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Eutrophication Scenaria from Reduced Nutrient Loads to the North Sea

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Abstract

The environmental effects of river nutrient loads to the North Sea have been investigated using a numerical biophysical model, NORWECOM, to perform different reduction scenarios. The simulations demonstrate that the river nutrients have a significant contribution on the annual primary production, both in the southern North Sea, in Skagerrak and along the Norwegian west coast. A 50% reduction in the loads of N and P reduces the primary production with 10-30% in the southern North Sea, and 5-10% in Skagerrak and along the Norwegian west coast. Scandinavian rivers only contribute to the 1-2% level in these reductions, thus continental rivers has the major effect on the environment in all downstream areas. However, it should be noted that this reduction, even in the southern North Sea, is less than the natural variability of the production of phytoplankton. A reduction only in the P values, shows that the production regime in the southern North Sea is phosphorous limited, while nitrogen is the limiting nutrient in the northern North Sea. Focusing on the N/P ratio as a possible proxy for eutrophication, a reduction in the N and P loads reduces this ratio by a similar factor, while a reduction in the P loads only, increases it. Based on this it is proposed to use the N/P ratio for eutrophication assessment.

Key words : ecosystem model, North Sea, eutrophication, river nutrients, reduction scenarios, N:P ratio

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1 Introduction

To look into the future of nature (including man) is a challenge which always will be a major issue for scientist. However, dealing with nature, especially on higher trophic levels, we are faced with the problem that individuals or communities may develop and/or take decisions on behavior never or rarely experienced before. Therefore predictions (based on historic knowledge) sooner or later will always fail since nature is in constant development. In addition the physical driving forces (climate), being a major regulator on the ecosystems, is highly variable and hard to predict, and we only know bits and pieces of the climatic effects on the marine biology.

In this paper we are dealing with mathematical model predictions in relations to certain scenario or *what-if* questions related to management issues. Clearly this is different from e.g. weather forecasting, since we are not predicting what the politicians/managers will do in the future with respect to nutrient loads, but rather the most probable effect of certain management actions. We also just make the study through some past years, due to the very large uncertainty with respect to future climate/ physics. Our knowledge on the biochemical processes is taken from the literature based on experiments in laboratories and mesocosms, or deduced from field measurements (Aksnes *et al.*, 1995; Pohlmann & Puls, 1994; Mayer, 1995; Gehlen *et al.*, 1995; Lohse *et al.*, 1995, 1996).

At the *2nd. International conference on the protection of the North Sea* (London 1987), all countries around the North Sea agreed on reducing the input of nutrients by 50 % between 1985 and 1995 for those areas where nutrients cause, or are likely to cause, pollution. This decision was based on the fact that the loads in many European rivers were extremely high, increasing frequency of harmful algal blooms seemed to occur, and in some areas significant oxygen reductions were occasionally observed in the bottom water (Anon., 1993). However, very little quantitative information was available at that time on the possible effects of the management decision, which was seen as a first step for later management actions based on thorough ecosystem understanding and approach toward a sustainable North Sea with clear ecological quality objectives.

Basically the goal for phosphorous has been achieved due to the improvement of municipal treatment plants and by the replacement of phosphorous by tensides as detergent in washing powder, while nitrogen loads have not been reduced by the same amounts (Behrendt *et al.*, 2000). This has probably lead to reduced primary production at times and in areas being typically phosphorous limited. However, in these areas the reduction of just phosphorous has probably lead to increased imbalance between the two nutrients, an imbalance which may change the algal species composition and increase the possibility of certain algae being toxic (Anon., 1993).

This paper deals with the probable environmental effects of reducing the nutrient loads to the North Sea. This is done through simulations of several nutrient reduction scenarios by the use of a coupled 3-dimensional physical, chemical and biological model system, NORWECOM, (The NORWegian ECOlogical Model system) (Skogen & Søiland, 1998). This model has been developed during the 1990s, and was the first coupled biophysical model with prognostic hydrodynamics (current, temperature, salinity, turbulence), nutrients (N, P, Si) and algae (diatoms and flagellates) in operation on the whole North Sea and surrounding areas (Skogen *et al.*, 1995). Today this model is run operationally with 7 days forecast at the Norwegian meteorological institute (`http://www.imr.no/~morten/nocomments`).

After a description of the model and experimental design, the results are demonstrated with emphasis on the effects on primary production and the N/P ratio in two different years (1988 and 1989). The results are also examined with focus on the natural occurring variability due to differences in the weather system (forcing fields) between the two years. The reduction scenarios include reduction just in phosphorous compared to both nutrients, and it also includes the effect of just reducing the loads in Scandinavian rivers. Finally, we also include some thoughts about eutrophication assessment and suggest how the model can contribute to a better quantitative analysis of the status and effects of management actions.

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 has been validated by comparison with field data in the North Sea/Skagerrak in Svendsen *et al.* (1996, 1995); Berntsen *et al.* (1996); Skogen *et al.* (1997); Søiland & Skogen (2000); Søiland *et al.* (2003).

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 Norwegian Meteorological Institute (DNMI), four tidal constituents at the lateral boundaries and freshwater runoff. In the lack of data on the surface heat fluxes, evaporation and precipitation, a relaxation toward climatology method is used for the surface layer (Cox & Bryan, 1984). During calm wind conditions, the surface field will adjust to the climatological values after about 10 days.

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, sedimental burial and denitrification. Phytoplankton mortality is given as a constant fraction, and is assumed to account also for zooplankton grazing which in this context is included as a forcing function. The incident irradiation is modeled using a formulation based on Skartveit & Olseth (1986, 1987). Due to the lack of

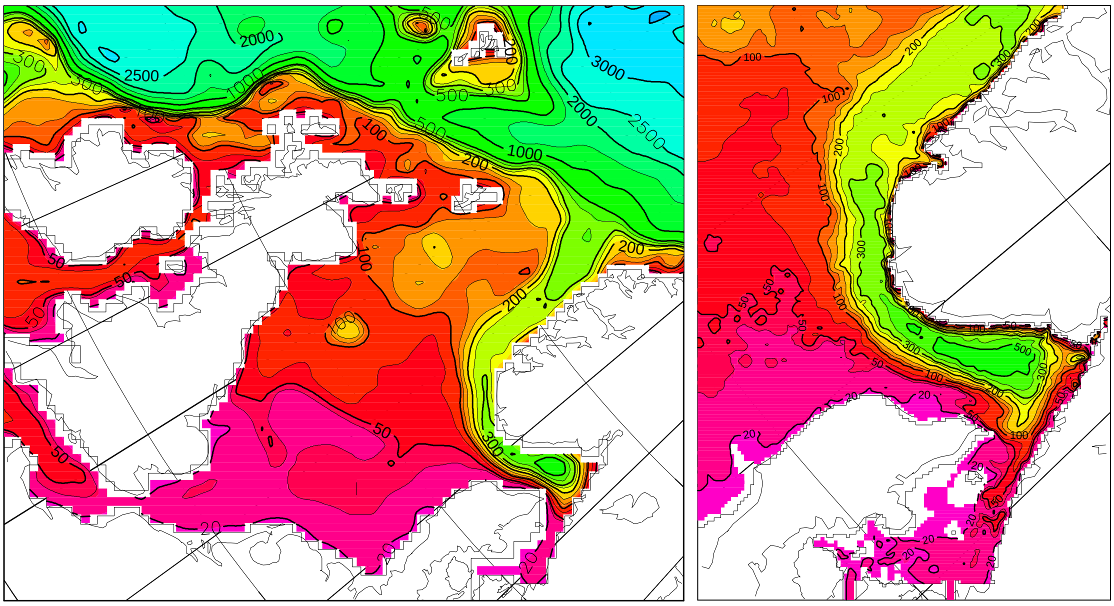

Figure 1: Model bathymetry. Coarse North Sea model domain (left) and fine Skagerrak model domain (right)

irradiance data from the period modeled, data for global daily radiation from 1990 is taken from a station at Taastrup (Denmark) (Anon., 1991). 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.

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 winter values (February 1990) obtained from ICES together with some small initial amounts of algae ($0.1mgN/m^3$).

2.2 Experimental set-up

The 20km North Sea model was spun up by running 1987 four times and then 1987 through 1989 was run sequentially. The fine grid model was initialized with results after the fourth year of the coarse model. Output for boundary conditions to be applied in the fine scale Skagerrak model was done for the last run of 1987 and 1988 and 1989. Thus the 4 km model was run for the years 1987-1989. The first year was considered as a spin up of the 4km model and only results from 1988 and 1989 are used in the present work.

The spin up of the models ensure that the models are in equilibrium with the boundary conditions and river loads, thus the effect of the initial condition is eliminated. The same spin up procedure was followed for all the four scenarios, thus the effects of reducing the nutrient river loads are effective from the first day of the period considered (1988-89). The reference run (Run 1) was run with realistic river loads, and the three reduction scenarios were run with: 50% reduction in N and P in all rivers (Run 2), 50% reduction of P in all rivers (Run 3) and 50% reduction in N and P in Scandinavian rivers (Run 4). Except for the change in nutrient river loads, the runs were identical. In particular we kept the nutrient concentration in the outflowing water from the Baltic the same in all runs, and likewise the atmospheric nitrogen load and nutrient open boundary condition in the North Sea model was not changed. Wind, light and boundary conditions are the same in all runs.

The reference run (fine grid) has been validated in 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 summary, the physical model reproduces the salinity data in a satisfactory way. For the nutrients the picture is mixed. In the deep layers there is a too high regeneration of inorganic nutrients. 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 which are clearly to low.

3 Results

3.1 The reference run (run1)

In Figure 2 the modeled annual depth integrated $(gC/m^2/year)$ primary production for 1988 is shown for the coarse model. In the North Sea the highest modeled production is along the southern North Sea continental coast with an annual production of more than $200gC/m^2/year$. This is more than 3 times the values in the central and northern North Sea. In the Skagerrak (except for the Danish coast), the model gives production estimates between 100 and 150 $gC/m^2/year$, while the production outside the Norwegian west coast is around 100 $gC/m^2/year$. These numbers are in general agreement with other model estimates (Delhez, 1998; Lenhart *et al.*, 1997; Moll, 1998). The early diatom spring bloom starts out in the south and east and moves like a wave toward the north and west, where the peak production is seen more than one month later.

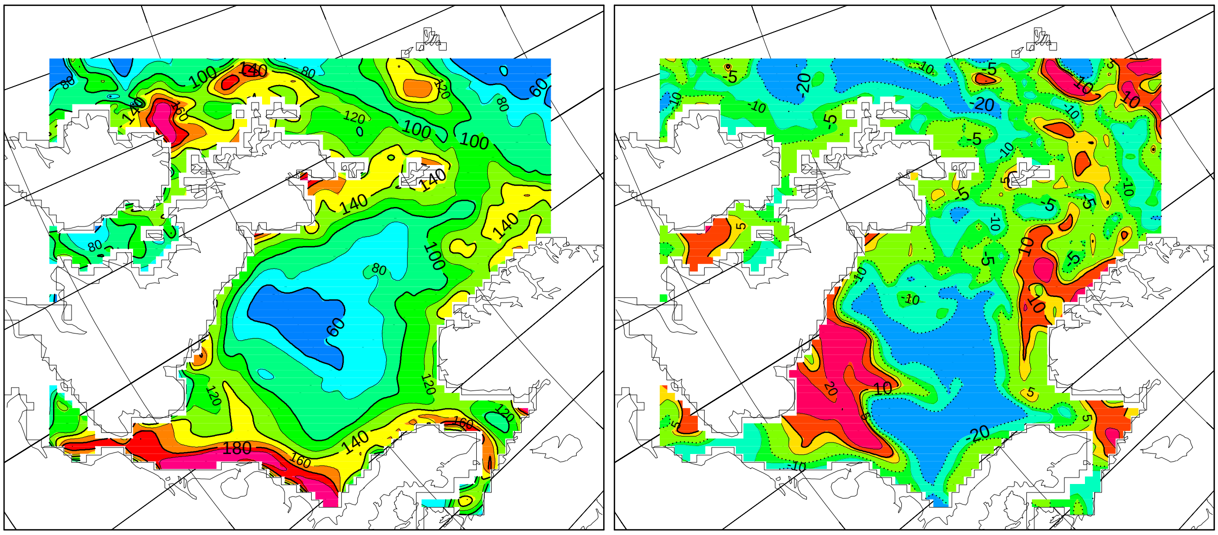

Figure 2: Annual depth integrated primary production $(gC/m^2/year)$ in 1988 (left), and the difference (in percentage) in production from 1988 to 1989 (right)

The peak phytoplankton production varies from just above $3gC/m^2/day$ outside the Dutch coast to approximately $1.5gC/m^2/day$ in the central North Sea.

Before investigating the effects of reduced river nutrient inputs on the primary production, it is important to examine the effects due to interannual variations in the forcing fields. Variations in the meteorological forcing from year to year have local effects on the primary production due to changes in light conditions, wind mixing etc, but indirectly the variations also results in changes in the wind driven circulation, and thus the long range transport of nutrients. Skogen & Moll (2000) concluded that the interannual variability of the mean North Sea primary production due to the wind forcing is around 15 %, and locally (mean ICES box) around 25 %. The total effects of the rivers was estimated to less than 10 % of the total production, and a reduction scenario, where all river nutrients was removed, concluded that even in the southern North Sea, the interannual variability might be larger than the total contribution from the rivers (using the same initial field for the nutrients). In the right panel of Figure 2 the change in production from 1988 to 1989 is shown for the reference run.

The annual mean production in the North Sea is 115 and 111 $gC/m^2/year$ in 1988 and 1989 respectively. The model simulation give a reduced production (in 1989) in the central and eastern North Sea, while the production on the British coast and Norwegian coast are higher in 1989 than in 1988. However, focusing on the absolute day to day differences $(gC/m^2/day)$ there are both periods with higher and lower production in 1989 than in 1988.

Oceanic inflow to the North Sea is the major source of new nutrients (e.g. Brockmann *et al.* (1990)), and Skogen & Moll (2000) concluded that the interannual variability in the primary production (fixed river runoffs and loads) could to a large extent be explained from the variation in this flow. The above production estimates should therefore indicate a somewhat higher modeled inflow to the North Sea in 1988 than in 1989. This is not the case. The modeled inflow through a transect from Orkney to Utsira-Norway (along $59.17\,^oN$) was higher in 1989, especially in the first quarter of the year. This higher inflow is reflected in the enhanced production in 1989 along the Norwegian coast and inside Skagerrak. However, the main contribution to a overall higher production in 1988 is the high production along the continental coast and west of Denmark (see Figure 2). These areas are highly exposed to the changes in river nutrients, and in 1988 the loads of DIN from continental rivers were 55% above those in 1989, while the numbers for PHO and SIL were 45% and 70% respectively (Lenhart & Pätsch, 2001).

The results from the fine scale Skagerrak model (not shown) confirms the results from the coarse North Sea model (Figure 2), except from a somewhat higher production along the Norwegian coast. Focusing on the diatom:flagellate ratio in this area the flagellates are dominating on the Danish coast and in the central Skagerrak, while there is an enhanced diatom production along the Norwegian coast. The main reason for a higher diatom production in this area, is new supplies of silicate brought to the surface during coastal upwelling events.

Also the difference between the 1988 and 1989 primary production agrees between the coarse and fine scale model, with a higher production in those areas dominated by the Atlantic inflow (Skagerrak and Norwegian coast), and a reduced production toward the southern and central North Sea.

3.2 N and P reduction scenario (run2 vs. run1)

In run2 the river loads of N and P are reduced with 50 % in all rivers. Except for this change, all forcing are identical. Since the diatoms are limited by silicate (which has not been reduced in the simulation) the rest of the discussion will focus on the flagellates only.

The changes in yearly total primary production have often been used to assess the effects of reducing nutrient loads (e.g. Skogen *et al.* (1995); Lenhart *et al.* (1997)), and in Figure 3 the reduction in annual flagellate production in the North Sea is shown for 1988. The figure clearly identifies the influence of river nutrients on primary production in large areas of the North Sea. The impact is largest close to the river outlets, thus in the southern North Sea a 50% reduction in N and P in the river waters reduces the flagellate production with 10-30%, while the reduction in the central North Sea, Skagerrak and along the Norwegian coast is 5-10%. The results for 1989 (not shown) give the same qualitative patterns, but with a smaller reduction in the southern and central North Sea, in accordance with the lower river loads (and higher Atlantic inflow) this year. The fine scale model (not shown) agrees with the results for the coarse model, except for a somewhat higher reduction level on the Norwegian coast. As a mean over the whole Skagerrak, the peak flagellate production in run1 was estimated to $1.40gC/m^2/day$ in 1988. In run2 this is reduced by less than 10% to $1.29gC/m^2/day$, slightly below the peak production in 1989 for run1 ($1.32gC/m^2/day$).

Even with a 50% reduction in the river nutrient loads, there are only small changes in the primary production fields, except for the areas close to the river outlets on the continental coast. However, focusing on the N/P ratio, a reduction is more significant. Calculating the mean weekly N/P ratio in the upper 20 meters for run 1 and run 2 in the fine scale model, the ratio is reduced by a factor of two between the two simulations during the productive season in large areas. On the other hand there is a remarkable difference between the two years, 1988 with high river loads and a very high N/P ratio, and 1989 with lower river loads, higher Atlantic inflow, and a much

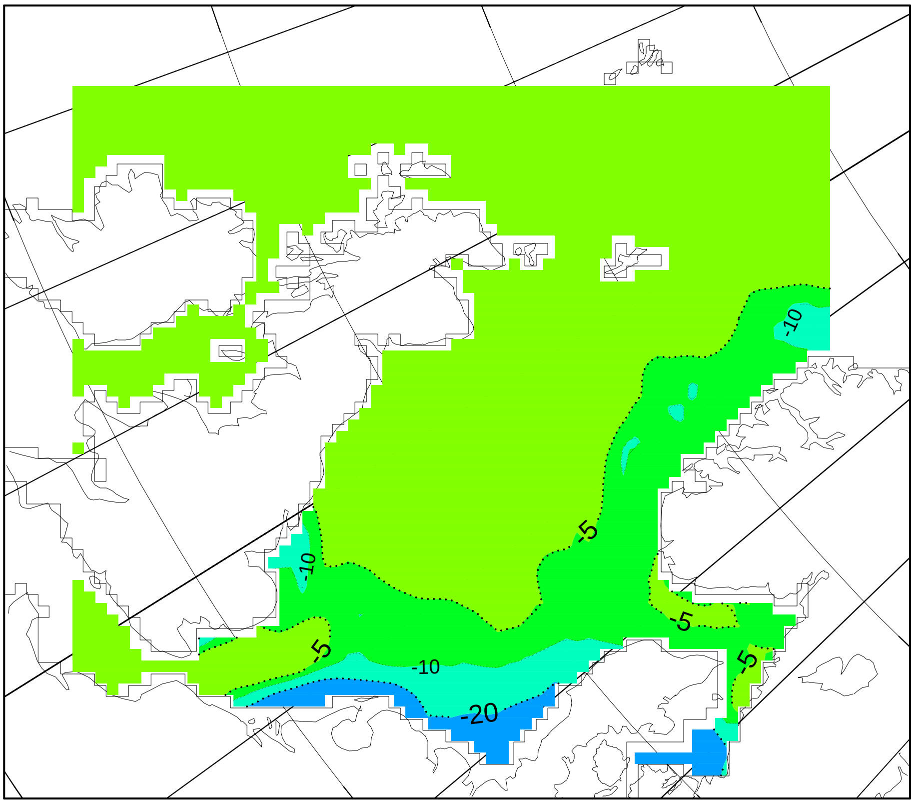

Figure 3: Difference (in percentage) in annual flagellate production 1988 between run1 and run2

lower N/P ratio.

3.3 P reduction only scenario (run3 vs. run1)

The difference between run 3 and run2 is that in run 3 only a 50 % reduction of P in the river waters are done (keeping N as in the reference run). The difference in flagellate production for 1988 between the reference run (run 1) and run 3 is shown in Figure 4. The figure has the same structure as the reduction between run 1 and run 2 (Figure 3), with a reduction of the production in the southern North Sea of the order 10-30 %, and a somewhat lower reduction in Skagerrak and along the Norwegian coast. The differences between run 2 and run 3 are highlighted in the right panel of Figure 4. This figure shows the change in production between run 2 and run 3. Compared to run 2, the effect of only reducing P from the rivers, is that the primary production along the Norwegian coast, on the British coast and in the central North Sea is higher than with an N and P reduction (5-10 %). This indicates that it is basically in the southern North Sea and in the Skagerrak that the flagellate production is P limited.

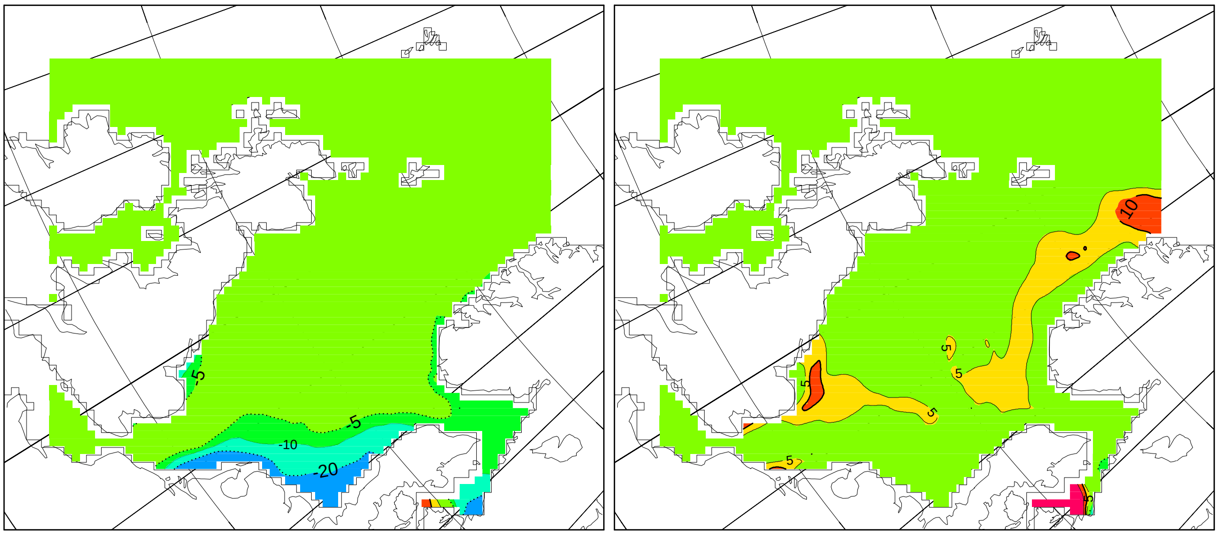

Figure 4: Difference (in percentage) in annual flagellate production 1988 between run1 and run3 (left) and run2 and run3 (right)

3.4 Scandinavian N and P reduction scenario (run4 vs. run1)

The difference between run 4 and run2 is that in run 4 the 50 % reduction in N and P loads is only done for Scandinavian rivers. A reduction in the Scandinavian loads has little impact on the yearly primary production except for the inner parts of Kattegat compared to the reference run. In Figure 5 the differences between run 1 and run 4 is shown to have no reduction potential above 5 % except for the Kattegat. The values in the rest of the domain is less than 1%, except for the Norwegian west coast were the annual flagellate production is reduced 1-2% with the N and P reduction in Scandinavian rivers. As a consequence the change in production between run 2 and run 4 (right panel in Figure 5), is almost identical to that between run 1 and run 2 for the fine scale model (not shown).

3.5 Eutrophication assessment

The supply of nutrients and the possible eutrophication of the open sea and coastal waters 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, 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.

Using these classes in an eutrophication assessment of the Skagerrak and Kattegat from modeled chlorophyll$_a$ and bottom oxygen, results in low or very low levels except for chlorophyll$_a$ values on the Danish east coast. This is consistent with the low effect on these variables between

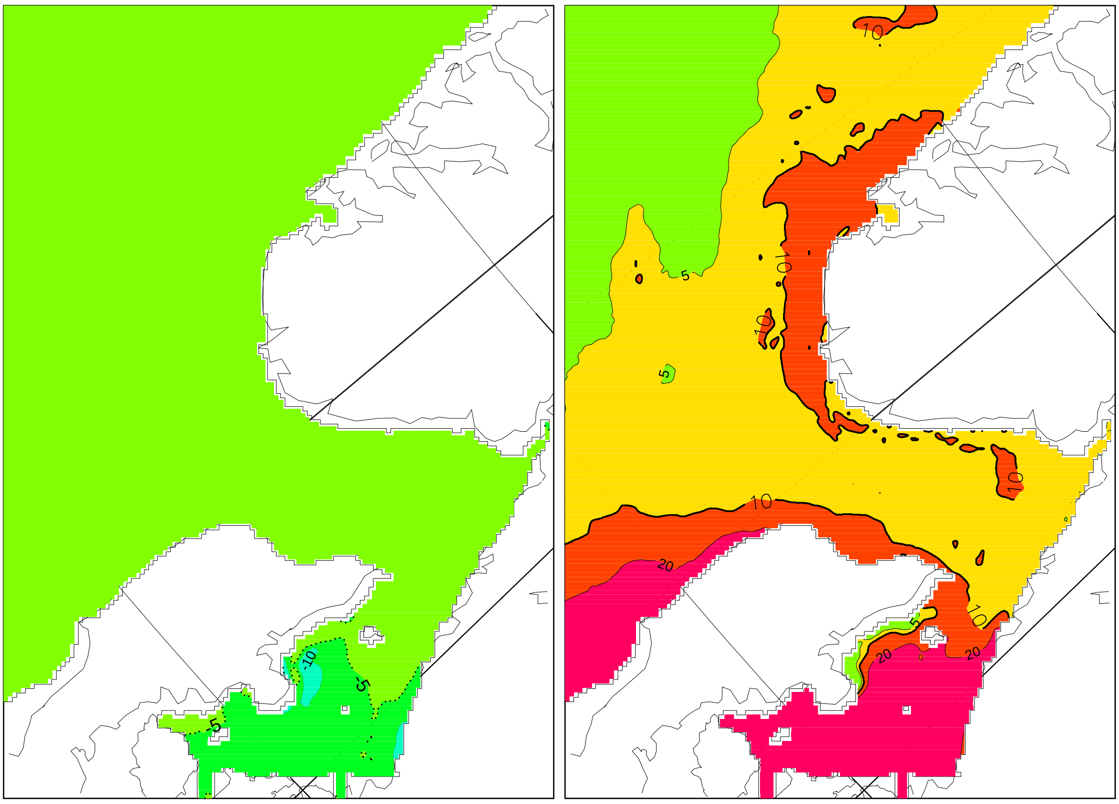

Figure 5: Difference (in percentage) in annual production 1988 between run1 and run4 (left) and run2 and run4 (right)

the different simulations performed. An assessment based on winter nutrients on the other hand, gives a clear evidence of eutrophication in the area with both high and very high levels. However, a complicating factor in using nutrients as an assessment for eutrophication is the large transport of Atlantic Water with high nutrient concentrations into the Skagerrak.

The results from the scenarios indicate that even with a 50% reduction in both N and P, there is only a small effect downstream on the annual production, peak chlorophyll and bottom oxygen content. The effect on the winter nutrient levels is significant, but with the high concentrations of nutrients in the Atlantic water, these state variables are difficult in use for assessing eutrophication levels in general. On the other hand, the N/P ratio show a clear effect from the reduction scenarios and is also a good indicator of eutrophication. It is therefore proposed to use the N/P ratio as a proxy to assess eutrophication. Focusing on the large surplus of nitrogen after the spring bloom (Anon., 1993), 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 (Riegmann, 1991; Skjoldal & Dundas, 1991), 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 6 the eutrophication assessment based on the N/P

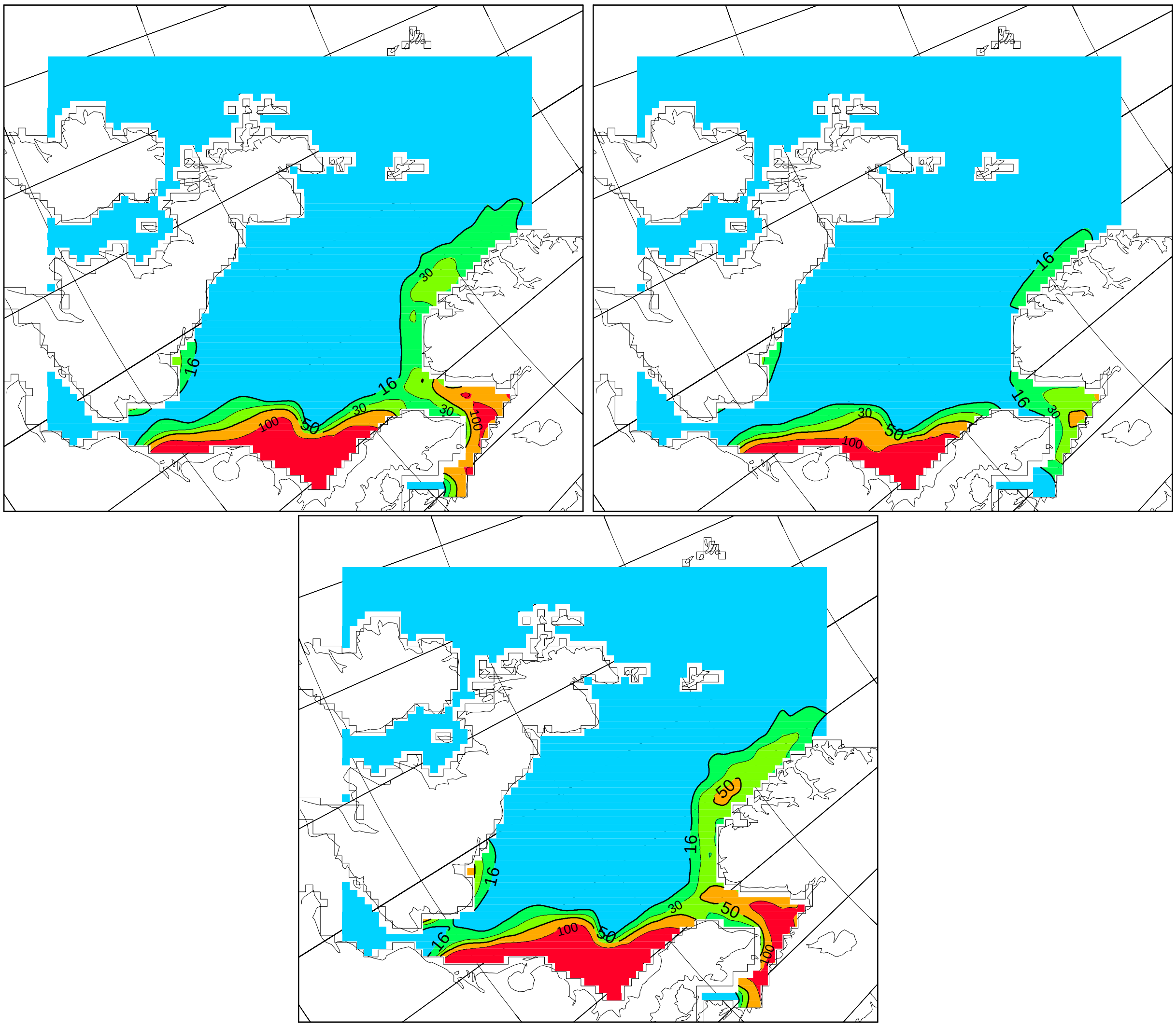

Figure 6: N/P ratio (May 5 m) eutrophication assessment for simulation 1-3

ratio for run1, run2 and run3 are shown.

The results from run1 shows how the water with elevated N/P ratio stretches from the southern North Sea, into the Skagerrak and up along the Norwegian west coast. The improved situation is clearly documented in run2, while there is an increased N/P ratio in all areas in run3.

4 Discussion

Even if more than 90 % of the nutrient inputs to the North Sea originates from oceanic waters (Brockmann *et al.*, 1990; Anon., 1993), also the contribution from rivers play an important role. This influence is of special importance in the coastal zone of the southern North Sea where about 75% of the freshwaterborne nutrients discharges are found. Obviously, the effects of reducing the river nutrients are more significant in these areas.

Both in 1988 and 1989 a 50% reduction of N and P in the river waters (run2) reduced the flagellate production with more than 30% close to the main river outlets, and with more than 10 % in large areas in the southern North Sea. Lenhart *et al.* (1997) has done a similar 50 % reduction experiment for 1988 and 1989 using the ERSEM box model (Baretta *et al.*, 1995). The annual primary production reduction patterns using the ERSEM model is quite similar to that in the present study, but generally a few percentage higher when taking the mean over an ICES box.

When only doing a 50 % reduction in P (run3), the results for the southern North Sea are quite similar to that of run2, while the effect on primary production is reduced farther away from the sources, leading to the conclusion that P is the limiting nutrient of flagellate production in southern areas, while N is limiting in the North. At the international conference on the protection of the North Sea (London 1987), all countries around the North Sea agreed on reducing the anthropogenic input of nutrients by 50 % between 1985 and 1995 for those areas where nutrients cause, or are likely to cause, pollution. For phosphorus there has been a declining trend in the inputs, while a decrease in nitrogen inputs are less pronounced (Behrendt *et al.*, 2000). This makes run3 the most realistic scenario for investigation of todays North Sea conditions, suggesting an increase in the eutrophication (Figure 6).

Nevertheless, by using annual or peak primary production as parameter for investigating the effects of changes in nutrient inputs to the North Sea, the large interannual variability occurring in phytoplankton production due to the variations in the meteorological forcing should be emphasized. Model experiments (Skogen & Moll, 2000) indicates that (even in the German Bight) this natural occurring variability might be larger than the total contribution from the rivers, and also in the present work the difference in total production between 1988 and 1989 for the reference run exceeds 20 % in large areas of the North Sea were river influences are negligible. This means that the effect on the flagellate production in run2 was similar to the difference between 1988 and 1989 in run1. This suggests that gross or peak primary production in the North Sea is not dominated by anthropogenic inputs, and that other parameters are better for examining this influence.

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 is reflected in the high N/P ratios in the reference run, and the way this ratio is reduced in run2. In run3 on the other hand, a reduction in P only, led to an increase in this ratio (Figure 6). 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. These different characteristics are reflected in the comparison between run2 and run3, where no change in production were seen in the southern North Sea (phosphorus limitation), while there was an increase along the Norwegian west coast (nitrogen limitation). The N/P ratio on the other hand, show a dramatic increase from run2 to run3 everywhere. 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). The present experiments show that this transport gives a large contribution to the phytoplankton productivity in the Skagerrak and Kattegat area (run2). This is in contrast to the local sources, that (except for the Kattegat) only has a minor effect on the primary production (run4).

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