ICES Annual Sciences Conference (ASC)

Vigo, Spain, 22-25 September 2004.

Session: **Physical-biological Interactions: Experiments, Models and Observation (Session P).**

ICES CM 2004/P:08

Modelling the relative impact of the rivers Scheldt, Rhine, Meuse and Seine on the availability of nutrients in Belgian waters (Southern North Sea) using the 3D coupled physical-biological model MIRO&CO-3D.

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ABSTRACT

There is evidence that nutrients from rivers have a substantial impact on the dynamics of phytoplankton blooms and their extent in the Southern Bight of the North Sea. This region is highly dynamic with water masses resulting from the mixing of Atlantic waters transported through the Straits of Dover and freshwater and nutrient inputs from the Scheldt, the Rhine and Meuse, the Seine, the Thames and other smaller rivers. However, the relative contribution of each river to the nutrient pool is not known. A 3D coupled physical-biological model (MIRO&CO-3D) has been used to assess the relative impact of a hypothetical reduction of the nutrients discharged from the Scheldt, Rhine, Meuse and Seine on the nutrient status of Belgian waters during the last decade. MIRO&CO-3D results from the coupling of the COHERENS 3D hydrodynamic model with the ecological model MIRO. The model has been set up for the region between 4°W (48.5°N) and 52.5°N (4.5°E). This model has been run to simulate the annual cycle of inorganic and organic nutrients, phytoplankton (diatoms & *Phaeocystis*), bacteria and zooplankton (microzooplankton & copepods) in the Southern Bight of the North Sea under realistic forcing (meteorology and river loads) for the period 1991-2000. The relative contribution of different rivers on the nutrient pool available for biological production is assessed by decreasing separately by 1% the nutrient loads from respectively the Scheldt, the Rhine (and Meuse) and the Seine (and smaller French rivers). This model scenario suggests that, on average for Belgian waters, a 1% reduction of nutrients loads from the river Seine would have a stronger impact on the nutrient (NO_3 and PO_4) status of Belgian waters than a 1% reduction from the Rhine or from the Scheldt.

Keywords: Ecosystem model, River discharges, Nutrient reduction, Southern Bight of the North Sea.

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Introduction

In order to manage effectively eutrophication problems in the Belgian Economic Exclusion Zone (EEZ), it is necessary to establish a scientific understanding of cause-effect relationships between changing human activities and ecosystem response (e.g. Lancelot et al., 1997; 2004). In particular, it is crucial to know the relative contribution of each river (in terms of both magnitude and spatial distribution) on the nutrient stock in order to design and legislate appropriate measures for nutrient reduction in this area.

It had generally been assumed that Belgian waters are influenced primarily by inflowing Channel waters from the South-west and by the Scheldt river plume presumably on the basis of the "coastal river" conceptual picture (Salomon, 1992) and on the proximity of the Scheldt. However, in a recent numerical study, Lacroix et al. (2004) have suggested a new conceptual picture of the origin of water masses in the region under consideration. This new view of the water masses considers not just the North-eastward residual current, which would advect Rhine water away from the Belgian EEZ, but also the horizontal diffusion of freshwater induced by tidal advection, which acts both north-eastward and south-westward and over a considerable distance. Using a hydrodynamical model with passive tracers for the different water masses, the spatial distribution of water from different origins (Channel, Central North Sea, Scheldt, Rhine/Meuse, Seine and Thames water) has been determined. This suggests that Belgian waters consist mainly (96.6%) of high salinity water originating from the Western Channel. Regarding freshwater, it was shown that about 1% of the water found at the French-Belgian coastal border originated from the Rhine estuary and that the salinity within the Scheldt estuary was significantly affected by freshwater from the Rhine intruding *via* the estuary mouth. In particular, it was shown that the freshwater influence at station 330 (the reference station of the Belgian water quality monitoring network, shown in Fig. 1) is mainly due to the Rhine/Meuse discharge (1.9% on average), then to the Scheldt (1.3% on average) and finally to the Seine (0.8% on average). Fig. 1 (adapted from Lacroix et al., 2004) shows the 1993-2002 average horizontal distribution of contributions to the total water mass from the Rhine/Meuse, Seine, Scheldt and Thames water. The Rhine water spreads a considerable distance southward from the estuary mouth, reaching both the nearshore and the central parts of the Belgian EEZ. Its southward extension is very similar to that of the Scheldt water. It is also striking that the northward spreading of Seine water reaches the whole Belgian EEZ. However, the conclusions from salinity and passive tracers simulations cannot be directly applied to consideration of nutrients because, as a result of biological activity, nutrients are not conserved over seasonal time scales.

In the present study the question of the river origin of nutrients available for biological production in the Belgian EEZ is investigated with the help of a 3D coupled circulation/ecosystem model. Fig. 2 shows the time series of the daily river loads for the period 1991-2000, which are used as river boundary conditions in the model. The relative contribution of different rivers to the nutrient pool in the Belgian EEZ is assessed by decreasing respectively nutrient loads of the Scheldt, the Rhine (and Meuse) and the Seine (and Somme, Authie and Canche) by 1%. This small decrease of 1% has been chosen in order to ensure a quasi linear ecosystem response and thus establish the magnitude and spatial distribution of sensitivity to these inputs for the *currently existing* ecosystem. A more significant decrease of nutrients could induce a qualitative change or bifurcation in the ecosystem behaviour because of the strong non-linearity of the biological equations. The impact on surface nutrient concentrations (NO_3 and PO_4) is evaluated by comparing the average 1993-2000 concentrations obtained by these nutrient reduction scenarios with those obtained with the "standard run". In order to identify more precisely which river has the largest impact on the nutrient status of the Belgian EEZ and estimate the region of influence of each river a comparison is further made between the results obtained with pairs of the "perturbed simulations" i.e. comparing a 1% reduction for the Seine with a 1% reduction for the Scheldt

Model

The 3D hydrodynamical model described in Lacroix et al. (2004) is based on the COHERENS model (Luyten et al., 1999) and has been coupled with the biogeochemical MIRO model (Lancelot et al., 2004) to simulate the transport and dynamics of inorganic and organic nutrients, phytoplankton, bacterioplankton and zooplankton biomass.

The 3D hydrodynamic model solves the continuity, momentum, heat and salinity transport equations on a staggered Cartesian, sigma coordinate grid with an explicit mode-splitting treatment of the barotropic and baroclinic modes. Advection of scalar quantities is discretised by a direction-split Total Variation Diminishing (TVD) scheme. Vertical diffusion is modelled using an evolution equation for turbulent kinetic energy and a quasi-parabolic vertical profile for turbulence macrolength scale. Minimal vertical diffusion and viscosity coefficients of $10^{-6}m^2s^{-1}$ are used. Horizontal diffusion is not considered explicitly, but the process of horizontal diffusion arising from the combination of horizontal advection with vertical diffusion is resolved. Advection of momentum is treated with a first order upwind scheme. Full details of all these methods as well as the original references can be found in Ruddick (1995) and Luyten et al. (1999).

The MIRO ecosystem model is represented schematically in Fig. 3. Thirty-two state variables and twenty-eight processes linking them were selected as important from knowledge of the structure and functioning of *Phaeocystis*-dominated ecosystems. The model results from the integration of 4 modules describing the dynamics of phytoplankton (3 groups), zooplankton (2 groups), bacteria and dissolved and particulate organic matter degradation and nutrient [nitrate (NO_3), ammonium (NH_4), phosphate (PO_4) and dissolved silica (DSi)] regeneration in the water column and the sediment. State variables, processes and conservation equations are detailed in Lancelot et al., (2004).

The coupled MIRO&CO-3D model has been set up for the region between 4° W (48.5°N) and 52.5°N (4.5°E) with the bathymetry shown in Fig. 4 using a 109 by 97 horizontal grid with resolution 5' longitude (approx. 5.6 km) by 2.5' latitude (approx. 4.6 km) and with 5 vertical sigma coordinate layers. The model is run with mode-splitting time steps of 60s and 900s respectively for 2D and 3D calculations.

At the Western ("Channel", 4°W) and Northern ("Central North Sea", 52.5°N) open sea boundaries the time series of cross-boundary transport (vertically-integrated current) and surface elevation are applied using data from a 2D model of the North Sea continental shelf also based on the COHERENS software (Luyten et al., 1999). This 2D model is forced by 6-hourly wind and atmospheric pressure fields from the analysed/forecast data of the UK Meteorological Office, and transfers this meteorological forcing in turn to the COHERENS-3D model. The wind forcing is spatially variable on a grid with resolution varying from 1.25° to 5° in longitude and 1.25° to 2.5° in latitude according to available data. At the two open sea boundaries the vertical current structure is determined by imposing the condition of zero normal derivative of the deviation of current from the vertically-averaged horizontal current (Deleersnijder et al., 1989), while at river boundaries a condition of zero vertical gradient of current is applied. The 10-day Scheldt and daily Rhine/Meuse river flow data, collected by the RIZA[1] and archived into the central data base DONAR, were downloaded from the Waterbase web site[2]. The daily river flow for the Seine, collected by the Cellule anti-pollution DDE[3], was downloaded from the web[4]. The daily river flow for the Somme, Authie and Canche were downloaded from the Artois-Picardie Water Agency web site[5]. Daily Thames flow data were collected under the responsibility of the UK Environment Agency and downloaded from the NRFA web site[6].

For temperature, zero flux is assumed at the sea bottom. The spatially variable temperature imposed at the surface is derived from the weekly sea surface gridded (on a grid of 20 km x 20 km) temperature obtained from the BSH[7] (Loewe, 2003). For periods without SST data (1991-1995), a weekly climatological SST (computed from 1996-2000 BSH data) is imposed. At the open sea boundaries and river boundaries, a zero horizontal cross boundary gradient of temperature is specified.

For salinity, a zero flux is assumed at the sea bottom and sea surface boundaries. The incoming salinity at the river boundaries is set to zero. At the open sea boundaries, no boundary condition is required when the current is directed out of the domain. For inflow periods, the salinity at the Channel boundary is specified as 35 psu and corresponds to an average from the ICES climatology. At the Central North Sea boundary a salinity of 34.45 psu is specified west of 4°E, based on the Damm (1989) climatology, while east of this longitude a zero horizontal cross boundary gradient of salinity is specified to allow realistic formation of the Rhine plume and associated Dutch coastal current.

At the Channel and Central North Sea open sea boundaries a zero horizontal cross boundary gradient is specified for biological state variables. At the Channel and Central North Sea (West of 4°E) open sea boundaries nutrient concentrations are specified as concentrations derived from the climatological database compiled by the European Union NOWESP and ERSEM projects and from ICES data, while East of this longitude a zero horizontal cross boundary gradient of nutrients is specified.

Dissolved and particulate nutrient discharges from the Scheldt and the Rhine/Meuse are obtained from monthly or bi-monthly RIKZ[8] measurements and have been downloaded from the DONAR waterbase[2]. Dissolved and particulate nutrient discharges from the Seine are specified as concentrations measured bi-monthly by the DDE-SNS Rouen and available from the RNB[9] (Ficht, 2003. pers. comm.). Dissolved and particulate nutrient discharges for the Somme, Authie and

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[1] Rijksinstituut voor Integraal Zoetwaterbeheer en Afvalwaterbehandeling, Ministerie van Verkeer en Waterstaat

[2] http://www.waterbase.nl

[3] Service de Navigation de la Seine de Rouen SNS

[4] http://seine-aval.crihan.fr/rubriques/estuaire_seine/rubriques/donnees_brutes/debits/debits-Seine.htm

[5] http://www.eau-artois-picardie.fr/bassin/index.htm

[6] National River Flow Archive, http://www.nwl.ac.uk/ih/nrfa/webdata

[7] Bundesamt fuer Seeschiffahrt und Hydrographie

[8] Rijksinstituut voor Kust en Zee

[9] Réseau National des bassins

Canche are specified as concentrations measured monthly and downloaded from the Artois Picardie Water Agency (RNB) web site[4]. Dissolved nutrient discharges for the Thames are specified as concentrations coming from the UK Environment Agency measurements (Lewis, 2003. pers. comm.). Organic nutrients are specified as concentrations derived from the North Sea Task Force guidance document (Rijkswaterstaat, 1992) and corresponding to the NSTF "reference year" of 1985.

Initial conditions for salinity and for biological state variables, except nutrients, are assumed horizontally and vertically homogeneous. The initial distribution of nutrients over the domain has been reconstructed making use of various databases (BMDC[10], DONAR waterbase[2], ICES[11]). To reduce the sensitivity of results to these initial conditions a two year spin-up MIRO&CO-3D simulation was run for the period January 1991-December 1992 with the aforementioned initial and open boundary conditions and forcing. A control or baseline simulation was then carried out for the period January 1993-December 2000 and is denoted as the "standard simulation (STD)".

The relative contribution of different rivers on the nutrient pool is indirectly assessed by decreasing respectively the Scheldt, the Rhine (and Meuse) and the Seine (and Somme, Authie and Canche) nutrient loads by 1%. These three scenarios will be hereafter called "Rhine simulation (TRM)", "Scheldt simulation (TSC)" and "Seine simulation (TSE)" respectively.

Results - Discussion

Fig. 5 compares seasonal trends of nutrients (NO_3, NH_4 and PO_4) over the period 1991-2000 as obtained with the standard simulation at the station 330 (51° 26.00' N, 2° 48.50' E) and observations. The latter time-series includes weekly or bi-monthly data measured between 1991 and 2000 in the scope of the AMORE project Rousseau, 2000; BMDC[10]). Fig. 5 shows that the seasonal cycle of nutrients is well reproduced by the model over a decadal time scale. The maximum winter concentrations of PO_4 and NO_3 seem nevertheless slightly underestimated.

The average 1993-2000 surface concentration of nutrients (NO_3 and PO_4) obtained with the standard run are presented in Fig. 6. Fig.7 shows the difference between the average surface distribution of respectively NO_3 and PO_4 over 1993-2000 of the "perturbed (Rhine, Scheldt or Seine)" and "standard" simulation. A negative (resp. positive) value means a reduction (resp. increase) of the nutrient of concern compared to the standard simulation. Because of the logarithmic scale the smallest absolute values (dark green) are not significant. The difference of min/max colour scale between NO_3 and PO_4 reflects the difference between their respective average values over the whole domain. Clearly, for the three perturbed simulations, the decrease of nutrient river loads has a direct impact on the surface nutrient (NO_3 and PO_4) concentrations, especially close to their respective estuary mouths as expected. Comparison of the results obtained for the nutrient reduction by the three rivers suggests that the impact of the Seine river appears to be the most important for the whole domain and reaches the Belgian EEZ up to the Scheldt estuary. Rhine and Scheldt nutrient reductions lead to a significant reduction of surface NO_3 from the coast to almost 50km offshore in the Belgian EEZ, while for PO_4, the reduction of surface concentrations seems only significant in the vicinity of the estuary mouths.

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[10] Belgian Marine Data Centre, http://www.mumm.ac.be/datacentre/

[11] International Council for the Exploration of the Sea, http://www.ices.dk

For both nutrients, the impact of a nutrient reduction of the Rhine leads to a reduction of the surface concentration in the Scheldt estuary.

The average 1993-2000 surface nutrient difference between paired perturbed simulations (Fig. 8) gives a clearer view of which river nutrient reduction leads to the most important nutrient reduction for the Belgian EEZ and shows the region of influence of each river in terms of nutrient reduction. Comparison of the Rhine and Scheldt simulations shows that, except within the Scheldt estuary itself, a reduction of nutrient input from the Rhine has the largest impact for the Belgian EEZ, affecting over half of the area for NO_3 but limited to a coastal band for PO_4. By comparing the Seine and Scheldt simulations it appears clearly that nutrient reduction for the Seine has the strongest impact, on PO4 over almost the whole area, except the Scheldt estuary and the Scheldt estuary mouth, and on NO3 for the central and offshore areas of the Belgian EEZ. For NO_3 only the Scheldt estuary, the Scheldt estuary mouth and the Eastern part of the Belgian EEZ are more affected by nutrient reduction from the Scheldt. The same results can be observed when comparing the Seine and the Rhine nutrient reduction simulations.

In order to quantify the relative importance of nutrient reduction for each model scenario, the percentage of variation (the ratio of the perturbed surface nutrient concentration minus "standard" surface nutrient concentration divided by the standard surface nutrient concentration) has been computed for station 330, for the Belgian EEZ (average) and for the whole domain (average). Results are shown in Table 1.

Table 1. Percentage of variation (%) of average 1993-2000 surface nutrient (NO_3 and PO_4) between each perturbed simulation and the standard simulation.

	Scheldt - 1% (all nutrients) **simulation TSC**	Rhine (& Meuse) - 1% (all nutrients) **simulation TRM**	Seine (& Somme, Authie, Canche) - 1% (all nutrients) **simulation TSE**
NO_3	$\frac{(NO3_{TSC} - NO3_{STD})}{NO3_{STD}} * 100$	$\frac{(NO3_{TRM} - NO3_{STD})}{NO3_{STD}} * 100$	$\frac{(NO3_{TSE} - NO3_{STD})}{NO3_{STD}} * 100$
Station 330	-0.18	-0.25	-0.24
Belgian EEZ	-0.11	-0.15	-0.25
Whole domain	-0.02	-0.05	-0.13
PO_4	$\frac{(PO4_{TSC} - PO4_{STD})}{PO4_{STD}} * 100$	$\frac{(PO4_{TRM} - PO4_{STD})}{PO4_{STD}} * 100$	$\frac{(PO4_{TSE} - PO4_{STD})}{PO4_{STD}} * 100$
Station 330	-0.03	-0.05	-0.19
Belgian EEZ	-0.03	-0.04	-0.18
Whole domain	-0.01	-0.03	-0.10

It appears that both for station 330 and for the Belgian EEZ (on average) and the whole domain (on average), the Scheldt nutrient reduction gives a smaller (but non negligible) relative reduction of NO_3 and PO_4 that reductions of the Rhine or Seine nutrients. Except for NO_3 at station 330, the Rhine nutrient reduction also gives a smaller relative reduction for this region than the Seine. The relative reduction for NO_3 is higher than that for PO_4 in each case (different areas and river loads decrease) expressing a stronger sensitivity of NO_3 to riverine nutrient reduction because rivers supply relatively more NO_3 than PO_4 as compared to the Atlantic inflow. For PO_4, the Seine nutrient reduction leads to relative reduction of nutrients within the region with order of magnitude greater than for the Rhine or Scheldt nutrient reductions. This suggests that the river Seine has a significant influence on the PO_4 concentration for the whole domain and in particular for the Belgian EEZ. This result is particularly interesting as PO_4 is pointed as a key nutrient in driving the diatom and *Phaeocystis* blooms found in recent years in the Southern North Sea (Gypens and Lancelot, 2004).

Conclusions

From this study it appears that, on average over the Belgian EEZ area, the reduction of surface nutrients (NO_3 and PO_4) at sea caused by a 1% reduction of nutrient river loads is larger for the Seine than the Rhine, which is in turn greater than for the Scheldt. The greater importance of the river Rhine compared to the Scheldt for the Belgian EEZ was already shown for the salinity and water mass tracers (Lacroix et al., 2004). More surprising here is the significant effect of Seine nutrient loads on the nutrient availability for the Belgian EEZ, with exception of the Scheldt estuary, the Scheldt mouth (NO_3 and PO_4) and the northern part of the Belgian coastal area (NO_3).

In the future this study will be extended to assess also the impact of riverine nutrient reductions on phytoplankton biomass and diatoms/*Phaeocystis* as well as the relative importance of nutrients from the Channel and Central North Sea and recycled in the benthos. The cycle of silicate, included in the present simulations but not analysed in detail, will also be considered in order to study the impact on the balance between diatoms and *Phaeocystis*.

Acknowledgements

This work has been carried out in the scope of the AMORE-II project (EV/36/19B) funded by the Belgian Federal Science Policy Office in the framework of the "Scientific Support Plan for a Sustainable Development Policy – Sustainable Management of the North Sea”. The CAMME team is acknowledged for computing support.

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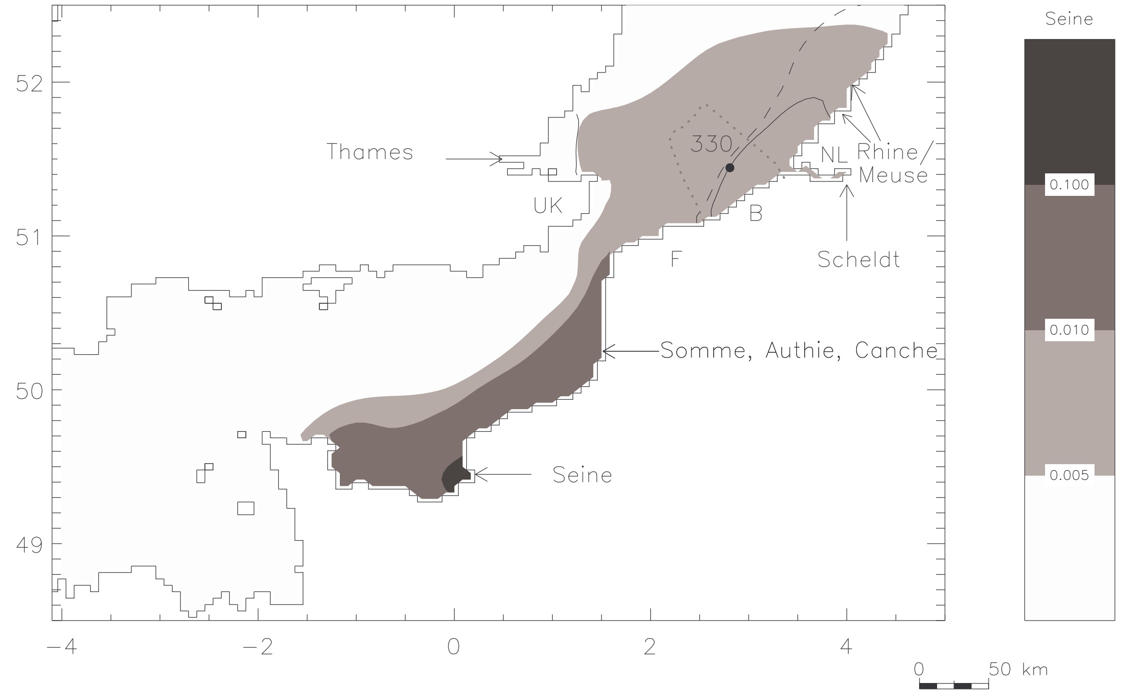

Fig. 1. Map showing model results averaged over the duration of the 1993-2002 simulation of tracer fractions for Seine water (grey scale colour map, 0.5%, 1%, 10%), for Scheldt and Thames water (superimposed solid line, 1%), for Rhine/Meuse water (superimposed dashed line, 1%). The Belgian EEZ is delimited by the dotted line and the dot denotes the station 330 of the Belgian water quality monitoring network. Redrawn from Lacroix et al. (2004).

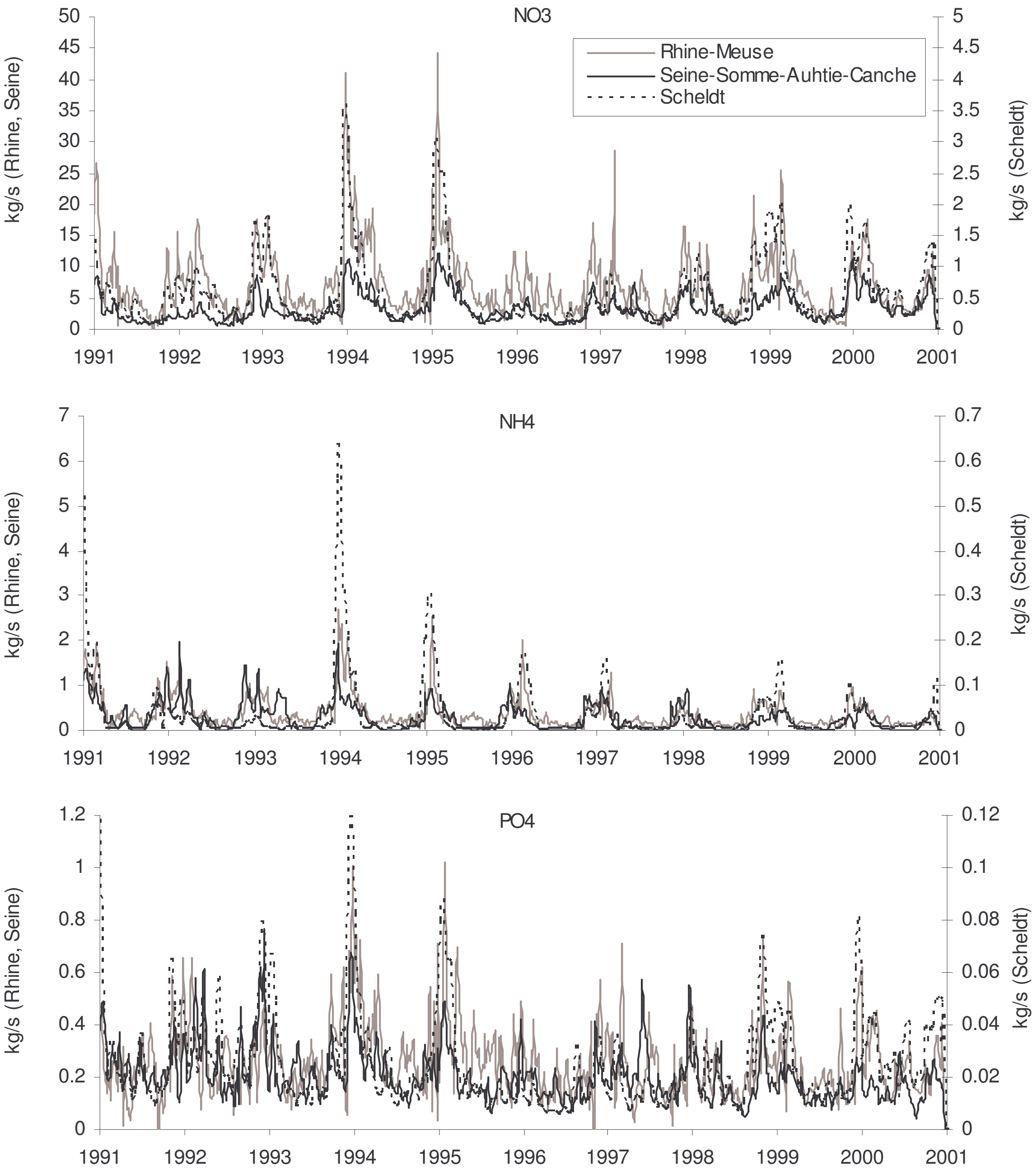

Fig. 2. Time series of measured nutrient river loads (kg/s), used as forcing for the 1991-2000 simulation. Rhine/Meuse: solid grey line, Seine/Somme/Authie/Canche: solid black line, Scheldt: dashed black line. Left axis for the Rhine and Seine rivers. Right axis for the Scheldt river. From top to bottom: NO_3, NH_4 and PO_4.

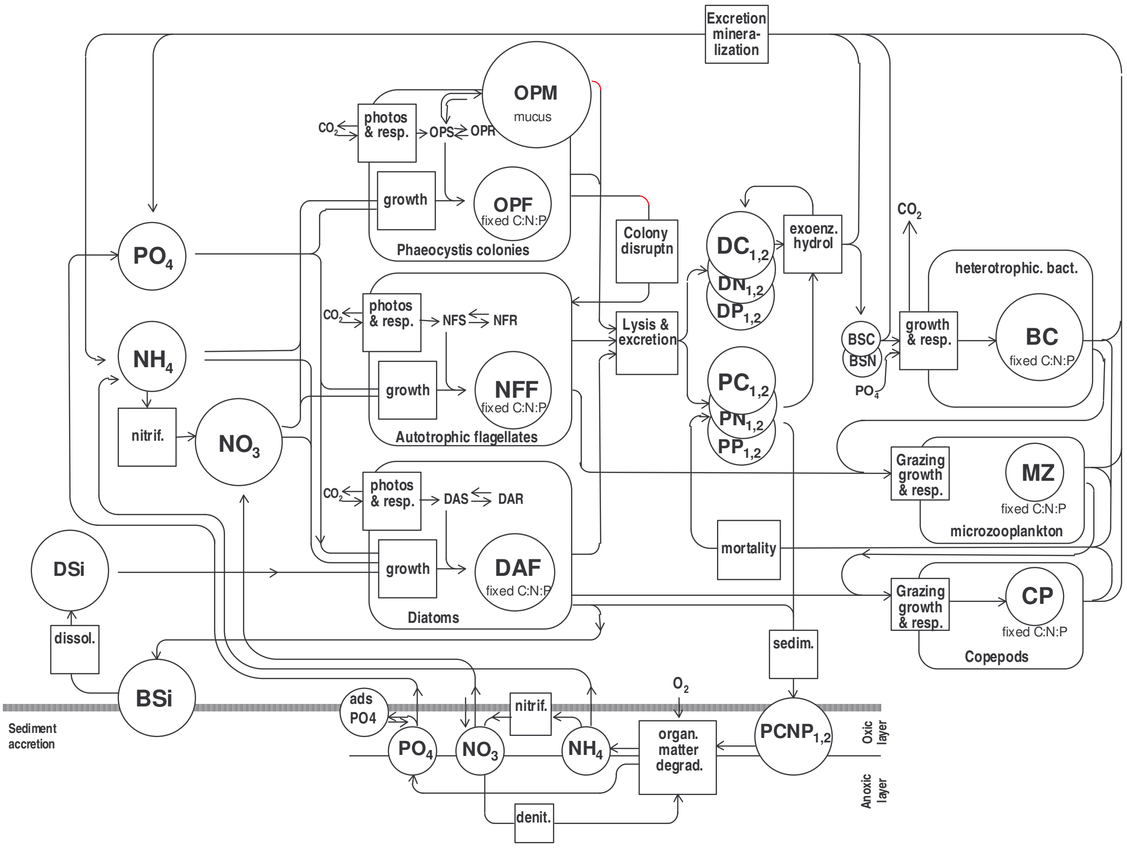

Fig. 3. Schematic representation of the biogeochemical MIRO model (from Lancelot et al., 2004).

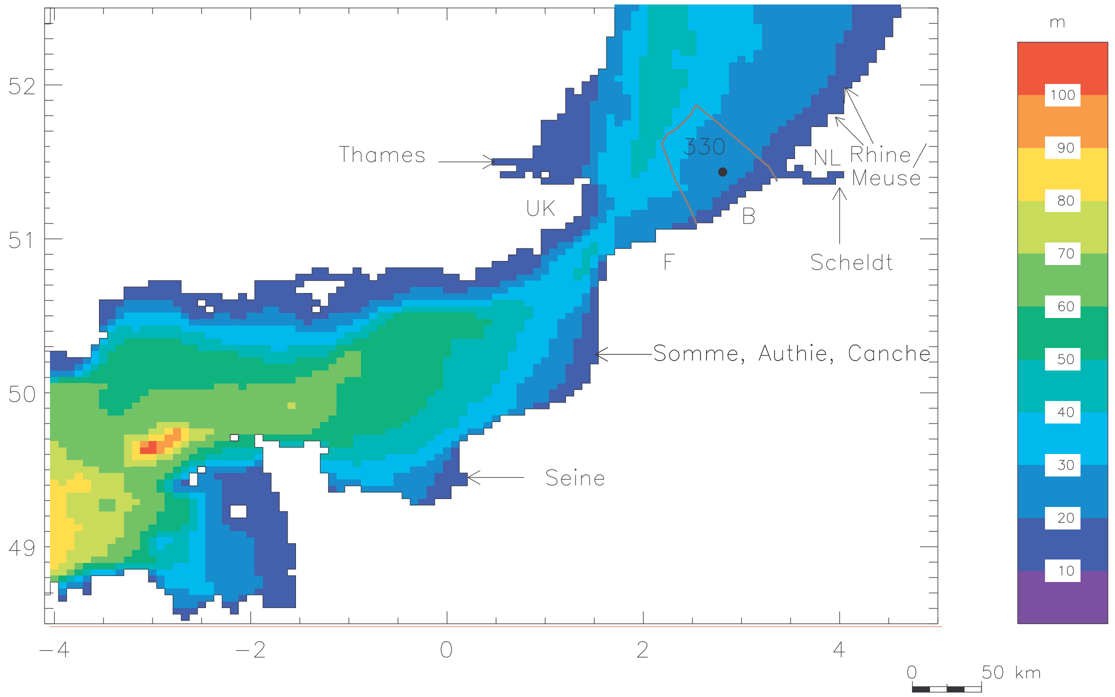

Fig. 4. Bathymetry of the Southern North Sea and Channel model. The Belgian EEZ is delimited by the solid grey line. The dot denotes the station 330 of the Belgian water quality monitoring network used to present the results of Fig. 5. The model domain is a 109 by 97 horizontal grid with resolution of 5' longitude by 2.5' latitude. Each pixel corresponds to one grid cell.

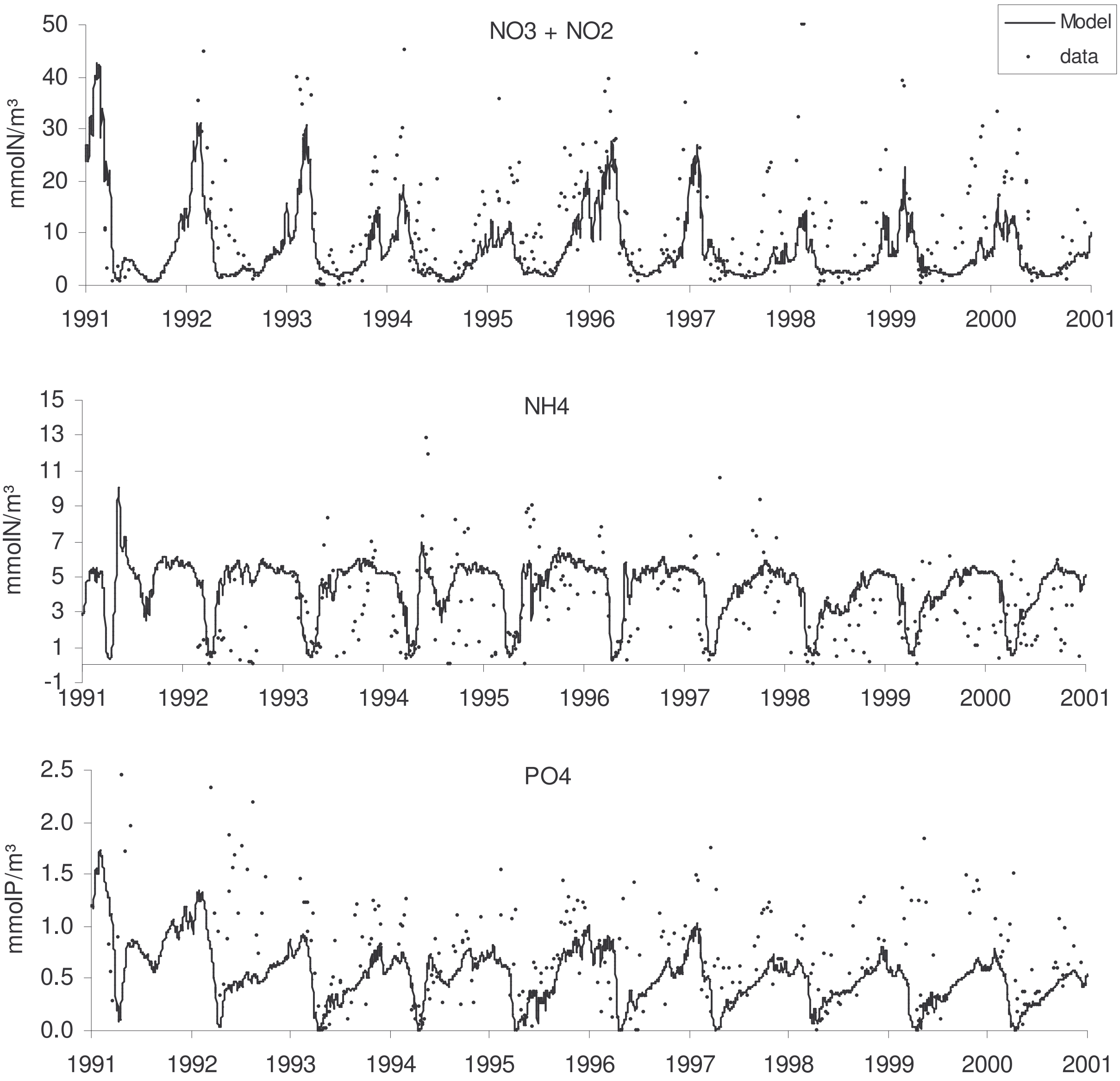

Fig.5. Time series of MIRO&CO-3D model results for nutrients in the Belgian EEZ for the station 330 shown in Fig.2 (solid line). Time series of *in situ* data (Lancelot 2003, pers. comm.; BMDC) for the station 330 (dots). From top to bottom: NO_3, NH_4, PO_4.

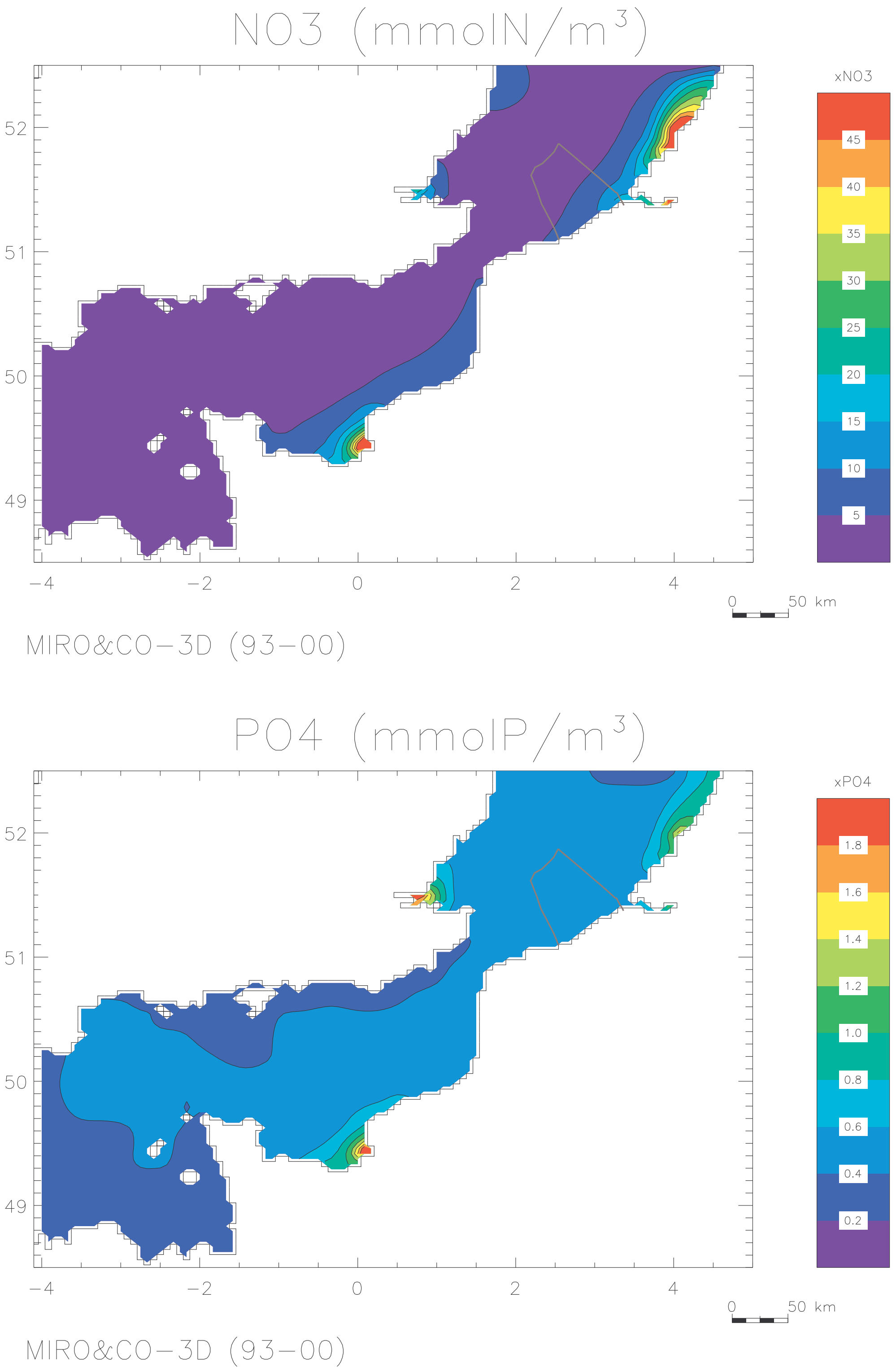

Fig. 6. Average 1993-2000 MIRO&CO-3D model results for surface nutrients ("standard simulation"). Top panel: NO_3 (mmolN/m³). Low panel: PO_4 (mmolP/m³).

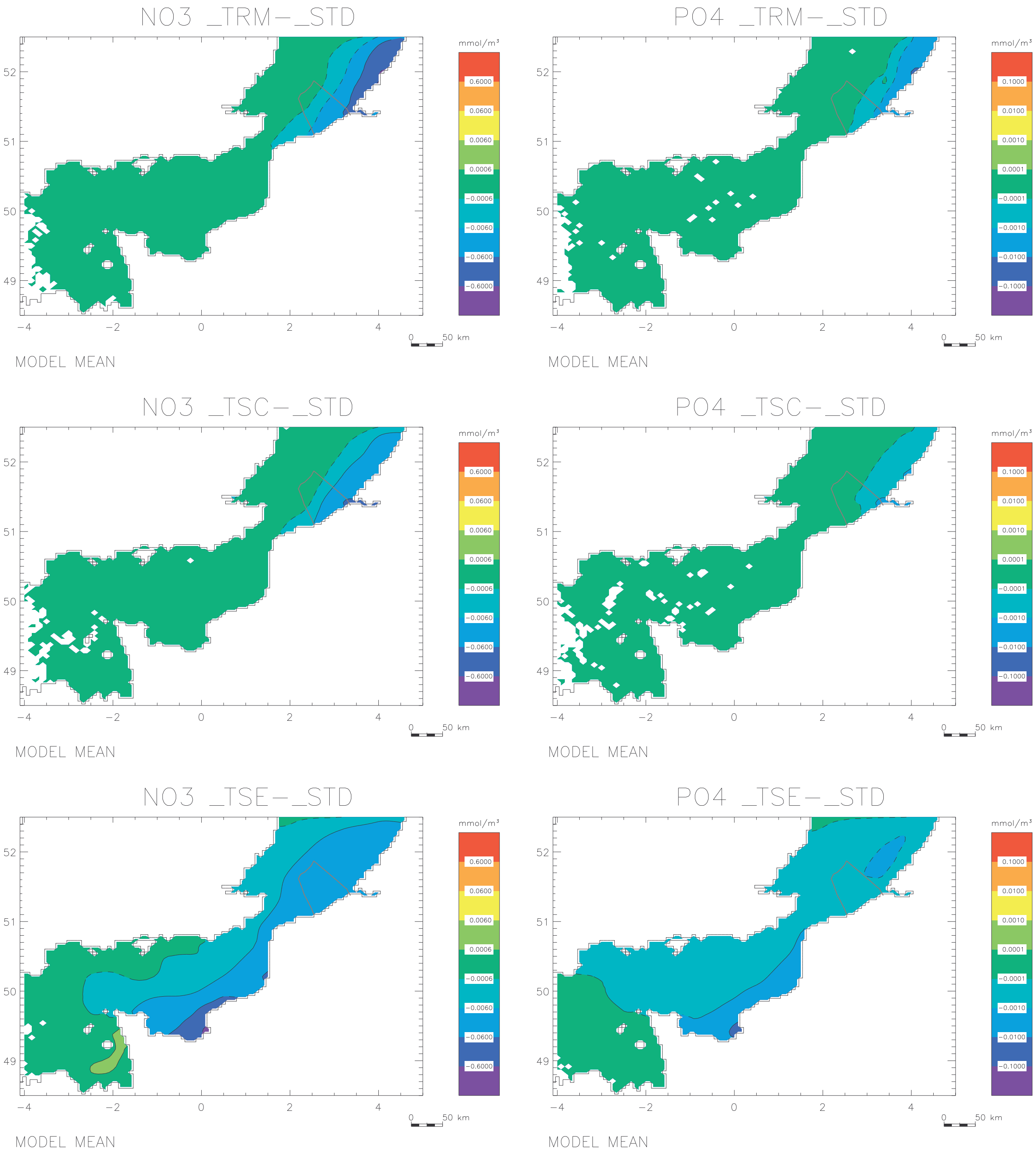

Fig. 7. Average 1993-2000 surface nutrient difference between perturbed and standard simulations. Left: NO_3 (mmolN/m³), right: PO_4 (mmolP/m³). Top panels: surface nutrient with Rhine nutrient reduction of 1% minus surface nutrient resulting from the standard simulation. Middle panels: surface nutrient with Scheldt nutrient reduction of 1% minus surface nutrient resulting from the standard simulation. Bottom panels: surface nutrient with Seine nutrient reduction of 1% minus surface nutrient resulting from the standard simulation.

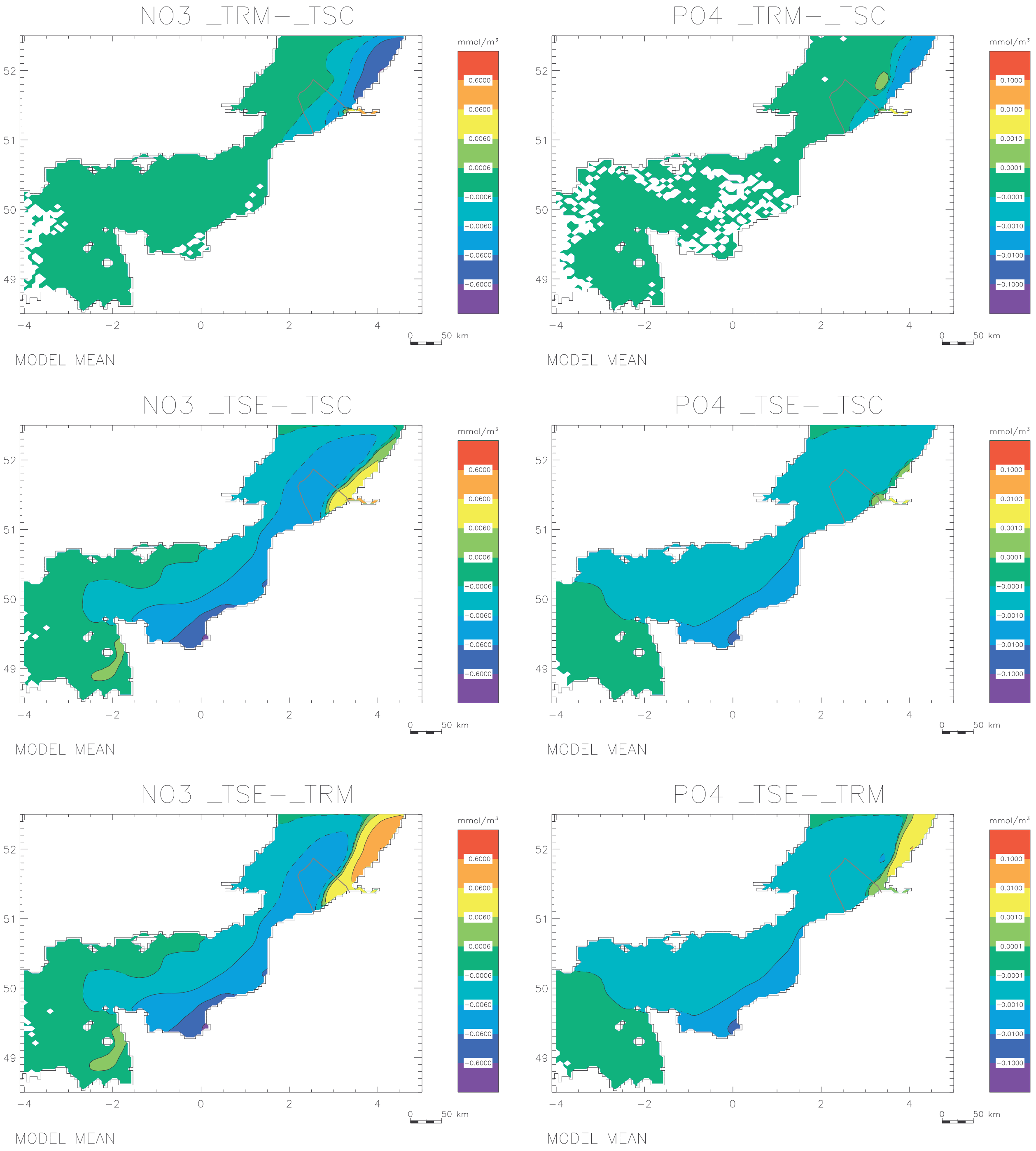

Fig. 8. Average 1993-2000 surface nutrient difference between paired perturbed simulations Left: NO_3 (mmolN/m³), right: PO_4 (mmolP/m³). Top panels: surface nutrient with Rhine nutrient reduction of 1% minus surface nutrient resulting from the simulation with Scheldt nutrient reduction of 1%. Middle panels: surface nutrient with Seine nutrient reduction of 1% minus surface nutrient resulting from the simulation with Scheldt nutrient reduction of 1%. Bottom panels: surface nutrient with Seine nutrient reduction of 1% minus surface nutrient resulting from the simulation with Rhine nutrient reduction of 1%.