Carbon dynamics and CO2 air-sea exchanges in the eutrophied coastal waters of the Southern Bight of the North Sea: a modelling study

N. Gypens, C. Lancelot, A. V. Borges

To cite this version:

HAL Id: hal-00297507
https://hal.archives-ouvertes.fr/hal-00297507
Submitted on 23 Dec 2004

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
Carbon dynamics and CO₂ air-sea exchanges in the eutrophied coastal waters of the Southern Bight of the North Sea: a modelling study

N. Gypens¹, C. Lancelot¹, and A. V. Borges²

¹Université Libre de Bruxelles, Ecologie des Systèmes Aquatiques, CP-221, Bd du Triomphe, B-1050, Belgium
²Université de Liége, MARE, Unité d’Océanographie Chimique, Institut de Physique (B5), B-4000 Sart Tilman, Belgium

Abstract. A description of the carbonate system has been incorporated in the MIRO biogeochemical model to investigate the contribution of diatom and Phaeocystis blooms to the seasonal dynamics of air-sea CO₂ exchanges in the Eastern Channel and Southern Bight of the North Sea, with focus on the eutrophied Belgian coastal waters. For this application, the model was implemented in a simplified three-box representation of the hydrodynamics with the open ocean boundary box ‘Western English Channel’ (WCH) and the ‘French Coastal Zone’ (FCZ) and ‘Belgian Coastal Zone’ (BCZ) boxes receiving carbon and nutrients from the rivers Seine and Scheldt, respectively. Results were obtained by running the model for the 1996–1999 period. The simulated partial pressures of CO₂ (pCO₂) were successfully compared with data recorded over the same period in the central BCZ at station 330 (51°26.05’ N; 002°48.50’ E). Budget calculations based on model simulations of carbon flow rates indicated for BCZ a low annual sink of atmospheric CO₂ (−0.17 mol C m⁻² y⁻¹). On the opposite, surface water pCO₂ in WCH was estimated to be at annual equilibrium with respect to atmospheric CO₂. The relative contribution of biological, chemical and physical processes to the modelled seasonal variability of pCO₂ in BCZ was further explored by running model scenarios with separate closures of biological activities and/or river inputs of carbon. The suppression of biological processes reversed direction of the CO₂ flux in BCZ that became, on an annual scale, a significant source for atmospheric CO₂ (+0.53 mol C m⁻² y⁻¹). Overall biological activity had a stronger influence on the modelled seasonal cycle of pCO₂ than temperature. Especially Phaeocystis colonies which growth in spring were associated with an important sink of atmospheric CO₂ that counteracted the temperature-driven increase of pCO₂ at this period of the year. However, river inputs of organic and inorganic carbon were shown to increase the surface water pCO₂ and hence the emission of CO₂ to the atmosphere. Same calculations conducted in WCH, showed that temperature was the main factor controlling the seasonal pCO₂ cycle in these open ocean waters. The effect of interannual variations of fresh water discharge (and related nutrient and carbon inputs), temperature and wind speed was further explored by running scenarios with forcing typical of two contrasted years (1996 and 1999). Based on these simulations, the model predicts significant variations in the intensity and direction of the annual air-sea CO₂ flux.

1 Introduction

Coastal waters are heavily impacted by nutrients and carbon inputs from rivers and estuaries that stimulate production and remineralization of organic matter. They also intensively exchange nutrients, and inorganic and organic carbon with the open ocean across marginal boundaries (e.g. Thomas et al., 2004a). Consequently, these areas play a key role in the global carbon cycle by linking the terrestrial, oceanic and atmospheric reservoirs (Gattuso et al., 1998; Mackenzie et al., 2004). There is nowadays a great uncertainty on the overall role of coastal ecosystems to act as a sink or a source for atmospheric CO₂ due to the large variability of recorded air-sea CO₂ exchanges across latitudinal and ecosystem gradients. Existing data of CO₂ air-sea fluxes suggest that temperate marginal seas act as sinks for atmospheric CO₂ (Tsunogai et al., 1999; Frankignoulle and Borges, 2001a; Borges and Frankignoulle, 2002a; DeGranpre et al., 2002; Thomas et al., 2004a, b). On the contrary sub-tropical marginal seas (Cai et al., 2003) and near-shore aquatic ecosystems influenced by terrestrial inputs such as inner and outer estuaries (Frankignoulle et al., 1998; Cai et al., 2000; Raymond et al., 2000; Borges and Frankignoulle 2002b; Bouillon et al., 2003), mangroves (Borges et al., 2003) and non-estuarine...
salt marshes (Wang and Cai, 2004) act as sources of CO$_2$ to the atmosphere. However, the paucity of field data prevents the comprehensive biogeochemical description of the very diverse coastal ecosystems that is needed for the integration of CO$_2$ fluxes on a global scale. Furthermore, little is known on the seasonal and interannual variability of CO$_2$ dynamics and fluxes in coastal ecosystems, although it has been shown to be highly significant in open oceanic waters in relation to large scale climatic forcings acting at various time-scales (e.g. Takahashi et al., 2003). In the absence of long term time-series, these aspects of CO$_2$ cycling in coastal ecosystems can only be approached with modelling tools (e.g. Ianson and Allen, 2002). Up to now, little mechanistic modelling effort has been devoted to the description of the dynamics of dissolved inorganic carbon (DIC) in coastal environments (Walsh et al., 1994, 1996; Mackenzie et al., 2004).

The North Sea is amongst the best-studied coastal areas in the World, with respect to its physical, chemical and biological characteristics. However, the spatio-temporal monitoring of DIC has been limited to near-shore waters such as the German Bight, the Wadden Sea or the Belgian coastal zone (Walsh et al., 1994, 1996; Mackenzie et al., 2001) detailing the seawater carbonate system and air-sea CO$_2$ exchange. MIRO is a mechanistic model that describes C, N, P and Si cycling through aggregated components of the Phaeocystis-dominated ecosystem of the North Sea. It includes thirty-two state variables assembled in four modules expressing the dynamics of phytoplankton, zooplankton, organic matter degradation and nutrients (NO$_3$, NH$_4$, PO$_4$ and SiO$_4$), regeneration by bacteria in the water column and the sediment. The phytoplankton module considers three phytoplankton groups (diatoms, free-living autotrophic nanoflagellates and Phaeocystis colonies) the growth physiology of which is described according to the AQUAPHY model of Lancelot et al. (1991). The latter model considers 3 intracellular constituents (small metabolites, reserve material, functional and structural metabolites) and distinguishes different processes: photosynthesis, reserve synthesis and catabolism, growth and associated nutrient uptake, respiration and lysis. The zooplankton module details the dynamics of two groups: the microzooplankton feeding on free-living autotrophic nanoflagellates and bacteria and the mesozooplankton grazing on diatoms and microzooplankton. Phaeocystis colonies escape grazing, but are submitted to colony disruption which releases in the ambient nanoflagellated cells and organic matter. The degradation of organic matter by planktonic bacteria is described according to the HSB model (Billen and Servais, 1989), considering two classes of biodegradability for both dissolved and particulate organic matter. Benthic organic matter degradation and nutrient recycling are calculated using the algorithms developed by Lancelot and Billen (1985) and Billen et al. (1989).

The physico-chemical module of Hannon et al. (2001) details the carbonate system in seawater and calculates CO$_2$ exchange between the surface water and the atmosphere. The speciation of the carbonate system (in particular pCO$_2$) is calculated based on the knowledge of DIC and total alkalinity (TA), using stoichiometric relationships and apparent equilibrium constants, which are function of temperature, pressure and salinity (Weiss, 1974; Millero et al., 1993). DIC and TA are computed taking into account, respectively, the...
biological uptake or release of carbon and the phytoplankton assimilation of nitrate, all provided by the MIRO model. Air-
sea CO$_2$ fluxes are calculated from the pCO$_2$ gradient across
the air-sea interface and the gas transfer velocity estimated
from wind speed and using the parameterisation of Nightingale
et al. (2000). The latter was chosen among several existing
empirical formulations since it was established from dual
tracer experiments in the Southern Bight of the North Sea.

2.2 Model runs

The MIRO-CO$_2$ model was applied in the coastal domain
of the eastern English Channel and Southern Bight of the
North Sea, between the Baie de Seine and the northern limit
of BCZ (Fig. 1). The model was implemented in a multi-
box frame delineated on the basis of the hydrological regime
and the river inputs. In order to take into account the cumu-
lated nutrient enrichment of Atlantic waters by the Seine
and Scheldt rivers, two successive boxes, assumed to be
homogeneous, were chosen from the Baie de Seine to the
BCZ (Fig. 1). Each successive box was characterized by
its own area, depth, water temperature and average salinity,
light conditions and water residence time and was treated
as an open system, receiving water from the southern adjac-
ent box and exporting water to the northern box (Lancelot
et al., 2004). The boundary conditions were provided by the
results of the calculations performed for the conditions ex-
isting in the Western Channel area, considered as a quasi-
oceanic closed system. Initial conditions of nutrients were
extracted from the database of Radach et al. (1995). Initial
conditions of DIC (2070 mmol C m$^{-3}$) and total alkalinity
(2290 mmol m$^{-3}$) were estimated from existing data in the
area for the 1996-1999 period (Borges and Frankignoulle,
2003). The seasonal variation of the state variables was cal-
culated by solving the equations expressing mass conserva-
tion, according to the Euler procedure, with a time step of
15 min. Conservation equations and parameters are detailed
in Lancelot et al. (2004).

Model simulations were run with 1996–1999 climatolog-
ical forcings for hydro-meteorological conditions and river
inputs. These functions were computed from recorded daily
global solar radiation (Oostende Station, Institut Royal de
Météorologie, Belgium), seawater temperature and monthly
nutrient loads for the rivers Seine (Cellule Antipollution de
Rouen du Service de la Navigation de la Seine, France) and
Scheldt (Institute for Inland Water Management and Waste
Water Treatment, The Netherlands) and Department of En-
vironment and Infrastructure (Ministry of Flemish Commu-
nity, Belgium). Organic carbon loads by the Scheldt were re-
trieved from the Dutch water base (http://www.waterbase.nl).
For the river Seine, we used data described in Servais et
al. (2003). Land-based fluxes of DIC and TA were esti-
mated based on a compilation of DIC and TA concentra-
tions in the Seine and the Scheldt rivers (Frankignoulle et al.,
1996, 1998; Frankignoulle and Borges, 2001b; Abril, per-
sonal communication) and river discharges, making use of
the “apparent zero end-member” method (Kaul and Froelich,
1984). Atmospheric pCO$_2$ was extracted from the Mace
Head (53°33′ N 9°00′ W, Southern Ireland) and the National
Oceanic and Atmospheric Administration/climate Monitor-
ing and Diagnostics Laboratory/Carbon Cycle Greenhouse
Gases Group (NOAA/CMDL/CCGG) air sampling network
(available at http://www.cmdl.noaa.gov/). Wind speed at
50.0° N 6.0° W was provided by the Pacific Fisheries En-
vironmental Laboratory (PFEL) and is based on Fleet Nu-
merical Meteorology and Oceanography Center (FNMOC)
synoptic pressure fields.

2.3 Validation data

Model results were daily-averaged and compared with avail-
able data sets in the central BCZ at the station 330
(51°26.05′ N; 02°48.50′ E) for the 1996–1999 period. Over
this period, nutrients, phytoplankton and chlorophyll data

Fig. 1. Map of the studied area showing the MIRO multi-box frame
(adapted from Lancelot et al., 2004) and the location of the station
330 (51°26.05′ N; 02°48.50′ E).

Fig. 2. Modelled (solid line for BCZ) and observed (♦ at station
330) temperature (black) and salinity (grey).
were collected at a weekly frequency except during winter when bimonthly (Rousseau, 2000). DIC was calculated from TA and pCO₂ measured between 1996 and 1999 in the BCZ and WCH (Borges and Frankignoulle, 1999, 2002b, 2003). Due to the inherent discrepancy between in situ temperature at the time of pCO₂ measurement and that imposed by the climatological forcing of the model (Fig. 2), field data of pCO₂ were corrected with respect to the modelled temperature. Similarly, DIC and TA data obtained at station 330 were normalized to the mean BCZ salinity of 33.5 imposed by the chosen box-model implementation in order to overcome the effect of salinity discrepancy (Fig. 2). The normalized DIC and TA are written DIC₁₃₃.₅ and TA₁₃₃.₅.

3 Results and discussion

3.1 Model validation

3.1.1 Biological state variables

Figure 3 compares MIRO-CO₂ predictions of diatom (Fig. 3a) and Phaeocystis (Fig. 3b) biomass, total phytoplankton (mg Chl a m⁻³, Fig. 3c), bacteria (Fig. 3d), microzooplanktonic (Fig. 3e) and copepods (Fig. 3f) biomass with field data collected between 1996 and 1999. The model describes reasonably well the main trends (timing and magnitude) of the diatom-Phaeocystis-diatom succession: spring diatoms (Fig. 3a) initiate the phytoplankton bloom in early March and are followed by Phaeocystis colonies (Fig. 3b) which reach concentrations of 20 mg Chl a m⁻³ in April (Fig. 3c). Summer diatoms bloom after Phaeocystis decline and maintain up to fall. In agreement with observations, MIRO-CO₂ results show non-negligible concentration of diatoms all over the year (Fig. 3a) contrasting with the unique bloom of Phaeocystis in spring (Fig. 3b). Phytoplankton decline in spring stimulates the development of diverse heterotrophs such as bacteria (Fig. 3d), microzooplankton (Fig. 3e) and copepods (Fig. 3f). The seasonal succession and magnitude of spring bacteria and microzooplankton biomass are well captured by the model. However, biomass
reached by copepods and bacteria in spring and fall, respectively, are not properly simulated. These weaknesses of the model are discussed in Lancelot et al. (2004) and is mainly attributed to some mismatch between the simulated seasonal succession of copepods and their prey which might be related to some unreliable description of either the mortality process and fate of *Phaeocystis* colonies and derived matter and/or the copepod feeding function. Experimental work in this matter is in progress.

### 3.1.2 Carbonate chemistry

Figure 4 compares MIRO-CO$_2$ simulations of DIC$_{33.5}$ (Fig. 4a), TA$_{33.5}$ (Fig. 4b) and surface water pCO$_2$ (Fig. 4c) with field observations. The seasonal evolution of DIC$_{33.5}$ and TA$_{33.5}$ is reasonably well captured by the model but concentrations obtained overestimate field data, especially in winter and late fall (Fig. 4a, b) when biological activity is low (Fig. 3). The simulated DIC$_{33.5}$ clearly reaches lowest values at the time of *Phaeocystis* bloom maximum (Fig. 3b; Fig. 4a) and increases in mid-May when heterotrophs prevail over autotrophs (Fig. 4a; Fig. 3d, e, f). In agreement, the highest TA$_{33.5}$ values (Fig. 4a) are modelled in end April-early May when phytoplankton biomass is elevated (Fig. 3a, b, c) and consumes NO$_3$. Lowest TA$_{33.5}$ are simulated in late fall (Fig. 4b) when phytoplankton growth has ceased but heterotrophic process and nitrification are still operating. The observed seasonal signal of TA$_{33.5}$ is well represented (Fig. 4b) but the modelled amplitude (110 mmol m$^{-3}$) is weak compared to that suggested by field data (∼200 mmol m$^{-3}$, Fig. 4b), mainly because of the failure of the model to capture the observed late fall-winter minima (Fig. 4b). At the annual scale, Atlantic waters bring 96% of TA in BCZ and river loads and biological processes contribute 3.9% and 0.1%, respectively. Sensitivity tests with varying initial TA corresponding to the range of observed values in WCH (Borges and Frankignoulle, 2003) indicate that a reduction of WCH initial conditions of TA by less than 2% improves significantly model simulations of DIC (Fig. 4a) and TA (Fig. 4b) in winter while fall observations remain overestimated by the model (Fig. 4a, b). Elevated modelled TA in fall could result from an overestimation of river inputs during this period. At that time of the year (October to January), river discharge is high and inputs of TA account for 45% of annual river loads. Due to the importance of biological processes on magnitude and seasonal variability of DIC, modification of DIC initial value in the Western Channel has no impact on DIC magnitude in the Belgian coastal zone.

The discrepancies in the BCZ between observed and modelled DIC and TA have no influence on the magnitude and seasonal evolution of the modelled pCO$_2$.

The comparison between modelled and measured pCO$_2$ (Fig. 4c) shows that our model is able to describe the observed seasonal variability, both in time and amplitude. The latter (defined as the difference between the maximum and minimum values) is evaluated at 300 ppm with pCO$_2$ values ranging between 445 ppm in summer and 145 ppm in spring (Fig. 4c). Model pCO$_2$ values generally agree fairly well with observations except in fall when field data are significantly higher than modelled values. Over the winter season, modelled surface pCO$_2$ are close to saturation (Fig. 4c). A marked decrease of pCO$_2$ is simulated in early March and coincides with the onset of the diatom bloom (Fig. 4c; Fig. 3a) and pCO$_2$ reaches its minimum (145 ppm) during the *Phaeocystis* bloom (Fig. 4c; Fig. 3b). Modelled pCO$_2$ increases as *Phaeocystis* declines and values above saturation with respect to atmospheric CO$_2$ are reached in July up to the end of October (Fig. 4c). The model early decrease of surface water pCO$_2$ in September compared to observations might be due to some underestimation of modelled bacterial biomass (and related activity) during fall (Fig. 3d).

### 3.2 Carbon budget

An annual budget of C flows was constructed for BCZ based on time integration of MIRO daily simulations of biological activities (photosynthesis and planktonic and benthic respiration), Atlantic inputs, Scheldt loads and air-sea CO$_2$ fluxes. Results of these calculations (Fig. 5) are given in Table 1.
From which 77 and 20% is remineralized in the water column – 0.1% of the total input of DIC. Autotrophic processes fix $2^{152}N$. Gypens et al.: Carbon dynamics and CO$_2$ air-sea exchanges in the Southern Bight of the North Sea

Biogeosciences, 1, 147–157, 2004 www.biogeosciences.net/bg/1/147/

3.3 Physical and biological controls of surface water $p$CO$_2$ and air-sea CO$_2$ fluxes in central BCZ at the seasonal and annual scales

Physical and biological mechanisms regulating $p$CO$_2$ (Fig. 4c) and air-sea exchanges of CO$_2$ (Fig. 6a) in central BCZ were first investigated based on the comparative analysis of MIRO-CO$_2$ daily forcing of temperature (Fig. 6b) and predictions of biological features (gross primary production GPP, community respiration R (including autotrophic and heterotrophic planktonic and benthic respiration) and net ecosystem production NEP (the difference between GPP and R), Fig. 6c). In winter (November to late February), NEP and R are close to zero (Fig. 6c) and $p$CO$_2$ fluctuations (Fig. 4c) are modulated by river inputs of carbon and seawater temperature (Fig. 6b). The system is near equilibrium and air-sea CO$_2$ fluxes are close to zero (Fig. 6a). From mid-March to end April, NEP is high enough to reverse the positive effect of temperature increase on $p$CO$_2$ that reaches extremely low values with respect to saturation (Fig. 4c; Fig. 6b, c). In accordance, our model calculates for this period an important sink of atmospheric CO$_2$ in central BCZ (up to $-20$ mol C m$^{-2}$ d$^{-1}$; Fig. 6a). In May, NEP is strongly negative (i.e. the system is heterotrophic) and surface water $p$CO$_2$ increases due to both respiration and temperature increase (Fig. 4c; Fig. 6b, c). As a consequence the system evolves progressively from a sink of atmospheric CO$_2$ during spring to a source during the period end of June to November (Fig. 6a). After November, the system is again close equilibrium (Fig. 6a). Overall MIRO-CO$_2$ estimates a weak annual sink of atmospheric CO$_2$ of $-0.17$ mol C m$^{-2}$ y$^{-1}$.

As a first attempt to appraise the relative importance of physical and biological controls of surface water $p$CO$_2$, we used the approach of Takahashi et al. (2002) that separates the seasonal effect of ‘net biology’ from that of temperature. As defined by these authors the ‘net biology’ effect includes the effect of biological processes, TA variation due to nitrate utilization, air-sea exchange of CO$_2$ and an addition of DIC and TA by external forcing (river inputs in the present study). Removal of the temperature effect on $p$CO$_2$ simulations is obtained after normalization of modelled daily values of $p$CO$_2$ to the annual mean temperature (11.9°C) using the equation:

$$p \text{CO}_2 \text{ at } T_{\text{mean}} = p \text{CO}_2 \text{ mod} \cdot \exp[0.0423 \cdot (T_{\text{mod}} - T_{\text{mean}})],$$

(1)

where $T_{\text{mean}}$ and $T_{\text{mod}}$ are, respectively, the climatological annual mean and daily temperature (in °C) used in model runs.
The seasonal effect of temperature on pCO$_2$ is further estimated by attributing to the mean annual pCO$_2$ deduced from model runs (i.e. 360 ppm) a correction factor based on the difference between $T_{mod}$ and $T_{mean}$ as above. According to these calculations, the effect of biology on pCO$_2$, represented by the seasonal amplitude of pCO$_2$ values corrected to the mean annual temperature, is estimated at 350 ppm (150 ppm in May to 500 ppm in February). The effect of temperature change is less, 230 ppm (260 ppm in January-February to 490 ppm in July-August). The relative importance of the temperature and ‘net biology’ effect (T/B) is given by the ratio between the above seasonal amplitudes and is evaluated at 0.66. Thus, based on MIRO-CO$_2$ results we conclude that temperature contributed less to the seasonal pCO$_2$ variability of central BCZ in 1996–1999 than biological processes. However, in areas influenced by river inputs of carbon and nutrients such as BCZ, the approach of Takahashi et al. (2002) includes their impact in the so-called ‘net biology’ effect.

As an alternate approach to resolve these contributions, we compared MIRO-CO$_2$ reference 1996–1999 simulations of the seasonal evolution of surface water pCO$_2$ in BCZ and the related annual air-sea CO$_2$ fluxes (Fig. 7a) with those obtained by closing separately biological processes, Phaeocystis only (Fig. 7b) and the river inputs of organic and inorganic carbon (Fig. 7c). For the latter scenario the river nutrient inputs were maintained. A supplementary MIRO-CO$_2$ scenario with closing both biological processes and river inputs of carbon was conducted to extract the solely thermodynamic effect of temperature change on pCO$_2$ (Fig. 7d).

Suppressing biological processes predicts in BCZ a significant annual source of atmospheric CO$_2$ (+0.53 mol C m$^{-2}$ y$^{-1}$, Fig 7b). This suggests that biology is responsible for the annual sink predicted in BCZ (Fig 7a) by taking up to 0.7 mol C m$^{-2}$ y$^{-1}$ of atmospheric CO$_2$. In the absence of biology, seasonal evolution of water pCO$_2$ is mainly determined by temperature and water CO$_2$ super-saturation with respect to the atmosphere is simulated in summer (Fig 7b) when water temperature is elevated (Fig 6b). Additional comparison with scenarios closing separately Phaeocystis colonies estimates at more than 50% the contribution of their bloom to this uptake (−0.47 mol C m$^{-2}$ y$^{-1}$, Fig. 7b). Comparison with the reference run (Fig. 6a) indicates that the simulated water CO$_2$ under-saturation in spring is mainly associated with Phaeocystis colony growth. Spring diatoms also contribute to spring water CO$_2$ undersaturation (Fig 7b) but to a lesser extent. Suppression of river inputs of organic and inorganic carbon has no detectable influence on the seasonal evolution of pCO$_2$ but increases significantly the annual CO$_2$ sink obtained with the reference run (Fig 7a, c). River inputs of carbon thus represent a significant source of atmospheric CO$_2$ (+0.87 mol C m$^{-2}$ y$^{-1}$) that is partly counter-acted by biology on an annual scale (−0.7 mol C m$^{-2}$ y$^{-1}$). Finally our scenarios predict an annual sink of atmospheric CO$_2$ of −0.32 mol C m$^{-2}$ y$^{-1}$ associated to the seasonal signal of temperature only (Fig. 7d). All together these scenarios shows the predominance of different controls of pCO$_2$ and air-sea CO$_2$ exchanges in central BCZ along the season. Clearly river inputs of carbon are responsible for the simulated emission of CO$_2$ to the atmosphere in late winter, counteracting the effect of decreasing temperature (Fig. 7c, d).
d). NEP mostly that associated to *Phaeocystis* colonies explains the predicted CO₂ sink in spring which, under these conditions of temperature should have been a CO₂ source towards the atmosphere (Fig. 7a, b). During summer, temperature first and then C remineralization are the most important controls (Fig. 7b, d).

3.4 Role of land-based nutrients

In order to better appraise the role of land-based nutrients and carbon in modulating the seasonal cycle of surface water pCO₂ and air-sea CO₂ fluxes, we compared model results in central BCZ with those obtained for the WCH boundary conditions (Fig. 8). For this purpose simulations of pCO₂ (Fig. 8a) and air-sea CO₂ exchanges (Fig. 8b) in both areas were compared with the temperature forcing (Fig. 8c) and the simulated NEP (Fig. 8d). In the WCH, a fairly good agreement is observed between daily simulations of pCO₂ and available field data (Fig. 8a). As a general trend surface water pCO₂ in WCH is driven by temperature variation, being under-saturated with respect to the atmosphere between October and mid-March and over-saturated during spring-summer (Fig. 8a). Over the latter period, two small decreases in pCO₂ are simulated, coinciding with events of elevated NEP (Fig. 8d) that are counteracting the effect of temperature increase (Fig. 8a, c, d). However and contrary to BCZ, the simulated pCO₂ never reaches under-saturated values in spring due to the low productivity of WCH compared to BCZ (Fig. 8a). At the annual scale indeed BCZ is net autotrophic (integrated NEP=+0.38 mol C m⁻² y⁻¹) while WCH is close to metabolic balance (integrated NEP ~0 mol C m⁻² y⁻¹). Accordingly, WCH is almost in equilibrium with respect to atmospheric CO₂ (~0.01 mol C m⁻² y⁻¹; Fig. 8b) when BCZ acts as a sink for atmospheric CO₂ (~0.17 mol C m⁻² y⁻¹).

Applying the approach of Takahashi et al. (2002) to WCH simulations allows us to conclude that temperature variation over the year contributes more to pCO₂ seasonal variation than biology (T/B=1.21). Comparing this result with T/B obtained in BCZ (0.66) points to the major contribution of nutrient river inputs (i.e. coastal eutrophication) in counteracting the temperature control on surface water pCO₂.
Table 1. Comparison between annual integrations of air-sea CO$_2$ fluxes, gross primary production (GPP), respiration (R) and net ecosystem production (NEP) computed for the reference run (1996–1999) and those obtained with separate modification to the reference of 1996 and 1999 river nutrient and carbon loads or temperature or wind speed forcing. The relative importance of temperature and biology effect on pCO$_2$ is expressed by the ratio T/B.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Air-sea CO$_2$ flux, mol C m$^{-2}$ y$^{-1}$</td>
<td>−0.17</td>
<td>−0.20</td>
<td>−0.14</td>
<td>−0.24</td>
</tr>
<tr>
<td>GPP, mol C m$^{-2}$ y$^{-1}$</td>
<td>18.8</td>
<td>18.8</td>
<td>18.8</td>
<td>17.2</td>
</tr>
<tr>
<td>R, mol C m$^{-2}$ y$^{-1}$</td>
<td>18.4</td>
<td>18.4</td>
<td>18.4</td>
<td>16.9</td>
</tr>
<tr>
<td>NEP, mol C m$^{-2}$ y$^{-1}$</td>
<td>+0.38</td>
<td>+0.38</td>
<td>+0.38</td>
<td>+0.32</td>
</tr>
<tr>
<td>T/B</td>
<td>0.66</td>
<td>0.66</td>
<td>0.65</td>
<td>0.68</td>
</tr>
</tbody>
</table>

3.5 Sensitivity to external present-day forcings

In this section we explore to what extent changing meteorological conditions (rainfall, river discharge, temperature, wind stress) could alter the seasonal and annual dynamics of pCO$_2$ in coastal waters. For this application, we choose to compare MIRO-CO$_2$ reference simulations relative to the 1996–1999 climatological year with results obtained when running the model with changing one by one either the river inputs of carbon or the water temperature or the wind speed forcing corresponding to the most contrasted “meteorological” years for the period (the dry 1996 and wet 1999 year). For each simulation, the other forcing were maintained equal to the reference 1996–1999 mean value. Over 1996–1999, nutrient loads were very variable, modulated by freshwater discharge that was higher in 1999 compared to 1996 (Fig. 9a). Nutrient concentrations in the Seine and Scheldt rivers were indeed unchanged over this period. Similarly, concentrations of organic and inorganic carbon were assumed constant. Significantly higher temperatures were observed in 1999 compared to 1996, especially between January and August (Fig. 9b). Daily wind speeds were quite variable with however a similar annual average of 6.25 and 5.16 m s$^{-1}$ in 1996 and 1999, respectively (Fig. 9c).

The relative impact of each forcing was explored based on a comparison of modelled pCO$_2$ along the season (Fig. 10) and MIRO-CO$_2$ annual budget of biological activity (GPP, R and NEP) and air-sea CO$_2$ flux (Table 1). Generally, the seasonal trends and magnitude of pCO$_2$ variations were not significantly modified. However, significant changes in the intensity and direction of the annual air-sea CO$_2$ flux were simulated (Table 1).

3.5.1 Wind speed forcing

We found a negligible effect of wind speed on the seasonal cycle of pCO$_2$ (Fig. 10a), since this forcing does not control NEP and temperature in our model (Table 1). Still, these model scenarios reveal that the daily variations of wind speed impacted significantly on the annual budget of air-sea CO$_2$ (18%; Table 1). The largest sink is predicted in 1996 (−0.2 mol C m$^{-2}$ y$^{-1}$, Table 1) and corresponds to lower gas transfer velocity, (8.38 and 8.58 cm h$^{-1}$ (normalized to a Schmidt number of 600) in 1996 than in 1999, respectively).

3.5.2 River forcing

Comparison of seasonal simulations of water pCO$_2$ obtained with 1996 and 1999 river loads, shows for 1996 lower values between January and March, similar in May and higher from May to August (Fig. 10b). The lower late winter pCO$_2$ simulated in 1996 are mostly due to the lower DIC river inputs as biological activity in winter is low. The initial winter pCO$_2$ value in 1996 also probably explains why minimal pCO$_2$ values simulated in spring are very similar for both years (Fig. 10b), although the maximum NEP value obtained during the Phaeocystis bloom is higher in 1999 than 1996 (0.28 mol C m$^{-2}$ d$^{-1}$ in 1996 compared to 0.21 mol C m$^{-2}$ d$^{-1}$ in 1999, not shown).

On an annual base we calculated a lower sink for atmospheric CO$_2$ in 1999 compared to 1996 (Table 1) which contrasts with the elevated NEP simulated in 1999 (Table 1) in response to the higher riverine nutrient inputs. This has to be related to the higher DIC river inputs in 1999 that induce higher initial pCO$_2$ values in winter (Fig. 10b). Altogether this scenario points the dual role of river inputs on the seasonal dynamics of pCO$_2$ in eutrophied coastal waters by modulating their carbon and nutrient conditions.

3.5.3 Temperature forcing

Clearly, the difference in time and magnitude of surface water pCO$_2$ simulated in 1996 and 1999 (Fig. 10c) corresponds with temperature records deviation over the period January–July (Fig. 9b). Over this period temperature is significantly higher in 1999 than in 1996 (~3°C, Fig. 9b). In order to eliminate the temperature effect, modelled pCO$_2$ were normalized to the mean BCZ temperature (11.9°C, Fig. 10d). From January to February, the lower pCO$_2$ simulated in 1996 are clearly due to lower temperature compared to 1999.
156 N. Gypens et al.: Carbon dynamics and CO\textsubscript{2} air-sea exchanges in the Southern Bight of the North Sea

(Fig. 10d). The 9 days delay obtained for the minimal simulated pCO\text sub{2} values in spring (Fig. 10d) is related to the late onset of Phaeocystis bloom in 1996 as a consequence of the temperature dependence of GPP. On an annual base, NEP is lower in 1999 than in 1996 (Table 1), in spite of a higher GPP in 1999 than in 1996 (Table 1), due to the stronger temperature dependence of heterotrophic processes.

The shift from an annual sink in 1996 to a source in 1999 of atmospheric CO\textsub{2} (Table 1) is related to a combination of temperature effect on the carbon chemistry and biology (increased respiration at higher temperature). Their relative importance can be assessed through the calculation of the T/B i.e. the ratio between ΔpCO\textsub{2} (temp) and ΔpCO\textsub{2} (bio) (Table 1). This suggests a higher temperature effect on biology than carbon chemistry. Indeed the T/B increase from 0.68 in 1996 to 0.69 in 1999 (Table 1) is due to a higher difference between ΔpCO\textsub{2} (bio) (362 ppm in 1996 compared to 353 ppm in 1999) than ΔpCO\textsub{2} (temp) (247 ppm in 1996 and 244 ppm in 1999).

4 Conclusions

The MIRO-CO\textsub{2} simulations, by showing stronger seasonal signals of pCO\textsub{2} and related air-sea CO\textsub{2} fluxes in the carbon and nutrient-enriched BCZ compared to more oceanic waters (WCH), is giving additional support to observation-based conclusions on the key role of coastal areas in the global carbon cycle (e.g. Frankignoulle and Borges, 2001a). We also demonstrated the advantage of model simulations and sensitivity analysis for the identification of the major physical and biological mechanisms controlling the seasonal dynamics of surface water pCO\textsub{2} and their external forcing. In particular, we highlighted the significance of the Phaeocystis bloom in the spring-time draw-down of atmospheric CO\textsub{2}. The model also allows us to explore how the intensity and direction of the annual air-sea CO\textsub{2} flux was changed in relation to realistic variations of environmental forcing such as water temperature, fresh water discharge or wind speed.

Model results revealed that the seasonal variation of pCO\textsub{2} in the BCZ is strongly driven by nutrient-enriched biological activity in spring that counteracts the effect of temperature increase. On an annual scale for the 1996–1999 period, the solely river inputs of organic and inorganic carbon are driving a source of CO\textsub{2} of +0.87 mol C m\textsuperscript{-2} y\textsuperscript{-1} that is balanced by an atmospheric CO\textsub{2} uptake of −0.7 and −0.32 mol C m\textsuperscript{-2} y\textsuperscript{-1} due to nutrient stimulated NEP and temperature change, respectively. Globally an annual weak sink is predicted for BCZ. However, based on a sensitivity analysis, we also showed that the present-day interannual variations of fresh water discharge (and related land-based nutrient and carbon inputs) and water temperature might have a significant impact on the air-sea CO\textsub{2} fluxes in the BCZ.

These simulations clearly illustrate the potentially significant but complex variations of CO\textsub{2} fluxes in near-shore coastal ecosystems in response to small environmental changes within the range of present-day variability. These variations in CO\textsub{2} fluxes are a small glimpse of those that can be expected from environmental changes predicted in the near future in context of global change and/or management strategies.

Acknowledgements. This work was carried out in the framework of the Belgium Federal Science Policy projects AMORE (EV/11/19) and CANOPY (EV/03/20), the EU-FP5 project EUROTRroph (EVK3-CT-2000-00040) and the project 2.4545.02 of the Fonds National de la Recherche Scientifique (FNRS). DIC and TA data in the Seine estuary were kindly provided by G. Abril (Département de Géologie et Océanographie, Université de Bordeaux 1). N. Gypens has financial support from the ‘Fond pour la Formation à la Recherche dans l’Industrie et dans l’Agriculture’ (FRIA, FNRS, Belgium). We also acknowledge the reviewers for their constructive feedback.

Edited by: J. Middelburg

References


Walsh, J. J. and Dieterle, D. A.: CO2 cycling in the coastal ocean, I – A numerical analysis of the Southeastern Bering Sea with applications to the Chukchi Sea and the northern Gulf of Mexico, Prog. Oceanog., 34, 335–392, 1994.

