Sætre and Aure (2007), but little is known about the effect of the mesoscale activity on the primary production (Rey, 2004). Observations from ocean color images give

evidence of high chlorophyll-*a* concentrations in eddies that are shed from the NCC (Are Folkestad, personal communication), some of these are very persistent and last for several weeks (Rey, 2004). Due to frequent cloud cover over the Norwegian Sea, it is difficult to use remote sensing data to find out how often these eddies occur, and thus study their total effect on the primary production. One approach to solving this problem is to use coupled physical–biological models.

Several model studies have explored the connection between the mesoscale activity and the primary production, see, e.g. Oschlies and Garçon (1998), Oschlies (2002), Garçon et al. (2001), Mahadevan and Archer (2000), McGillicuddy and Anderson (2003). These models were run in the oligotrophic gyre in the North Atlantic to investigate if eddies are able to close the gap between estimated and observed primary production. The general conclusion is that increasing the horizontal model grid will enhance the primary

\* Corresponding author.

E-mail address: [cecilie.hansen@nersc.no](mailto:cecilie.hansen@nersc.no) (C. Hansen).

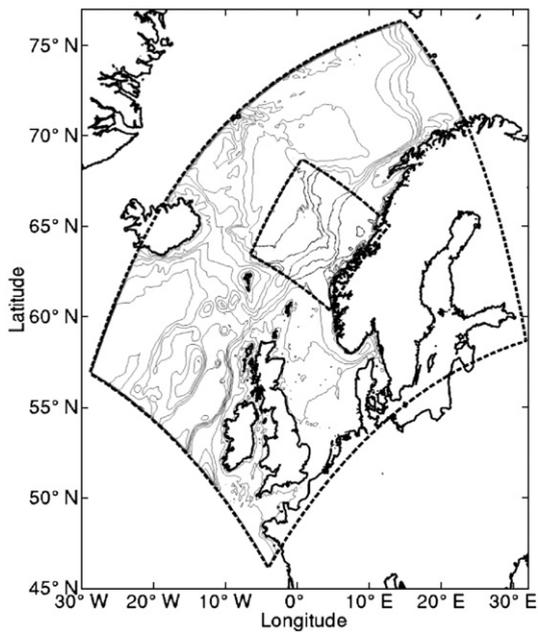


Fig. 1. The model domains of MEDIUM and FINE are shown, with the bathymetry in the area as contour lines.

production, but the magnitude of the impact of the resolved mesoscale activity is still uncertain. Mahadevan and Archer (2000) showed that, by increasing the horizontal model grid resolution from  $0.4^\circ$  to  $0.2^\circ$  and finally to  $0.1^\circ$ , the largest changes occur when going from a model that does not resolve the Rossby radius of deformation to one that resolves it. Their results show that it is necessary to resolve the mesoscale activity to capture the vertical transport of nutrient rich waters to the euphotic zone, and that although the changes are small on an annual timescale, they can be significant on longer timescales. The primary production model used in this study includes two phytoplankton classes, therefore we also examined the importance of resolving the mesoscale activity on the composition of the phytoplankton groups included in the model.

We have used a nested system consisting of three model grids to explore the effects of model resolution along the west coast of Norway (Fig. 1). The horizontal resolutions in the focus area were 50 km, 16 km and 4.5 km (hereafter COARSE, MEDIUM and FINE), respectively. All three model grids were run with the same physical and biological models, and they also had the same forcing and parameters to make it easy to identify the effect resulting from the horizontal resolution alone. Two main results emerged from this study. First, when the horizontal resolution changed, the composition of the phytoplankton groups changed. In FINE, the diatoms had a higher part of the total net primary production than the flagellates had, whereas in COARSE and MEDIUM, the two phytoplankton classes provided approximately equal amounts to the annual spatial mean net primary production. Second, increasing the horizontal model grid resolution also increased the spatial mean net primary production, particularly when going from a model that does not permit mesoscale variability to one that does.

## 2. Methods

The experiment was performed using a nested system consisting of three model grids, where the horizontal

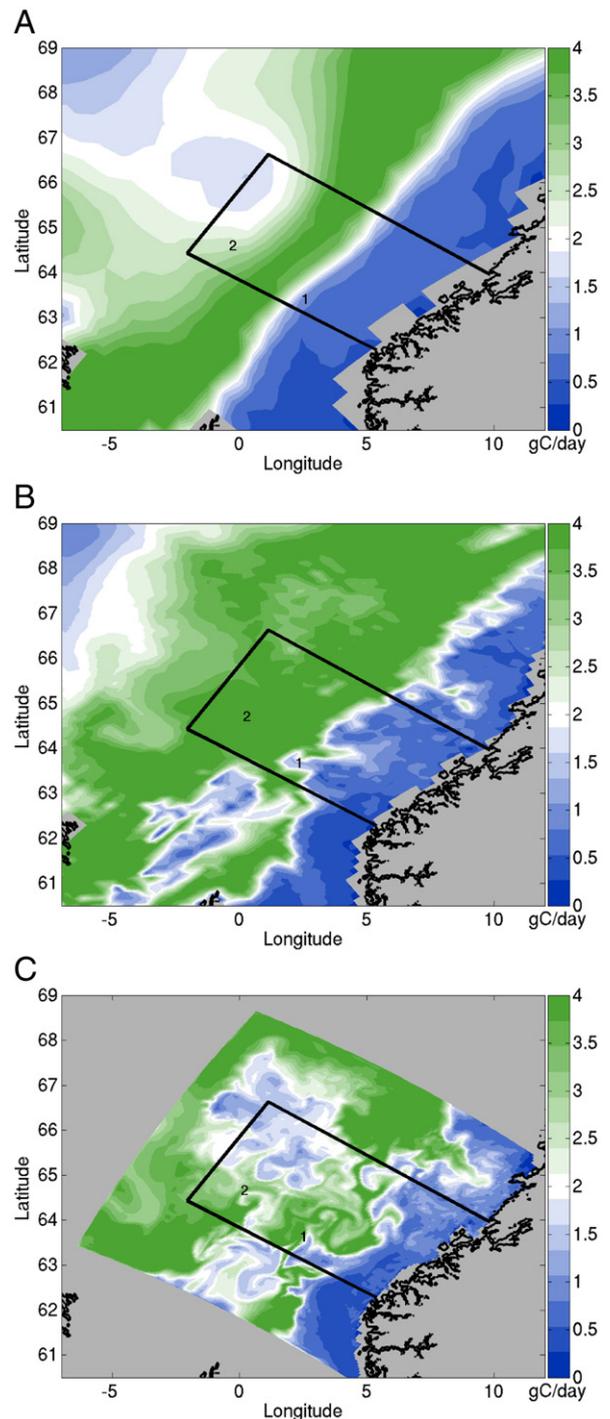


Fig. 2. Illustration of the influence of mesoscale activity on the primary production. Here the depth integrated, daily averaged primary production from diatoms on Julian day 145 in 1995 from (A) COARSE, (B) MEDIUM and (C) FINE. The area inside the black box is the area where the models were compared.

resolution varied from 50 km to 4.5 km in the region of interest (Fig. 2). One-way nesting was used, the larger model giving boundary conditions to the smaller model. The model grid domains of MEDIUM and FINE and the focus area used in the study are shown in Figs. 1 and 2, respectively.

### 2.1. Physical model

The model grids were created by the conformal mapping tool by Bentsen et al. (1999). The physical model was the HYbrid Coordinate Ocean Model (HYCOM; Bleck, 2002), this model has been demonstrated for use in coastal areas by Winther and Evensen (2006) and for basinwide simulation by e.g. Chassignet et al. (2003). The layers are isopycnic in the open, stratified ocean, and change to  $z$ - and  $\sigma$ -layers in coastal and shallow water areas. In this experiment the option for  $\sigma$ -layers was turned off, and the model therefore only included  $z$ - and isopycnic layers. The vertical spacing of the three model grids was the same, 23 layers. In HYCOM, each layer has an assigned density, called the target density (Bleck, 2002). The target densities referred to  $\sigma_0$  (i.e. density at atmospheric pressure minus  $1000 \text{ kg/m}^3$ ), and the lower 18 layers ranged from 24.05 to 28.10. By setting the surface target densities to low values, a  $z$ -model description of the upper mixed layer is ensured. Here, the target densities of the first five layers were set to 0.1–0.5. This was done to resolve the upper mixed layer, as this is important when coupling with biological models. It also prevents a collapse in the vertical coordinates when adding the river runoff (Winther and Evensen, 2006). In the isopycnic layers, the density of the watermass in the layer is the same as the target density, in the  $z$ -layers the density in the watermass can be different from the target density. When a target density does not exist in the watercolumn, the corresponding layer will be transformed to a constant-thickness layer.

HYCOM uses a KPP-mixing scheme, see Large et al. (1994) for more details. Winther and Evensen (2006) show that this scheme introduces too much mixing, however, other mixing schemes have not yet been tested extensively with HYCOM, therefore, we have chosen to use the KPP-mixing. The North Atlantic model was coupled with an ice module, containing two ice models; one thermodynamic model described by Drange and Simonsen (1996) and a dynamic model using the elastic-viscous-plastic rheology of Hunke and Dukowicz (1999).

The model domain of COARSE included both the Arctic Ocean and the Atlantic Ocean from  $30^\circ\text{S}$ . To check the physical model system, COARSE had a spinup period of 46 years, starting in 1958. A common problem with coarse models of the North Atlantic is the overshooting of the Gulfstream. The northward delocalization of the Gulfstream will introduce warm and saline water south of Greenland, and the surface relaxation in the model will force this watermass towards colder and fresher values. When the watermass finally enters the Nordic Seas, the surface relaxation has caused a drift in the salinity and temperature, giving too fresh and cold watermasses in the Nordic Seas. This will eventually weaken the North Atlantic Current. The surface relaxation in the model was weak, with a relaxation timescale of 180 days, but this was still enough to cause a significant drift in the model. To limit the drift caused by this overshoot, the model was run the first 14 years with a sill on the relaxation (Mats Bentsen,

personal communication). By comparing 10 year model means with GDEM climatology (Teague et al., 1990), the results demonstrated that there was no significant drift in temperature and salinity in the model during the spinup (figures not shown). The physical system was run alone until 1987 before the biological system was initiated with climatological nutrient fields (Conkright et al., 2002) and constant plankton and detritus fields, and then run until 1996. The baroclinic timestep of COARSE was 1200 s and the barotropic timestep was 75 s. COARSE had no barotropic fluxes included on the boundaries.

MEDIUM was initiated in 1990 from interpolated fields from COARSE. The physical part was run alone until 1993, then coupled with the primary production module and run until 1996. The baroclinic timestep in MEDIUM was 720 s and the barotropic timestep was 45 s. The brackish water inflow from the Baltic Sea was included as a barotropic port at the entrance from the Baltic Sea. It provided a volume transport of  $0.015 \text{ Sv}$  ( $1 \text{ Sv} = 10^6 \text{ m}^3$ ). The model was run with a 4th order advection scheme, this means that the model was able to resolve more or less the same features as an 8 km model grid would do with a 2nd order advection scheme (Winther et al., 2007).

FINE was initiated from both physical and biological interpolated fields from MEDIUM, and run from Julian day 120 in 1994 until the end of 1995. It was run with a baroclinic timestep of 240 s and a barotropic timestep of 12 s. Because the other two model grids had long spin-ups and were showing no drift in the transports into the Nordic seas, six months of spinup was enough for FINE to stabilize. This model was also run with the 4th order advection scheme.

All three models were forced with ERA40 synoptic fields (Uppala et al., 2005) and they were run with the same climatological river runoff, the rivers did not include nutrients. None of the models had tides included, as this would introduce more mixing, and thus influence the primary production, making it difficult to isolate the differences caused by the horizontal grid resolution.

### 2.2. Primary production model

The primary production module was the NORwegian ECOlogical Model system (NORWECOM; Skogen and S¸oiland, 1998; Aksnes et al., 1995). The model consists of 10 compartments, including two phytoplankton classes, diatoms and flagellates, nitrate, silicate, phosphate, biogenic silica, detritus, oxygen inorganic suspended particulate matter (ISPM) and yellow substances. In this study, the model was run without ISPM and yellow substances. It was originally designed to model the North Sea, but is also well fitted to the Norwegian Sea. Originally, the NORWECOM system included the Princeton Ocean Model as the physical module (Skogen and S¸oiland, 1998), however, in this experiment it was replaced with HYCOM. The biological model was coupled to the physical model through mixing, advection and light. The bottom stress used in the sediment part of the biological model was computed from the currents in the lower 10 m. All the biological components got nesting conditions from the larger model. As the area of the FINE model grid was quite small, the nesting conditions were important to get good results. Because of the poor resolution of climatological data in this area, it was concluded that a stable primary production

model could provide better boundary conditions than relaxing towards climatology, and therefore all the biological parameters were included in the nesting.

COARSE was not relaxed towards climatological values at the southern boundary, mainly because it was considered not to have any significant influence on our focus area. The nutrients in COARSE were initialized from annual mean nutrient fields (Conkright et al., 2002), and the other variables from homogeneous fields. Both phytoplankton classes and detritus were initiated with the same value of  $0.1 \text{ mg N/m}^3$ , biogenic silica was initiated at  $0.1 \text{ mg Si/m}^3$ , and oxygen at  $4300 \text{ mg O/m}^3$ . The biological model did not provide any information back to the physical system. The sediment layer in MEDIUM and FINE was given from restart-files from the larger model. The sediment layer in COARSE was initialized with  $40 \text{ mg N/m}^3$  for nitrate,  $20 \text{ mg P/m}^3$  for phosphate,  $200 \text{ mg Si/m}^3$  for silicate,  $30 \text{ mg N/m}^3$  for detritus,  $20 \text{ mg N/m}^3$  for biogenic silica, and  $3000 \text{ mg O/m}^3$  for oxygen. In this experiment, the sediment layer was defined as 2-dimensional, with a burial rate of 120 days. Sinking rates for the different components were kept at the same level as defined in Skogen and S oiland (1998);  $3.0 \text{ m/day}$  for detritus,  $0.25 \text{ m/day}$  for flagellates,  $1.0 \text{ m/day}$  for sediments and  $3.0 \text{ m/day}$  for biogenic silica. As an exception, the sinking rate for the diatoms was kept at a constant rate of  $0.3 \text{ m/day}$ . The area indicated in Fig. 2 was used to compare the spatial mean net primary production in the three model grids. The initiation of the phytoplankton bloom was defined as the time when the depth-integrated phytoplankton concentration reached 10% of the maximum value.

A one year run where nutrient regeneration was disabled was also performed to check the differences between new and regenerated production in the model grids. The runs were started in December 1994 and run to January 1996.

### 3. Results

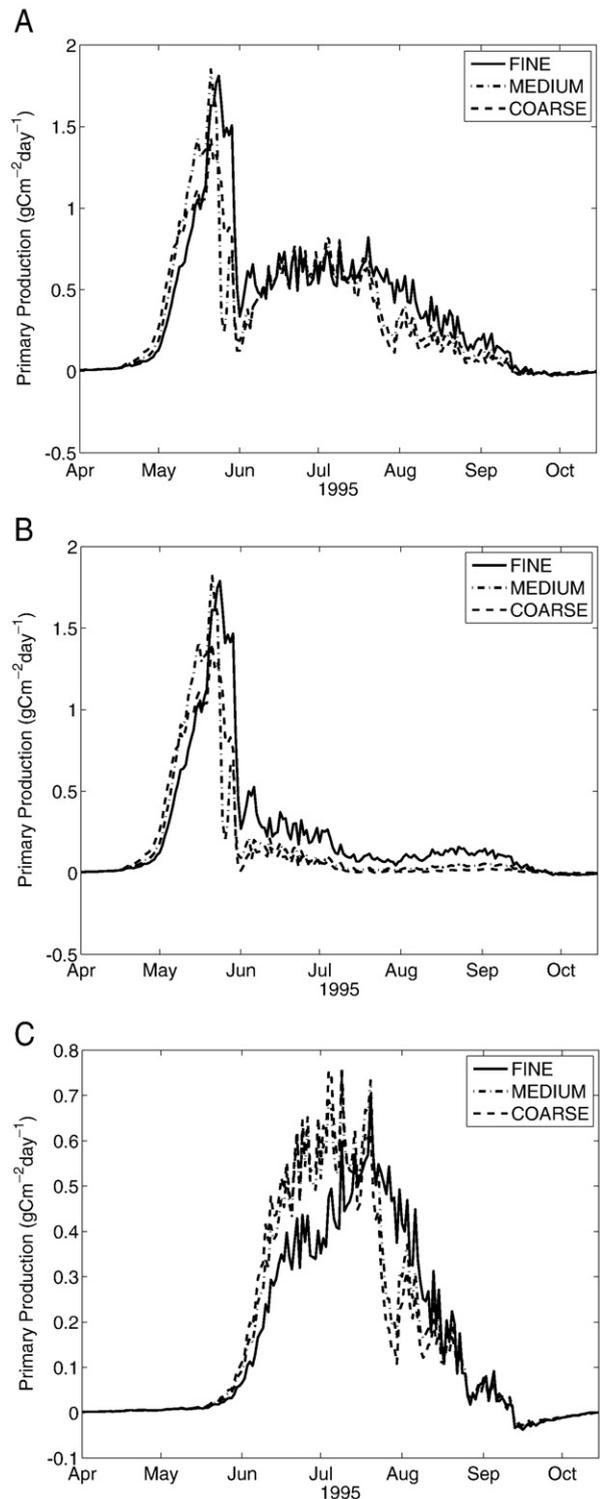
The increase of the model grid resolutions from  $50 \text{ km}$  to  $16 \text{ km}$  and then finally to  $4.5 \text{ km}$  introduced considerable changes to both physical and biological results. The vertical velocities were roughly three times higher in FINE than in COARSE, with maximum values of about  $20 \text{ m/day}$ , whereas COARSE showed no such peaks. MEDIUM had more variability in the vertical velocity field compared to COARSE, but did not produce the high maximum values and the energetic fields that could be seen in FINE. The increased vertical velocities in FINE resulted in higher transport of nutrients into the euphotic zone, which in turn led to an increase in the spatial mean annual net primary production (Table 1).

The net primary production was defined as the primary production minus respiration, and will from now on be

**Table 1**

The spatial mean net primary production from the three model grids, first total, then the contribution from the two phytoplankton classes

Model	Total ( $\text{gC/m}^2/\text{year}$ )	Diatoms ( $\text{gC/m}^2/\text{year}$ )	Flagellates ( $\text{gC/m}^2/\text{year}$ )
FINE	78.46	47.78	30.68
MEDIUM	68.82	35.13	33.69
COARSE	65.05	31.91	33.14



**Fig. 3.** (A) Spatial mean net primary production in the three model grids. FINE had a five day delay in the initiation of the spring bloom compared to COARSE; (B) Spatial mean net primary production for diatoms. FINE had a higher primary production during the summer and autumn compared to the two coarser model grids. (C) Spatial mean net primary production for flagellates. FINE had a delay in the maximum of the flagellate bloom, and lacked the autumn bloom which could be observed both in MEDIUM and COARSE around julian day 220.

referred to as primary production. We noticed changes in both new and regenerated production due to the increase in vertical velocities caused by the horizontal model grid resolution. Therefore, we have chosen to look at the new, regenerated and total primary production, not just the total primary production or the new production. The spatial mean annual primary production was 20% higher in FINE than in COARSE, whereas there was only a 5% increase from COARSE to MEDIUM, see Table 1. This estimate was an average over the whole area, and did not differentiate between costal and off-shelf areas. The primary production estimates from the three model grids are a little too low compared to the estimates from Rey (1981, 2004), where the primary production in the NCC is approximately 90–120 gC/m<sup>2</sup>/year and around 80 gC/m<sup>2</sup>/year for the Norwegian Sea. This was expected, due to the tides being turned off and the rivers not including nutrients. When comparing time series on spatial mean primary production, the difference can be difficult to notice (Fig. 3 (A)), but when the annual primary production from diatoms and flagellates were considered separately, it was clear that during the summer and autumn, the diatoms in FINE continued to have a higher daily primary production than in COARSE and MEDIUM (Fig. 3(B) and (C)). The flagellates in FINE, on the other hand, had a somewhat lower production than in COARSE and MEDIUM, especially during the start of the bloom. Diatoms were responsible for 50% of the spatial mean annual primary production in both COARSE and MEDIUM, in FINE this increased to 60%. The increase in the spatial mean annual primary production from the diatoms in COARSE to FINE was nearly 50%, whereas there was an 8% decrease in the spatial mean annual primary production from the flagellates (Table 1).

It was primarily new production that increased when the grid resolution was increased (Table 2). The total annual regenerated primary production was the same in all three grids (Table 3). The new production in FINE was 63% of the spatial mean primary production, for MEDIUM this part had decreased to 58% and in COARSE it was 55% (Table 2). In FINE, the flagellate new production lasted longer, and was a couple of days delayed compared to MEDIUM and LARGE (figures not shown).

In all three model grids, the new production was primarily from diatoms, whereas only roughly 15% was from the flagellates. The differences between the contributions to the primary production from the two phytoplankton classes, developed in the regenerated production. In COARSE and MEDIUM, close to 95% of the regenerated production was from the flagellates, whereas in FINE the flagellates contributed with only 80% of the total regenerated production. The difference in the diatom contribution to the regenerated

**Table 2**

The spatial mean new production from the three model grids, first total and then the contribution from the two phytoplankton classes

Model	Total (gC/m <sup>2</sup> /year)	Diatoms (gC/m <sup>2</sup> /year)	Flagellates (gC/m <sup>2</sup> /year)
FINE	49.29	42.12	7.17
MEDIUM	39.67	33.27	6.41
COARSE	36.05	30.37	5.69

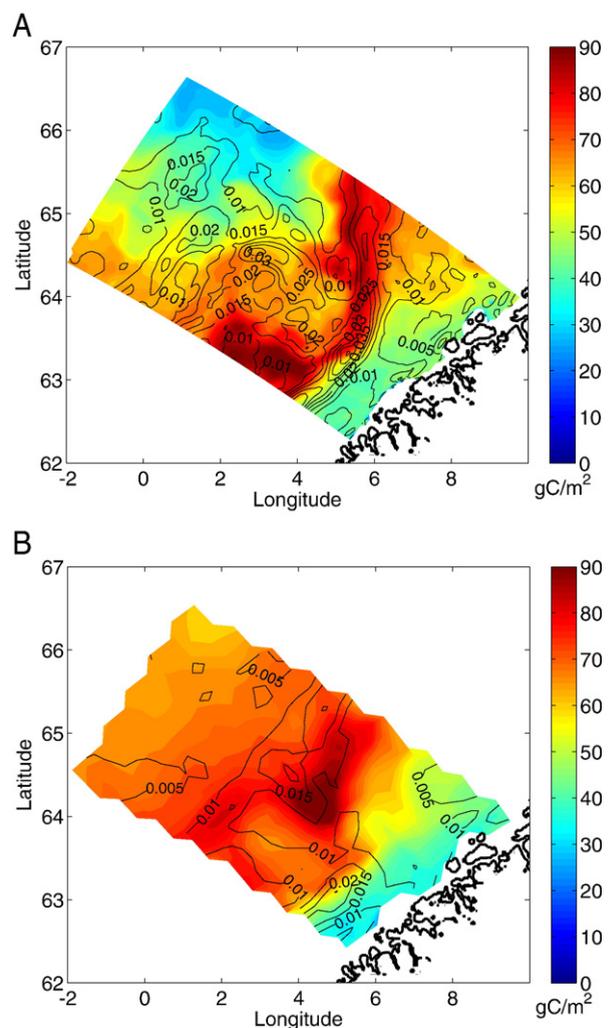
**Table 3**

The spatial mean regenerated production from the three model grids, first total and then the contribution from the two phytoplankton classes

Model	Total (gC/m <sup>2</sup> /year)	Diatoms (gC/m <sup>2</sup> /year)	Flagellates (gC/m <sup>2</sup> /year)
FINE	29.17	5.66	23.51
MEDIUM	29.15	1.86	27.28
COARSE	29.00	1.54	27.45

primary production was closely linked to the higher vertical velocities and the increased transport of silicate into the euphotic zone.

The primary production from the flagellates was closely connected to the eddy kinetic energy (EKE) in the models (Fig. 4). The regenerated production from the diatoms is shown in Fig. 5. Figure from COARSE is not shown, as there was almost no EKE due to the crude horizontal resolution. The EKE was computed as a mean over the months March to



**Fig. 4.** The flagellate gross primary production from March to August with the EKE (m<sup>2</sup>/s<sup>2</sup>) from the same timeperiod as contour lines from (A) FINE and (B) MEDIUM. The gross production was defined as the pure primary production.

August, and the phytoplankton primary production was summed up over the same months.

Even though the spatial mean annual flagellate production was lower in FINE compared to MEDIUM and COARSE, large horizontal variability in the flagellate production existed, giving locally enhanced flagellate production compared to the two coarser model grids. These differences were especially distinct at the front between the NAC and the NCC. Here, FINE had up to 40% higher flagellate production than COARSE.

In FINE the upper mixed layer developed later compared to the other two model grids. This led to a three day delay of the start of the spring bloom in FINE compared to MEDIUM and COARSE in the focus area. When comparing results from different locations in the focus area, the delay of the spring bloom could reach up to 16 days in FINE compared to COARSE. The temporal development of the primary production in the three model grids from two locations (Fig. 2), one at the front and one offshore is shown in Figs. 6 and 7. Rapid horizontal

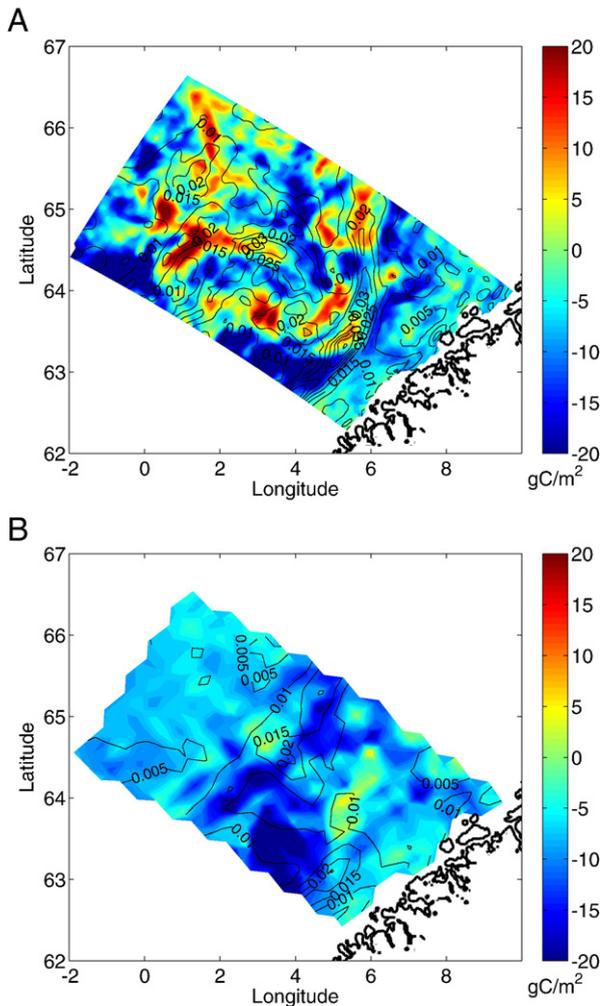


Fig. 5. The diatom regenerated gross production (gross primary production minus new gross production) from March to August with the EKE ( $m^2/s^2$ ) from the same timeperiod as contour lines from (A) FINE and (B) MEDIUM.

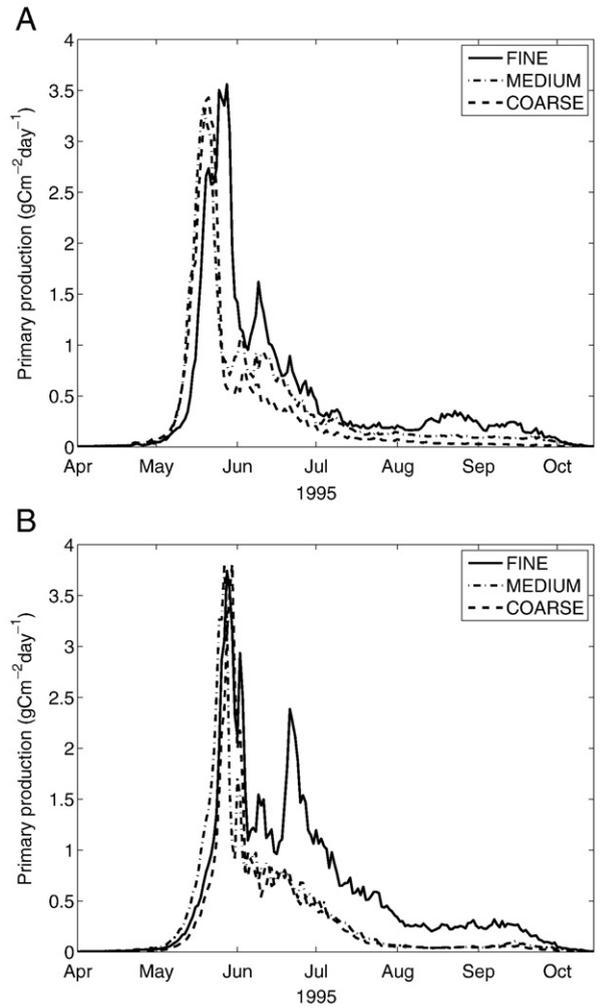
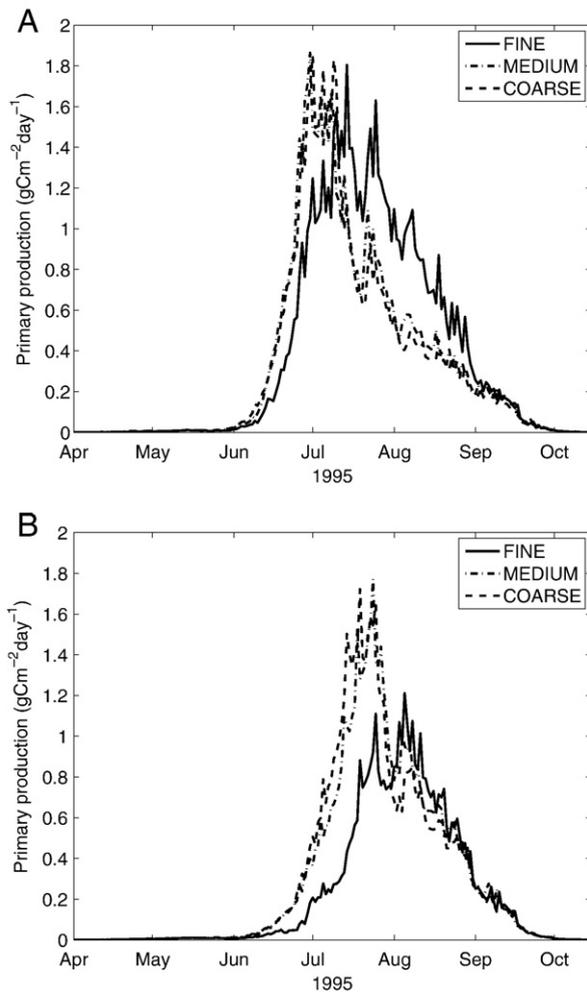


Fig. 6. (A) The timeseries of diatom primary production in location 1, at the front between NAC and NCC. The spring bloom in FINE is a couple of days delayed compared to MEDIUM and COARSE, but stays at higher levels toward the end of the bloom. (B) Same as in (A) but for location 2, located offshore. The large peak in the end of June was following an increased nutrient event. The diatom primary production in FINE stays at a higher level from June to the end of the bloom, due to increased concentrations of silicate in the euphotic zone.

variations in the physics in FINE introduced high temporal variability in the biology. The flagellate production in FINE at location 2 was lower than the flagellate primary production at location 1, which was close to the front.

#### 4. Discussion and concluding remarks

In this study, a nested system consisting of three model grids of varying horizontal resolution was used to explore the influence of the mesoscale activity on the primary production. By running the exact same physical and primary production models in all three model grids, the effects from the increasing horizontal resolution were isolated, and thus possible to observe. Further, the two phytoplankton groups included in the primary production model made it possible to



**Fig. 7.** (A) The timeseries of flagellate primary production in location 1. (B) Same as for (A), but at location 2. At the front, the flagellate production in FINE lasted longer compared to COARSE and MEDIUM, due to increased transport of nutrients into the euphotic zone. Offshore, the flagellate production was much lower at this location, caused by a strong diatom bloom.

examine the importance of resolving the mesoscale activity to the composition of the phytoplankton functional groups.

Mahadevan and Archer (2000) show that the vertical transport in their model grids becomes largest when the Rossby radius of deformation is resolved. The Rossby radius along the Norwegian coast in the focus area is  $\sim 5$ – $10$  km, and an abrupt change in the results appeared when the model grid resolution increased from 16 km to 4.5 km, that is, reached the same scale as the Rossby radius of deformation in the area. From Haugan et al. (1991), Johannessen et al. (1989), Ikeda et al. (1989) and Oey and Chen (1992), the recommended horizontal grid size in order to be able to reconstruct the mesoscale processes in the focus area properly, is 2–3 km. The 4.5 km resolution of FINE is therefore somewhat crude, however, the 4th order advection scheme compensates for this (Winther and Evensen, 2006).

Even though MEDIUM resolves some mesoscale features, there is only a small difference between this and COARSE,

indicating that it is the smaller mesoscale features that need to be resolved to introduce large changes in the system. Lévy et al. (2001) performed a process study in an oligotrophic context, where the impacts of resolving mesoscale and submesoscale activity were examined. They found that the submesoscale activity (scale at  $\sim 5$ – $20$  km) will increase the primary production even more compared to the mesoscale activity (scale at  $\sim 20$ – $50$  km). In their model study, the primary production increased by 100% in the submesoscale experiment, compared to a 30% increase in the mesoscale experiment. They had a Rossby radius of deformation at 30 km, and the sub- and mesoscale experiments were performed using models of 2 km and 6 km, respectively. Reducing the horizontal model resolution at the same rate as Lévy et al. (2001) ( $1/15$  of the Rossby radius of deformation) would be a demanding task with our model system, but a more moderate decrease from 4.5 km might introduce a further increase in the changes between FINE and COARSE. At present time the computational costs of running the model are too high to perform this experiment.

As referred to in the introduction, increasing the horizontal resolution will introduce an overall increase in the primary production. The results from Falkowski et al. (1991) give an increase of 20% in the primary production by eddy pumping. This agrees well with the increase from COARSE to FINE, which shows the same increase in the primary production. Oschlies (2002) has performed a comparison between a  $(1/9)^\circ$  model grid and a  $(1/3)^\circ$  model grid, and notice only a small increase of 10% in the basin mean nitrate supply in the  $(1/9)^\circ$  model run compared to the  $(1/3)^\circ$  model run. It is emphasized that the  $(1/9)^\circ$  model does not resolve small scale and frontal processes, and hence lack some of the vertical transport introduced by these. Along the Norwegian coast, it is important to resolve the strong front dynamics to be able to model the primary production. This was seen in the results, where high primary production occurred along the front.

In contrast to Oschlies (2002), McGillicuddy and Anderson (2003) get a large increase in the nutrient supply in the subtropics when increasing the horizontal model resolution in their model, from  $2^\circ$  to  $0.3^\circ$  and finally to  $0.1^\circ$ . The largest difference between these two studies is the relaxation towards climatology beneath the euphotic zone in McGillicuddy and Anderson (2003). The forcing towards climatological values below the euphotic zone might have introduced an artificial increase, which in turn made the impact of the resolved mesoscale activity in the experiment of McGillicuddy and Anderson (2003) larger than the horizontal resolution implies.

The models in our study do not use this approach, but the differences in the magnitude of the results can also originate from regional differences. The numerical advection scheme used in the models also plays an important role. The model studies mentioned have all been performed in the oligotrophic subtropical gyre, whereas this study focuses in an area close to the coast. The Norwegian Sea gets nutrient supply from the NAC and the NCC, the last one through rivers and nutrient rich water from the Baltic Sea. In this study, the river nutrients and the tides were turned off. This caused less mixing, reduced the nutrient levels, and hence decreased the primary production. Still, one might expect that an area that

receives the amount of nutrients that the Norwegian Sea does, would not be as dependent on the mesoscale activity for the primary production as the primary production in the oligotrophic ocean seems to be. This was proven wrong in this study. For instance, the depth integrated nutrient transport over the upper 200 m in MEDIUM was approximately the same as in FINE, but without the high vertical velocities, the surface soon get drained of nutrients, and the nutrients below the euphotic layer was not transported upwards at the same rate as in FINE. In COARSE, the transports of nutrients were lower compared to the other two, probably due to a wide and less defined NAC (figures not shown).

The amount of new production in the model grids, ranging from 55% in COARSE to 63% in FINE was reasonable for the area (Rey, 1981). The enhanced mesoscale activity in FINE introduced a 36% increase in the spatial mean new production compared to COARSE. Roughly 95% of the new production in all three model grids was from the diatoms, whereas the flagellate production mainly was regenerated production. The large amount of diatom new production was not surprising, due to the fact that they bloom first, and that silicate was regenerated at a lower rate than nitrate and phosphate in the model. The increase of the diatom contribution to the regenerated production in FINE compared to COARSE and MEDIUM, however, was more interesting. This showed that the amount of silicate transported into the euphotic zone was large enough for the diatoms to consume more of the regenerated nitrate and phosphate, leaving less nutrients for the flagellates. Hence, a lower part of the production came from the flagellates in FINE, causing the observed shift in the contribution to the primary production from the two phytoplankton groups. Comparing the EKE and the flagellate production, it was noticed that the flagellate primary production followed closely the areas with high EKE (Fig. 4), as did the regenerated production from the diatoms (Fig. 5).

Rodríguez et al. (2001) suggest that there is a relationship between the phytoplankton size classes and vertical velocities, independent of the nutrient supply. This is explained by the interaction between the sinking velocity of the phytoplankton and the vertical velocities, and is true for velocities between  $-5$  m/s and  $5$  m/s. This leads to a shift toward larger phytoplankton size classes. The sinking velocities of the two phytoplankton classes included in our study did not differ by more than  $0.1$  m/s, and it is unlikely that this would be enough to see the effect that Rodríguez et al. (2001) reported of. Lima et al. (2002) show that mesoscale activity influenced the community structure towards higher concentration of the largest phytoplankton size class included in their model. This was due to an uplift of the nutricline along the fronts and eddies. They also pointed out that differences in the two phytoplankton classes included in their model also could come from differences in the definition of nutrient limitation and death rate. As one of our phytoplankton classes had a silicate limitation, and the other was only limited by the availability of nitrate and phosphate, this had a large influence on the differences in the primary production from the two phytoplankton classes. In this study it was the availability of silicate that prevented larger diatom primary production, hence, the enhanced silicate concentration due to increased mesoscale activity was especially favorable for this phytoplankton class.

The change in the phytoplankton dynamics due to the increase of horizontal resolution can be of great importance on longer timescales and for the carbon export prediction. One assumes that the carbon export is different in different phytoplankton species (Hood et al., 2006). The diatoms sink fast, both due to their silicate shell and their aggregation, and can therefore be a larger contributor to the export of carbon than the flagellates. Here, the sinking velocities of the two phytoplankton classes were almost the same, and aggregation was not included, but this is something that should be tested in later runs, to check if this introduces even larger differences. Also, even though 20% increase in primary production does not seem large on an annual scale, it can introduce large changes on longer timescales.

A delay of 5 days in the initiation of the spring bloom was observed between FINE and COARSE. The upper mixed layer in COARSE developed a few days earlier compared with the upper mixed layer in FINE, due to the increased mixing in FINE. The enhanced mixing had a net positive impact on the primary production in FINE, but by also transporting phytoplankton out of the euphotic zone, it might as well have contributed to the delay in the initiation of the spring bloom.

The conclusion is that the horizontal model grid size is very important to catch all vertical transport into and out of the euphotic zone, and to reconstruct the sharp fronts found in the area. Silicate was regenerated at a much lower rate than nitrate and phosphate in the model, causing the diatoms to be more sensitive to a higher transport of nutrients into the euphotic zone. Observations give an indication of increased impact of mesoscale activity on diatoms, McNeil et al. (1999) reported of higher diatom biomass compared to other phytoplankton groups during a mesoscale event, and Benitez-Nelson et al. (2007) characterized a cyclonic eddy west of Hawai'i as a silica pump. These are important findings to reflect on when constructing a new model study. If a model study should be used to complement the sparse in-situ and satellite data in our areas, one needs to consider the obvious sill in the horizontal model grid size before starting the study, as our results show that this introduce large changes, in new production, total primary production, spatial variability and last but not least, the phytoplankton dynamics.

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