Testing an integrated river–ocean mathematical tool for linking marine eutrophication to land use: The *Phaeocystis*-dominated Belgian coastal zone (Southern North Sea) over the past 50 years

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Abstract

The RIVERSTRAHLER model, an idealized biogeochemical model of the river system has been coupled to MIRO, a complex biogeochemical model describing diatom and *Phaeocystis* blooms in the marine domain, to investigate the link between changing human activities over the past 50 years and coastal eutrophication in the eastern Channel and Southern Bight of the North Sea with a focus on the Belgian coastal zone (BCZ). The whole area, submitted to the influence of two main rivers (Seine and Scheldt) is invaded each spring by massive blooms of *Phaeocystis* colonies which impact on the structure and functioning of the coastal ecosystem. For the present application MIRO is implemented in a simplified multi-box description of the coastal zone and is run over the last 50 years using average 1989–1999 meteorological conditions (global solar radiance and temperature) and RIVERSTRAHLER simulations of Seine and Scheldt nutrient loads as forcing conditions. Model validation is obtained by visual and statistical comparison of nutrients, Chl *a*, diatom and *Phaeocystis* simulations with data collected in the central BCZ (51°26.05 N; 02°48.50 E) over the 1992–1998 period.

The simulated *Phaeocystis* and diatom trends (yearly average and maxima reached) in BCZ, over the past 50 years are discussed with respect to changing nutrient loads, especially NO_3 and PO_4. Historical reconstruction back to the fifties suggests that *Phaeocystis* colonies were already blooming in BCZ in the early 1950's and were sharing almost equally with diatoms, the bulk of annual primary production. Over the 1960–1992 period, the increased loads of both N and P were beneficial to both *Phaeocystis* colonies and summer diatoms with however a little advantage to the latter. Since 1989, the decrease in P loads subsequent to the removal of PO_4 in washing powders and the maintenance of elevated NO_3 loads had a positive feedback to both diatoms and *Phaeocytis* production with however a significantly larger impact on diatoms than on *Phaeocytis*. This is due to the fact that *Phaeocystis* has strong affinity for low PO_4. Consequently *Phaeocystis* development is mainly controlled by NO_3 loads. We conclude that future management of nutrient emission reduction aiming at decreasing *Phaeocystis* blooms in BCZ without impacting on diatoms would target decrease of NO_3 loads by both the rivers Seine and Scheldt.

Keywords: Eutrophication; Diatoms; *Phaeocystis*; Modeling; Southern North Sea; Scheldt

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1. Introduction

Due to their impact on the marine biota and the environment, *Phaeocystis* colony blooms in the North-European coastal seas are generally reported as undesirable (Lancelot, 1995). Historical records of *Phaeocystis* blooms in the Eastern Southern Bight of the North Sea trace back to the end of the 19th century (Cadée and Hegeman, 1991). Nowadays, these blooms are recurrent and occur after an early-spring diatom bloom controlled by dissolved silicate availability (Rousseau et al., 2002). *Phaeocystis* colonies grow on nitrogen and phosphorus and form with diatoms the bulk of phytoplankton biomass during the growing season but their magnitude varies from year-to-year (Lancelot et al., 1998). Attempt has been made to relate long-term fluctuations of *Phaeocystis* blooms in the Southern Bight of the North Sea to changes either in climate (Owens et al., 1989) or in anthropogenic nitrogen and phosphorus river loads (Cadée and Hegeman, 1991), but the outcome is still unclear.

Over the past 50 years, several quantitative and qualitative changes in nutrient delivery by the NW European rivers to the Channel and the North Sea have been recorded (OSPAR, 2000; Soetaert et al., 2006), due to changing land use and human activity on the watershed. The link between the variations over the past 50 years in watershed agricultural, domestic and industrial activities and the nitrogen, phosphorus and silica delivery to the sea, has been recently established for the river Seine (Billen et al., 2001) and the river Scheldt (Billen et al., 2005), based on results obtained with the idealized RIVERSTRAHLER model. This model was developed for establishing the link between the biogeochemical functioning of large river systems and the constrains set by the meteorological conditions, the morphology of the drainage network and the human activity on the watershed (Billen et al., 1994; Garnier et al., 1995; Billen et al., 1999; Garnier et al., 2002; Garnier and Billen, 2002). As a general trend, the annual RIVERSTRAHLER fluxes of nutrients delivered to the North Sea show after 1965, a severe depletion of silica with respect to nitrogen compared with the requirements of coastal diatoms (Brzezinski, 1985), and a clear shift from nitrogen to phosphorus potential limitation after 1990 (Billen et al., 2001; Billen et al., 2005; Cugier et al., 2005).

In this paper we use the RIVERSTRAHLER nutrient fluxes of Billen et al. (2001, 2005) as nutrient load forcing of the marine biogeochemical MIRO model (Lancelot et al., 2005) to reconstruct the interannual variations of nutrient enrichment and diatom and *Phaeocystis* blooms in the Belgian Coastal Zone (BCZ) over the past 50 years. BCZ, located in the Southern Bight of the North Sea (Fig. 1), is a relevant site to investigate links between phytoplankton blooms and continental forcings. This area is a highly dynamic system with water masses resulting from mixing of English Channel Water inflows from Atlantic origin (Pingree and Maddock, 1977; Salomon and Breton, 1993) and freshwater inputs from the Scheldt river (Fig. 1; Brockmann et al., 1988). Overall the nutrient enrichment of BCZ mainly results from inputs of the river Scheldt but also of the English
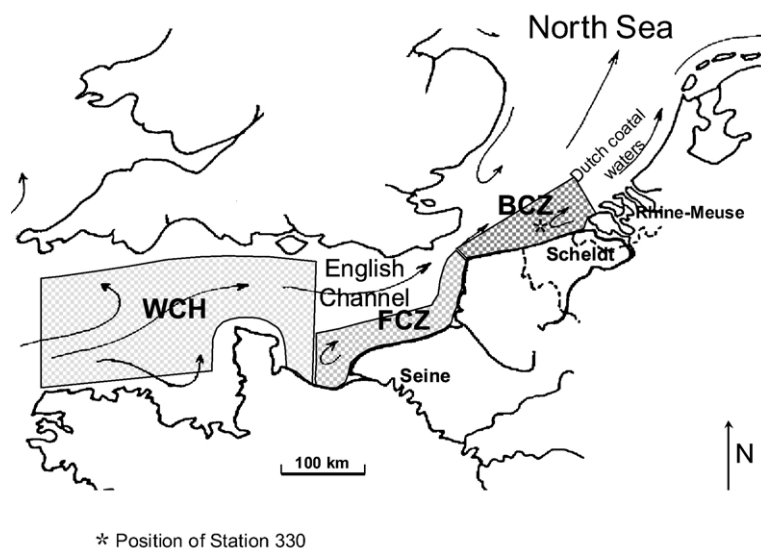

Fig. 1. Map showing the multi-box implementation geographical domain of MIRO, the location of Seine and Scheldt rivers and of the station 330 in BCZ, as adapted from Lancelot et al., 2005.

Channel Waters enriched by the Seine river discharges (Fig. 1; Lancelot et al., 1987). Nutrient and phytoplankton concentrations have been intensively monitored at the station 330 (Rousseau, 2000; Breton et al., 2006) located in central BCZ (Fig. 1) over the 1992–1998 period i.e. when P riverine loads to the coastal sea were decreased (OSPAR, 2000; Rousseau et al., 2004). Unfortunately such data are not detailed for the early seventies when both N and P loads increased (Billen et al., 2005).

A similar long-term simulation (1955–1993) has been performed for the Southern North Sea making use of the multi-box ERSEM-II constrained by actual (1977–1993) and supposed (1955–1976) river inputs (Pätsch and Radach, 1997). Novel here are the explicit description of undesirable *Phaeocystis* colonies in the MIRO model (Lancelot et al., 2005) and the use of river nutrient load simulations for constraining the marine model. This integrated approach is unique for understanding the impact of human activity on marine eutrophication and is of great value for guiding realistic nutrient reduction policies.

After a first verification of the prediction capability of the coupled RIVERSTRAHLER–MIRO (R–MIRO) model, obtained by a visually- and statistically-based comparison of nutrient and phytoplankton simulations with available historical data at the station 330, the link between land use and coastal eutrophication is established based on a suite of correlation analysis between RIVERSTRAHLER nutrient fluxes and eutrophication-related indicators (winter nutrient concentrations, mean and average phytoplankton biomass, annual primary production) computed from R–MIRO nutrient, phytoplankton and primary production simulations.

2. Material and methods

2.1. RIVERSTRAHLER

RIVERSTRAHLER (Billen et al., 1994; Garnier et al., 1995) is a generic model of the biogeochemical functioning of the whole river system. The model results from the coupling of a hydrological module (HYDROSTRAHLER) calculating the water flows through the drainage network, with a module describing the kinetics of the biological and physical–chemical in-stream processes (RIVE). Structure and parameterization of RIVE processes are detailed in Garnier et al. (1999,b; 2002). RIVERSTRAHLER implementation and description of meteorological forcing and nutrient point and diffuse sources at the scale of the Seine and Scheldt river systems over the past 50 years are reported in respectively Billen et al. (2001) and (2005). For both basins, the following forcing functions to the model were documented for the period

1950–2000: year-to-year variation of rainfall by 10 days periods; land use modifications by 10 year periods; changes in annual urban and industrial wastewater discharges by 5 year periods. The model was validated based on its capability to describe the observed trends of discharge and nutrient concentrations at the outlet of the two river systems (Billen et al., 2001, 2005).

2.2. MIRO

MIRO is a mechanistic biogeochemical model describing C, N, P and Si cycling through aggregated components of the planktonic and benthic realms of *Phaeocystis* dominated ecosystem (Lancelot et al., 2005). Its structure includes thirty-eight state variables assembled in four modules describing the dynamics of phytoplankton (diatoms, nanoflagellates and *Phaeocystis*), zooplankton (copepods and microzooplankton), dissolved and particulate organic matter (each with two classes of biodegradability) degradation and nutrients (NO_3, NH_4, PO_4 and $Si(OH)_4$) regeneration by bacteria in the water column and the sediment. Equations and parameters were formulated based on current knowledge on the kinetics and the factors controlling the main auto- and heterotrophic processes involved in the functioning of the coastal marine ecosystem. These are fully documented in Lancelot et al. (2005) and www.int-res.com/journals/suppl/appendix_lancelot.pdf. The MIRO model is implemented in a multi-box frame delineated on the basis of the hydrological regime and river inputs. In order to take into account the cumulated nutrient enrichment of Atlantic waters by the Seine and Scheldt rivers, two successive boxes, assumed to be homogeneous, have been chosen from the Seine Bight (French Coastal Zone, FCZ) to the BCZ (Fig. 1). Each box has its own morphological characteristics (Table 1 in Lancelot et al., 2005) and is treated as an open system, receiving waters from the upward adjacent box and exporting water to the downward box. MIRO was first calibrated for 1989–1999 climatic conditions of river loads, global solar radiation and temperature calculated from available data. The prediction capability of the model was demonstrated by its ability to reproduce the SW–NE nutrient enrichment gradient observed from the Western Channel to the Belgian Coastal Zone as well as the mean seasonal nutrient and ecological features recorded in the central BCZ during the last decade (Lancelot et al., 2005).

2.3. Coupling RIVERSTRAHLER to MIRO

For the present application, the data-derived climatology of river loads in Lancelot et al. (2005) is replaced by

RIVERSTHRALER 10-daily fluxes of dissolved silica and organic and inorganic forms of nitrogen and phosphorus, for both the river Seine (Billen et al., 2001) and Scheldt (Billen et al., 2005) and over the period 1950–1998. This coupling is possible because of the high similarity between the structure and parameterization of the two idealized models. For the coupling between RIVERSTRAHLER and MIRO state variables, however, freshwater phytoplankton, zooplankton and bacteria are assumed to lyse and to be remineralized in the estuarine part of the river. This was concluded from results of sensitivity tests (not shown) with varying assumptions about the fate of freshwater biomass state variables and their comparison with MIRO results obtained with actual nutrient river loads data (Lancelot et al., 2005).

Also distinct from the 1989–1999 climatology run which assumes specific but constant residence time of water masses within the BCZ and FCZ boxes (Table 1 in Lancelot et al., 2005), the 1950–1998 variations of the 10-daily residence time of water mass in FCZ and BCZ boxes are here estimated from river discharges using the relationships:

$$\text{residence time(day)} = a * \text{discharge}(\text{m}^3\text{s}^{-1})^{-b}$$

in which $a=4105$ and 6657 (for BCZ and FCZ respectively) and $b=0.86$ (BCZ) and 0.69 (FCZ). These parameterizations (Gypens et al., in press) were established based on monthly budgets of water masses (Atlantic water and freshwater discharge of respectively Seine and Scheldt) calculated from 1993–2003 simulations of the three-dimensional hydrodynamical model COHSNS-3D (Lacroix et al., 2004). Use of these equations over the 48-year period, shows large fluctuations of the monthly water residence time, between 13 and 216 days (BCZ) and 44 and 233 days (FCZ), when assuming a full spreading of the river waters within each box domain. As a general trend lowest and highest values are calculated in winter and summer respectively (Gypens et al., in press).

Finally, global solar radiation, suspended matter and seawater temperature are those corresponding to the 1989–1999 climatological run (Lancelot et al., 2005).

2.4. Validation data sets

2.4.1. Scheldt loads

Monthly Scheldt runoff (m^3 s^{-1}) was obtained from the Department of Environment and Infrastructure (Ministry of Flemish Community, Belgium). Nutrient loads were calculated based on runoff and nutrient concentrations measured at the downstream monitoring station 'Doel' by the Institute for Inland Water Management and Waste Water Treatment (RIZA, The Netherlands) and archived into the central data base DONAR (http://www.waterbase.nl).

2.4.2. BCZ

Station 330 located in the central BCZ (51°26.05 N; 002° 48.50 E; Fig. 1) was chosen for the assessment of R–MIRO results. Historical data of nutrients (NO_3, NH_4, PO_4, $Si(OH)_4$) and Chl a at station 330 were retrieved from unpublished reports related to the Research Programs funded between 1970 and 1990 by the Belgian Science Policy. For the 1992–1998 period, nutrient and phytoplankton (Chl a and diatom and *Phaeocystis* carbon biomass) data were obtained from the high time-resolution monitoring at the station 330 (Breton et al., 2006), i.e. a weekly sampling frequency except during winter (2 per month). Nutrient and phytoplankton analysis methods are detailed in Rousseau et al. (2002).

2.5. Cost function

The goodness of fit between 1950–1998 R–MIRO simulations and historical data was estimated based on the cost function C recommended by OSPAR (Villars et al., 1998) and discussed in Radach and Moll (2006):

$$C = \frac{\Sigma|M_t - D_t|/n}{SD} * (0.5 + 0.5(1-r))$$

In which:

M_t and D_t are respectively the model and data monthly (annual) value at station 330 ; SD is the standard deviation of the annual mean derived from monthly (annual) data; n is the number of monthly (annual) values; r is the correlation between M_t and D_t. Validation assessment is taken from Radach and Moll (2006) rating $0<C<1$ as 'very good'; $1<C<2$ as 'good'; $2<C<3$ as 'reasonable' and $C>3$ as poor. The cost function calculation was however limited to the 1992–1998 dataset which has the necessary time resolution.

3. Results and discussion

3.1. RIVERSTRAHLER annual nutrient delivery to BCZ by the Scheldt: 1950–1998

Fig. 2 shows the year-to-year variations of the annual freshwater and nutrient deliveries to the BCZ by the Scheldt, as calculated from RIVERSTRAHLER daily fluxes over the 1950–1998 period (Billen et al., 2005). Due to RIVERSTRAHLER idealization, Ntot and Ptot

fluxes represent bioavailable forms of N and P and can best be compared to DIN (NO_3+NH_4) and total PO_4 data. Visual comparison with estimates based on available measurements of discharge and nutrient concentrations at Doel, indicates a good agreement between simulations and actual freshwater (Fig. 2a) and nutrient fluxes (Fig. 2b–d). Supporting this, the cost function calculated for Scheldt discharge, total nitrogen (Ntot), phosphorus (Ptot) and dissolved silicate is <1 (Table 1). Based on the ranking of Radach and Moll (2006) such a low value rates as 'very good' the RIVERSTRAHLER ability to simulate the observed

Table 1
Cost function C for interannual resolving of RIVERSTRAHLER freshwater and nutrient annual delivery by the Scheldt

State variable	Period	Cost function C
Discharge, $m^3 \, s^{-1}$	1966–1998	0.46
Ntot, kT year^{-1}	1977–1998	0.79
Ptot, kT year^{-1}	1971–1998	0.36
Si, kT year^{-1}	1974–1998	0.39

Calculation period is defined by data availability.

changing trends in Scheldt freshwater and nutrient annual deliveries over the 1950–1998 period.

A clear increase in total bioavaliable nitrogen (Ntot, Fig. 2b), from some 10 kT N year^{-1} in the 1950–60's up to values >30 kT N year^{-1} in the 1980's is simulated by the RIVERSTRAHLER model. This increase results from the combined effect of increasing leaching of agricultural soils and rising emissions from domestic and industrial activities (Billen et al., 2005). After 1980, the N loading is almost stabilized and annual fluctuations of RIVERSTRAHLER Ntot fluxes (20 to 35 kT N year^{-1}; Fig. 2b) are mainly driven by the river discharge variations (Fig. 2a). This is particularly visible when comparing N delivery for two successive years with contrasted rainfall conditions (Fig. 2a,b), the dry year 1996 (23 kT N year^{-1}) and the wet year 1995 (32 kT N year^{-1}).

Nitrate (NO_3) is the dominant N form (>50%) except during the 1968–1979 period (Fig. 2b), when the oxygenation of the river was very low, allowing significant denitrification along the river system (Billen et al., 2005). Interestingly enough RIVERSTRAHLER simulations of NO_3 Scheldt inputs to BCZ suggest an increasing trend up to the end of the simulated period (Fig. 2b), contributing for more than 85% of Ntot delivery after 1990.

Phosphorus load originates mostly from point sources, so that the phosphorus delivered by the Scheldt shows little fluctuation with river discharge (Fig. 2a,c). Throughout 10 years, an increase of Ptot delivery by a factor 5 (i.e. from <0.5 kT P year^{-1} before 1965 up to 2.6 kT P year^{-1} in 1975; Fig. 2c) is simulated by RIVERSTRAHLER and is due to increasing domestic and industrial activities (Billen et al., 2005). Since the late eighties, RIVER-STRAHLER fluxes of Ptot and PO_4 decrease significantly down to about 1 kT P year^{-1}, however still twice their values in the 1950–60's (Fig. 2c). This decrease results from the eradication of PO_4 in washing powders as well as the improved treatment of urban effluents (Billen et al., 2005). Overall PO_4 delivery represents about 50% of Ptot except in the 1950–60's (∼20%; Fig. 2c).

Dissolved silicate ($Si(OH)_4$) originates nearly exclusively from diffuse sources (Billen et al., 2005) so that
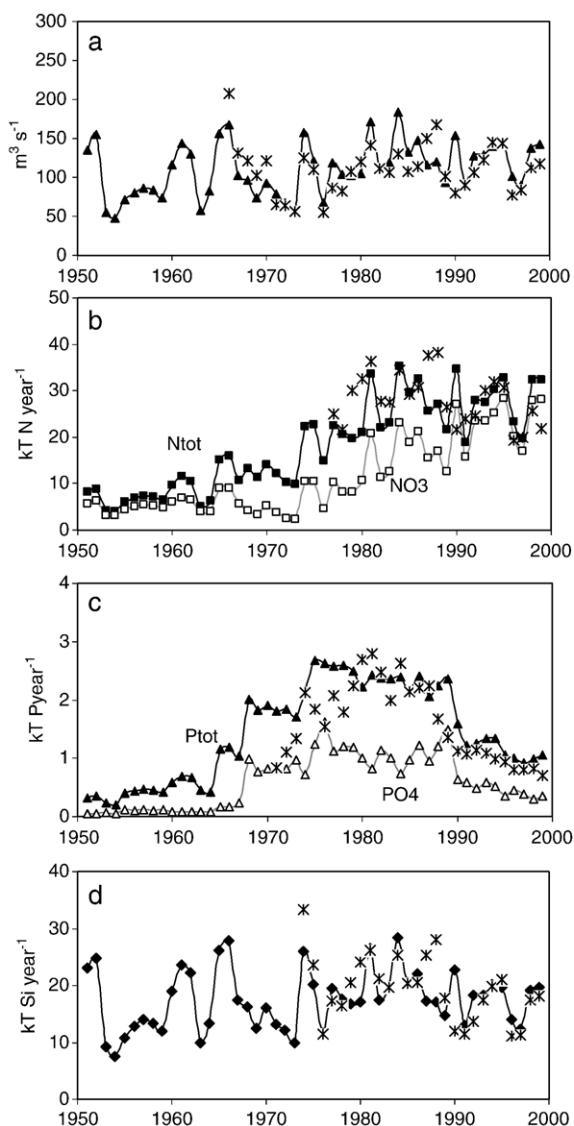

Fig. 2. 1950–1998 variations of available observations (symbols) and RIVERSTRAHLER simulations (lines) of Scheldt freshwater discharge (a) and nitrogen (b), phosphorus (c) and $Si(OH)_4$ (d) annual loads.

RIVERSTHRALER delivery by the Scheldt is correlated to the fluctuations of the river discharge (Fig. 2a,d).

The molar ratios (N:P, Si:N, Si:P) of nutrient fluxes delivered to the sea are important to analyze because they relate on the coastal nutrient balance and determine which element is controlling coastal production and ecosystem structure (Billen and Garnier, 1997; Conley, 1999; Lancelot et al., 2004). The past 50 year analysis of these ratios estimated from RIVERSTRAHLER fluxes (Fig. 9 in Billen et al., 2005) shows a regular decreasing trend of Si:N and Si:P shifting from N and P limitation towards Si limitation after 1965 when compared with marine diatom stoichiometry (Redfield et al., 1963; Brzezinski, 1985). The molar N:P of RIVERSTRAHLER annual Scheldt deliveries is always above the Redfield value of 16 except during the 1968–1980 period, when N is the limiting nutrient. After 1990, a rapid N:P increase is simulated and is mainly the result of the rapid decrease in P delivery when N delivery is maintained at its high level.

3.2. RIVERSTRAHLER–MIRO (R–MIRO) simulations of nutrients and phytoplankton

Fig. 3 shows the 1950–1998 variations in R–MIRO daily simulations of nutrients and phytoplankton in BCZ and compares them with available records at the station 330 with zooming in on the 1992–1998 period. Statistical analysis indicates a significant correlation between 1992–1998 (R–MIRO) simulations of nutrients and phytoplankton and MIRO simulations obtained by forcing the model with measured river inputs (Table 2). This gives an additional support of the RIVERSTRAHLER performance and to the use of its results for constraining MIRO runs.

The cost functions calculated for assessing the seasonal and interannual resolving capability of R–MIRO simulations in BCZ are reported in Tables 3 and 4 respectively. The 'very good' or 'good' rating obtained for the 1992–1998 period suggests that the coupled R–MIRO model is valuable for capturing seasonal signals as well as interannual trends in nutrient enrichment and algal blooms. These are discussed in details below.

3.2.1. Nutrients

The R–MIRO 48-year trend of NO_3 (Fig. 3a) suggests a doubling of the winter values over the period, from some 15 μM before the 1960's up to 30–35 μM after 1980. Spring values are close to a depletion level up to 1990 after which simulated NO_3 concentrations never reach depletion, ranging between 1.5 and 15 μM (Fig. 3a). Visual and statistical comparison with the 1992–1998

experimental data (Fig. 3a; Table 4) shows that R–MIRO reproduces reasonably the NO_3 winter maxima but over-estimates the observed spring minima in 1994, 1995, 1997 and 1998. The comparable spring NO_3 consumption, deduced from R–MIRO simulated and observed NO_3 values for the wet years 1994 and 1995 in BCZ, suggests that the model failure to reproduce properly low NO_3 in spring, results from the overestimated winter level (Fig. 3a). This might be a consequence of the simplified box representation of the hydrodynamics that imposes full mixing of the Scheldt within the BCZ box. Indeed recent water budget analysis at station 330 suggests that during these particular years, part of the Scheldt river plume is directed to the North, influencing the adjacent Dutch coastal waters (Breton et al., 2006). This explanation seems not true for the dry years 1997 and 1998 when R–MIRO NO_3 elevated minima would result more from a strong limitation in PO_4 (Fig. 3b). Indeed the 48-year simulation of PO_4 (Fig. 3b) shows a four-stage evolution of maximal winter values including: (i) stable value of ~ 1 μM up to 1960; (ii) increasing trend up to $PO_4 > 2$ μM from 1960 to 1978; (iii) maintenance of elevated PO_4 between 1978 and 1990; and (iv) decreasing trend down to values close to those found in the 1960's after 1990 (Fig. 3b). For the latter period the model predicts recurrent PO_4 depletion in spring, in agreement with the observations (Fig. 3b). Globally, comparison between simulations and 1992–1998 PO_4 data shows the fair ability of R–MIRO to describe the nowadays decreasing trend in winter PO_4 level (Table 4) as well as the spring PO_4 depletion (Fig. 3b).

Maximal winter $Si(OH)_4$ concentration show little variation over the simulated period, between 15 and 18 μM (Fig. 3c), reflecting the low influence of human activity on Si delivery. However, the simulated $Si(OH)_4$ minima in spring largely fluctuate between 1.5 and 6 μM (Fig. 3c) with the lowest values found during the period of elevated NO_3 (Fig. 3a) and PO_4 (Fig. 3b) i.e. within the 1970–1990 period. Comparison with the 1992–1998 observations indicates that winter values are generally well simulated, except for the wet years 1994 and 1995. However, the minima concentrations in spring–summer are generally overestimated, particularly in 1994, 1995, 1997 and 1998 (Fig. 3c), as found in the NO_3 simulations (Fig. 3a). This similarity would suggest that this overestimation is due to a severe PO_4 limitation in the model.

3.2.2. Phytoplankton

R–MIRO simulations show two Chl a maxima, respectively in spring and summer (Fig. 3d). The simulated spring maximum increases from 10 mg Chl a m^{-3} in the 1960's up to 25 mg Chl a m^{-3} between 1980 and 1992
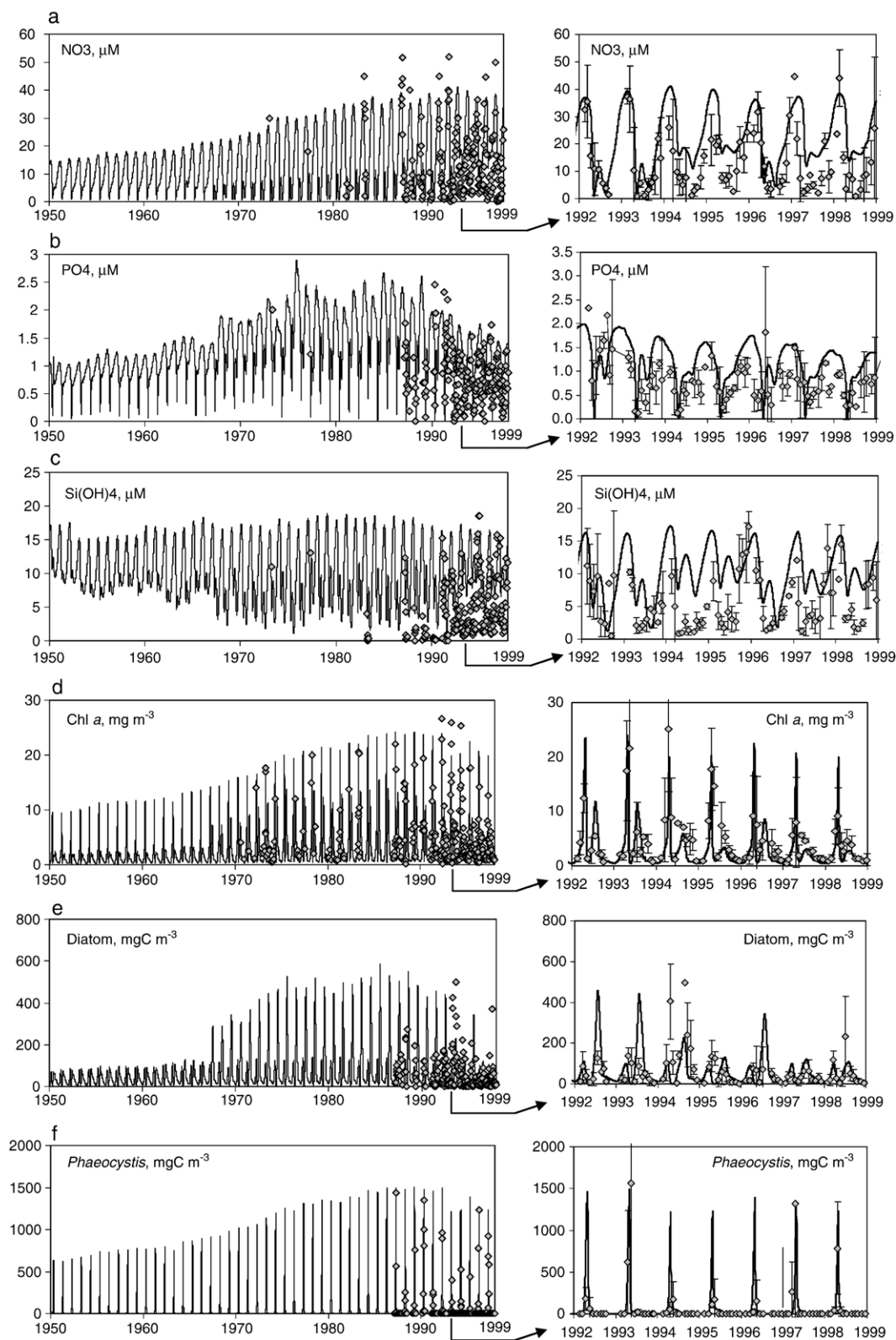
Fig. 3. Left panel: 1950–1998 R–MIRO simulations (line) and available observations (symbol) at the station 330 (Fig. 1) of NO₃ (a), PO₄ (b), Si(OH)₄ (c), Chl *a* (d) and diatom (e) and *Phaeocystis* (f) carbon biomass. Right panel: Focus on R–MIRO 1992–1998 simulations and observations (monthly mean + SD).

Table 2
Correlation analysis between 1992–1998 R–MIRO simulations and MIRO results obtained when using measured freshwater and nutrient loads as forcings

State variable	r^2	p
NO_3, μM	0.82	<0.001
PO_4, μM	0.80	<0.001
$Si(OH)_4$, μM	0.87	<0.001
Diatom, mgC m^{-3}	0.76	<0.001
Phaeocystis, mgC m^{-3}	0.84	<0.001

after which it decreases to some 20 mg Chl a m^{-3} (Fig. 3d). Up to 1967, the R–MIRO summer bloom is very low (~2 mg Chl a m^{-3}; Fig. 3d) but increases to values >10 mg Chl a m^{-3} over the 1968–1990 period and, as the spring maximum, decreases from 1992 onward (Fig. 3d). The decreasing trend simulated in spring and summer maximum Chl a after 1992 agrees very well with the observations (Fig. 3d). The fair comparison between simulated and observed Chl a attests to the model ability to describe the timing and magnitude of the spring and summer blooms in BCZ (Fig. 3d; Table 3).

The R–MIRO simulations of diatoms within the period 1950–1998 show two biomass maxima, one very constant over years in spring (~100 mg C m^{-3}; Fig. 3e) and the second in summer with values ranging from <100 to 600 mg C m^{-3} before and after 1968 respectively (Fig. 3e). After 1992, biomasses close to those of mid-1960 are simulated by the model. The comparison between the simulations and the 1992–1998 diatom records shows the reliability of the model to simulate the first diatom bloom, in time and magnitude (Fig. 3e). Less well reproduced is the observed year-to-year variability of the maxima reached by the summer diatom blooms (Fig. 3e).

The R–MIRO simulations of Phaeocystis colony blooms within the period 1950–1998 show an increasing

Table 3
Cost function (C) for seasonal resolving of R–MIRO simulations of nutrients and phytoplankton at station 330

Year	Cost function C					
	NO_3	PO_4	$Si(OH)_4$	Chl a	Diatom	Phaeocystis
1974				0.76		
1982				0.99		
1992	0.17	0.47	0.17	0.39	1.15	0.81
1993	0.23	0.86	1.17	0.37	1.7	0.25
1994	0.89	1.04	2	0.40	0.89	1.24
1995	0.95	0.75	1.17	0.43	0.90	0.89
1996	0.33	1.41	0.42	0.3	1.12	1.59
1997	0.78	0.85	1.25	0.36	0.42	0.12
1998	0.62	0.94	0.89	0.27	0.20	0.03

Calculation years are defined by data availability.

Table 4
Cost function (C) for interannual resolving of R–MIRO simulations of winter nutrients and phytoplankton spring maxima at station 330 for the 1992–1998 period

Cost function C					
Average winter concentration			Average spring maximum		
NO_3	PO_4	$Si(OH)_4$	Chl a	Diatom	Phaeocystis
1	1	1.3	1.2	1	0.8

trend of biomass maxima, from 600 mg C m^{-3} in 1950 up to 1500 mg C m^{-3} in the late eighties (Fig. 3f). After 1992, the model predicts a decrease of about 20% in the Phaeocystis biomass (Fig. 3f). Comparison of R–MIRO simulations with 1992–1998 data shows the remarkable ability of the model to simulate the timing of Phaeocystis blooms (Fig. 3f). However, R–MIRO seems to systematically overestimate blooms for years where records indicate very low biomass (1992, 1994, 1995 and 1996; Fig. 3f) and underestimate those with high records (1993, 1997; Fig. 3f). Phaeocystis bloom growth and decay is very transient in the area (Fig. 2 in Breton et al., 2006) and it might be that the 10-day time scale of RIVERSTRAHLER nutrient loads is too long for properly considering extreme events which are taken in the data.

3.3. Historical trends of nutrient enrichment and phytoplankton in BCZ for the 1950–1998 period

Nutrient enrichment can be estimated from the winter stock of nutrients that corresponds to the time of the year when regeneration processes are completed and primary production extremely low. The stoichiometry of winter nutrient forms when compared to phytoplankton requirements, adds information on the most probable element limiting primary production in spring.

Fig. 4 shows the 1950–1998 variations in winter nutrient concentrations and stoichiometry, as estimated from R–MIRO simulations in BCZ. Over the whole period, the winter stock of inorganic nitrogen is dominated by NO_3 and its amount increases with time (Fig. 4a). This is due to both the little variation around 5 μM of R–MIRO winter NH_4, and the simulated increase of winter NO_3 from 15 μM in 1950 up to 40 μM in 1994 (Fig. 4a). The maximal yearly increases take place between 1965 and 1985, after which winter NO_3 level is more or less stabilized around 38 μM (Fig. 4d). In contrast with NO_3, winter $Si(OH)_4$ shows little variation circa a value of about 17 μM (Fig. 4b). Winter PO_4 shows the most complex behavior over the simulated period, being minimal in early 1950 at a value of about 1 μM, doubling

its level between 1960 and 1980, maintaining values of ~2 μM up to 1990 and in 1998, decreasing to concentrations close to those of 1960's (i.e. 1.3 μM; Fig. 4c). These historical trends compare well with ERSEM-II long-term simulations of winter nutrients obtained for the Southern North Sea, notably the Dutch coastal waters under influence of the Rhine-Meuse (Fig. 6a in Pätsch and Radach, 1997). However, as expected from the mean SW–NE residual circulation in this area, R–MIRO winter nutrients in BCZ are significantly lower than ERSEM-II simulations in the Dutch coastal waters.

The R–MIRO-derived interannual variations of the winter N:P (Fig. 4d), Si:N (Fig. 4e) and Si:P (Fig. 4f) molar ratios show contrasted trends over the 1950–1998 period. N:P ratios are maintained close to phytoplankton requirements (16; Redfield et al., 1963) up to 1990 after which their values increase up to 30 (Fig. 4d) indicating a potential P limitation of phytoplankton growth in spring.

When compared to the diatom Si:N stoichiometry (~1, Brzezinski, 1985), the simulated winter stock of nutrient in BCZ suggests Si limitation over the whole simulated period (Si:N<1; Fig. 4e). However, due to the simulated increase of NO_3, the N excess with respect to Si is exacerbated over the period with R–MIRO-derived Si:N ratios reaching values as low as 0.4 in 1998 (Fig. 4d). Finally the interannual variations of Si:P molar ratios suggest that, except in the first five years of the simulated period, diatom growth in BCZ is more P- than Si-limited, especially after 1970 (Si:P<16; Fig. 4f).

Historical trends of phytoplankton blooms can be analyzed based on either the maximum biomass reached or the time-integrated biomass which takes into consideration the bloom duration. Fig. 5 shows the 1950–1998 variations in yearly maximum and mean phytoplankton biomass as estimated from R–MIRO simulations of Chl *a* (Fig. 5a), diatom and *Phaeocystis* carbon biomass (Fig. 5b–c).
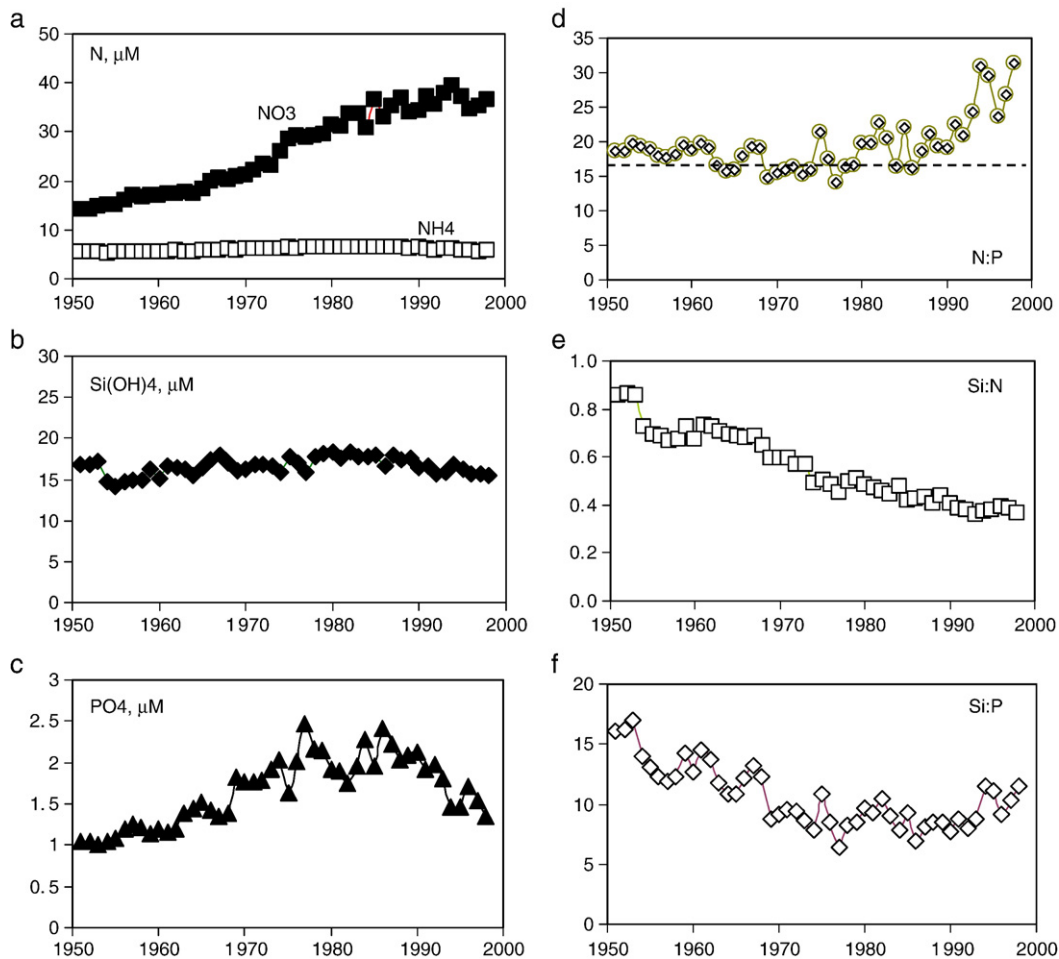

Fig. 4. 1950–1998 variations in winter concentrations of NO_3, NH_4 (a), $Si(OH)_4$ (b), PO_4(c) and of the winter molar ratios N:P (d), Si:N (e) and Si:P (f), all computed from R–MIRO simulations.

Between 1950 and 1985, the simulated Chl a maximum increases by a factor of 2.5 (from 10 to 25 mg Chl a m^{-3}; Fig. 5a). At the end of the simulated period, a clear decrease in Chl a maxima is suggested (from 25 to 20 mg Chl a m^{-3}; Fig. 5a). A similar trend is simulated for the mean Chl a which varies between 1.8 mg Chl a m^{-3} in 1950 and 20 mg Chl a m^{-3} in 1985 (Fig. 5a). The 1950–1998 variations in the averaged carbon biomass of diatoms and *Phaeocystis* identify three periods (Fig. 5b). Between 1950 and 1968, diatom and *Phaeocystis* mean biomass increase by about 20%, with an unchanged contribution to the total biomass (50%; Fig. 5b). From 1968 to 1989, the averaged diatom biomass doubles and diatoms become the dominant phytoplankton group compared to *Phaeocystis*, in terms of annual mean biomass (Fig. 5d). After 1990, the trend reverses as the mean diatom biomass decreases more rapidly than that of *Phaeocystis* (Fig. 5b). In terms of maxima reached,
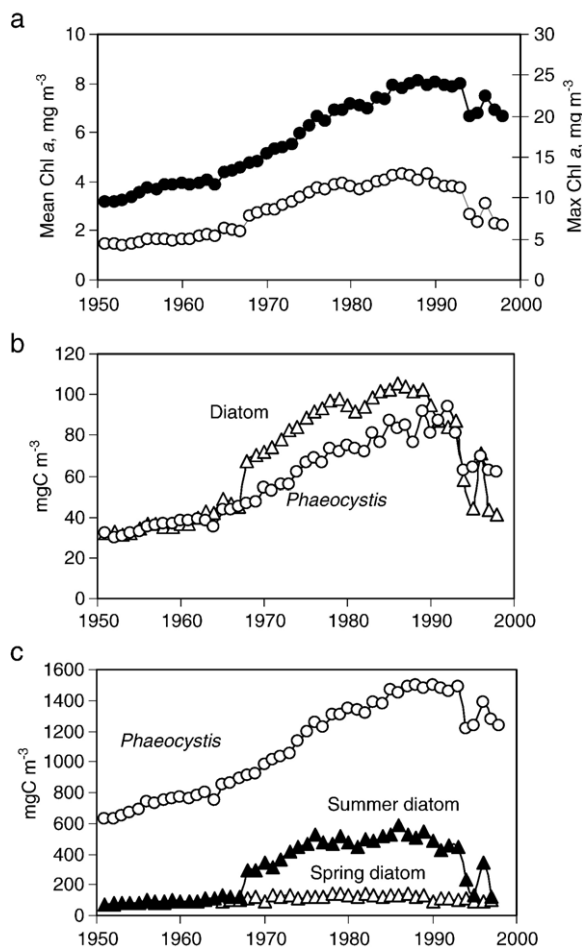

Fig. 5. 1950–1998 variations in annual mean and maximum Chl a (a), mean diatom and *Phaeocystis* carbon biomass (b) and maximum diatom and *Phaeocystis* biomass (c), all computed from R–MIRO simulations.

Phaeocystis dominates spring and summer diatoms over the whole simulated period (Fig. 5c). Values simulated in the late eighties (1500 mg C m^{-3}) are more than twice their amount in 1950 (600 mg C m^{-3}). Interestingly, the maximum carbon biomass of spring diatom is maintained constant over the simulated period (~100 mg C m^{-3}; Fig. 5c) while the summer diatom maxima increases dramatically after 1968 and maintains at values as high as 500 mg C m^{-3} up to 1992, after which it decreases (Fig. 5c). Historical (1955–1993) trends of ERSEM-II diatoms and flagellates in the Dutch coastal waters also suggest little impact of nutrient enrichment on spring diatoms but enhancement of spring–summer flagellate blooms (Fig. 6a in Pätsch and Radach, 1997). Rather different between the two models is the R–MIRO enhancement of summer diatoms during the period of N and P enrichment (1968–1989; Fig. 5c) that is not simulated by ERSEM-II (Fig. 6a in Pätsch and Radach, 1997). This could result of the trophic resolution difference between the two models with MIRO considering explicitly the competition between *Phaeocystis* colonies and summer diatoms, the latter being characterized by a parameterization distinct from that of spring diatoms (Lancelot et al., 2005).

Until 1968, the R–MIRO annual primary production is low, i.e. 100–150 gC m^{-2} y^{-1}, and equally distributed among diatom and *Phaeocystis* (Fig. 6). Between 1968 and 1985, total primary production increases by a factor of 2 and is slightly dominated by diatom production (52%; Fig. 6). After 1990, both diatom and *Phaeocystis* productions are shown to decrease but, at this time, primary production is dominated by *Phaeocystis* (Fig. 6).

3.4. Link between nutrient loads, nutrient enrichment and phytoplankton blooms

The link between changing nutrient loads and coastal eutrophication was investigated based on a suite of statistical correlations between RIVERSTRAHLER nutrient loads and R–MIRO-derived eutrophication indicators such as the winter nutrient concentrations, the maximum phytoplankton biomass and the annual primary production.

The link between nutrient enrichment and phytoplankton bloom in BCZ was first explored by relating yearly maxima of diatom and *Phaeocystis* carbon biomass (Fig. 5c) to winter nutrient maxima (Fig. 4) estimated from 1950–1998 R–MIRO simulations. Significant correlation was obtained between maxima reached by diatom spring ($r^2 = 0.64$, $p < 0.001$) and summer ($r^2 = 0.85$, $p < 0.001$) biomass and winter PO_4; and between *Phaeocystis* colony biomass and winter NO_3

($r^2 = 0.91$, $p < 0.001$). Interestingly, when results of the 5 latest years of the simulated period, i.e. those with strong PO_4 depletion (N:P ~ 25), are discarded from the correlation analysis, the correlation coefficient is the highest, explaining 98% of the variability.

Nutrient enrichment in BCZ results however from Scheldt river inputs that add to inflowing Atlantic waters themselves enriched by river Seine nutrient loads (Fig. 1). In order to assess the relative importance of these nutrient sources in BCZ, a nutrient budget based on daily R–MIRO simulations of nutrient fluxes was constructed. Fig. 7 compares the 1950–1998 evolutions of the computed annual Atlantic and Scheldt inputs of PO_4 and NO_3 into BCZ. Examination of Fig. 7 suggests that both the NO_3 and PO_4 enrichment of BCZ are largely determined by the Atlantic inputs. The nutrient enrichment of Atlantic waters by the river Seine is clearly visible for the 1970–1990 period (Fig. 7). Over the simulated period, the relative contribution of Scheldt inputs to PO_4 enrichment of BCZ is less than 10%, with maxima obtained during the period of increased P loads (1968–1989; Figs. 2b, 7a). Scheldt contribution to NO_3 enrichment of BCZ is more significant, varying between respectively 20% and $\sim 40\%$ before and after 1970 (Fig. 7b). The link between the nutrient enrichment in BCZ and Scheldt and Atlantic nutrient loads and hence between nutrient loads and phytoplankton blooms is further demonstrated, based on the significant correlations obtained between R–MIRO-derived winter NO_3 and PO_4 and RIVERSTRAHLER loads by the Scheldt (NO_3: $r^2 = 0.56$, $p > 0.001$; PO_4: $r^2 = 0.66$, $p > 0.001$) on the one hand and Atlantic inputs (NO_3: $r^2 = 0.39$, $p > 0.001$; PO_4: $r^2 = 0.16$, $p > 0.01$) on the other hand.

Supporting this, statistical analysis between primary production and total nutrient loads to BCZ also shows significant correlation between diatom annual production and PO_4 loads ($r^2 = 0.44$, $p > 0.001$) and, between
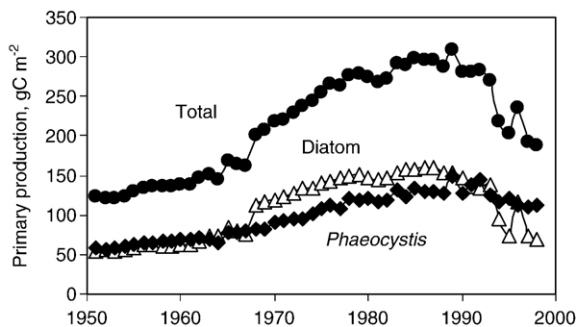

Fig. 6. 1950–1998 variations in annual primary production and diatom and *Phaeocystis* production computed from daily R–MIRO simulations of primary production.
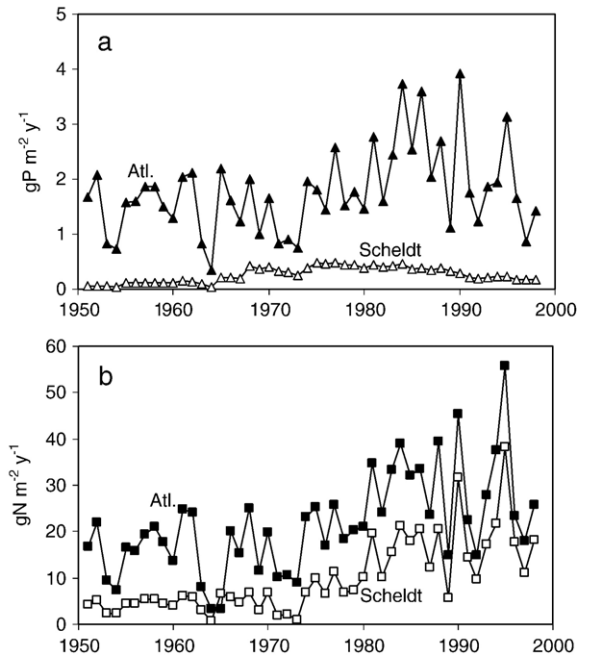

Fig. 7. 1950–1998 variations in Scheldt and Atlantic (Atl) inputs of PO_4 (a) and NO_3 (b) into BCZ as based on nutrient budget computed from R–MIRO simulations.

Phaeocystis production and NO_3 loads ($r^2 = 0.35$, $p > 0.001$).

4. Conclusion

The coupling between RIVERSTRAHLER, an idealized biogeochemical model of the river system and MIRO, a complex biogeochemical model describing diatom and *Phaeocystis* blooms in the marine domain, has been shown useful for establishing the link between changing human activities over the past 50 years and coastal eutrophication in the BCZ. Nutrient budget reconstruction shows that, due to its geographical position the BCZ is influenced directly by the Scheldt river inputs but indirectly by river Seine waters discharging in the Atlantic waters. Historical reconstruction back to the fifties suggests that *Phaeocystis* colonies were already blooming in BCZ in the early 1950 and were sharing almost equally with diatom, the bulk of annual primary production. Over the 1960–1992 period, the increased loads of both N and P were beneficial to both *Phaeocystis* colonies and summer diatoms with however a little advantage to the latter. Since 1989, the decrease in P loads subsequent to the removal of PO_4 in washing powders and the maintenance of elevated NO_3 loads had a positive feedback to both diatoms and *Phaeocytis* production with however a significantly larger impact on diatoms than on *Phaeocytis*; *Phaeocystis* production was

mainly controlled by N loads. As a consequence, future management of nutrient emission reduction aiming at decreasing *Phaeocystis* blooms in BCZ without impacting on diatoms would target decrease of N loads. The coupled RIVERSTRAHLER–MIRO model described here, constitutes a powerful mathematical tool for testing the impact of realistic scenarios of N point and diffuse emission reductions in the Seine and Scheldt watershed, on *Phaeocystis* blooms in BCZ.

Finally, coastal eutrophication problems in the Southern Bight of the North Sea have been perceived as a shift from diatoms towards *Phaeocystis* dominance due to an over-enrichment of N and P with respect to Si, the latter being considered as limiting factor for diatom growth. R–MIRO runs applied in the Southern Bight of the North Sea over the past ~ 50 years point out the key role played by PO_4 in driving present day diatom and *Phaeocystis* blooms in the studied area. Insufficient P with respect to Si slows down diatom growth, challenging the currently admitted concept of diatoms being better competitors than other undesirable algae for N and P when Si is sufficient.

Ackowledgements

References

Billen, G., Garnier, J., 1997. The Phison River Plume: coastal eutrophication in response to changes in land use and water management in the watershed. Aquatic Microbial Ecology 13, 3–17.

Billen, G., Garnier, J., Hanset, P., 1994. Modelling phytoplankton development in whole drainage networks: the RIVERSTRAHLER model applied to the Seine river system. Hydrobiologia 289, 119–137.

Billen, G., Garnier, J., Deligne, C., Billen, C., 1999. Estimates of early industrial inputs of nutrients to river systems: implication for coastal eutrophication. The Science of the Total Environment 243/244, 43–52.

Billen, G., Garnier, J., Ficht, A., Cun, C., 2001. Modeling the response of water quality in the Seine river estuary to human activity in its watershed over the last 50 years. Estuaries 24 (6B), 977–993.

Billen, G., Garnier, J., Rousseau, V., 2005. Nutrient fluxes and water quality in the drainage network of the Scheldt basin over the last 50 years. Hydrobiologia 540, 47–67.

Breton, E., Rousseau, V., Parent, J.Y., Ozer, J., Lancelot, C., 2006. Hydroclimatic modulation of diatom/*Phaeocystis* blooms in the nutrient-enriched Belgian coastal waters (North Sea). Limnol. Oceanogr. 51 (3), 1401–1409.

Brockmann, U., Billen, G., Gieskes, W.W.C., 1988. North Sea nutrients and eutrophication. In: Salomons, W., Bayne, B.L., Duursma, E.K., Forstner, U. (Eds.), Pollution of the North Sea. An assessment. Springer-Verlag Berlin, pp. 348–389.

Brzezinski, M.A., 1985. The Si:C:N ratio of marine diatoms: interspecific variability and the effect of some environmental variables. J. Phycol. 21, 347–357.

Cadée, G.C., Hegeman, J., 1991. Historical phytoplankton data of the Marsdiep. Hydrobiol. Bull. 24, 111–118.

Conley, D.J., 1999. Biogeochemical nutrient cycles and nutrient management strategies. Hydrobiologia 289, 87–96.

Cugier, P., Billen, G., Guillaud, J.F., Garnier, J., Ménesguen, A., 2005. Modelling the eutrophication of the river Seine (France) under historical, present and future nutrient loading. J. Hydrol. 304, 381–396.

Garnier, J., Billen, G., 2002. The Riverstrahler modelling approach applied to a tropical case study (The Red-Hong-River, Vietnam): nutrient transfer and impact on the Coastal Zone. SCOPE, Coll. Mar. Res. W. 12, 51–65.

Garnier, J., Billen, G., Coste, M., 1995. Seasonal succession of diatoms and chlorophyceae in the drainage network of the River Seine: observations and modelling. Limnol. Oceanogr 40, 750–765.

Garnier, J., Billen, G., Palfner, L., 1999. Understanding the oxygen budget of the Mosel drainage network with the concept of heterotrophic/autotrophic sequences: the Riverstrahler approach. Hydrobiologia 410, 151–166.

Garnier, J., Billen, G., Hannon, E., Fonbonne, S., Videnina, Y., Soulie, M., 2002. Modeling transfer and retention of nutrients in the drainage network of the Danube River. Estuar. Coast. Shelf Sci. 54, 285–308.

Gypens, N., Lacroix, G., Lancelot, C., in press. Understanding the 1989–2003 variability of diatom-*Phaeocystis* blooms in the Belgian coastal waters: the MIRO model. Journal of Sea Research.

Lacroix, G., Ruddick, K., Ozer, J., Lancelot, C., 2004. Modelling the impact of the Scheldt and Rhine/Meuse plumes on the salinity distribution in Belgian waters (southern North Sea). J. Sea Res. 52, 149–163.

Lancelot, C., 1995. The mucilage phenomenon in the continental coastal waters of the North Sea. Sci. Total Environ. 165, 83–102.

Lancelot, C., Billen, G., Sournia, A., Weisse, T., Colijn, F., Veldhuis, M., Davies, A., Wassmann, P., 1987. *Phaeocystis* blooms and nutrient enrichment in the continental coastal zone of the North Sea. Ambio 16 (1), 38–46.

Lancelot, C., Keller, M., Rousseau, V., Smith Jr., W.O., Mathot, S., 1998. Autoecology of the marine haptophyte *Phaeocystis sp*. In: Anderson, D.A., Cembella, A.M., Hallegraef, G. (Eds.), NATO Advanced Workshop on the Physiological Ecology of Harmful Algal BloomsNATO-ASI Series, Series G: Ecological Science, vol. 41, pp. 209–224.

Lancelot, C., Staneva, J., Gypens, N., 2004. Modelling the response of coastal ecosystem to nutrient change. Oceanis 28, 531–556.

Lancelot, C., Spitz, Y., Gypens, N., Ruddick, K., Becquevort, S., Rousseau, V., Lacroix, G., Billen, G., 2005. Modelling diatom and *Phaeocystis* blooms and nutrient cycles in the Southern Bight of the North Sea: the MIRO model. Mar. Ecol., Prog. Ser. 289, 63–78.

OSPAR Commission, 2000. Quality Status Report. OSPAR Commission.

Owens, N.J.P, Cook, D., Colebrook, M., Hunt, H., Reid, P.C., 1989. Long term trends in the occurrence of *Phaeocystis* sp. in the North-East Atlantic. J. Mar. Biol. Assoc. U.K. 69, 813–821.

Pätsch, J., Radach, G., 1997. Long-term simulation of the eutrophication of the North Sea: temporal development of nutrients, chlorophyll and primary production in comparison to observations. J. Sea Res. 38, 275–310.

Pingree, R.D., Maddock, L., 1977. Tidal residual in the English Channel. J. Mar. Biol. Assoc. U.K. 57, 339–354.

Radach, G., Moll, A., 2006. Review of the three-dimensional ecological modelling related to the North Sea shelf system: Part 2: model validation and data needs. Oceanogr. Mar. Biol. 44, 1–60 (an Annual review).

Redfield, A.C., Ketchum, B.A., Richards, F.A., 1963. The influence of organisms on the composition of sea-water. In: Hill, M.N. (Ed.), The Sea. Wiley, pp. 26–77.

Rousseau, V., 2000. Dynamics of *Phaeocystis* and diatom blooms in the eutrophicated coastal waters of the Southern Bight of the North Sea. PhD Thesis, Université Libre de Bruxelles, Belgium.

Rousseau, V., Leynaert, A., Daoud, N., Lancelot, C., 2002. Diatom succession, silicification and silicic acid availability in Belgian coastal waters (Southern North Sea). Mar. Ecol., Prog. Ser. 236, 61–73.

Rousseau, V., Breton, E., De Wachter, B., Beji, A., Deconinck, M., Huijgh, J., Bolsens, T., Leroy, D., Jans, S., Lancelot, C., 2004. Identification of Belgian maritime zones affected by eutrophication (IZEUT). Towards the establishment of ecological criteria for the implementation of the OSPAR Common Procedure to combat eutrophication. Belgian Science Policy, Brussels, Final report. (77 pp.).

Salomon, J.C., Breton, M., 1993. An atlas of long-term currents in the Channel. Oceanol. Acta 16, 439–448.

Soetaert, K., Middelburg, J.J., Heip, C., Meire, P., Van Damme, S., Maris, T., 2006. Long-term change in dissolved inorganic nutrients in the heterotrophic Scheldt estuary (Belgium, The Netherlands). Limnol. Oceanogr. 51, 409–423.

Villars, M., de Vries, I., Bokhorst, M., Ferreira, J., Gellers-Barkman, S., Kelly-Gerreyn, B., Lancelot, C., Menesguen, A., Moll, A., Pätsch, J., Radach, G., Skogen, M., Soiland, H., Svendsen, E., Vested, H.J., 1998. Report of the ASMO modelling workshop on eutrophication Issues, 5–8 November 1996. OSPAR Commission Report 102, RIKZ, The Hague (The Netherlands). The Hague, The Netherlands (90 pp.).