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Eutrophication issues attacked by a numerical model of the North Sea/Skagerrak

Morten D. Skogen [1], Henrik Søiland and Einar Svendsen.

Abstract

Several issues of eutrophication in the North Sea and Skagerrak have been attacked using a three dimensional ecological model, NORWECOM. The focus have been on two different years, 2000 and 2001, their characteristics and the differences between them. The results show that the annual depth integrated primary production in the whole North Sea is higher in 2001 than in 2000, but with large spatial differences. In the North Sea an extreme oxygen minimum were found in 2000 south of Dogger Bank that were not seen in 2001. Both the Atlantic inflow to the northern North Sea and the inflow through the English Channel were lower in 2001 than in 2000. Estimates from a long term modeling experiment, rank the Atlantic inflow in 2001 among the lowest since 1955, and the English Channel net flow in 2000 as the highest. The cross boundary flow of inorganic nitrogen from the German Bight to the Skagerrak was 50% higher in 2000 than in 2001. An eutrophication assessment from the modeled N/P ratio gives significant higher levels in 2000. The effect on this level is also documented from a reduced input of inorganic nitrogen in the river waters.

Key words : North Sea, Skagerrak, numerical model, eutrophication

[1]Institute of Marine Research, Pb. 1870 Nordnes, N-5817 Bergen, Norway, morten@imr.no

1 Introduction

During the 1980s there was an increasing effort on the development of 3-dimentional numerical ocean circulation models in parallel with the development of stronger computers (e.g. Blumberg & Mellor (1980); Backhaus (1985); Bleck & Boudra (1986)). However, it was basically during the 1990s that these models, set up for larger ocean basins like the North Sea, demonstrated realistic results with respect to prognostic fields of temperature and salinity (e.g. Delhez & Martin (1992); Svendsen *et al.* (1996); Skogen *et al.* (1997)). It was also during the 1990s that these circulation models were extended with eutrophication processes, including nutrients and one or more phytoplankton groups (e.g. Baretta *et al.* (1995); Moll (1997); Skogen *et al.* (1995)). This required especially prognostic fields of currents, temperature and stratification (thus salinity and turbulence), and the input of light and nutrients from rivers and the atmosphere.

This paper deals with the first coupled physical-chemical-biological model (NORWECOM, the NORWegian ECOlogical Model system) set up for the whole North Sea and surroundings (Aksnes *et al.*, 1995; Skogen *et al.*, 1995; Skogen & Søiland, 1998). It includes the above mentioned physical variables, inorganic nitrogen, phosphorous and silicate, plus simply two phytoplankton groups, diatoms and flagellates. It also includes processes and variables related to oxygen consumption, remineralisation, sedimentation and resuspension, and denitrification. Some validation experiments using the present set-up have been published by Søiland & Skogen (2000); Skogen *et al.* (2002b, 2003).

The model has been run for 2000 and 2001 to demonstrate the usefulness of such models in describing the environmental status of the North Sea and Skagerrak, preferably seen in relation to possible management issues. The issues dealt with here are: variable annual primary production, short term and seasonal production, oxygen depletion in late summer, cross-border transports of water-masses and nutrients and eutrophication assessment.

Validation of this type of models is essential if they are to be used to give management advice. We are therefore referring to a more extensive paper by Søiland *et al.* (2003) which basically is discussing strength and weaknesses with NORWECOM, and the problems with lack of relevant data for proper validation.

2 Material and methods

2.1 The model design

The NORWegian ECOlogical Model system (NORWECOM) is a coupled physical, chemical, biological model system (Aksnes *et al.*, 1995; Skogen *et al.*, 1995; Skogen & Søiland, 1998) applied to study primary production, nutrient budgets and dispersion of particles such as fish larvae and pollution. The model has been used for a long term study of primary production in the North Sea (Skogen & Moll, 2000) and been validated by comparison with field data in the North Sea/Skagerrak in Svendsen *et al.* (1995, 1996); Berntsen *et al.* (1996); Skogen *et al.* (1997); Søiland & Skogen (2000).

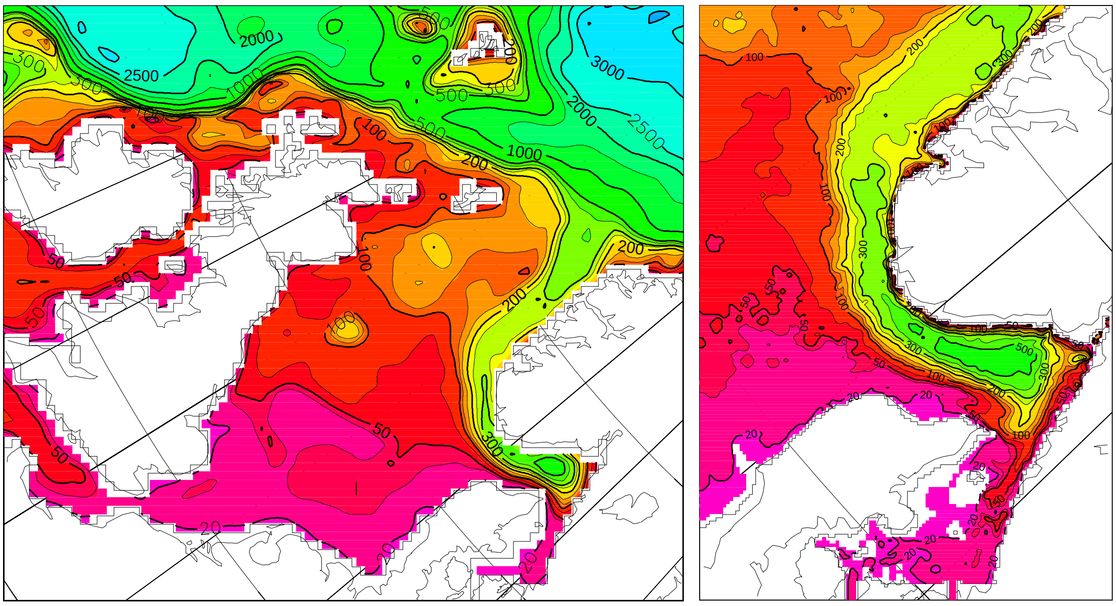

Figure 1: Model bathymetry. Coarse North Sea model domain (left) and fine Skagerrak model domain (right)

In the present study a nested version of the model is used, with a coarse 20 × 20 km. grid on an extended North Sea, and a fine 4 × 4 km. mesh in the Kattegat/Skagerrak area (see Figure 1). The coarse model was run initially, providing the necessary boundary and initial values for the fine grid. In the vertical 12 bottom-following sigma layers are used. The physical model is based on the primitive equation, wind and density driven Princeton Ocean Model (Blumberg & Mellor, 1987). The forcing variables are six-hourly hindcast atmospheric pressure fields and wind stress from the European Center for Medium-Range Weather Forecasts (ECMWF), four tidal constituents at the lateral boundaries, surface heat flux and freshwater runoff.

The chemical-biological model is coupled to the physical model through the subsurface light, the hydrography and the horizontal and the vertical movement of the water masses. The prognostic variables are dissolved inorganic nitrogen (DIN), phosphorous (PHO) and silicate (SI), two different types of phytoplankton (diatoms and flagellates), detritus (dead organic matter), diatom skeletals (biogenic silica), inorganic suspended particulate matter (ISPM), oxygen and light. The processes included are primary production, respiration, algae death, regeneration of dead organic matter, self shading, turbidity, sedimentation, resuspension and denitrification. The incident irradiation is modeled using a formulation based on Skartveit & Olseth (1986, 1987), with surface solar radiation data from ECMWF as input data. Nutrients (inorganic nitrogen, phosphorous and silicate) are added to the system from the rivers, from the atmosphere (only inorganic nitrogen) and through the open boundary. Particulate matter has a sinking speed relative to the water and may accumulate on the bottom if the bottom stress is below a certain threshold value and likewise resuspension takes place if the bottom stress is above a limit. Input data on suspended particulate matter, are taken from Pohlmann & Puls (1994). Regeneration of organic particulate matter takes place both in the water column and in the sediments. The bottom stress is due to both currents (including tides) and surface waves.

Surface heat fluxes (short and long wave radiation, sensible and latent heat fluxes) are calculated using data available from the ECMWF archive. Initial values for velocities, water elevation, temperature and salinity in the coarse model are taken from monthly climatologies (Martinsen *et al.*, 1992). Interpolation between monthly fields are used at all open boundaries, except at the inflow from the Baltic where the volume fluxes have been calculated from the modeled water elevation in the Kattegat and the climatological mean fresh water runoff to the Baltic, using an algorithm from Stigebrandt (1980). To absorb inconsistencies between the forced boundary conditions and the model results, a 7 grid cell "Flow Relaxation Scheme" (FRS) zone (Martinsen & Engedahl, 1987) is used around the open boundaries. To calculate the wave component of the bottom stress, data from DNMI's operational wave model, WINCH (SWAMP-Group, 1985; Reistad *et al.*, 1988), are used. The initial nutrient fields are derived from data obtained from ICES together with some small initial amounts of algae.

2.2 Experimental set-up

Three different simulations were done. In the first one simulating 2001, the 20km North Sea model was spun up by running 1999 three times and then 2000 through 2001 was run sequentially. The fine grid model was initialized with results from the coarse model January 5, 2000. The 4 km model was run from January 5, 2000, through 2001 with boundary conditions from the 20 km North Sea model. With such a spin up of the models, it is ensured that the models are in equilibrium with the boundary conditions and river loads, thus the effect of the initial condition is eliminated. The results section will have the main focus on the 2001 simulation, but with some comparisons and results also from a 2000 simulation. In this second simulation, 2000 is run with an identical set-up only shifted one year earlier. Finally, a second 2000 simulation is run with the only difference that the river inputs of nitrogen is reduced by 30%.

This experimental set-up has been validated in Skogen *et al.* (2002b, 2003); Søiland *et al.* (2003), using data from the Torungen (outside Arendal on the southeast coast of Norway) to Hirtshals (Denmark) transect in the Skagerrak (monthly data). In general, the physical model reproduces the salinity variability in a satisfactory way. For the nutrients the picture is mixed. In the deeper parts of Skagerrak there is a too high regeneration of inorganic nutrients, while at intermediate levels there is a good correspondence at the mean levels of nutrient concentrations in the inflowing Atlantic water and also the level of variation is realistic. In the inflowing water to Skagerrak there is good agreement for the phosphate values, but the modeled dissolved inorganic nitrogen values are too high especially in the fall and early winter. There is a bias in the modeled silicate concentration and these are clearly to low. A thorough validation is given by Søiland *et al.* (2003).

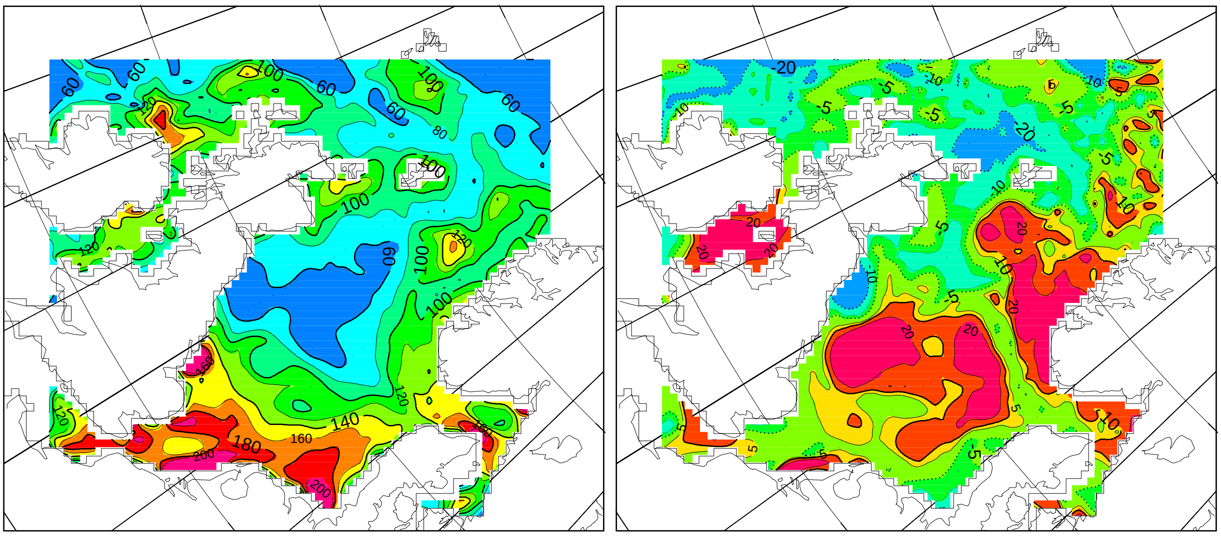

Figure 2: Modeled annual depth integrated primary production in 2001 for the coarse North Sea model. In the left panel the absolute values ($gC/m^2/year$) and in the right panel the change (in percentage) compared with 2000

3 Results

3.1 Algae and primary production

The annual depth integrated primary production ($gC/m^2/year$) in 2001 for the 20 kilometer North Sea model is shown in Figure 2. For the North Sea the highest modeled production is along the southern North Sea continental coast with an annual production of more than $200 gC/m^2/year$. This is more than 3 times the values in the central and northern North Sea, and is caused by the high support of nutrients from European rivers. In the Skagerrak the coarse model gives production estimates between 100 and 200 $gC/m^2/year$, while the production outside the Norwegian west coast is just above 100 $gC/m^2/year$. These general patterns are also seen in the fine scale model.

Comparing the annual production in 2001 with 2000, the mean North Sea production in 2001 is somewhat higher (112 compared to 107 $gC/m^2/year$). However, there are large spatial differences (see Figure 2, right panels). In 2001 there was a higher production in the central North Sea and along the Norwegian coast, while the production was lower than 2000 in the northwestern North Sea.

Inside Skagerrak, the primary production along the Norwegian coast is dominated by diatoms because of new supplies of silicate during coastal upwelling events, while the production in the central Skagerrak is dominated by flagellates. To get an idea about the day to day variability in the primary production, the spatial averaged modeled daily production ($gC/m^2/day$) in Skagerrak are shown in Figure 3. The production has an average of 0.38 and a maximum level of 1.32 $gC/m^2/day$ (in 2000 the numbers were 0.36 and 1.45 $gC/m^2/day$). The production shows large day to day variations. In the figure

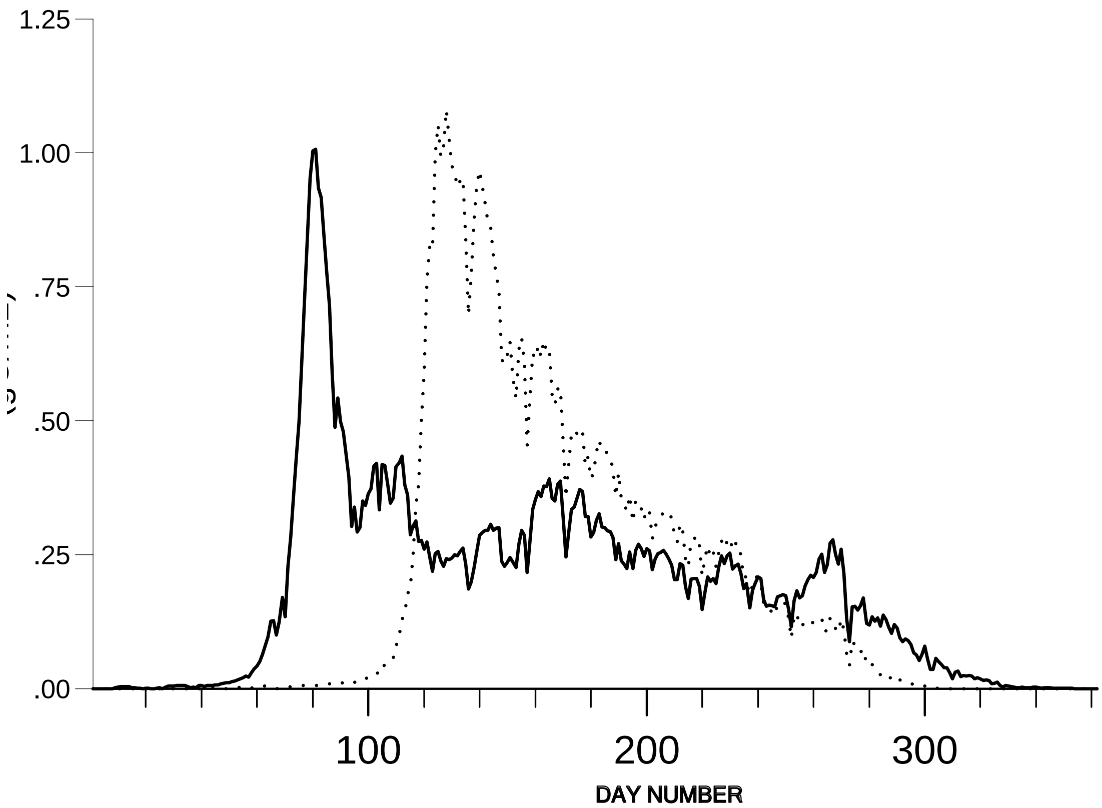

Figure 3: Modeled daily primary production ($gC/m2/day$) in Skagerrak from the fine scale model. Diatom production solid line and flagellate production dotted line

an early spring diatom bloom with a maximum after middle of March, followed by a peak bloom of flagellates during May can clearly be seen. The flagellate production decreases as the nutrients are depleted, while the diatom production continues on a lower level during summer and fall. Focusing the time series to only small areas on the Norwegian coast (not shown) illustrates the full effect of coastal upwelling to the diatom production. Several production maximas lasting for only a few days with comparable production intensity as the early spring bloom are seen up to the middle of September. This also illustrates the difficulties of estimating mean production only based on sporadic measurements.

3.2 Oxygen

One of the main concerns related to eutrophication is oxygen depletion. High production, sinking of dead organic matter and biochemical decomposition of organic matter, can locally give rise to low oxygen values in stagnant water. In Figure 4 the modeled oxygen concentration in the lowermost model level (within 2.5 % of the total water depth above the sea bottom) are shown at the time of overall North Sea minimum oxygen concentration. The situations are from week 37 (early September) in 2000 and week 35 (late August) in 2001.

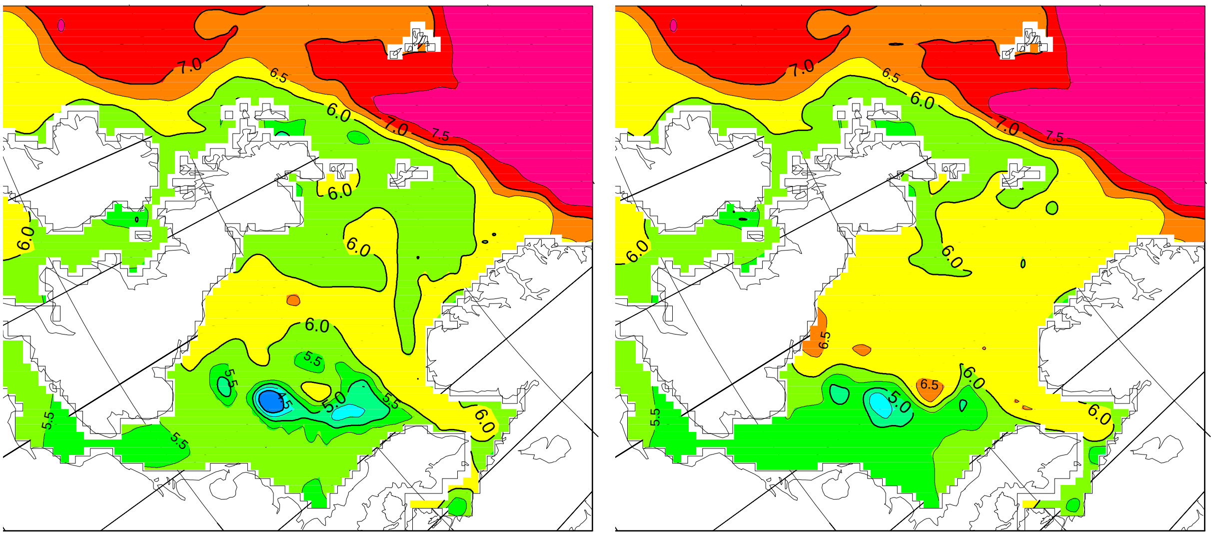

Figure 4: Modeled oxygen, ml/l, (left) in the lowermost model level (2.5 % above bottom) from the coarse North Sea model. Week 37 (early September) 2000 in the left panel and week 35 (late August) 2001 in the right panel

In the beginning of the year (not shown) the oxygen conditions are good all over the North Sea. Except for the Norwegian trench and some local mimimas east of Scotland (coincides with local minimas in the topography), the modeled oxygen levels are higher than $6.5ml/l$. During summer, oxygen are reduced in the whole North Sea partly due to the reduced saturation level due to to increased temperature. However, especially in 2000 south and east of the Dogger Bank, two local oxygen minimas (extending toward the Skagerrak) are seen in this area. They are both connected to local mimimas in the topography, where stagnant waters are apparent. At this time the modeled minimum oxygen levels are just below $3ml/l$. One of these minimas also extends into the 4 km domain (not shown) where a plume of low oxygen water are following the shelf break into Skagerrak. The model shows the appearance of this low oxygen water during a three weeks period in mid September. Measurements on September 11, 2000 along the Torungen - Hirtshals transect (measured approximately once every month by IMR), shows the appearance of an oxygen minimum on the shelf break on the Danish side (30-75 m depth). On the Norwegian coast a similar minimum is observed, with a second extreme minima 15 nm. off the Norwegian coast at the same depth. The oxygen level at the second point off the Norwegian coast, is the lowest measured at this position in the period 1990-2000 (D.Danielssen, Flødevigen, pers.comm.). An oxygen minimum is also seen outside Hirtshals August 14, 2000, and the corresponding salinity values indicates that the low oxygen water originates from the North Sea. The oxygen minimum outside Norway is never seen in the model, and we assume this is due to too coarse model resolution, and/or too much mixing in the model. Nevertheless, the model reproduces the observed advection of low oxygen North Sea water into the Skagerrak.

In late August and early September (week 35 and 36) the modeled minimum in 2001 are found with oxygen levels between 4.5 and $5.5ml/l$ in the southern North Sea (minimum

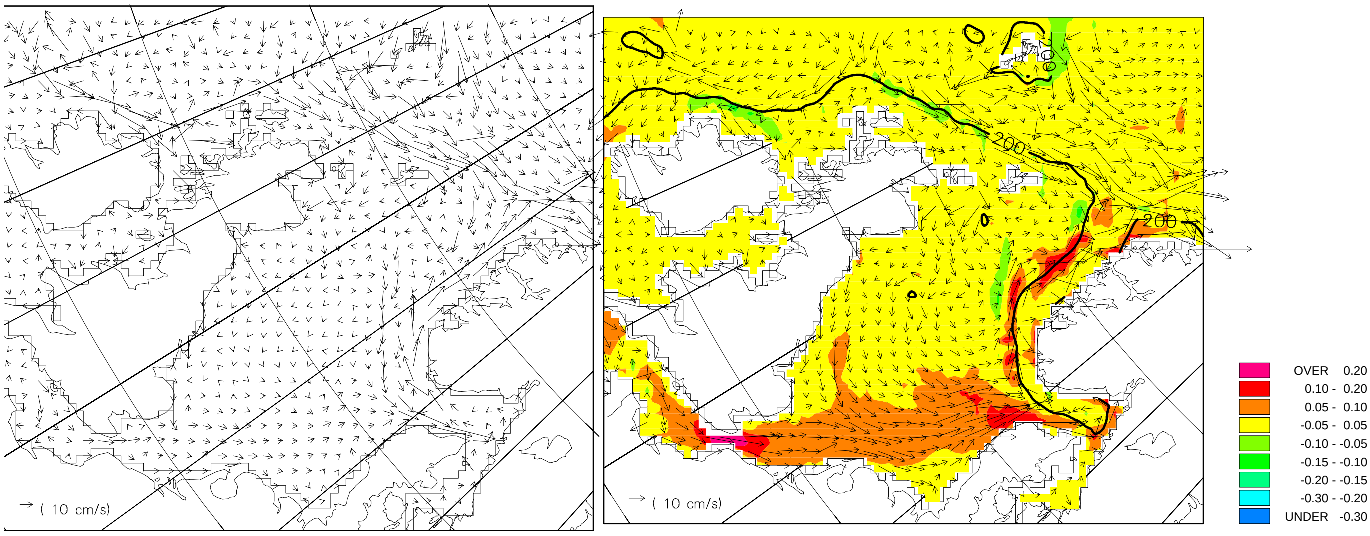

Figure 5: Modeled 2001 annual mean velocity field (10 m depth) from the coarse North Sea model (left) and 4th quarter 2000 velocity field and speed anomaly (right)

value just below $4ml/l$). However, during 2001 no oxygen minimum similar to that in 2000 were found. Sudden disappearance of sandeel in these areas (as reported by fishermen) may be caused by depletion of oxygen below certain threshold levels for the fish.

The modeled bottom water in most of Skagerrak and Kattegat has oxygen levels all through the year higher than 5.0 ml/l. In December (not shown) the model gives a similar picture as January with no oxygen depleted areas in the North Sea due to the strong winds causing vertical mixing to the bottom, except for the lower oxygen levels in the Norwegian trench and Skagerrak being too deep and stratified for surface wind mixing to reach the bottom. The model shows a clear annual cycle in oxygen concentrations in this areas, with an oxygen maximum in May/June and a minimum in January in agreement with measurements (Skogen *et al.*, 2003).

3.3 Circulation and transports

The modeled annual mean year 2001 North Sea circulation are shown in Figure 5. The model reproduces the well known cyclonic circulation pattern, with a well defined Norwegian Coastal Current, Atlantic and English Channel inflow and the eastward Dooley current at about 58 ^oN.

The North Sea inflows in 2000 and 2001 have been compared through one transect from Orkney to Utsira and one crossing the English Channel (Figure 6). The Atlantic inflow through the east-west section from the Orkney to Utsira (along 59.17 ^oN) are much lower in the first quarter of 2001 compared to 2000, and somewhat higher in the fourth quarter. The net transport through the English Channel is more equal between the years, except for the very high inflow in the end of 2000.

The transports can also be classified from a long time modeling experiment. The

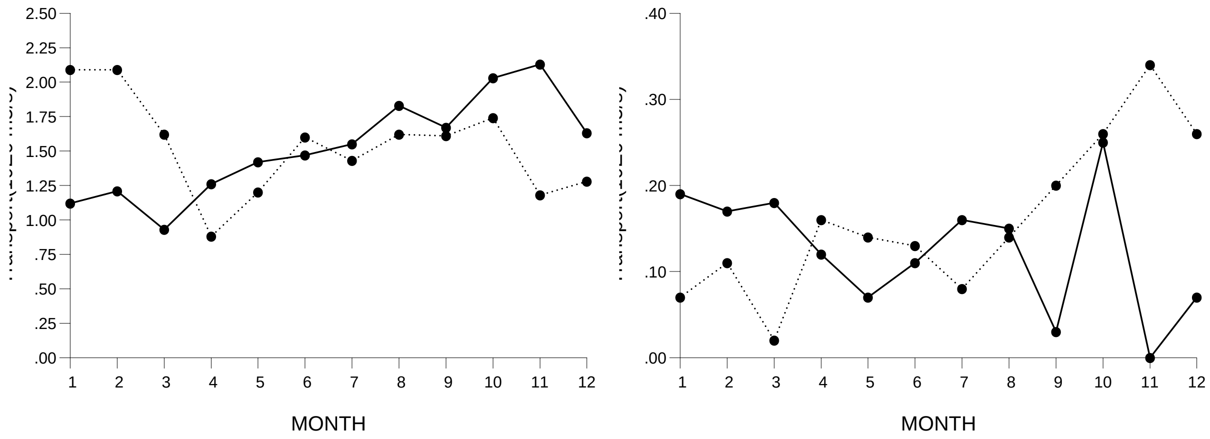

Figure 6: Modeled monthly mean inflow through the Orkney-Utsira transect (left), and net flow through the English Channel (right). 2001 (solid line) and 2000 (dotted line)

physical part of NORWECOM has been run for an area covering the whole shelf area from Portugal to Norway (including the North Sea) for all years back to 1955 (Iversen *et al.* (2002); Skogen(unpubl.data)). Focusing on the North Sea inflow, this experiment puts 2001 with the second lowest first quarter inflow, and the lowest first half of the year Atlantic inflow through the Orkney-Utsira transect. Altogether this ranks 2001 the fourth lowest annual Atlantic inflow. On the contrary, the inflow in 2000 are approximately 20 % above the mean in the first quarter, while the flux is approximately 10% below the mean for the rest of the year. The net transport through the English Channel in 2001 is above the mean in the first quarter, but the mean annual net inflow is ranked as 35 out of 47. In 2000 the southern inflow have a quite normal values in the three first quarters, but for the last quarter there is a dramatic change. The net inflow is about 6 times higher than the longterm mean for this quarter, and has the maximum fourth quarter value through the whole 47 year model period. This is shown in the right panel of Figure 5 where the 4th quarter 2000 modelled velocity field in 10 m depth together with the long term (1955-2001) speed anomaly is given. The figure clearly shows the large transport of water entering the North Sea through the English Channel. This extreme event also makes 2000 the highest year of modeled annual mean net inflow through the English Channel. This may be the cause for an unusual early bloom in March 2001 of the harmful algae *Chatonella* in Skagerrak. Previously it has several years occurred in May.

An important issue, especially concerning primary production and sedimentation of pollutants in the Skagerrak/Kattegat area, is the transport of nutrient rich water from the southern North sea and the German bight into this region. Much effort have been put into the work of identifying and quantifying the different water masses entering and leaving the Skagerrak area and their variation over time. It has also been important to investigate the mechanisms that drive the circulation and to study their effect on biological processes Danielssen *et al.* (1997). Defining water entering Skagerrak from the German Bight as water with salinity between 31 and 34 psu. and inorganic nitrogen higher than $1\mu M$,

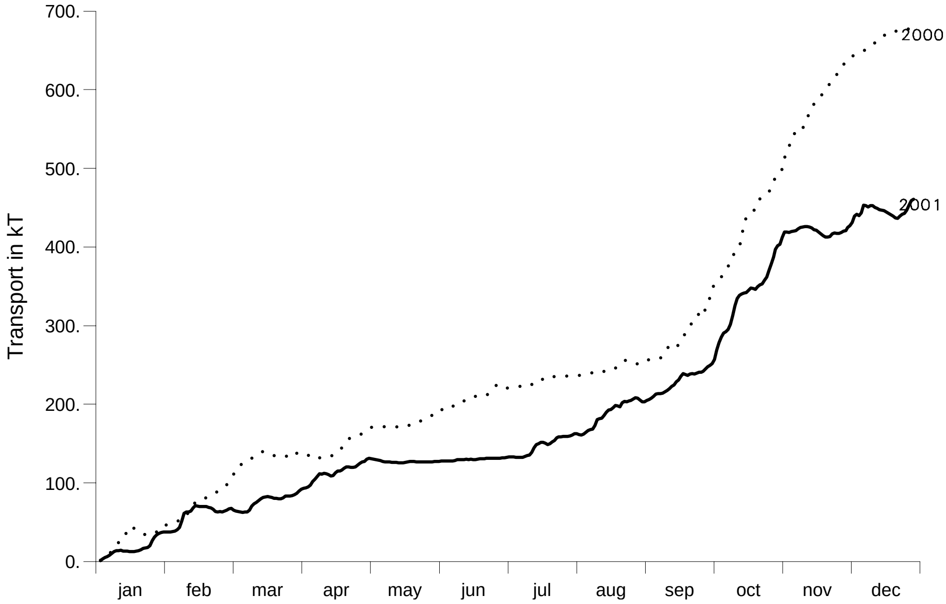

Figure 7: Modeled accumulated net cross boundary transport of inorganic nitrogen through the Tyborøn section in water with salinity between 31 and 34 and inorganic nitrogen $> 1\mu M$ in 2001 (solid line) and 2000 (dotted line)

the mean (25 hours) net advective transport of inorganic nitrogen from the German bight through a section going west (100 km) from Tyborøn (along 56.43°N) at the Danish west coast at the Limfjorden outlet have been estimated. The accumulated transport $(in - out)$ excluding the dispersive exchange due to tides, are given in Figure 7.

The total net advective transport of inorganic nitrogen with the Jutland current from the German Bight and into Skagerrak is from the model calculated to 460 kT (kilo tons), in an average flow of 0.13 Sverdrup in 2001, and 676 kT and 0.15 Sv in 2000. This agrees quite well with some other estimates of the same transport of about 400 kT and 0.15 Sverdrup Skjoldal (1993).

The large difference between 2000 and 2001 is mainly due to the large northward transport in the last months of 2000, which again is due to the very large inflow through the English Channel in this period.

3.4 Eutrophication assessment

The supply of nutrients and the possible eutrophication of the open sea and coastal waters (e.g. extensive algal blooms, oxygen depletion in bottom waters, extinction of bottom living species) can be studied with various types of measurements and observations. Accordingly, a number of parameters are needed as an assessment criteria for eutrophication. The Swedish Environmental Protection Agency (`http://www.internat.environ.se`) has made a set of assessment criteria for Swedish and adjacent waters which can highlight the effect of eutrophication. Based on levels of several state variables (chlorophyll$_a$, bottom oxygen,

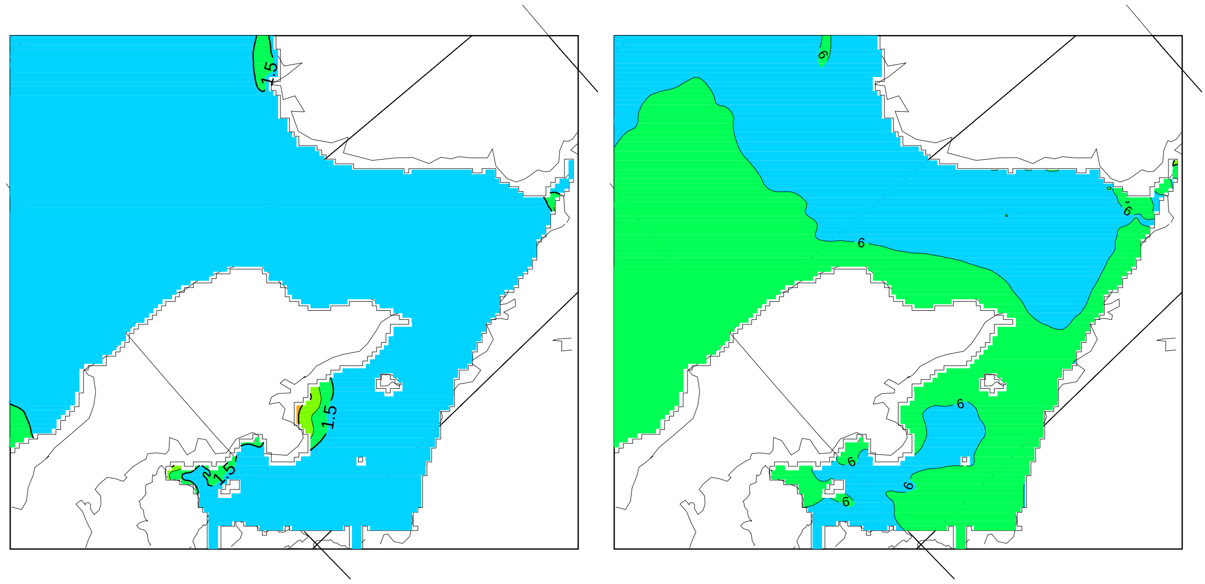

Figure 8: Modeled eutrophication assessment levels (2001) of Chlorophyll$_a$ in August (left) and oxygen in mid September (right). The colors, referring to the eutrophication levels, should be read as: very high (red), high (yellow), moderatly high (light green), low (green) and very low (blue)

winter nutrients, water transparency) measured along the Swedish coast around 1990, the level of eutrophication are classified in five different classes as: very low, low, moderate, high and very high.

3.4.1 Chlorophyll

Using these proposed levels for Swedish waters, the mean modeled chlorophyll$_a$ concentration at 5 m depth in August have been calculated to assess the level of eutrophication from chlorophyll. The results from the fine scale model in Skagerrak and Kattegat (note the somewhat reduced view) is shown in Figure 8. The model gives very low levels ($< 1.5\mu g/l$) in most of Skagerrak and Kattegat. In the Oslofjord and west of Jutland there are areas with Low values (1.5-2.2 $\mu g/l$), while there are large areas along the Danish east coast which are classified as Moderate to High ($2.2 - 5.0\mu g/l$). Compared with the 2000 simulation (not shown), these chlorophyll values on the Danish east coast, are almost equal.

3.4.2 Bottom level oxygen

Eutrophication implies an increased risk of oxygen depletion in bottom-level waters. The lowest level of oxygen during the course of the year is decisive for the survival of the bottom fauna. That annual minimum may therefore be used to indicate the negative consequences of eutrophication. The lowest oxygen levels during the year usually occur during late summer and autumn. The week averaged oxygen in the bottom layer of the model have

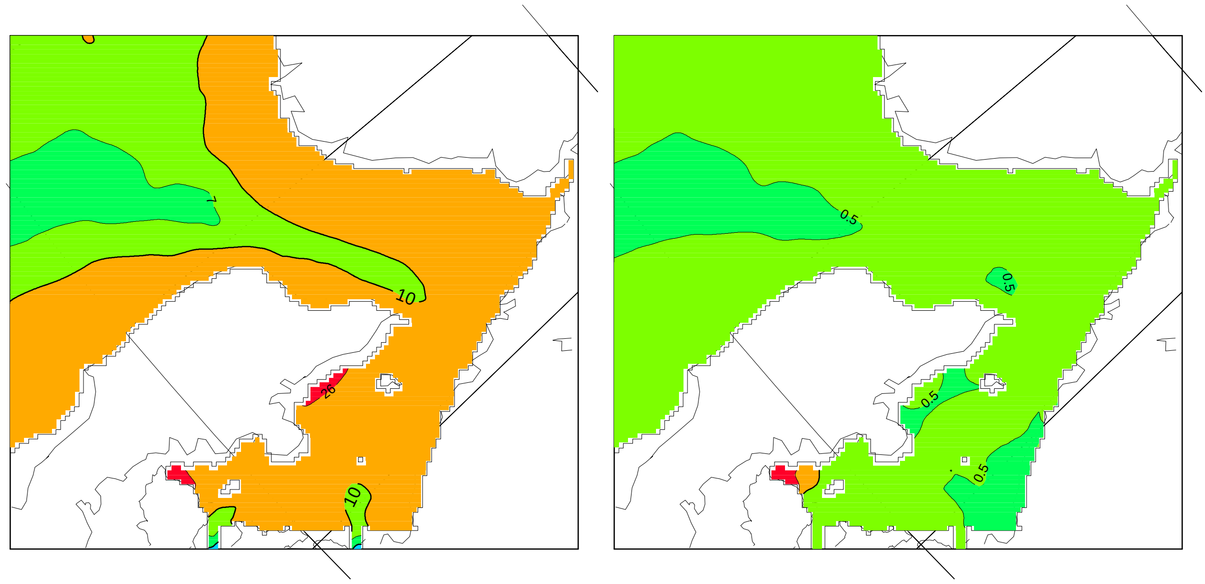

Figure 9: Modeled eutrophication assessment levels of nitrate (left) and phosphate (right) in January 2001. The colors, referring to the eutrophication levels, should be read as: very high (red), high, moderately high, low and very low (blue)

been examined in late summer and fall 2001 to search for episodes of low oxygen levels. The situation from week 35 (late August) is shown in Figure 8. The modeled bottom layer show high (=very low eutrophication level) ($> 6ml/l$) or moderately high ($4-6ml/l$) oxygen levels in all areas except for some small areas outside the Belts where low oxygen levels ($2-4ml/l$) occurs. The situation are almost identical to that in 2000.

3.4.3 Winter nutrients

The winter levels of nutrients provide an indication of how large the production of plankton algae and other vegetation is likely to be during the following season of primary production. Therefore the winter values of the nutrients should be assessed before the spring bloom of the plankton algae.

The mean modeled nitrate and phosphate concentrations in January at 5 m depth have been used to assess the level of winter nutrients. These results are shown in Figure 9. The model shows high ($> 10\mu mol$) nitrate levels in most of Skagerrak and Kattegat. The Atlantic inflowing water are classified as low ($< 7\mu mol$) and moderately high. The only area with very high levels ($> 26\mu mol$) in 2001 is on the Danish east coast. This is very different from 2000 when very high nitrate levels, originating form the southern North Sea, were found along most of the Danish west coast. For phosphate the only area of high levels is outside the Belts, while in the rest of the area (in both 2000 and 2001) the levels are low to moderately high.

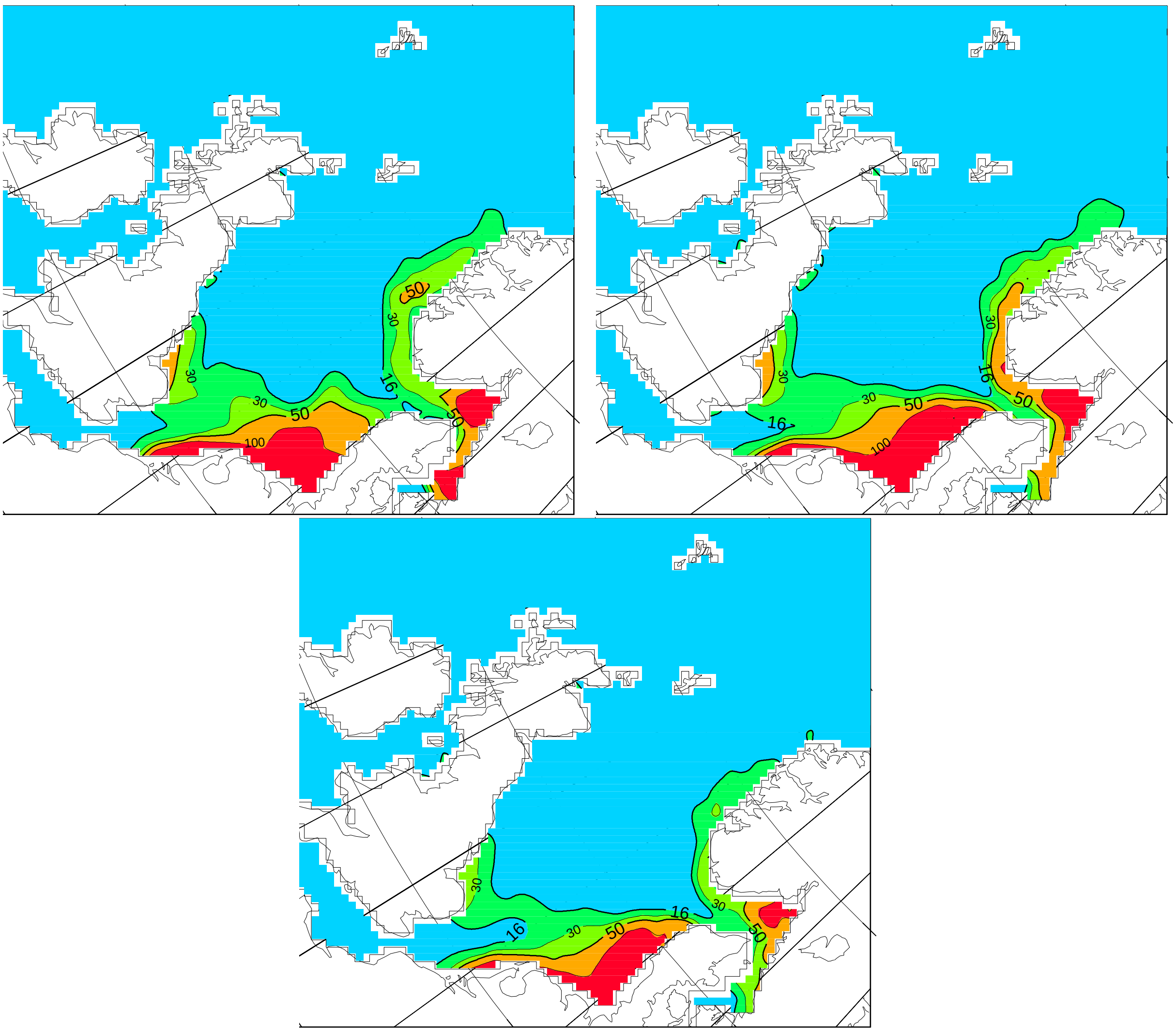

Figure 10: N/P ratio (May 5 m) eutrophication assessment for 2001 (upper left), 2000 (upper right) and 2000 with 30% reduced inputs of river nitrogen (lower)

3.4.4 An N/P ratio eutrophication assessment

The above results indicates only minor differences in eutrophication levels between 2000 and 2001 with the proposed state variables. A similar exercise using outputs from the third simulation (30% reduction in river nitrogen) also gave very small differences. This suggests that these state variables are not perfect for assessing eutrophication levels and effect of management strategies in general. Skogen *et al.* (2002a) proposed to use the N/P ratio to assess eutrophication. Oceanic waters are characterized by a nitrogen to phosphorus (atomic) ratio of 16 to 1 (Redfield ratio). The ratio in the river inputs are much higher, and this is reflected in measurements off the coasts. A surplus of about 300.000 tonnes of nitrogen would remain of the inputs (1990) when phosphorus is used with a normal consumption ratio by phytoplankton in spring (Anon., 1993). This surplus will be reflected in the modeled fields. The consumption of the surplus nitrogen occurs under conditions of phosphorus limitation, and represents a significant change in the ecological characteristics of the coastal water masses of the North Sea, from a more balanced situation on the side of nitrogen limitation to the present situation of marked phosphorus limitation. A further reduction in P (without a similar decrease in N) will disturb this balance even more, and it is known that phosphorus limitation and elevated N/P ratios can be responsible for changes in phytoplankton species composition and harmful algae blooms (e.g. the *Chrysochromulina polylepis* bloom in Skagerrak and Kattegat in May/June 1988 (Dundas *et al.*, 1989; Maestrini & Graneli, 1991; Skjoldal & Dundas, 1991) and the colony formation of *Phaeocystis* (Riegmann, 1991)). On the other hand, a reduction of N (and P) will decrease the N/P ratio and have a possible positive effect on harmful algae blooms. The surplus of anthropogenic nitrogen is transported by the Jutland coastal current from the southern North Sea and into the Skagerrak and Kattegat were large amounts of nitrate are found in late spring (Skjoldal, 1993; Aure *et al.*, 1998). In Jutland Coastal Water, N/P ratios above 200 have been observed in April due to excess nitrate (Aure *et al.*, 1998).

Focusing on the surplus of nitrogen after the spring bloom, and the potential for changes in phytoplankton species composition and harmful algae blooms under the consumption of this surplus nitrogen under phosphorous limitation and with elevated N/P ratios, the N/P ratio in May when several harmful algae blooms have been observed, will be used. The proposed new eutrophication assessment is the mean N/P ratio at 5 m depth in May. The different classes is set to very low (≤ 16), low (between 16 and 30), moderate (between 30 and 50), high (between 50 and 100) and very high (≥ 100). In Figure 10 the eutrophication assessment based on the N/P ratio is given.

The figure shows clear differences in large areas between the three different simulations. The N/P ratio in 2001 are significant lower than in 2000 both in the German bight, along the Danish west coast, in Skagerrak and outside the Norwegian west coast. A clear effect of the reduction of river nitrogen is also documented, but less than the natural variability seen between 2000 and 2001.

Acknowledgment

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