Simulated primary production in the Norwegian Sea - Interannual variability and impact of mesoscale activity

Cecilie Hansen

Dissertation for the degree Philosophiae Doctor

Geophysical Institute
University of Bergen
Norway
November 2008
Simulated primary production in the Norwegian Sea - Interannual variability and impact of mesoscale activity

Cecilie Hansen

PhD Thesis in Oceanography
November 2008

Geophysical Institute
University of Bergen
Acknowledgements

Thanks to my supervisors, Dag L. Aksnes, Laurent Bertino, Helge Drange and Annette Samuelsen for support and motivation along the way!

Thanks to Trond Mohn c/o Frank Mohn AS, which made the work possible by a private donation.

Thank you, Annette, for your everlasting patience with all my questions and worries. Knut, without you, I would still be stuck with the first bug!

Thanks to my co-authors; Annette and Erik, for interesting and amusing discussions, and invaluable contributions!

Thank you, all my colleagues and friends at the Nansen Center, for making the days so interesting and always being there for me!

Thank you, my fantastic parents, for support, motivation and love. Mamsi, I wish you could have been here with us today.

Thank you, the two best grannies in the world, for always asking how things are going.

Thank you, family and friends for understanding and support!

Thank you, Anders ♥ Without you, I would never have had the strength or courage to finish.
Preface

This synthesis and three papers are submitted for the degree of Philosophiae Doctor in oceanography at the Geophysical Institute, University of Bergen. In this work, an ocean general circulation model has been coupled with a primary production model. The objective has been to explore the impact of horizontal model grid resolution, atmospheric forcing and mesoscale activity on the simulated primary production in the Norwegian Sea.

The thesis is divided into an introductory part and a part consisting of three papers. The first part gives the scientific rationale, presents the main conclusions and provides suggestions for future work. The second part consists of the following papers:

**Paper I**  Influence of horizontal model grid resolution on the simulated primary production in an embedded primary production model in the Norwegian Sea, **Hansen, C. and Samuelsen, A.**, Revised and resubmitted to Journal of Marine Systems

**Paper II**  Interannual variability of the primary production in the Norwegian Sea: Relation to the NAO in a numerical model, **Hansen, C. and Samuelsen, A.**, Submitted to Marine Ecology Progress Series

**Paper III**  Anticyclonic eddies in the Norwegian Sea; Their origin, evolution and influence on primary production, **Hansen, C. and Kvaleberg, E. and Samuelsen, A.**, To be submitted
Contents

Acknowledgements v
Preface vii

1 Introduction 1
  1.1 Scientific rationale ........................................ 1
  1.2 Summaries of papers ....................................... 6
  1.3 Conclusions .................................................. 10
  1.4 Future perspectives ....................................... 11

Papers 16
  Influence of horizontal model grid resolution on the simulated primary production in an embedded primary production model in the Norwegian Sea . . 18
  Interannual variability of the primary production in the Norwegian Sea: Relation to the NAO in a numerical model .......................... 38
  Anticyclonic eddies in the Norwegian Sea; Their origin, evolution and influence on primary production ............................................... 62
1 Introduction

1.1 Scientific rationale

Phytoplankton are small, unicellular organisms that constitute a large part of the lowest trophic level in the food chain in the oceans. They are an important food source for zooplankton and fish, and they can have a large impact on the water quality. Pollution of water, for instance in connection with releases of nutrients from industry or agriculture, can trigger large phytoplankton blooms, which can be hazardous for both marine life and humans.

Phytoplankton production depends on light, nutrients and CO$_2$. The nutrient concentrations in the upper part of the water column in the Norwegian Sea are controlled by the transport of nutrients into the area, and the mixed layer depth during winter. A deep mixed layer supplies sub-surface nutrients to the surface, but at the same time it prevents the onset of the spring bloom. The onset of the spring bloom is controlled by the availability of light, as the phytoplankton need a certain amount of light to maintain a net growth (Sverdrup, 1953). A deep mixed layer mixes the phytoplankton down, and out of the zone where the light levels are sufficient; the *euphotic zone*. Hence, the mixed layer needs to be shallower than a certain depth, the so-called critical depth, for the phytoplankton to initiate growth (Sverdrup, 1953).

The shoaling of the mixed layer in spring is mainly governed by warming by the sun, increased freshwater input and decreased wind-stirring. When the critical depth is reached, typically early May in the Norwegian Sea (Rey, 2004), the spring bloom starts. As long as there are sufficient levels of nutrients and light, the phytoplankton will grow. By the end of summer, the nutrients are partially or fully depleted in the upper part of the water column, the light is fading, and cold and strong winds force the mixed layer to deepen. This break up of the shallow upper mixed layer introduces nutrients into the upper part of the water column. If the nutrient levels get sufficiently high and there is enough light, often in combination with temporarily calm weather, the phytoplankton can produce a secondary bloom; the autumn bloom.

Both the Norwegian Coastal Current (NwCC) and the Norwegian Atlantic Current (NwAC) transport nutrients into the Norwegian Sea. NwCC is a fresh, chaotic current that flows in parallel with the Norwegian coast northward, ending in the Barents Sea. It has its origin in the Skagerrak, and a large part of the water comes from the Baltic Sea (Røed and Albretsen, 2007). The NwCC also receives nutrients and freshwater from the rivers along the coast of Europe, and the rivers and fjords along the Norwegian coast.

The warm, saline NwAC enters between Iceland and the Shetland Islands. It has two branches, and the eastern branch flows in parallel with the NwCC along the Norwegian
coast. At roughly 62°N it divides in two parts (not shown in Fig. 1.1). The innermost follows the NwCC, the outer follows the shelf break. They reunite in the Lofoten area and continue toward the Barents Sea and the Arctic (Hansen and Østerhus, 2000). The western branch is topographically steered, and flows for a short distance in parallel with the eastern branch, before it turns northwestward toward the Fram Strait (Orvik, 2002) (Fig. 1.1).

In addition to transport, nutrient concentrations can be enhanced by mesoscale activity. Locally, mesoscale activity can increase and prolong the phytoplankton bloom. This can be observed for instance in fronts and eddies (Lee and Williams, 2000; McGillicuddy et al., 1998; Lima et al., 2002). Falkowski et al. (1991) found that eddy pumping increased the primary production by roughly 20 %, and the results of Oschlies and Garçon (1998) indicated that one-third of the nitrate flux into the euphotic zone in the North Atlantic sub-tropical gyre originates from mesoscale processes.

The timing and amount of primary production have large interannual fluctuations,
which are controlled by transport of water masses, weather conditions and locally by mesoscale activity. The primary production can be divided into two parts, new and regenerated production. The new production is defined as the production due to ‘new’ or upwelled nutrients entering the euphotic zone (Eppley and Peterson, 1979), whereas regenerated production comes from nutrients that are regenerated within the euphotic zone. If oxygen measurements are used to estimate the biological production, one gets the total production (which adds oxygen) minus the respiration (which uses oxygen), called the net community production. At a seasonal to annual basis, net community production can be equivalent to the new production (Falck and Gade, 1999), although this has been discussed (Laws, 1991). However, there are a few estimates of the primary production in the Norwegian Sea, both model and observation based. According to Rey (1981), the primary production in the NwCC is approximately 90–120 g-C m$^{-2}$ yr$^{-1}$. In the Norwegian Sea, the primary production is estimated to be somewhat lower than in the NwCC, roughly 80 g-C m$^{-2}$ yr$^{-1}$ (Rey, 2004). Both estimates are based on observations. The new production is estimated to be roughly 60% of the total primary production at Ocean Weather Station Mike (OWSM) at 66°N, 2°E (Rey, 2004). The rate of new production is also believed to be dependent on the latitude, increasing from south to north (Rey, 2004). In Falck and Gade (1999), the net community production in the Nordic Seas is estimated to $\sim$ 36 g-C m$^{-2}$ yr$^{-1}$, and roughly 40 g-C m$^{-2}$ yr$^{-1}$ at OWSM, whereas Skjelvan et al. (2001) estimate the net community production to 24 g-C m$^{-2}$ yr$^{-1}$ for a section in the northern Norwegian Sea. Both estimates are based on observations. Skogen et al. (2007) use a three-dimensional ocean general circulation model coupled with a primary production model, and get an estimate of 79 g-C m$^{2}$ yr$^{-1}$ in the Norwegian Sea, with a new production rate of 55%. Finally, Haupt et al. (1999) use a one-dimensional model to estimate the primary production at OWSM, and get an estimate of 90 g-C m$^{-2}$ yr$^{-1}$ total primary production, and 63 g-C m$^{-2}$ yr$^{-1}$ new production. The values are more or less in agreement with each other, but the uncertainties and the spatial variability in the primary production are high.

The timing of the spring bloom varies from year to year, and differences in the timing of peak primary production at OWSM of six weeks have been reported (Rey, 2004). No other locations in the Norwegian Sea have frequent observations over long enough time intervals to provide an estimate of the interannual differences. In principle, analysis of remotely sensed ocean color could be used to estimate the spring bloom. Unfortunately, no such studies have been performed, in parts because of the high degree of cloudiness in the region. In conclusion, the general seasonality in the Norwegian Sea is fairly well known, but details about the timing of the spring bloom and the total primary production are still somewhat uncertain.

The phytoplankton blooms, their development, duration and strength can, as already mentioned, be monitored by in-situ observations and from space. Unfortunately, the cloud cover prevents continuous remote sensing of the chlorophyll concentrations in the Norwegian Sea. Even with seven-day mosaics, there can still be large areas without data. Similarly, in-situ observations cannot cover the whole area both in time and space, and field campaigns are also labour and cost demanding. Due to these obstacles, there are still many unanswered questions about the simulated dynamics of the phytoplankton in the Norwegian Sea.

Coupled physical-primary production models can be used to fill some of the gaps in the
observation-based information. For model evaluation, a certain amount of observations are needed. There are, for many areas and long time periods, numerous temperature and salinity observations, but observations of nutrients and chlorophyll concentrations are unfortunately sparse in time and space and are not always easily accessible. This study aims, by using a coupled physical-primary production model, to gain more knowledge about the primary production in the Norwegian Sea. Further, both remote sensing observations and in-situ observations are used to test the models ability to reproduce the primary production.

Skogen and Moll (2005) showed that different primary production models coupled with the same physical ocean model might not produce very different results. Their conclusion is that a requirement for a well functioning ecosystem model is a proper physical system. In my study, the Nansen/Mohn-Sverdrup Center version of the Hybrid Coordinate Ocean Model (HYCOM; Bleck, 2002) was coupled with the Norwegian Ecological Model System (NORWECOM; Skogen et al., 1995; Skogen and Soiland, 1998) (Fig. 1.2), to model the primary production in the Norwegian Sea. HYCOM has been tested for relevant coastal and shelf ocean areas (Winther and Evensen, 2006), and found to reproduce the currents, salinities and temperatures well. By choosing z-levels as the upper five vertical coordinates in HYCOM, it is ensured that the upper mixed layer is resolved. NORWECOM was originally designed for the North Sea, but could easily be adapted to fit the Norwegian Sea system as well.

A one-way nested system consisting of three model grids, where the larger models provide lateral nesting conditions for the smaller ones, is used. Using this methodology, a high resolution model is set up along the west coast of Norway. This model has been named FINE in the first paper and HIGH in the two last ones, here it will be referred to as HIGH. In the area of prime interest, the Rossby radius of deformation is $\sim 5$-10 km, and the horizontal resolution of the model should preferably be about 2 km, based on the studies by Johannessen et al. (1989); Haugan et al. (1991) and Oey and Chen (1992). With the high computational cost incurred by the primary production model, this was not practically feasible. Still, a high resolution model with 4.5 km resolution run with a $4^{th}$ order momentum QUICK scheme (Holland et al., 1998; Webb et al., 1998) tend to resolve similar features as a model with doubled resolution and a $2^{nd}$ order momentum scheme (Winther et al., 2007). In this area, the primary production has not, to the best of our knowledge, been modelled using a high resolution model, and there are still many unanswered questions about the primary production and its spatial and temporal development.

Based on this, the main objective of the thesis is:

To investigate the primary production in the Norwegian Sea using a coupled physical-primary production model.

The specific objectives are to:

- Couple HYCOM to a primary production model, NORWECOM, and test the system in the Norwegian Sea.

- Gain knowledge about the influence of horizontal model grid resolution on the simulated primary production in a near-coastal, high mesoscale activity area at
Figure 1.2: Illustration of the model system. NORWECOM was coupled to HYCOM through mixing, advection and light. DIA is diatoms, FLA is flagellates, DET is detritus, SIS is biogenic silica, OXY is oxygen, NIT is nitrate, PHO is phosphate and SIL is silicate.
high latitudes.

- Study the interannual variability in the primary production in the Norwegian Sea, and explore possible connections to the North Atlantic Oscillation.

- Use the model system to study the influence of anticyclonic eddies on the primary production in the Norwegian Sea, and compare the results with the available remote sensing observations.

1.2 Summaries of papers

**Paper I: Influence of horizontal model grid resolution on the simulated primary production in an embedded primary production model in the Norwegian Sea**

The Norwegian Sea is an area of high mesoscale activity, especially along the coast of Norway, where the warm, saline Norwegian Atlantic Current (NwAC) meets the fresher, meandering Norwegian Coastal Current (NwCC). At the boundary between the two currents there are frequently formation of frontal eddy and meander structures. The focus of this study is to explore the influence of the mesoscale activity in a high-latitude, coastal area with high nutrient supply from the currents. Previous studies, see e.g. Oschlies (2002); Mahadevan and Archer (2000); McGillicuddy and Anderson (2003), have in general concluded that the mesoscale activity in the oligotrophic ocean increases the primary production, however, to what extent is still somewhat unclear. Mesoscale activity is also known to have an impact on the phytoplankton dynamics; Lima et al. (2002) showed that mesoscale activity trigger a shift in the phytoplankton community toward larger size classes.

The coupled physical-primary production model mentioned in Section 1.1 was used. The primary production model had eight components; two phytoplankton classes (diatoms and flagellates), three nutrients (nitrate, phosphate and silicate), biogenic silica, oxygen and detritus. Three model grids with horizontal resolution of 50 km, 16 km and 4.5 km (hereafter COARSE, MEDIUM, HIGH) were compared in an area off the west coast of Norway, from 60°N to 70°N. The models were run without tides and nutrient inputs by the rivers, in order to isolate the effects of the horizontal resolution. All three model grids had 23 vertical layers, and were forced with the 6-hourly ERA40 1.125 × 1.125 degree resolution fields (Uppala et al., 2005); provided by the ECMWF (www.ecmwf.int). The results from the three models from 1995 were compared in an area inside HIGH, excluding the nesting zone.

The difference in the primary production between COARSE and MEDIUM is not large, only 5%, but there is a 20% difference between COARSE and HIGH. The largest differences in the primary production occur when the model grid resolution reaches the same scale as the Rossby radius of deformation, which in this area is 5–10 km. This result agrees with earlier findings, but from model studies in the oligotrophic part of the North Atlantic (Mahadevan and Archer, 2000).

An interesting feature is the obtained differences in the phytoplankton dynamics. The two phytoplankton classes provides equal parts to the annual primary production in both
COARSE and MEDIUM, but in HIGH the part of the primary production coming from the diatoms is 10% higher than in the other two model configurations. In HIGH, there is a close connection between areas with high mean kinetic energy and areas with the largest increase in the diatom primary production. Silicate is regenerated at a lower rate than nitrate and phosphate in the model, and the diatom primary production is limited by the supply of silicate. When the mesoscale activity increases, the vertical velocity increase by up to 300%, and there is an increase in the silicate supply to the euphotic zone. Due to the enhanced silicate concentration, the diatoms consume more of the regenerated nitrate and phosphate. This leaves less nutrients for the flagellates, and cause the shift in the composition of the phytoplankton community.

The main conclusion is that the resolution of the horizontal grid mesh is important not only for the total primary production, which increases by roughly 20% when the grid resolution reaches the Rossby radius, but also for the dynamics of the phytoplankton species.

**Paper II: Interannual variability of the primary production in the Norwegian Sea: Relation to the NAO in a numerical model**

The interannual variations in the primary production in the Norwegian Sea and possible connections to the North Atlantic Oscillation (NAO) index are studied using the results from a 50 km horizontal resolution model for the period 1990–2000. The results from the years 1995-1997 are compared to those from a high resolution model with 4.5 km resolution.

The NAO index is here defined as the difference in sea level pressure between Stykkisholmur, Iceland, and Lisbon, Portugal (Hurrell, 1995), and is a measure of the strength of the westerly winds over the northern North Atlantic. A high winter NAO index forces the Norwegian Atlantic Current (NwAC) closer to the Norwegian Coast, and introduces more Arctic waters in the eastern part of the Norwegian Sea (Blindheim, 2004). During winters with low (negative) NAO index the NwAC is located further away from the Norwegian Coast, and there is a reduced contribution of Arctic water to the Norwegian Sea (Blindheim, 2004).

Several studies have shown statistical relationships between the NAO index and the marine biology in the region (Skogen et al., 2007; Ottersen et al., 2001; Reid and Edwards, 1998). For instance are winters with high (positive) NAO index correlated with an increase in the growth rate of the Arcto-Norwegian cod (Ottersen et al., 2001). A strong negative correlation has been reported between the abundance of *Calanus finmarchicus* in the North Sea and the eastern North Atlantic and the winter NAO index (Fromentin and Planque, 1996). The latter relationship did, however, break down in 1996. The breakdown was later connected to the decline in the *C. finmarchicus* abundance in deep water the Norwegian Sea (Heath et al., 1999; Planque and Batten, 2000), which caused less *C. finmarchicus* individuals to be advected into the North Sea. In the Norwegian Sea, no such study has been performed, likely due to less frequent plankton observations. A potential relationship between the primary production and the NAO index has been more difficult to identify (Barton et al., 2003). Because fluctuations in the primary production are thought to be transferred to higher trophic levels, studying these variations might yield more knowledge about what determines the interannual variations at higher
trophic levels.

In this study, the variations in the winter (December through March) NAO index are compared to the annual primary production in an area along the west coast of Norway, from 60°N to 70°N. It is found that the winter NAO index explained roughly 65% of the variations in the simulated annual primary production, with a one year time lag. The connection between the winter NAO index and the simulated primary production is explained by the variability in the nutrient transports following changes in the winter NAO index. The advected signal has a one year delay compared to the winter NAO index.

The timing of both the diatom and flagellate bloom has a strong negative correlation with the winter NAO index. This can be explained by changes in the water mass properties due to variations in the volume transport into the Norwegian Sea, impacting the mixed layer. High volume transports following a year with high winter NAO index may lead to an early stratification, and hence to an early bloom.

Following a year with low winter NAO index, the model produces a low and late spring bloom. The model also indicates a connection between the local effects of the winter NAO index, like in 1996, when the spring bloom was very early compared to 1995 and 1997, due to low winds in March. Still, almost 50% of the variations in the timing of both the flagellate and diatom blooms can be accounted for by the winter NAO index of the previous year.

The main conclusion from the study is that there exists a strong connection between the annual primary production in the Norwegian Sea and the winter NAO index of the previous year. This is due to changes in the transport of nutrients and water masses into the area, and will also be evident in the timing of both the flagellate and diatom blooms. Rapid drops in the winter NAO index, like the one from 1995 to 1996, will have an impact on the primary production. The one year delay between the winter NAO index and the primary production might enable us to estimate the magnitude and timing of next years bloom.

Paper III: Anticyclonic eddies in the Norwegian Sea; their origin, evolution and influence on primary production

The origin and development of anticyclonic eddies at two locations in the Norwegian Sea and their influence on primary production are studied. This is done by using a combination of remote sensing observations and results from a high resolution coupled primary production-physical model. The study was motivated by ocean color images, which showed an anticyclonic eddy with high concentrations of chlorophyll-a (chl\textsubscript{a}) in the Norwegian Sea in May 2008.

At the boundary between the Norwegian Coastal Current (NwCC) and the Norwegian Atlantic Current (NwAC) there are frequently frontal meander and eddy formation. Several studies have explored the origin of the eddies at or close to the front, such as Johannessen et al. (1989) and Ikeda et al. (1989). They found several mechanisms for the formation of the eddies, for instance topographic effects, in addition to barotropic and baroclinic instabilities. The generation mechanisms for the numerous anticyclonic eddies found offshelf in the Norwegian Sea have not, to the best of our knowledge, been described in conjunction with primary production.
Previous work on the impact of eddies on marine organisms along the Norwegian coast include Fossheim et al. (2005); Pedersen et al. (2005); Skarðhamar et al. (2007). These studies focus on higher trophic levels, such as zooplankton and fish larvae from in-situ observations, and do not address phytoplankton in particular. Several studies have explored the connection between mesoscale activity and primary production, see e.g. Oschlies (2002); McGillicuddy et al. (2007); Benitez-Nelson et al. (2007), but not with a focus on high-latitude coastal areas.

The coupled physical-primary production model mentioned in Section 1.1 was used. A model grid with 4.5 km horizontal resolution (hereafter: HIGH) was set up along the west coast of Norway from 60°N to 70°N. The model received nesting conditions, both biological and physical, from a 16 km resolution model covering the North Sea and Norwegian Sea, and was run from 1995 to 1997. The results from HIGH were compared to the merged sea level anomaly maps from AVISO and to ocean color images provided by MERIS.

Shifts in the wind in the north/south direction set up baroclinic instabilities, some of which form eddies. A good correlation is found between the wind forcing and mesoscale activity. The eddies in HIGH that are shed prior to the shoaling of the upper mixed layer are deep, almost 500 m initially, and the depressing of the isobaths are traced throughout the whole water column. They have a diameter of about 50 km, and a life time up to four months. Due to the warming by the sun, a density stratification develops in the upper 100 m, and the anticyclones develop into Intra Thermocline Eddies (ITEs) (Gordon et al., 2002). An ITE consists of a lens of well mixed water, with a bowl-shaped bottom and a doming shape at the top.

The phytoplankton bloom in both HIGH and in the ocean color images are delayed compared to the main spring bloom in the surroundings due to a deep mixed layer within. When the anticyclones develop into ITEs, the high nutrient levels within and the shoaling of the upper mixed layer trigger a phytoplankton bloom. The ocean color images from May 2008 give evidence of advection of high chl $a$ concentrations toward the center of the anticyclone, but also of production within the anticyclone. In HIGH, the model resolution is not high enough to capture the spiraling bands of high chl $a$ concentration toward the center of the anticyclone, but it gives evidence of a high production in the center of the eddy. The total primary production within the ITE in HIGH is not higher than the primary production in the area around it.

In conclusion, the transformation of anticyclones into ITEs explain the high chl $a$ concentrations within them, as seen both in ocean color images and in HIGH. Their ability to support a phytoplankton bloom of their own is due to their initially high nutrients concentration, in combination with the shoaling of the upper mixed layer. The results deviate from those of McGillicuddy et al. (2007), which showed a prolonged phytoplankton bloom in the middle of an ITE in the Sargasso Sea. The primary production in the ITE in HIGH does not last longer than in the surrounding waters, as the doming of the upper part of the ITE is not strong enough to introduce new nutrients. Mahadevan et al. (2008) show that the high chl $a$ concentration in the center of an anticyclone in the oligotrophic ocean is due to advection of phytoplankton from the periphery of the eddy and not production. Here, the results show that the high chl $a$ concentration in the middle of the ITE in HIGH is due to production and not only advection. The results probably deviate due to difference in the nutrient levels in both the eddies and in the surrounding
waters, and also because a permanent thermocline does not exist in the Norwegian Sea.

In the Norwegian Sea, where information on primary production is sparse, partly due to cloudy conditions, combined studies like the one performed here can provide additional knowledge about the three dimensional structure and development of eddies and their impact on the primary production. Still, more observations are needed for evaluation of the physical-primary production models.

1.3 Conclusions

This thesis has shown that the coupled physical-biological system is able to describe the physical processes and primary production in the Norwegian Sea in a fairly realistic way. In paper II, salinity, temperature, nutrients and chlorophyll were compared to observations, and only chlorophyll was found to be poorly represented. The poor chlorophyll result is explained by a too sluggish and delayed spring bloom. The system has, nevertheless, been used to gain new knowledge about the influence of horizontal model grid resolution, eddies, and variations in the winter NAO index. The following conclusions are obtained (all for the before mentioned region between $60^\circ$N and $70^\circ$N):

- The primary production increases by 20% when the model resolution is decreased from 50 km to 4.5 km. The largest change appears when the resolution of the model grid approaches the Rossby radius.

- Changes in the horizontal grid resolution also introduce differences in the phytoplankton dynamics. When the resolution in the model grid increases, a shift in the phytoplankton community structure occurs, from similar composition of flagellates and diatoms in the coarse resolution versions of the model, to a higher contribution of diatoms for the 4.5 km resolution version of the model.

- The variations in the winter NAO index accounted for, with a one year lag, 65% of the variations in simulated mean primary production in the Norwegian Sea. The connection is explained by a high positive correlation between the nutrient transports and the winter NAO index the previous year.

- The timing of both the diatom and flagellate spring bloom is also connected to the winter NAO index, with the same one year lag.

- In conclusion: The year following a winter with low NAO index has a late and weak phytoplankton bloom, whereas the year following a winter with high NAO index has an early and strong phytoplankton bloom.

- The formation of meanders at the boundary between the NwCC and NwAC is triggered by shifts in the wind direction. The meanders might eventually detach from the boundary as anticyclones at the western side.

- During spring and summer, the development of an upper thermocline leads to a transformation of the anticyclones into Intra Thermocline Eddies (ITEs).
The anticyclones, if shed prior to the spring bloom, have relatively high nutrient concentrations. This, in addition to the development of a shallow upper mixed layer in connection to the transformation to ITEs, enable the eddies to support a phytoplankton bloom of their own.

1.4 Future perspectives

The coupled HYCOM-NORWECOM system has shown promising results in the Norwegian Sea. Both the biological and physical systems are quite realistic, with the exception of the simulated chlorophyll concentrations.

Concerning the poor chlorophyll results, they were explained by a delay in stratification of the water column. From previous studies (Winther and Evensen, 2006), it is known that the K-Profile Parameterization scheme (KPP; Large et al., 1994) provides too much mixing in HYCOM. This needs to be addressed, and other vertical mixing schemes already implemented should be thoroughly tested and verified. If none of these are found to be satisfactory, further development of the vertical mixing schemes is needed.

The vertical resolution of the model is another issue that should be addressed. The winter mixed layer depth in the model is dependent on the vertical resolution, and at some locations adding layers can reduce the mixed layer depth by several hundred meters. This probably has an influence on the entrainment of nutrients into the upper mixed layer and, hence, on the primary production.

When the model has been further improved and tested, assimilation is a natural step towards an improved primary production system. This might enable forecasts of the onset and duration of the spring bloom in the area.

The main part of the water mass in the NwCC origins from the Baltic Sea. At present, this outflow is incorporated in the model using a climatological value of 0.015 Sv with monthly variations. An interesting study would be to use realistic outflow values, including nutrient fluxes, and explore how variations in the outflow propagates along the coast of Norway, and how much these variations may influence the primary production. Also, the difference in the impact from variations in the river outflows compared to variations in the Baltic Sea outflow should be studied.

In the NAO study it was discovered that it was not only the total primary production that had large interannual fluctuations; also the fraction of diatom primary production vs. the fraction of flagellate primary production changed. The reason for this has not been explored, neither the spatial variability of it. Connections to harmful algae blooms merit also consideration.

The interannual variations in the primary production should be compared to the survival rates and strength of the year classes of fish species that live and/or spawn in the Norwegian Sea. Potential connections could be useful in exploring fish stock variability.

The high resolution model should be extended to include more of the Nordic Seas, in order to explore connections between different areas in the Nordic Seas. For instance, propagation of heat and salt and their influence on primary production could be addressed. Such simulations should be performed for longer time periods than in this study, to better explore the interannual variations of the Nordic Seas.
Bibliography


Paper I

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

Hansen, C. and Samuelsen, A.

accepted, Journal of Marine Systems
Influence of horizontal model grid resolution on the simulated primary production in an embedded primary production model in the Norwegian Sea

C. Hansen a, A. Samuelsen a

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

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 were equal. 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.

Key words: Primary production, NAO, Norwegian Sea, Ecological model, HYCOM

* Corresponding author
Email address: cecilie.hansen@nersc.no (C. Hansen).
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 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° to 0.2° and finally to 0.1°, 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 was 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 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 Fig. 1 and Fig. 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 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) shows 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°S. 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 Sv (1 Sv = 10^6 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, 6
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 Søiland (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 Søiland, 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 meters. 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 initialized with the same value of 0.1 mgN/m³, biogenic silica was initiated at 0.1 mgSi/m³, and oxygen at 4300 mgO/m³. 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 mgN/m³ for nitrate, 20 mgP/m³ for phosphate, 200 mgSi/m³ for silicate, 30 mgN/m³ for detritus, 20 mgN/m³ for biogenic silica, and 3000 mgO/m³ 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 Søiland (1998): 3.0 m/day for detritus, 0.25 m/day for flagellates, 1.0 m/day for sediments and 3.0 m/day for biogenic silica. As an exception, the sinking rate for the diatoms was kept at a constant rate of 0.3 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.
Table 1

<table>
<thead>
<tr>
<th>Model</th>
<th>Total (gC/m²/year)</th>
<th>Diatoms (gC/m²/year)</th>
<th>Flagellates (gC/m²/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FINE</td>
<td>78.46</td>
<td>47.78</td>
<td>30.68</td>
</tr>
<tr>
<td>MEDIUM</td>
<td>68.82</td>
<td>35.13</td>
<td>33.69</td>
</tr>
<tr>
<td>COARSE</td>
<td>65.05</td>
<td>31.91</td>
<td>33.14</td>
</tr>
</tbody>
</table>

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

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 km to 16 km and then finally to 4.5 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 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 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 new, regenerated and total primary 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 coastal 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) and Rey (2004), where the primary production in the NCC is approximately 90-120 gC/m²/year and around 80 gC/m²/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 Fig. 3(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).
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.
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.

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 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
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 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. In FINE there was a three day delay of the start of the spring bloom 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 offshelf are shown in Fig. 6 and 7. Rapid horizontal 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
Fig. 4. The flagellate gross primary production from March to August with the EKE (m$^2$/s$^2$) from the same timeperiod as contourlines from (a) FINE and (b) MEDIUM. The gross production was defined as the pure primary production.

thus possible to observe. Further, the two phytoplankton groups included in the primary production model made it possible to examine the importance of resolving the mesoscale activity to the composition of the phytoplankton functional groups.

Mahadevan and Archer (2000) shows that the vertical transport in their model grids become 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 oligothropic context, where the impacts of resolving mesoscale and submesoscale activity were examined. They found that the submesoscale (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 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.
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.

production. Oschlies (2002) has performed a comparison between a (1/9)° model grid and a (1/3)° model grid, and notice only a small increase of 10% in the basin mean nitrate supply in the (1/9)° model run compared to the (1/3)° model run. It is emphasized that the (1/9)° 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° to 0.3° and finally to 0.1°. The largest difference between these two studies is the relaxation towards climatology beneath the euphotic zone in McGillicuddy
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 COARE 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.

and Anderson (2003). Another source to the dissimilarities, is the horizontal resolution. A (1/9)° model will not be able to resolve front dynamics, something Oschlies (2002) pointed out. 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 available online).

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 the 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 the areas with high EKE closely (Fig. 4), as did the regenerated production from the diatoms (Fig. 5).

Rodríguez et al. (2001) suggests 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) shows 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.

5. Acknowledgments

This work was funded by a private donation from Trond Mohn A/S. We would like to thank Norwegian Supercomputing Project (NOTUR) for grant of CPU time, and Laurent Bertino and Dag L. Aksnes for useful comments on the manuscript.

LITERATURE CITED


Paper II

Interannual variability of the primary production in the Norwegian Sea: Relation to the NAO in a numerical model

Hansen, C. and Samuelsen, A.

Submitted to Marine Ecology Progress Series
Interannual variability of the primary production in the Norwegian Sea: relation to the NAO in a numerical model

C. Hansen\textsuperscript{a,}\textsuperscript{*}, A. Samuelsen\textsuperscript{a}

\textsuperscript{a}Nansen Environmental and Remote Sensing Center/Mohn-Sverdup Center, Thormøhlensgate 47, N-5006 Bergen, Norway

Abstract

A primary production model coupled to an Ocean General Circulation Model (OGCM), has been used to study connections between the North Atlantic Oscillation (NAO) index and changes in simulated primary production in the Norwegian Sea. To study the long-term trends a coarse model with 50 km horizontal resolution, covering the Arctic and Atlantic Ocean, was run from 1990 to 2000. The OGCM was spun up from 1957, and had realistic forcing. The results from 1995 to 1997 were compared to those from a nested 4.5 km horizontal resolution version of the same model covering the region off the western coast of Norway. The primary production and the onset of both the diatom and flagellate blooms were highly correlated with the winter NAO index, but with a time lag of one year. The connection was explained by the high correlation between the transports into the Norwegian Sea and the winter NAO index the previous year. A low and late phytoplankton bloom was explained by a low (negative) winter NAO index the previous year, whereas an early and high phytoplankton bloom by a high (positive) winter NAO index the previous year.

Key words: Primary production, NAO, Norwegian Sea, Ecological model, HYCOM

1. Introduction

The North Atlantic Oscillation (NAO) index is defined as the difference in sea level pressure between Stykkisholmur, Iceland, and Lisbon, Portugal (Hurrell, 1995), and is a measure of the strength of the westerly winds across northern North Atlantic. During

\textsuperscript{*} Corresponding author

Email address: cecilie.hansen@nersc.no (C. Hansen).
winters with high NAO index, the westerlies are strong, and Northern Europe experiences higher surface temperatures and more precipitation. Winters with weak westerlies, hence low NAO index, are colder and drier. The NAO index has a strong influence on the North Atlantic Ocean dynamics and thermodynamics (Visbeck et al., 2003; Blindheim, 2004; Furevik and Nilsen, 2005). During winters with a high NAO index, the Norwegian Atlantic Current (NAC) will be closer to the Norwegian coast (Blindheim, 2004) and force more Atlantic water into the North Sea. During winters with low NAO index the NAC is located further away from the Norwegian Coast, leading to reduced Atlantic water transport into the North Sea. In the Norwegian Sea, less Arctic water enters during winters with low NAO index, whereas an enhanced transport is observed for winters with high NAO index (Blindheim, 2004). Hence, the NAO will have a strong influence on the temperature, salinity and presumably the nutrient distribution in the Norwegian Sea.

Statistical relationships have been identified, linking the NAO to several marine organisms (Ottersen et al., 2001). One example is the Arcto-Norwegian cod, for which warm years (positive NAO index) yield higher growth rates. It is not clear whether such statistical relationships are more effected by the NAO, e.g. through temperature, or the response of the phytoplankton to the NAO, and subsequent energy transfer through the food chain, or a combination of the two. Abundance of Calanus finmarchicus has been connected to the variations in the NAO in several papers, see e.g. Fromentin and Planque (1996); Planque and Reid (1998); Greene et al. (2003). Fromentin and Planque (1996) show that there has been a strong, negative correlation between the C. finmarchicus and the winter NAO index in the eastern North Atlantic and North Sea. In 1996, however, this correlation broke down (Planque and Reid, 1998). The explanation for the breakdown has been widely discussed, but was finally linked to oceanic inflow and advection of C. finmarchicus into the North Sea (Stephens et al., 1998; Reid et al., 2003). Reid et al. (2003) found that a deep water inflow event was present in 1996, but due to the decline in the C. finmarchicus population in the deep water of the Norwegian Sea (Heath et al., 1999; Planque and Batten, 2000), the advection of the organisms into the North Sea was weak, hence a breakdown in the correlation occurred. Later, Greene et al. (2003) showed that the negative correlation between the C. finmarchicus population in the North Sea and the winter NAO index for the years 1957 to 1996 peaks when C. finmarchicus lags the winter NAO index by one year.

A more thorough understanding of the mechanisms that control the variability of the primary production in the Norwegian Sea will improve the understanding of the zooplankton variability in the area. With the link to higher trophic levels, it could potentially explain some of the variation in the fish stocks in the Norwegian Sea, such as the Spring Spawning herring. The links between the NAO and the phytoplankton has been less clear than the connections between the zooplankton and the winter NAO index (Barton et al., 2003).

In the Norwegian Sea, cloudy conditions make continuous ocean color images difficult to obtain. In addition, in-situ observations are sparse in time and space. A combination of model results and available observations is therefore required to gain more knowledge about the timing, duration and concentration of the phytoplankton bloom. Skogen et al. (2007) performed a model study covering the Nordic Seas, based on a model with 20 km horizontal resolution. The NAO index used in the study was computed over the six first months of the year. They found a negative correlation of 0.63 between the modeled
primary production along the Norwegian west coast and the NAO index. They also found a strong positive correlation between the annual transport through the Fram Strait and the mean primary production in the Nordic Seas.

In this study, a coupled Ocean General Circulation Model (OGCM) and primary production model with a 50 km horizontal resolution (hereafter: COARSE) was used to simulate the years 1990 to 2000. To be able to relate this analysis to earlier studies of connections between the abundance of *C. finmarchicus* and the NAO, it is focused on the winter NAO index. The main objective of our work is to explore the mechanisms behind the interannual variability in the primary production in the Norwegian Sea, and whether it could be related to the winter NAO. Provided a relationship to the winter NAO, this might provide an opportunity to predict the primary production in the area, and thus give information of part of the energy transfer up the food chain.

2. Material and methods

In this study the same OGCM, but with three different horizontal resolutions, was adopted. The higher resolution models were one-way nested into the coarser models. The physical model used was the HYbrid COordinate Ocean Model (HYCOM; Bleck, 2002), online coupled to the NORWegian ECOlogical Model System (NORWECOM; Skogen et al., 1995; Skogen and Seiland, 1998). All three model domains were created using the conformal mapping tool by Bentsen et al. (1999). In the vertical, the models had 23 layers.

2.1. Physical model

The COARSE model domain covered the Atlantic Ocean from 30°S and the Arctic Ocean, and had a varying horizontal resolution of 30-120 km (Fig. 1). It was spun up from 1957 (Fig. 2), starting from the Generalized Digital Environmental Model Data Base climatology (GDEM; Teague et al., 1990). Eventual drift in salinity, temperature and transports (Fig. 3) were checked, and were found to be weak prior to 1990 and negligible after 1990. This finding holds for both hydrography and nutrients. COARSE provided nesting conditions, both physical and biological, to the medium sized model (hereafter: MEDIUM).

The physical part of MEDIUM was initiated from interpolated fields from COARSE in January 1990 (Fig. 2). The MEDIUM model domain covered the North Sea and the Norwegian Sea (Fig. 1), and had a horizontal resolution of 16 km. MEDIUM provided nesting conditions to the high resolution model (hereafter: HIGH) from June 1994 (Fig. 2), when HIGH was initiated from interpolated fields from MEDIUM. HIGH had a horizontal resolution of 4.5 km, and the domain is displayed in Fig. 1 and Fig. 4 (area B).

In hybrid models, each layer has an assigned density, called the target density (Bleck, 2002). The target densities are given in \( \sigma_0 \), i.e. in units of potential density referenced to the surface. To ensure a z-level resolution at the top, which is necessary to always resolve the upper mixed layer in the model, the first five layers has been assigned with low target densities, 0.1 to 0.5. If the target density does not exist in the water column, which will be the case with the 0.1 to 0.5 target densities, the layers in question change to a z-level.
Fig. 1. The three level nested system used in the study, with the COARSE model domain covering the Atlantic Ocean from 30° S, including the Arctic Ocean in north. MEDIUM covers the North Sea and the Norwegian Sea, whereas HIGH covers a smaller area along the coast of Norway.

Fig. 2. An overview over the time period the three models were run, COARSE at the bottom, MEDIUM in the middle and FIN E at the top. The gray-shaded area is the period when the coupled physical-primary 7 production model system was used.
This also prevents a collapse in the layers when adding the river runoff (Winther and Evensen, 2006). The target densities in the lower 18 layers ranged from 24.05 to 28.10. The z-levels were defined to have a spacing maximum and minimum thickness of 3 m, and a stretching factor of 1.125. This gave us a depth of the first z-level of 3 m, the next one would then be 3.375 m (layer depth × stretching factor), etc.

The tides were included in MEDIUM, and were part of the nesting conditions provided for HIGH. MEDIUM was also run with a barotropic port at the entrance to the Baltic Sea, with a 0.015 Sv (1 Sv=10⁶ m³ s⁻¹) transport into the North Sea. The 6-hourly synoptic fields used in all three models were ERA-40 with a 1.125×1.125 degree resolution (Uppala et al., 2005), provided by the European Centre for Medium-Range Weather Forecasts (ECMWF; www.ecmwf.int). COARSE was run until January 2001, MEDIUM and HIGH until January 1998 (Fig. 2). COARSE was run with a Mellor and Yamada 2.5 mixing scheme (Mellor and Yamada, 1982), while the two smaller models were run with a KPP mixing scheme (Large et al., 1994). All three models were run with climatological river runoff, this included nutrients for the major rivers in the North Sea and along the Norwegian Coast. These data were provided by the Institute of Marine Research, Bergen, Norway, as 20 years time series (Morten Skogen, personal communication). The mean of these observations was used as model input. For the rivers along the coast of the United Kingdom the mean was computed for the last five years only, because of known errors in the observations (Morten Skogen, personal communication).

MEDIUM and HIGH were run with a 4th order momentum QUICK scheme (Holland et al., 1998; Webb et al., 1998), which increases the models ability to resolve mesoscale activity at almost the same degree as doubling the horizontal resolution (Winther et al., 2007). A model with 50 km horizontal resolution is, however, not sufficient to resolve the high mesoscale activity in the Norwegian Sea (Haugan et al., 1991; Johannessen et al., 1989; Oey and Chen, 1992). Therefore, to check if COARSE was able to obtain the same trends as HIGH did, we compared the results from COARSE to those from HIGH for the period from 1995 to 1997.

2.2. Primary production model

The primary production model had eight components; two phytoplankton classes (diatoms and flagellates), three nutrients (nitrogen, phosphate and silicate), and detritus, biogenic silica and oxygen, and was coupled with the physical part of the system through mixing, advection and light. The solar insolation was climatological, but the surface irradiance was modified by the synoptic cloud cover from ERA-40 and the self-shading by the phytoplankton. The primary production part in COARSE was initiated in January 1987 from climatology (Conkright et al., 2002) for the nutrient fields. Diatoms, detritus and flagellates was initiated with 0.1 mg-N m⁻³, biogenic silica with 0.1 mg-Si m⁻³ and oxygen with 4300 mg-O m⁻³. The coupled COARSE was run until January 2001. The primary production part of MEDIUM was initiated from interpolated fields from COARSE in January 1993, and was run until January 1998.

The nutrients were checked for drift in COARSE (Fig. 3), and the drift was small compared to the differences in interannual nutrient concentrations. For instance, the drift in nitrate was approximately 0.11% per year, while the interannual differences in area A in COARSE was roughly twenty times larger. Without sources and sinks, the
model preserves the nutrient concentrations. Therefore, the drift is probably due to a mismatch between the sinking and burial rate of biologic matter, the remineralization rate and the strength of vertical mixing. Importantly, no relaxation was used on the nutrient fields.

After seven years of integration with COARSE and 1.5 year with MEDIUM, the seasonal evolution for the ecosystem compartments approached a quasi steady-state behavior. Furthermore, it followed that six months of spin-up was sufficient for HIGH.

The primary production model used was originally developed for the North Sea, where the water clarity is different from that in the Norwegian Sea. The contribution from the water itself to the light attenuation coefficient for downwelling irradiance was originally set to 0.07 m$^{-1}$, but was changed to 0.04 m$^{-1}$, as Seawifs data (http://oceancolor.gsfc.nasa.gov) showed that the values in the Norwegian sea are closer to 0.04-0.05 m$^{-1}$ during winter when the chlorophyll contribution is low. Otherwise, the parameterization for the primary production model was the same as in Skogen and Søiland (1998), except the sinking rate for diatoms, which was kept constant at 0.3 m day$^{-1}$. The sinking routine was exchanged with the sinking routine used in the carbon cycle version of the Nansen/Bjerknes version of MICOM (Karen Assmann, personal communication). The start date of the spring bloom was defined as the time when the concentration of the depth integrated phytoplankton from the whole water column reached 10% of its maximum value. The annual primary production and the timing of the spring bloom were computed over area A in Fig. 4. The annual primary production was defined as the gross production minus the respiration, and was integrated over the whole water column.

2.3. Model error calculation

Following the study by Allen et al. (2007), we used two different tests to compare in-situ observations with the results from HIGH: the Nash Sutcliffe Model Efficiency and the percentage model bias. The model efficiency test is defined as:
Fig. 4. The area for computing the annual primary production (A). All transports are computed over the southern boundary of area A (dotted line). Area B is the HIGH model domain. The stars marked on the map are the locations for all the silicate observations in 1995.

\[
ME = 1 - \frac{\sum_{n=1}^{N}(D_n - M_n)^2}{\sum_{n=1}^{N}(D_n - \bar{D})^2}
\]  

where \(D_n\) is the observations, \(M_n\) the corresponding model estimate, and \(\bar{D}\) is the mean of the observations. The total number of observations is \(N\), and \(n\) is the \(n\)th comparison.

The performance levels are as follows: > 0.65 excellent, 0.65-0.5 very good, 0.5-0.2 good, < 0.2 poor (Allen et al., 2007; Maréchal, 2004). The test gives the ratio between the model error and the variability in the observations, and as it is squared, a realistic model result will be rewarded. The percentage model bias is defined as:

\[
Pbias = \frac{\sum_{n=1}^{N}(D_n - M_n)}{\sum_{n=1}^{N}D_n} \times 100
\]  

The performance levels for \(|Pbias|\) are as follows: < 10 excellent, 10-20 very good, 20-40 good, > 40 poor (Allen et al., 2007; Maréchal, 2004). For the observation-model comparison, some in-situ observations are available from the International Council for the Exploration of the Sea (ICES) at www.ices.dk, but the majority of the nutrient and chlorophyll observations were provided by the Institute of Marine Research, Bergen, Norway.

The comparison between model results and observations were performed for HIGH in area B (Fig. 4), whereas the comparisons with the winter NAO index, and model-model comparisons were performed in area A (Fig. 4), both for COARSE and HIGH.
3. Results

3.1. Comparisons between model results and observations

The model biases (Fig. 5a) showed that HIGH did not systematically under- or overestimate the physical or biological variables. There was some bias, especially in the chlorophyll-a results. For every year of comparison, roughly 5000 chlorophyll-a and nutrient observations, and two to three times more temperature and salinity observations, were available. All observations located inside area B (Fig. 4) were included in the comparison. The model efficiency for most variables was good (Fig. 5b), except for the chlorophyll-a. The poor quality of the chlorophyll-a results was due to a delay of approximately two weeks in the spring bloom. The KPP mixing scheme that was used in HIGH is known to provide too strong vertical mixing (Winther and Evensen, 2006). This enhanced mixing caused a delay in the shoaling of the upper mixed layer, which again was the reason for the simulated delay in the onset of the spring bloom. A delayed spring bloom is also a well-known problem in primary production models (Allen et al., 2007).

Both COARSE and HIGH showed little variability in the timing of the start of the diatom and flagellate blooms, maximum ten days between earliest and latest start. Rey (2004) refers to a three-weeks difference in the timing of the start of the spring bloom between 1997 and 1998 at Ocean Weather Station Mike (M), whereas COARSE had five days. Both in the observations and in COARSE, the initiation of the spring bloom in 1997 was later than it was in 1998. One has to take into consideration that the start of the spring bloom in both COARSE and HIGH was a mean over the whole area, and that locally the differences can be up to three weeks in the simulated spring bloom as well.

In the Norwegian Coastal Current, the production is estimated to approximately 90-120 g-C m\(^{-2}\) year\(^{-1}\) (Rey, 1981). The model had too low production in this area compared to the estimates, due to insufficient inflow of nutrients from the Baltic Sea. As only MEDIUM had a port at the entrance to the Baltic Sea, and this did not include nutrients, it was difficult to get the right levels of nutrients along the coast (Fig. 6). In addition, few fjords provided nutrient input to the NCC. We do not expect these differences in the production to be of any importance to the findings in this study, as it is the variability in the Atlantic water, and hence the production here, that is most important for our conclusions.

The annual primary production in COARSE, which varied between 70 and 87 g-C m\(^{-2}\) year\(^{-1}\) in the years 1990 to 2000, fitted well with the estimate of 80 g-C m\(^{-2}\) year\(^{-1}\) (Rey, 2004) for the Norwegian Sea. The annual primary production in HIGH was somewhat high, probably caused by a combination of too much mixing and not enough grazing from zooplankton (which is included in the mortality rate) at high phytoplankton concentrations.

3.2. Variations in primary production

All comparisons between COARSE and HIGH, and COARSE and the winter NAO index was performed with results from area A (Fig. 4).

The annual primary production (g-C m\(^{-2}\) year\(^{-1}\)) in COARSE from 1990 to 2000 had a correlation of \(r=0.81\) with the winter NAO index from 1989 to 1999 (Tab. 1 and
Fig. 5. (a) Percentage model bias (Eq. 2 in the text), and (b) model efficiency (Eq. 1 in the text). The three columns for each variable represents the years 1995 to 1997. TEMP is temperature, SALN salinity, NIT nitrate, PHO phosphate, SIL silicate and CHLA chlorophyll-a. All comparisons were done with model results from HIGH. In (c) the number of silicate observations each month from January 1995 until December 1997 are shown.

Fig. 7). In COARSE, the annual primary production was lower in 1997 than in previous years. The same drop was observed in HIGH that year. When the integrated nutrient concentrations over the upper 200 m in HIGH were explored (Fig. 8), a drop in the nutrient concentrations appeared this year compared to the concentrations in 1995 and 1996. The upper 200 m were considered as the most important part of the water column for the primary production.

The volume and nutrient transports were computed for the months November through February, as the phytoplankton bloom will influence the concentrations and hence the nutrient transports for the rest of the year. The nutrient transports in COARSE in the upper 200 m into area A (section specified in Fig. 4) had good correlations with the winter NAO index for the ten years studied (Fig. 9a), with the same one year lag as was found between the winter NAO index and annual primary production (Tab. 1). The correlation between the winter NAO index with one year lag and the volume transport was somewhat lower than for the nutrient transports (Fig. 9b).

The correlations between the annual primary production and the nutrient transports
were high, especially for phosphate and silicate (Tab. 2).

The annual primary production in HIGH was roughly 35% larger than in COARSE. The annual values for 1995 to 1997 from HIGH are provided in Table 3. The large difference in the primary production between HIGH and COARSE was caused by HIGH’s ability to resolve the mesoscale activity, which added more nutrients into the euphotic layer (Mahadevan and Archer, 2000; Hansen and Samuelsen, revised, J. Mar. Syst., 2008).
<table>
<thead>
<tr>
<th>Winter NAO index (no lag)</th>
<th>Winter NAO index (one yr lag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start fla</td>
<td>-0.04 n.s.</td>
</tr>
<tr>
<td>Start dia</td>
<td>0.10 n.s.</td>
</tr>
<tr>
<td>Prim. prod.</td>
<td>0.37 n.s.</td>
</tr>
<tr>
<td>Prim. prod. dia</td>
<td>0.04 n.s.</td>
</tr>
<tr>
<td>Prim. prod. fla</td>
<td>0.61*</td>
</tr>
<tr>
<td>Gross prod.</td>
<td>0.53 n.s.</td>
</tr>
<tr>
<td>Transport.</td>
<td>0.32 n.s.</td>
</tr>
<tr>
<td>Transport nit.</td>
<td>0.31 n.s.</td>
</tr>
<tr>
<td>Transport pho.</td>
<td>0.25 n.s.</td>
</tr>
<tr>
<td>Transport sil.</td>
<td>0.17 n.s.</td>
</tr>
<tr>
<td>Transport NCC</td>
<td>0.52 n.s.</td>
</tr>
<tr>
<td></td>
<td>-0.73 **</td>
</tr>
<tr>
<td></td>
<td>-0.68*</td>
</tr>
<tr>
<td></td>
<td>0.81 **</td>
</tr>
<tr>
<td></td>
<td>0.75 **</td>
</tr>
<tr>
<td></td>
<td>0.63*</td>
</tr>
<tr>
<td></td>
<td>0.74 **</td>
</tr>
<tr>
<td></td>
<td>0.51 n.s.</td>
</tr>
<tr>
<td></td>
<td>0.68*</td>
</tr>
<tr>
<td></td>
<td>0.76 **</td>
</tr>
<tr>
<td></td>
<td>0.75 **</td>
</tr>
<tr>
<td></td>
<td>0.30 **</td>
</tr>
</tbody>
</table>

Table 1

Correlations (correlation coefficient r) between timeseries from COARSE and NAO in the period 1990-2000. NAO one year lag is from the period 1989-1999. Here, ** means significant for \( p < 0.01 \), * means significant for \( p < 0.05 \) and n.s. means not significant. The transports are computed over the upper 200 m over the section showed in Fig. 4. The primary production is defined here as the gross production minus the respiration. Start fla and Start dia are the day of the onset of the blooms, defined as the day when the depth integrated concentration reaches 10% of the peak concentration.

Fig. 7. Primary production (solid line) in 1990-2000 from COARSE compared to the winter NAO index (dashed line) from 1989 to 1999. The primary production was computed over area A.

3.3. Timing of primary production bloom

Negative correlations of 0.73 and 0.68 were found between the winter NAO index and the start of both the diatom and the flagellate bloom in COARSE, respectively, with the same time lag as for the annual primary production (Tab. 1, Fig. 10). The spring bloom in both COARSE and HIGH was earlier in 1996 compared to 1995.
Fig. 8. (a) Mean nitrate concentration and (b) silicate concentration for the upper 200 m offshelf in HIGH.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary production</td>
<td>0.53**</td>
<td>0.71*</td>
<td>0.64*</td>
<td>0.30n.s.</td>
</tr>
<tr>
<td>Prim. prod. dia</td>
<td>0.48**</td>
<td>0.69*</td>
<td>0.65*</td>
<td>0.24**</td>
</tr>
<tr>
<td>Prim. prod. fla</td>
<td>0.40**</td>
<td>0.50**</td>
<td>0.42**</td>
<td>0.27**</td>
</tr>
<tr>
<td>Gross production</td>
<td>0.46**</td>
<td>0.60**</td>
<td>0.52**</td>
<td>0.26**</td>
</tr>
<tr>
<td>Start dia</td>
<td>-0.54**</td>
<td>-0.63**</td>
<td>-0.61**</td>
<td>-0.42**</td>
</tr>
<tr>
<td>Start fla</td>
<td>-0.62**</td>
<td>0.71*</td>
<td>-0.70*</td>
<td>-0.52**</td>
</tr>
</tbody>
</table>

Table 2
The correlation (correlation coefficient $r$) between the annual primary production in COARSE and the nutrient transports in the years 1991-2000. Here, ** means significant for $p < 0.01$, * means significant for $p < 0.05$ and n.s. means not significant. The transports were computed over the upper 200 m of the watercolumn, and in the months November-February.

and 1997 (Fig. 11). In 1996, the winter mixed layer depth was shallower compared to 1995 and 1997 (Fig. 12). The wind fields from the ERA40-fields (Uppala et al., 2005) in
Fig. 9. The winter NAO index from 1989-1999 (dashed line) together with (a) the phosphate transport (solid line) into the area in 1990-2000, and (b) the volume transport (in Sverdrup) into the focus area in the Norwegian Sea (solid line). The transports were computed as weekly means over the period November through February, over the section shown in Fig. 5.

<table>
<thead>
<tr>
<th>Model</th>
<th>Total</th>
<th>Diatoms</th>
<th>Flagellates</th>
</tr>
</thead>
<tbody>
<tr>
<td>FINE 1995</td>
<td>114.45</td>
<td>55.76</td>
<td>58.69</td>
</tr>
<tr>
<td>FINE 1996</td>
<td>114.50</td>
<td>60.32</td>
<td>54.18</td>
</tr>
<tr>
<td>FINE 1997</td>
<td>106.60</td>
<td>56.33</td>
<td>50.29</td>
</tr>
</tbody>
</table>

Table 3
Total annual primary production (g-C m$^{-2}$ year$^{-1}$) and annual primary production for diatoms (g-C m$^{-2}$ year$^{-1}$) and flagellates (g-C m$^{-2}$ year$^{-1}$) in the years 1995 to 1997 in FINE. The primary production is defined as the gross production minus the respiration.

late March and April show that in 1996, there were weaker wind compared to 1995 and 1997 (Fig. 12d). Also, there were large differences in the surface heat flux, the surface heat flux in 1996 being much higher than in 1995 and 1997 (Fig. 12e). The wind and the surface heat flux had a negative correlation of $r = 0.63$.  

13
Fig. 10. (a) Day for the onset (solid line) of (a) the diatom bloom and (b) the flagellate bloom for the years 1990-2000, plotted with the winter NAO index (dashed line) from 1989-1999. The day for the onset was computed as the mean of the area given in Fig. 2. Larger differences in the onset of the bloom occurred locally.

4. Discussion

In this study, the connections between the winter NAO index and the simulated primary production in the Norwegian Sea is examined. This has been done by applying a coarse resolution model to study the long term trends, and a smaller, high resolution model to describe the interannual variations in the period 1995 to 1997.

The representation of salinity, temperature and nutrient concentrations in HIGH was classified as very good compared to observations according to the criteria by Allen et al. (2007), and the spatial mean primary production in both HIGH and COARSE had similar development for the years 1995 to 1997. These were three years with large alterations in the NAO index, which suggests that both HIGH and COARSE were able to pick up the variations in the physical system and transfer this onto the primary production.
4.1. Impact of winter NAO index on transports

The transport into the Norwegian Sea is known to be of great importance to the primary production, as the NAC is a large source of nutrients to the area (Rey, 2004). Variations in the transport can alter the water mass properties, and hence the primary production. Orvik and Skagseth (2003) found that there was a lag of 15 months between the volume transport of Atlantic water at the Svinoy section (Fig. 4), and the wind stress curl at 55°N in the period from 1995 to 2003. Sandø and Furevik (2008) compared the findings of Orvik and Skagseth (2003) with the volume transports of Atlantic water (salinities > 35.1 and densities less than or equal to 27.38 sigma units) from a model run in the Norwegian Sea for the same period. They found that this correlation was only present for the period after 1995, whereas it could not be found for 1990-1995. We have compared the volume transport in winter in the upper 200 m to the winter NAO index, and found good correlations. These correlations break down at depths greater than 200 m. The 15 months lag found both in Orvik and Skagseth (2003) and Sandø and Furevik (2008) corresponds to the lag of one year that we found in our correlations.

A lower, not significant correlation was noticed between the volume transport into area A and the winter NAO index, than between the winter NAO index and the nutrient transports. This might be explained by the location of the section the volume and nutrient transports were computed for. The section also included the NCC, and signals from the NCC not connected to the variations in the NAO might have influenced the correlation. The results showed that the volume transport of coastal water (salinity < 35) had a positive correlation of 0.52 although not significant, with the winter NAO index of the same year (Tab. 1). As we already have pointed out, the NCC had too low nutrient
concentrations in both HIGH and COARSE compared to observations (Fig. 6). This means that the main part of the nutrient transport over the section was from the NAC, which had a stronger connection to the winter NAO index.
4.2. Connections between the primary production and the transports

The variations in the nutrient transports affected the nutrient concentrations in the Norwegian Sea, and hence the primary production. Almost 50% of the variations in the primary production was connected to the phosphate transport, 41% by the silicate transport and roughly 28% by the nitrate transports, but the correlation between the primary production and the nitrate transport was not significant. Our simulations suggest that the drop in the spatial mean primary production in 1997 is explained by lower nutrient transports into the area, providing less nutrients for the phytoplankton. The lower primary production in 1997 could not be explained by a shallower mixed layer depth during winter, because the mixed layer depth in late March and April 1996 was much shallower than in 1997, but the primary production was higher than in 1997. Skogen et al. (2007) shows that there are good correlation between the volume transport in the Fram Strait and the primary production in the Nordic Seas, but the areas of comparisons are not the same as used here, which makes it difficult to comment the differences between these two studies. Also, the NAO index used in Skogen et al. (2007) was computed over the months January through June, while a winter NAO index was used in this study.

Alterations in the volume transport into the area would also change the water mass stability properties. This will have an influence on the depth of the mixed layer, and also on the timing of the shoaling of the upper mixed layer. The depth of the upper mixed layer is important for the phytoplankton, as they will not start growing as long as the mixed layer depth exceeds the critical depth (Sverdrup, 1953). The high correlation between the winter NAO index and the onset of both the flagellate and diatom blooms might be due to changes in mixed layer depth, following changes in temperature and salinity in the water masses advected into the Norwegian Sea.

The upper mixed layer is also locally affected by the NAO, like we notice in 1996, when there are weak winds and high surface heat flux and we got an earlier spring bloom than in 1995 and 1997. This gives an indication that it is not only the advected, delayed signal from the winter NAO index of the previous year that will have an effect on the primary production, local effects are probably responsible for part of the variation not accounted for in our study. Annual variations in irradiance are another such potential source of variation.

4.3. Links between the NAO and primary production

In Fromentin and Planque (1996), it is noted that a high winter NAO index will delay the spring bloom and reduce the primary production. This is explained by the increased wind stress, which generates a strong mixing of the surface layer, hence delays the spring bloom. This was not supported in our simulations. If this had been true, the simulated spring bloom in 1995 would have been late and weak, while it actually was strong and relatively early. The simulations presented here showed that the year following a low winter NAO index will have a late and relatively weak primary production, while years following a high winter NAO index will have relatively strong and early primary production (Fig. 13). Changes in the water masses explain over 60% of the variations in the strength of the bloom, and close to 50% of the variations in the onset of the bloom. The area for the study of Fromentin and Planque (1996) was the eastern North Atlantic.
Fig. 13. A schematic figure of the connections between the primary production, transports and the winter NAO index. High primary production due to increased nutrient transports will follow one year after a winter with high NAO index. These years, the onset of the primary production bloom was earlier than years following a winter with low NAO index. To the right, the situation that follows a winter with low NAO index is illustrated, with lower primary production due to lower nutrient concentrations, and a later onset of the spring bloom.

and North Sea, and did not include the area that was explored here. Also, it needs to be taken into consideration that the winter NAO index was defined differently in our study. This might have caused our results to deviate from the prediction of Fromentin and Planque (1996).

Another suggestion that was not supported in our study, is that a single year drop in the winter NAO index might not be enough for a response in the marine biology (Greene et al., 2003). The reason for this suggestion was the breakdown of the negative correlation between the *Calanus finmarchicus* in the North Sea and the winter NAO index in 1996 (Planque and Reid, 1998). In 1996, the winter NAO index suddenly dropped to a large negative value after several years with high positive values. According to the correlation shown in Fromentin and Planque (1996), the population of *C. finmarchicus* in the North Sea was expected to increase that year, but instead it decreased. This breakdown was later found to be caused by the decline in the Norwegian Sea *C. finmarchicus* population, and was also connected to oceanic inflows to the North Sea. Similar studies have not been performed in the Norwegian Sea, hence, it is unknown if such a breakdown occurred here as well. It is unlikely that these factors would have had the same impact on the primary production, and no such breakdown was evident in the primary production concentration in our area. From our simulations, the drop in the winter NAO index caused a late and weak phytoplankton bloom the following year. In 1998, the phytoplankton bloom was earlier and stronger than in 1997, hence following the variations in the winter NAO index. Thus, we can conclude that a rapid drop in the winter NAO index, even if it lasts for only one year, had an impact on the phytoplankton bloom.

Statistics based on time series of only eleven years, like in this study, have large uncertainties. Barton et al. (2003) emphasizes this in their study, and we need to do the same here. The results from Fromentin and Planque (1996) show that only one year with data can alter previous conclusions. Despite of this, we can conclude that for the period considered, the primary production and timing of the diatom and the flagellate blooms
were strongly dependent on the winter NAO index of the previous year. Even though Sandø and Furevik (2008) show that the connection between the wind curl stress at 55°N and the transport of Atlantic water does not exist in the period 1990-1995, we found a high correlation between the volume transport in the upper 200 m and the winter NAO index also for this period. This was due to the connection between the wind strength and the transport in the upper part of the water column.

The abundance of *Calanus finmarchicus* is believed to depend on both the timing of the spring bloom and the duration of it (Rey, 2004). Even though the model shows small variations in the timing of the spring bloom in the spatial mean primary production, larger differences occurred locally. We might expect that in years following a winter with low NAO index, the primary production is less favorable for the zooplankton, as a late and weak phytoplankton bloom will provide less food. This hypothesis can be tested against zooplankton abundance in the Norwegian Sea, provided observational overlap in time and space. As already pointed out, local differences can vary a lot in primary production, and we expect this to be the case with *C. finmarchicus* too.

4.4. Conclusions

From this study, we have gained new knowledge about the variability of the primary production in the Norwegian Sea. The comparison between the observations and the model results from HIGH showed an overall good agreement. As HIGH and COARSE show the same variations during the years 1995-1997, we can conclude that the model results can be used for some careful conclusions. It was discovered that the bloom in the Norwegian Sea was affected by the inflow of nutrient rich waters. The one year delay between the winter NAO index value and the response in the primary production might provide an opportunity to predict the timing and the size of the next year’s bloom. The study provided the mechanism for the link between the primary production and the winter NAO index, in the high correlation between the variability of the transport of nutrients into the Norwegian Sea and the winter NAO index. It also showed that the onset of the bloom was to a large extent dependent on the transport of water masses, not only the local meteorological conditions. The onset of the diatom and the flagellate spring blooms had a strong negative correlation with the winter NAO index, which was explained by the transport of water masses into the Norwegian Sea. Changes in water mass transport altered the stability of the water column, thus influenced the shoaling of the upper mixed layer, which is important for the onset of the spring bloom. Last, but not least, the response of the phytoplankton to the sudden drop in the winter NAO index showed that rapid drops had an effect at the basis of the food chain, but it is unknown whether this will propagate to higher trophic levels.

5. Acknowledgments

This work was funded by a private donation from Trond Mohn A/S. We would like to thank Norwegian Supercomputing Project (NOTUR) for grant of CPU time, the Institute of Marine Research (www.imr.no), Bergen, Norway, for providing observations from the Norwegian Sea and the Climate Analysis Section, NCAR, Boulder, US, for providing the
NAO Index Data (Hurrell(95)). Thanks to Dag L. Aksnes, Laurent Bertino and Helge Drange for useful comments on the manuscript.

LITERATURE CITED


Paper III

Anticyclonic eddies in the Norwegian Sea; Their origin, evolution and influence on primary production

Hansen, C. and Kvaleberg, E. and Samuelsen, A.

To be submitted
Anticyclonic eddies in the Norwegian Sea; Their origin, evolution and impact on primary production

C. Hansen a,∗, E. Kvaleberg b, A. Samuelsen a

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

bNorwegian Naval Training Establishment, Tactics and Doctrine/METOC, P.O. Box 5 Haakonsvern K-21, N-5886 Bergen, Norway

Abstract

Altimetry and ocean color observations are used in combination with a high resolution, coupled physical-primary production ocean model to investigate anticyclonic eddies at two locations in the Norwegian Sea. Of particular interest are the formation of the anticyclonic eddies, and their influence on primary production. The formation of these anticyclonic eddies are due to baroclinic instabilities set up by shifts in the wind in north/south direction, leading to simultaneously formation of eddies throughout the area. A good correlation is found between wind forcing and mesoscale activity. After a density stratification develops in the upper 100 m of the water column, the anticyclones become a subsurface lens of well mixed water with the characteristics of intra-thermocline eddies. The deep mixed layer inside anticyclonic eddies delay phytoplankton blooms by approximately two weeks compared to the surrounding areas. As the mixed layer within the anticyclones become smaller than the critical depth, the high nutrient levels support phytoplankton blooms. There is evidence of phytoplankton being advected toward the center of the eddies, but also of isolated phytoplankton blooms within the intra-thermocline eddies. The combined use of a numerical model and satellite observations provide three-dimensional information on the structure and properties of both eddies and primary production. The presented model is particularly useful in cloud-covered areas where ocean color images are frequently unavailable.

Key words: Baroclinic instability, mesoscale eddies, primary production, HYCOM, ecological model, Norwegian Sea

∗Corresponding author
Email address: cecilie.hansen@nersc.no (C. Hansen).
1. Introduction

The Norwegian Sea is an area with high mesoscale activity, particularly in the frontal region between the fresh Norwegian Coastal Current (NCC) and the eastern branch of the Norwegian Atlantic Current (NAC). Both currents flow north off the west coast of Norway. Typically, meanders and eddies are formed by interactions between time-varying winds and the irregular bathymetry in the area (Mork, 1981). In this study, the focus is on several large eddies off the Norwegian shelf between 62°N and 65°N. Of particular interest is the generation mechanism and evolution of the eddies, and the impact of these eddies on primary production. The study is motivated by satellite images of ocean color, which showed an anticyclonic eddy with high concentrations of chlorophyll-a (chl-a) in the region of interest.

Several previous studies have explored mechanisms for eddy and meander formation at the front between the NAC and NCC. Ikeda et al. (1989) used a numerical model to study eddies off the south-western coast of Norway, and found that baroclinic instability is essential to forming meanders at the front. These meanders occasionally grow and detach from the main current, forming anticyclones on the Atlantic (western) side and cyclones on the coastal (eastern) side. Ikeda et al. (1989) also noted that topographic effects are important to the formation of eddies in their focus area, due to a submarine ridge in the eastern part of the Norwegian trench that triggers instabilities.

Furthermore, Johannessen et al. (1989) examined the west coast of Norway between 60°N and 61°N, and concluded that eddies form through a combination of topographic steering, vortex stretching and barotropic instability. In addition, the authors mention that eddies can be generated upstream by baroclinic instabilities that either grow or propagate into the area. The off-shelf eddies that are considered in this study are numerous both in the remotely sensed observations and model results. The formation and evolution of these eddies have not, to the best of our knowledge, been described before in conjunction with primary production.

The studies of Johannessen et al. (1989) and Ikeda et al. (1989) were based on a combination of in-situ data, remote sensing observations, and numerical ocean models. Here, altimetry observations are used to identify anticyclonic eddies from positive sea surface height (SSH) anomalies. Ocean color images are used to infer chlorophyll concentrations, but unlike SSH data, the amount of observations is limited by the rather persistent cloud cover over the Norwegian Sea. Even when using seven-day mosaics, cloud covered patches can be quite large. Nonetheless, occasionally chl-a concentrations can be observed during cloud-free conditions (Fig. 1). Because of the difficulties of monitoring chl-a, many unanswered questions about the development, patchiness, and duration of phytoplankton blooms in the Norwegian Sea remain.

Previous work on the impact of eddies on marine organisms off the Norwegian coast include Fossheim et al. (2005); Pedersen et al. (2005) and Skarðhamar et al. (2007). These studies focus on higher trophic levels, such as zooplankton and fish larvae from in-situ observations, and do not address phytoplankton in particular. Several studies have explored the connection between mesoscale activity and primary production, see e.g. Oschlies (2002); McGillicuddy et al. (2007); Benitez-Nelson et al. (2007), but not with focus on high-latitude coastal areas.

In the following, the results from a high-resolution numerical model along with remote
Fig. 1. The observed anticyclone on the 23 May 2008 (a), and on the 29 May 2008 (b) from MERIS, expressed in terms of chl \(\text{a} (\text{mg m}^{-3})\). Note that the color scales differ by a factor of two.

Remote sensing observations is described in order to explore the three-dimensional structure of anticyclonic eddies. The marine life is rich in abundance and species in the Norwegian Sea, and connections between primary production and mesoscale dynamics might also provide knowledge relevant to higher trophic levels. Details of the numerical model and remote sensing data are given in section 2. Results are described in section 3, followed by discussions and conclusions in section 4.

2. Materials and methods

A coupled physical-primary production model in a one-way nested model system consisting of three model grids is used. All three model configurations are created with the conformal mapping tool by Bentsen et al. (1999). The models have identical discretization in the vertical, with 23 layers of constant density.

2.1. Physical model

The physical model used is the Hybrid Coordinate Ocean Model (HYCOM; Bleck, 2002). The largest model domain (hereafter: COARSE) covers the Arctic and Atlantic Oceans from 30°S. It is spun up from 1957, and the drift in temperature and salinity is found to be negligible (Hansen and Samuelsen, submitted). COARSE provides physical and biological nesting conditions for a 16 km resolution model grid that covers the Norwegian Sea and the North Sea (hereafter: MEDIUM). MEDIUM is initiated in 1990 from interpolated fields from COARSE, and provides nesting conditions for the high resolution model grid (hereafter: HIGH). HIGH has a horizontal resolution of 4.5 km, and covers an area off the West coast of Norway from 60°N to 70°N (Fig. 2). It is initiated from interpolated fields from MEDIUM in June 1994, and is run until January 1998.

In hybrid models, each layer has an assigned density called the target density (Bleck, 2002). The target densities are given in \(\sigma_0\), i.e. in units of potential density referenced to the surface. The upper five layers have been assigned with target densities from 0.1 to 0.5 \(\sigma_0\), to ensure a z-resolution and prevent a collapse of layers when adding river runoff (Winther and Evensen, 2006). When the target density does not exist in the water
column, as will be the case with $0.1$–$0.5 \sigma_0$, they automatically transfer to $z$-levels. The target densities in the lower 18 layers ranges from 24.05 to 28.10 $\sigma_0$. The space between $z$-levels is defined to be minimum 3.0 m with a stretching factor of 1.125. Thus, the first layer thickness is 3.0 m, the next one 3.375 m (layer thickness $\times$ stretching factor) etc.

Tides are included in MEDIUM, and are part of the nesting conditions for HIGH. MEDIUM also has a barotropic port at the entrance to the Baltic Sea, with a volume transport of 0.015 Sv ($1$ Sverdrup=$10^6$ m$^3$ s$^{-1}$) into the North Sea. The synoptic forcing used in all three models is 6-hourly ERA-40 fields with $1.125 \times 1.125$ degree resolution (Uppala et al., 2005), provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). COARSE is run with a Mellor and Yamada 2.5 mixing scheme (Mellor and Yamada, 1982), while HIGH and MEDIUM are run with a K-Profile Parameterization mixing scheme (Large et al., 1994). All three models are run with climatological river runoff, this includes nutrients for the major rivers in the North Sea and Norwegian Sea. The river data was provided by the Institute of Marine Research, Bergen, Norway, as 20 years time series. From these, monthly climatological river runoffs were calculated and used as input for the models. For the rivers along the coast of the United Kingdom, the climatology was calculated from the last five years only, because of known errors in the observations (Morten Skogen, personal communication).

MEDIUM and HIGH are run with a 4th order momentum QUICK scheme (Holland et al., 1998; Webb et al., 1998), which enables the model to resolve mesoscale activity on the same scale as a model grid run with a 2nd order scheme and twice the resolution. (Winther et al., 2007).

2.2. Primary production model

The primary production model used in this study is the Norwegian Ecological Model System (NORWECOM; Skogen et al., 1995; Skogen and Soiland, 1998). In this run eight components are included: two phytoplankton classes (diatoms and flagellates), three nutrients (nitrate, silicate and phosphate), detritus, biogenic silicate, and oxygen. It is
coupled to the physical system through mixing, advection and light. Solar insolation is climatological, however surface irradiance is modified by the synoptic cloud cover from the ERA-40 fields, and the self-shading by the phytoplankton.

The primary production part of COARSE is spun up from January 1987, MEDIUM is initiated in January 1993 with interpolated fields from COARSE. HIGH is initiated in June 1994, with interpolated fields from MEDIUM. COARSE shows negligible drift in the nutrients (Hansen and Samuelsen, submitted), and reaches a steady-state behavior after three years of spin-up for the coupled system. In addition, the coupled system in MEDIUM reaches stability after one year, and due to this fast stabilization six months of spin-up is found to be sufficient for HIGH.

The primary production model was originally developed for the North Sea, where the water clarity is lower than that in the Norwegian Sea. This is due to high riverine inputs, as the compounds that causes less clarity has a high correlation with the salinity (Høyerslev et al., 1996). Therefore, the non-chlorophyll light attenuation coefficient was changed from $0.07 \text{m}^{-1}$ to $0.04 \text{m}^{-1}$. SeaWiFS data show that the values in the Norwegian Sea during winter when chlorophyll concentrations are low, are approximately $0.04-0.05 \text{m}^{-1}$. Otherwise, the parameterization for the primary production model is kept identical to that of Skogen and Seiland (1998) except the sinking rate of diatoms, which is kept constant at $0.3 \text{m day}^{-1}$. The sinking routine is the one used in the carbon cycle version of the Nansen/Bjerknes version of the Miami Isopycnic Coordinate Ocean Model (Karen Assmann, personal communication).

2.3. Observations

The ocean color data originates from MERIS, an optical sensor installed onboard the ESA satellite ENVISAT. The images are first geometrically corrected, then the chlorophyll concentrations are retrieved by using a bio-optical semi-analytical algorithm developed by Pozdnyakov et al. (2005). The processed images are available at hab.nerc.no, as one-day and seven-days mosaics. The observations used in this study are the one-day mosaics, with a spatial resolution of 1-by-1 km.

Altimetry data is provided by AVISO as weekly gridded sea-level anomaly maps (Ducet et al., 2000). The gridded maps are merged from TOPEX/Poseidon, Jason-1, ERS-1/2, GFO, and ENVISAT. The horizontal resolution of the gridded data is 15–20 km. The weekly merged sea-level anomaly fields are weighted with a Gaussian function, which is centered on every Tuesday. The weights are therefore largest on this week day, and all comparison with model results have been performed with daily fields from the day of centering. In addition to the merged maps, track data from Jason-1 are used.

3. Results

3.1. High-resolution model

Based on both remote sensing data and numerical results two locations where anticyclonic eddies appear frequently have been identified. These locations are shown in Fig. 2, and both are associated with sharply curving isobaths. Location 1 is centered at 4.3°E,
<table>
<thead>
<tr>
<th></th>
<th>MKE</th>
<th>EKE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed</td>
<td>0.32**</td>
<td>0.41**</td>
</tr>
<tr>
<td>East wind</td>
<td>0.18*</td>
<td>0.24**</td>
</tr>
<tr>
<td>West wind</td>
<td>0.13n.s.</td>
<td>0.08n.s.</td>
</tr>
<tr>
<td>North wind</td>
<td>0.52**</td>
<td>0.48**</td>
</tr>
<tr>
<td>South wind</td>
<td>0.37**</td>
<td>0.31**</td>
</tr>
</tbody>
</table>

Table 1

The correlation (correlation coefficient r) between the weekly mean kinetic energy (MKE) and the weekly eddy kinetic energy (EKE) at location 1 from HIGH and the weekly wind speed and weekly wind in all directions for the period 1995 to 1997. Here, ** means significant for $p < 0.01$, * means significant for $p < 0.05$ and n.s. means not significant.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Anticyclones at location 1</td>
<td>100.0</td>
<td>116.7</td>
<td>127.3</td>
</tr>
<tr>
<td>Anticyclones at location 2</td>
<td>55.6</td>
<td>42.1</td>
<td>500.0</td>
</tr>
<tr>
<td>Cyclones at location 1</td>
<td>-60.0</td>
<td>200.0</td>
<td>125.0</td>
</tr>
<tr>
<td>Cyclones at location 2</td>
<td>-50.0</td>
<td>-10.0</td>
<td>-83.3</td>
</tr>
<tr>
<td>None at location 1</td>
<td>-33.3</td>
<td>-47.2</td>
<td>-44.7</td>
</tr>
<tr>
<td>None at location 2</td>
<td>-18.2</td>
<td>-4.3</td>
<td>23.1</td>
</tr>
</tbody>
</table>

Table 2

The percentage rate of anticyclones, cyclones and ‘calm periods’ compared to the merged sea level anomaly maps. None means no eddies present at the two locations in the three years of the simulation. The results are calculated by subtracting the number of anticyclones/cyclones or none events in HIGH from the number of anticyclones/cyclones or none events in the merged sea level anomaly maps, dividing by the number from the merged sea level anomaly maps, and multiplying by 100.

Eddies shed from meanders at the boundary between the NCC and the NAC are typically 50–100 km in diameter (Mork, 1981), while mesoscale dynamics take place on smaller length scales. Because the resolution of satellite altimetry data was 15–20 km, much of the mesoscale activity was filtered out, leaving only the larger scale features. The patchiness in ocean color images often indicate mesoscale activity, and can therefore be used to identify mesoscale activity at smaller length scales than those detected by satellite altimetry. The numerical results compared better to the higher resolution (1-by-1 km) ocean color images, as these observations show much more mesoscale activity. The numerical model sustained a rich eddy field throughout the simulation years, however the mesoscale features were somewhat exaggerated (Tab. 2) compared to the altimetry observations. It is possible that the model had too many eddies, which were unrealistically circular and intense.

The model reproduced the large scale current features of the region realistically, with the NCC flowing north close to the coast, and the inner branch of the NAC further...
The currents followed the bathymetry closely, however some degree of meandering was evident. Several eddies, both cyclonic and anticyclonic, were seen in the velocity fields from HIGH (Fig. 3 a), the cyclonic eddies tended to be smaller in size and had less intense velocities. This was also seen in the simulated relative vorticity field (Fig. 3 b), where cyclonic features (positive vorticity) were often elongated bands resulting from the current shear. Anticyclones (negative vorticity) were more often isolated circular features disconnected from the main flow pattern.

The simulated anticyclone at location 1 (hereafter named A1) grew from a meander to a detached eddy at the front between the NAC and the NCC around March 15, 1995 (Fig. 4). It was thus bordered by two currents flowing north, and surrounded by bands of positive vorticity. A1 was surprisingly long-lived, retaining a signature in sea surface anomaly fields from HIGH of 5–15 cm for 110 days. The horizontal diameter was 60 km, and the interior homogeneous water mass extended to about 500 m depth. A1 was manifested as a depression of density surfaces throughout the water column. Several additional eddies were formed from meanders in the same area during the simulation period 1995–1997. A1 is interesting, as it as an anticyclone seemed to support its own phytoplankton bloom during the spring bloom in 1995. Consequently, the focus will be on the characteristics and dynamics of A1, and its associated primary production.

The simulated velocity of A1 was highest in the upper 150 m, at the surface it reached $0.4 \text{ m s}^{-1}$, but anticyclonic flow could be traced to 900 m depth. The horizontal shear between A1 and the surface currents was large, $3 \times 10^{-5} \text{ s}^{-1}$, the usual values are on the order of $10^{-6} \text{ s}^{-1}$. Vertical mixing was largest on the eastern side, facing the boundary between NAC and NCC, where Atlantic water upwelled from ${\sim}300$ m depth to the surface. A1 consisted of mixed coastal and Atlantic water, and this gave A1 a salinity of 35.05, slightly fresher than the surroundings (Fig. 4 d). The density of A1 changed by less than $0.06 \text{ kg m}^{-3}$ in the four months it was present in the fields from HIGH. During the first days after it formed, the density increased by $0.03 \text{ kg m}^{-3}$, probably because Atlantic water was entrained into the eddy.

A1 underwent a notable transformation around day 140, when a density stratification developed in the upper 100 m of the eddy. This stratification gave A1 the characteris-
Fig. 4. The formation of A1 for (a) day 72 (13 March), (b) day 75 (16 March) and (c) day 78 (19 March) expressed in terms of sea surface height anomalies (cm). (d) shows the density (kg m\(^{-3}\)) in layer 10 in HIGH at day 78. A1 is the southernmost eddy labelled in panels (b), (c) and (d). Contour intervals is 2 cm.

tics of an intra-thermocline eddy (ITE); a lens of weakly stratified water with doming isopycnals above, and concave isopycnals below (Fig. 5). The lens spanned 70 km horizontally and 300 m vertically (at depths 100–400 m). Defining properties of ITEs include potential vorticity minimum within the eddy, and maximum current speed in the interior surrounding the eddy (Gordon et al., 2002). Although anticyclones are routinely associated with central downwelling, both upwelling and downwelling (both on the order of 10 m week\(^{-1}\)) was found within A1.

Toward the end of its lifetime A1 shoaled, and after 100 days the depth was less than 200 m. It also moved into fresher water, which caused a decrease in density, especially in the upper 50 m. In most cases, the simulated eddies at location 1 propagated southwest, unless they interacted or merged with other anticyclones at location 2. The path of A1 is given in Fig. 6 a. After staying in the same location for about two months, it moved east toward shallow water due to wind forcing and interaction with the western branch of the NAC. Finally, it moved south along the bathymetry with a maximum propagation speed of 10 km day\(^{-1}\).

In November and December 1995, an anticyclone (hereafter A2) is visible in the model fields at location 2. This eddy was associated with a sea surface height anomaly of 6–7 cm, but the vertical structure was less pronounced than for A1. A2 originated from the western branch of the NAC, and it detached from a meander in the current at location 2.
Fig. 5. Vertical sections showing the density (kg m$^{-3}$) of A1 on day 93 (3 April) (a) and day 145 (25 May) (b).

Fig. 6. (a) The track of A1 from day 74 (15 March) to day 181 (30 June), and (b) the track of A2 from day 300 (27 October) to day 350 (16 December). At day 350 A2 interacts with an eddy at location 1, and the track changes. The isobaths show every 100 m.
Fig. 7. (a) The sea surface height anomaly (cm) of A2 from HIGH, and (b) the sea surface anomaly (cm) from the 11 November 1995 is displayed. Note the differences in the colorbar.

(Fig. 7). The diameter was 50 km, and a depression in the density surfaces was discernible to a depth of 700 m. Maximum simulated anticyclonic velocity was 0.25 m s$^{-1}$, and occurred in the upper 150 m. The path of A2 is shown in Fig. 6 (b). Simulated eddies at location 2 were either advected northward with the western branch of the NAC, or drifted south because of interaction with anticyclones at location 1. A2 existed for approximately one month, after which it merged with an anticyclonic eddy at location 1.

3.2. Influence on simulated primary production

The simulated spring bloom in HIGH started around day 120, which is the end of April. Diatoms bloom first, followed by flagellates about one month later. The bloom was delayed by approximately 14 days compared to the observations, likely because of too vigorous vertical mixing in the model (Hansen and Samuelsen, submitted). Only diatoms were blooming at the same time as A1 existed. When the flagellate bloom was initiated, A1 was too weak to have a large impact on them.

The coastal water contained low concentrations of nutrients, while Atlantic water had high concentrations. A1 was composed of both types, and the initial nutrient concentration within A1 was slightly below the surrounding Atlantic water masses. However, compared to observational data the model underestimated nutrient concentrations in the NCC (Hansen and Samuelsen, submitted). Because A1 was formed before the spring bloom began in the NCC, the low nutrient concentration was not a result of biologically driven nutrient depletion, but instead the above mentioned model bias.

Phytoplankton blooms require shallow mixed layers, and when the mixed layer depth had shoaled sufficiently in the surrounding waters, the mixed layer depth of A1 was still 350 m. The mixed layer within A1 remained too deep for another two weeks, then shoaled to $< 100$ m depth when a density stratification was established in the upper layers, i.e. when A1 progressed to an ITE. The phytoplankton bloom started as a weak spiraling pattern around the perimeter of A1, both at the surface and in the depth integrated bloom (Fig. 8 a). First, primary production was high in the upper 20 m, whereas a deep maximum at 40–50 m developed toward the end of the bloom. The deep primary production and ensuing high phytoplankton concentration was located in the center of the eddy (Fig. 9).
Fig. 8. Phytoplankton bloom development in anticyclone, (a) and (b) from HIGH (mg-N m$^{-3}$) and (c) and (d) from MERIS (mg-chla m$^{-3}$). The anticyclones from the observations and from HIGH show the same development, by first having no bloom at all, and then having an isolated bloom captured in the eddy. The diatoms concentrations from HIGH are a mean over the upper 10 m.

Fig. 9. The vertical sections of (a) diatom and (b) nitrate concentrations (mg-N m$^{-3}$) at day 148 (28 May) in 1995. Note the different vertical scales.

The deep simulated phytoplankton blooms in A1 and the surrounding waters ended simultaneously, and mixing at the periphery of A1 did not seem strong enough to support a prolonged bloom. Also, the doming of the upper layers in A1 was not strong enough to introduce further nutrients into the euphotic zone. Primary production within A1 was comparable to production in surrounding waters at depths >1000 m, 135 g-C m$^{-2}$ from days 74–180. Peak primary production was 5% higher in A1 compared to the surroundings, but were otherwise comparable in size (Fig. 10). Primary production in A1 might have been underestimated by the estimation technique used here, as primary production
at the periphery of A1 may have been excluded from the calculation. The low nutrient concentration in the NCC, and hence in A1, might also have decreased the simulated primary production within the eddy.

3.3. Remotely sensed ocean color

Altimetry data from 17 May 2008 show an anticyclonic eddy (hereafter AOBS) present at location 2. This was a relatively cloud-free day, and ocean color data reveal a patch of low chl$\text{a}$ at the same location (Fig. 8 c). Clouds obstructed the view of location 2 during 18–20 and 22 May; on 21 May there was little sign of a phytoplankton bloom in AOBS. Then, on 23 May there was a spiraling pattern of high chl$\text{a}$ concentration, with minimum concentration in the center of AOBS (Fig. 1 a, Fig. 8 d). One week later, on 29 May, the phytoplankton bloom spanned the whole eddy (Fig. 1 b). The enhanced chl$\text{a}$ concentration within AOBS was visible until 4 June.

3.4. Satellite altimetry

Satellite altimetry observations showed an anticyclonic eddy at location 1 with diameter of 50 km from week two of April until week three of June 1995 (Fig. 11 b). The sea surface height anomaly was 5 cm. In November and December 1995, an anticyclone was observed at location 2 (Fig. 7 b) in the altimetry observations. It was formed at location 2 from a mesoscale feature in the western branch of the NAC, and lasted about one month before disappearing. The diameter was 50 km, and the sea surface height anomaly was 15
Fig. 11. The sea surface height anomalies (cm) of A1 from (a) HIGH the 24 May and from (b) observed sea level anomalies (cm) from the same period. There is 1 cm between the contour lines in both (a) and (b). Note the differences in the colorbars.

It was not possible to track the propagation of either eddy using the weekly merged sea-level anomaly fields. It is therefore unclear whether the eddy at location 2 merged with another eddy, or propagated north out of the area.

AOBS was visible in altimetry observations at location 2 from the beginning of May 2008. AOBS had a diameter of 50 km. The sea surface height anomaly was around 8 cm, but a comparison with track data from Jason-1 showed an anomaly of up to 15 cm when the satellite passed right above the eddy. Daily merged maps were available for this period, and the propagation of AOBS was tracked for three weeks. It moved little during the first two weeks, but started to move south toward location 1 in week three. AOBS merged with an anticyclone at location 1 in mid June (Fig. 12).

During the whole simulation period of HIGH, from 1995 to 1997, anticyclones were frequently observed in the altimetry data.

4. Discussion

Both satellite data and model results showed that meanders and eddies were ubiquitous off the Norwegian coast, and that patterns of chl could be connected to these features. In the following, possible processes that control the formation and path of anticyclonic eddies in the focus area, and links between eddy characteristics and primary production are discussed.

4.1. The origin and path of the eddies

There are several papers that explain aspects of coastal currents over various sloping bathymetry configurations. Cenedese and Linden (2002) performed experiments with a rotating annulus using different idealized bottom types, and found that large amplitude instabilities required a topographic step (continental ridge), either by itself or in combination with a topographic slope. They also found that instabilities formed over a topographic slope alone were suppressed. Contrary to this study, Reszka and Swaters (2004) numerically simulated buoyant coastal currents considering the effects of differ-
ent bathymetry, and found that a general criterion of instabilities is bottom topography sloping in the opposite sense compared to isopycnals in the front.

The results from HIGH are consistent with both the above results, as the bathymetry in the offshore direction at location 1 is very similar to the continental ridge case in Cenedese and Linden (2002), and the isopycnals slope upward in the opposite direction to the bottom topography, as in Reszka and Swaters (2004). This can explain why model results frequently show meanders and eddies developing at location 1.

In addition to the effect of the bottom topography, the positive correlation between the simulated mean and eddy kinetic energy at location 1 and the southerly and northerly wind (Tab. 1) indicates that shifts in the wind forcing has an influence on the meander formation. Such links between the variability in NCC and the wind have previously been discussed in Mork (1981). The author speculated that changes in the wind forcing trigger perturbations in the mean flow, which grow to meanders and eddies due to baroclinic instability and bathymetry effects.

Mork (1981) also found a connection between northwesterly winds and maximum volume transport, contrary to Ekman theory, but consistent with larger scale cyclonic circulation resulting from northwesterly winds. Mork (1981) mentions, however, that Pingree and Griffiths (1980) attributed maximum transport to southwesterly winds. In HIGH, no correlations between the volume transport and the wind was found at a weekly timescale, where the correlations between the mean and eddy kinetic energy and the wind forcing

Fig. 12. The merging of AOBS with anticyclone at location 1 in June 2008, resulting in anticyclone M1. Contour interval is 2 cm.
was found (Tab. 1).

A meander in the flow increases the length of the boundary between the fresh NCC and the denser offshore water, promoting enhanced mixing in the area. The initial formation stage of A1 is therefore seen as an offshore intrusion of intermediate-density water (Fig. 3 d), which subsequently becomes a coherent anticyclone. Both Ikeda et al. (1989) and Johannessen et al. (1989) conclude that baroclinic effects were more important than barotropic effects in anticyclones. The results from HIGH corroborate these findings, as the baroclinic velocity component was larger compared to the barotropic component.

The propagation direction of A1 was initially eastward for 26 days, and during this time A1 moved into slightly shallower water. This motion is contrary to both Cenedese and Linden (2002), who find that anticyclones drift westward, and Nof (1983), who predicts propagation along isobaths with shallower depths to the right. A1 then moved west for 23 days, in closer accordance with the laboratory experiments of Cenedese and Whitehead (2000), but contrary to the prediction of an eddy influenced by bottom topography Nof (1983). In comparison, A2 first propagated northward along isobaths, followed by south-eastward drift into shallower water (Fig. 6 b). An example of the southward propagation is seen in the altimeter observations of AOBS in May 2008 (Fig. 13). It has previously been assumed that eddies in the area are advected by strong, northward flowing surface currents (Pedersen et al., 2005). However, eddies at location 1 detached from the meander some distance from the front in the comparatively quiescent Atlantic water masses. Still, the seemingly random drift of both A1 and A2 can only be a result of advection by the variable currents in the area, the wind forcing, and interaction between other eddies.

Both A1 and A2 are stationary for periods of time at locations where the bottom slope vanishes and the theory predicts purely westward eddy drift (Nof, 1983; Cushman-Roisin et al., 1990). However, the NAC flows eastward here, such that the advective forces can balance the inherent eddy drift and eventually, through the added force from northwesterly winds push the eddies eastward.

After a density stratification has developed in the upper layers, A1 evolves into an ITE with characteristics described in section 3.1. ITEs have previously been observed in the Japan/East Sea by Gordon et al. (2002). Later, Hogan and Hurlburt (2006) identified three formation mechanisms of ITEs in the Japan/East Sea based on HYCOM simulations; (1) advection of stratified water above a pre-existing anticyclone, (2) restratification of the upper layers, for example due to spring and summer heating, and (3) subduction of water beneath a front.

Spall (1995), Ou and Gordon (2002) and Thomas (2008) all focus on ITE formation mechanisms involving subduction of a water mass with low potential vorticity into interior stratified layers. The proposed subduction processes in the different papers differ, however. Spall (1995) and Thomas (2008) argue that frontal instabilities drive vertical motions that subduct low-PV water, whereas Ou and Gordon (2002) describe how a balance between advective and diffusive PV fluxes leads to subduction when the thermocline outcrops in a warmer mixed layer. Common in all papers is the formation of an interior lens-shaped anticyclonic eddy.

The subduction process is of minor importance for the simulated eddies at location 1, as A1 was initially composed of nearly homogeneous water from the surface and downward. Only later does it develop into an ITE, because of the spring and summer heating of the Norwegian Sea that created an upper stratification. Although ITEs are connected to upwelling of nutrients, and hence positive vertical velocities within the eddy
McGillicuddy et al. (2007), the vertical velocities within A1 indicated both downwelling and upwelling (on the order of 10 m week$^{-1}$). Nevertheless, the transformation of A1 into an ITE had a significant impact on the primary production, this will be discussed further below.

### 4.2. The impact of eddies on primary production

Phytoplankton patchiness in the ocean has been discussed for decades, ever since the first ocean color images revealed a chaotic pattern of phytoplankton in the oceans. Chl$a$ patchiness has been shown to have a close connection to mesoscale activity (Kahru et al., 2007a; Wilson and Adamec, 2001), and there is general agreement that mesoscale activity enhances primary production in the oceans (Falkowski et al., 1991; Oschlies and Garçon, 1998; McGillicuddy and Anderson, 2003), but to what extent is still unclear.

McGillicuddy et al. (2007) used both satellite altimetry data and in-situ observations to compare biological production within different eddies in the Atlantic Ocean. They found large concentrations of biomass at depth within ITEs compared to cyclonic eddies, although both types are associated with upwelling. This was attributed to wind effects, because uniform wind blowing over an anticyclone gave rise to differential stress on either side of the eddy, thereby creating a divergence in the eddy center. The resulting upwelling velocity was between 0.1–1.6 m day$^{-1}$. In a comment to McGillicuddy and Anderson (2003), Mahadevan et al. (2008) suggests an alternative mechanism for upwelling nutrients, where submesoscale processes and nonlinear Ekman transport can lead to intense upwelling and biological production along the fringes of an anticyclone. Phytoplankton is then advected toward the center of the eddy.

It may be that both mechanisms described above are relevant to primary production in the simulated anticyclone A1, because of the transition from ‘regular’ anticyclone to an ITE. In the ocean color data from the 23 May 2008, the spiraling bands of high chl$a$ that are characteristic for anticyclones, were evident. The spiraling bands are possibly caused by advection of phytoplankton from the periphery, a process that is discussed in Lehahn et al. (2007). In anticyclones, the center of the eddy is characterized by a chl$a$ minimum, but with time this may change to a maximum due to a build-up of old phytoplankton (Mahadevan et al., 2008)

After May 29, the chl$a$ pattern in AOBS changed, as there was then high chl$a$ concentration in the eddy center compared to the periphery. The large chl$a$ concentration in the center of AOBS was not caused by converging advection, as the peripheral bloom was too small to account for the central maximum. At this time, AOBS resembles the simulated A1 from HIGH, which did not capture the radial bands of chl$a$, but did have an internal chl$a$ maximum. The numerical model resolution was not sufficiently high to simulate the chl$a$ bands, but we believe that simulating the bands would not have changed the results presented here to a significant extent.

The development of the characteristic ITE upper layer stratification in A1 and hence a shoaling of the upper mixed layer triggered an isolated phytoplankton bloom within the eddy. The similarities between the chl$a$ pattern in the observed AOBS and the simulated A1 indicates that the same happened in AOBS. The transformation from an anticyclone to an ITE in combination with high nutrient concentrations, supported the interior phytoplankton bloom.
Ledwell et al. (2008) report of a high chl\textsubscript{a} maxima observed in the center of an ITE in the subtropical North Atlantic. The simulated deep chl\textsubscript{a} maxima seen in A1 resembles much the one found in Ledwell et al. (2008), as it had the same circular shape and was located in the center of the eddy. Still, it did not last any longer or have a higher concentration than the deep chl\textsubscript{a} maxima in the surrounding water mass contrary to the chl\textsubscript{a} maxima observed in Ledwell et al. (2008). This can be explained by the differences between ITEs and anticyclones in the subtropical North Atlantic compared to eddies in the Norwegian Sea. The Norwegian Sea eddies have higher nutrient concentrations, and in addition there is no permanent thermocline there.

Anticyclones generally have no or a negative effect on the total primary production, whereas an ITE may have a positive effect (McGillicuddy et al., 1998, 2007; Mahadevan et al., 2008). When comparing primary production within A1 to the surrounding waters, no discernible influence of A1 on the total production can be seen. However, HIGH had lower nutrient concentration in the NCC (Hansen and Samuelsen, submitted), which led to too low concentration within A1 than in the surrounding water. This possibly had an negative effect on the primary production, which might have been larger than in the surrounding waters if the nutrient concentration in the NCC had been higher. Similarly, AOBS might have supported a larger interior bloom compared to its surroundings, as there were high production at the periphery before the central bloom was triggered. The doming upper layers of ITEs can introduce more nutrients into the euphotic layer, which has a positive effect on the primary production (McGillicuddy et al., 1998). In this study, though, this effect was not clearly depicted in the model.

Due to the timing of A1, only the diatoms were affected by it. Without observations, which phytoplankton group that formed the bloom in AOBS cannot be decided, but in previous studies it has been shown that the larger phytoplankton classes, often diatoms, dominate the bloom within eddies (Lima et al., 2002; Benitez-Nelson et al., 2007; McNeil et al., 1999). It is still uncertain what the effects, if any, would be if anticyclonic eddies or ITEs had been present during the flagellate bloom.

4.3. Conclusions

It is shown here that meanders form in the frontal area between the NCC and NAC at specific locations that are associated with a gentle inshore topographic slope and a steep offshore drop. The appearance of meanders in the flow field correlates with shifts in the wind direction. The growing meanders may eventually detach from the main flow as anticyclonic eddies consisting of intermediate-density water due frontal mixing of Atlantic and coastal water. During spring and summer, a surface density stratification develops, and the anticyclones acquire the characteristics of ITEs. The eddies were seen both in remote sensing observations and the numerical model.

When present during the spring bloom, anticyclones were shown to influence primary production. The deep mixed layer inside the eddies caused a delay in the phytoplankton bloom of approximately two weeks compared to the surrounding bloom. Conversely, eddies with high nutrient concentrations could sustain a phytoplankton bloom of their own. Primary production can occur at the edges of an anticyclone leading to advection of chl\textsubscript{a} toward the center of the eddy, and production may also occur locally in the center provided that the eddies have high nutrient concentrations and a mixed layer depth which
is shallower than the critical depth. For example, the large amount of chl in the remote
sensed anticyclone AOBS can not be attributed only to advection from the periphery of
the eddy, indicating that some primary production must occur locally.

In the Norwegian Sea, ocean color images are sparse due to a persistent cloud cover,
and even the seven days mosaics can contain large patches of missing data. A combina-
tion of ocean color images, altimetry data, and results from a coupled physical-primary
production numerical model have given additional information about the development
of the phytoplankton bloom coincident with the presence of anticyclonic eddies. Some
features were not adequately simulated in the numerical model, perhaps the most im-
portant of these were the spiraling patterns of chl seen in the ocean color images, which
are also a reflection of submesoscale dynamics. Increased resolution might improve the
results, but it does not guarantee that the model reproduces mesoscale activity correctly.
Including data assimilation in the model would improve the timing and location of the
eddies, but high resolution altimetry data would then be required.

5. Acknowledgments

This work was funded by a private donation from Trond Mohn A/S. We would like
to thank Norwegian Supercomputing Project (NOTUR) for grant of CPU time, and
H. Drange, L. Bertino and D. L. Aksnes for useful comments on the manuscript. The
www.hab.nersc.no website is provided under the ESA GMES MarCoast Consortium and
the Norwegian SatOcean programme. The Jason-1 track data was provided by AVISO.

LITERATURE CITED

Benitez-Nelson, C., Bidigare, R., Dickey, T., Landry, M., Leonard, C., Brown, S., Nen-
cioli, F., Rii, M., Maisti, K., Becker, J., Bibby, T., Black, W., Cai, W.-J., Carlson, C.,
Chen, F., Kuwahara, V., Mahaffey, C., McAndrew, P., Quay, P., Rappé, M., Selph,
K., Simmons, M., Yang, E., 2007. Mesoscale eddies drive increased silica export in the
Bleck, R., 2002. An oceanic general circulation model framed in hybrid isopycnic-
Cenedese, C., Linden, P. F., 2002, Stability of a buoyancy-driven coastal current at the
Ducet, N., Traon, P., Reverdin, G., 2000. Global high-resolution mapping of ocean circu-
enhancing primary production in the ocean. Nature 352, 55–58.


the Sargasso Sea. Nature 394, 263–266.


