

Interactive comment on “Carbon dynamics and CO₂ air-sea exchanges in the eutrophied coastal waters of the southern bight of the North Sea: a modelling study” by N. Gypens et al.

N. Gypens et al.

Received and published: 5 December 2004

Answers to reviewer 1.

- Model reliability

We agree with the referee that it was difficult to judge on the reliability of the model without a proper description of the model runs and observations.

Model initialisation

In the revised version, key points of the biogeochemical MIRO model were added in section 2.1 and model runs including initialisation has been specified in section 2.2 as follows:

“The MIRO-CO₂ model was applied in the coastal domain of the eastern English Chan-

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nel 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 cumulated 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 adjacent 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 existing 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 calculated by solving the equations expressing mass conservation, according to the Euler procedure, with a time step of 15 minutes. Conservation equations and parameters are detailed in Lancelot et al. (2004).”

Normalisation of observations to model temperature and salinity

For a first application of the complex biogeochemical model we choose a simplified multi-box representation of the hydrodynamics of the studied area. Model boxes are assumed thermo-hydrodynamically homogeneous and each box is characterized by mean physical properties. A constant salinity of 33.5 has been calculated for the Belgian coastal box BCZ. This salinity corresponds to the long-term mean salinity measured at the reference station 330 located in the central BCZ. In the same way, an annual temperature cycle was imposed for each box and was constructed based temperature 5-day averages for the period 1996-1999. Available total alkalinity and pCO₂ observations correspond to occasional sampling at station 330 with the corresponding

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salinity and temperature values which can deviate from that of the model (1.4 and 4°C respectively for salinity and temperature). In order to take into consideration the discrepancy between field salinity and that imposed in the model, field data of DIC and alkalinity were normalized to the model salinity. The normalized DIC and alkalinity are written DIC33.5 and Alk33.5. On the same way, pCO₂ data were corrected for the model temperature. This section has been improved in the revised version (section 2.3) and a figure showing the discrepancy between model and observed temperature and salinity deviation with respect to 33.5 has been added.

“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. In the same direction, 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 DIC33.5 and Alk33.5.”

- Seasonal evolution of DIC and alkalinity

We agree with the referee that our model is unable to accurately capture the magnitude of DIC and total alkalinity in winter and late fall. The revised version now includes a sensitivity test with changing initial conditions as an attempt to explain the discrepancy between model results and data. However, these discrepancies have no influence on the magnitude and seasonal evolution of the modelled pCO₂ which is mainly driven by biological processes in this coastal area (see Figs. 5a,b). The added text is:

“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. 4 a,b). Elevated modelled TA in fall could result from an overestimation

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of river inputs during this period. At that time of the year (October to January), river discharge is high and inputs of TA contribute to 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 are due to the structure of the model since initial conditions are not forced in the BCZ but result from the transformations of chemical water properties from the WCH (model initial conditions) due to river inputs and biological activity during transport through the FCZ and BCZ boxes. Altogether, these discrepancies between observed and modelled DIC and TA have no influence on the magnitude and seasonal evolution of the modelled pCO₂.”

- pCO₂

Modelled pCO₂ results from model simulations without tuning of parameters. The computation procedure was detailed in section 2.1. as follows:

“The physico-chemical module of Hannon et al. (2001) details the carbonate system in seawater and calculates CO₂ exchange between the surface water and the atmosphere. The speciation of the carbonate system (in particular pCO₂) is calculated based on the knowledge of only 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 CO₂ fluxes are calculated from the pCO₂ 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.”

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All minor comments were considered and clarified

Reviewer 1's second minor comment has been almost fully addressed by the reply to a similar comment by Wei-Jun Cai (see below). Concerning the additional comment that "Cai et al. (2003) clearly describe a sink for atmospheric CO₂ in their overall system and not a source" : this is true when looking at CO₂ fluxes in both aquatic and terrestrial compartments; however, Cai et al. (2003) also clearly show that the aquatic compartment is unambiguously a source of CO₂ to the atmosphere while the terrestrial one is a (stronger) sink for atmospheric CO₂. Since our paper deals with CO₂ fluxes in aquatic systems it is obvious that we are talking in the introduction about CO₂ fluxes in aquatic systems (the first sentence of introduction starts with "coastal waters"). This has nevertheless been clarified in the text.

We are grateful to reviewer 1 for his/her constructive comments on our manuscript and we hope we answered most of his/her questions.

Answers to reviewer W.-J. Cai.

- Model description and implementation

We agree with Dr Cai that, without any description of the model, it was difficult to understand and evaluate the model results. Revised version of the manuscript now, includes a short description of concepts behind the complex biogeochemical MIRO model (§2.1) and some details on the model implementation and runs (§2.2), as follows:

"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 (NO₃, NH₄, PO₄ and SiO), 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

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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).

2.2 Model runs

The MIRO-CO₂ 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 cumulated 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 adjacent 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 existing 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

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estimated from existing data in the area for the 1996-1999 period (Borges and Frankignoulle, 2003). The seasonal variation of the state variables was calculated by solving the equations expressing mass conservation, according to the Euler procedure, with a time step of 15 minutes. Conservation equations and parameters are detailed in Lancelot et al. (2004).”

In the meantime the manuscript “Modelling diatom-Phaeocystis blooms and nutrient cycles in the Southern Bight of the North Sea with focus on the Belgian coastal zone: the MIRO model” by C. Lancelot, Y. Spitz, N. Gypens, K. Ruddick, S. Becquevort, V. Rousseau, G. Lacroix, G. Billen, has been accepted for publication in MEPS on 9th November 2004 (<http://www.int-res.com/journals/meps/mepsForthcomingphp.php>). If the reviewer would like more information on equations and parameter values, a pdf version of the accepted manuscript is available on request to the first author.

- Detailed comments

1. DIC and TA reliability

We agree that model results of DIC and TA have not been sufficiently discussed in the first version of the manuscript. The section 3.1.2 entitled ‘Carbonate chemistry’ has now been extended with a discussion on possible reasons for the elevated DIC and TA simulated in winter and fall. This section also includes a sensitivity analysis with varying initial conditions in the boundary box.

“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. 4 a,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 contribute to 45 % of annual river loads. Due to the importance of biological processes on magnitude and seasonal variability of DIC,

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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 are due to the structure of the model since initial conditions are not forced in the BCZ but result from the transformations of chemical water properties from the WCH (model initial conditions) due to river inputs and biological activity during transport through the FCZ and BCZ boxes. Altogether, these discrepancies between observed and modelled DIC and TA have no influence on the magnitude and seasonal evolution of the modelled pCO₂.”

2. Takahashi et al. (2002) separate the seasonal effect of ‘net biology’ from that of temperature on the seasonal pCO₂ cycle. As defined by these authors the ‘net biology’ effect includes the effect of biological processes, total alkalinity variation due to nitrate utilization, air-sea exchange of CO₂ and an addition of DIC and total alkalinity by external forcing (river inputs in the present study). We are aware that there is a non-conservative behaviour of pCO₂ when DIC and TA are diluted. However, the range of salinity of the observations is rather small (34.9 to 35.2 in the Western Channel box and 32.7 to 34.7 for the Belgian coastal zone box, at the station 330), thus, this effect can be neglected for the model purposes and derivation of the ratio of temperature/biology effects on pCO₂. Furthermore, Takahashi et al. (2002) clearly state: “This [temperature effect on pCO₂] is nearly independent of temperature and chemical composition (i.e. alkalinity/total CO₂ ratio) of seawater, and may be considered constant.”

3. In the studied area the mean residual circulation is flowing SW-NE. Hence the WCH is located upwards and has negligible river input. It is considered has a quasi oceanic closed system and provides initial conditions for the downward FCZ box. An more detailed description of model implementation and runs is provided in section 2.1.

4. Considering that modelled pCO₂ is mainly driven by biological processes, river inputs and temperature, the integrated flux computed from simulations obtained when running the model without biology and river inputs evaluates the only thermodynamic effect of temperature.

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5. A negative relationship between DIC and discharge has been found in some aquatic systems usually the most pristine ones. From our large data set of DIC in the Scheldt estuary (more than 20 cruises between 1993 and 2003), we did not find a conclusive relationship. This is probably related to the highly polluted nature of this estuary where biogeochemical cycling in tributaries is highly dynamic and complex (e.g. Abril & Frankignoulle 2001). Finally, note that model uses the inputs from the estuary to the BCZ (using the AZE method) and not the river inputs per se. Thus even under changes of DIC inputs with river discharge in the freshwater reaches, these will to some extent be “smoothed” during estuarine transit. TA and DIC concentrations were assumed constant but loads change due to changes in fresh water discharge.

6. The relative contributions of the submitted manuscript are wrong and probably result from some mismatch in the model result transcription. Relative contributions of biological, river inputs and temperature to the C budget have been corrected in revised version. However, the sum of the separate contribution of biological processes, river inputs and temperature is not exactly equal to $-0.17 \text{ mol C m}^{-3}$. Remineralization of organic carbon supplied by rivers explains this difference. Through biological mineralization processes, river input of organic carbon generates an indirect input of DIC, which is already estimated and counted in the biological processes contribution.

All specific comments have been taken into consideration to improve the manuscript.

We are grateful to W.-J. Cai for his interest and his comments on the manuscript. We hope we answered most of his questions.

Answers to reviewer W.-J. Cai.

Although this manuscript specifically deals with biogeochemical modelling in a temperate near-shore coastal system, we feel that it is nevertheless important to place this study in the framework of the emerging picture of global CO₂ fluxes in the Coastal Ocean. In particular, it seems important to the authors to stress the geomorphological and ecological diversity of the Coastal Ocean in C and CO₂ cycling and biogeochem-

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ical cycles in general. This complexity is a stimulating challenge to those who attempt global integration of CO₂ fluxes in one of the most biogeochemically active regions of the biosphere. We do not agree with Dr. Cai when he states that the latitudinal variability of CO₂ fluxes we describe in the Introduction is “speculative”. This is based on a recent and careful literature survey of CO₂ dynamics in coastal aquatic systems (Borges 2004) that is to a large extent confirmed by another similar and independent literature survey (Ducklow & McAllister 2004). We are in fact surprised that Dr. Cai considers our introduction “speculative” when incidentally it is along the lines of his recent technical comment (Cai and Dai, 2004).

Answers to reviewer 3.

- Multi-box model implementation

We agree that application of the biogeochemical MIRO model in a model-box configuration constitutes a simplification of the Southern North Sea physical environment. However, we are convinced that box implementation of complex biogeochemical models still constitute useful tools to investigate mechanisms of ecosystem functioning and the related biogeochemical cycles. In a deep stratified environment, the description of water depth is needed to correctly describe depth dependant-processes and biological response. However, this is not true in a tidally permanently well-mixed coastal environment, like considered in our box-model for both the French coastal zone and the Belgian coastal zone. For the application of the MIRO-CO₂ model to the continental coastal waters of the North Sea, a multi-box frame has been considered based upon the hydrological regime. The offshore limit of the boxes is taken along a residual streamline so that inshore-offshore exchanges by residual advection can be neglected and the residence time of water masses in each box was calculated based on water fluxes and salinity. A simplified description of the biogeochemical MIRO model was added to the manuscript (Section 2.1).

- MIRO model

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Equations and parameterization of the MIRO model is fully detailed in the manuscript “Modelling diatom-Phaeocystis blooms and nutrient cycles in the Southern Bight of the North Sea with focus on the Belgian coastal zone: the MIRO model” by C. Lancelot, Y. Spitz, N. Gypens, K. Ruddick, S. Becquevort, V. Rousseau, G. Lacroix, G. Billen, accepted for publication in MEPS. Parameters and forcing functions have been estimated based on independent targeted process-level studies performed under field and/or laboratory conditions over the last 20 years and on a review of literature on Phaeocystis ecology and physiology (Schoemann et al. 2004). If the reviewer would like more information on equations and parameter values, we propose to send him a pdf version of the accepted manuscript. We consider that, despite the hydrodynamic simplification, the ecological MIRO model gives a correct description of ecosystem dynamics in the Eastern English Channel and Southern Bight of the North Sea. Indeed, it quite well reproduces the observed SW-NE nutrient gradient in nutrients and biomass (shown in Lancelot et al., 2004) and reasonably well resolves the diatom-Phaeocystis-diatom and heterotrophs successions in time and magnitude (Fig.3). However, we agree with the reviewer that the hydrodynamic processes could not be fully resolved and that this coarse resolution represents a first approach in this area. Implementation of the biogeochemical MIRO model in the 3D physical model of Lacroix et al. (2004) is in progress.

- Data assimilation

The objective of our numerical work is to understand mechanisms controlling the seasonal evolution of pCO₂ in the studied area and identify the relative contribution of physical and biological mechanisms on the magnitude of pCO₂ and not obtain the best reproduction of observations. Data assimilation was thus not required.

- The sediment loading

Water transparency is taken into account in the model by considering light attenuation by a mean suspended matter content for each box (thus reflecting river inputs of sedi-

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ments and sediment resuspension) and chlorophyll a concentration calculated at each time step from simulated phytoplankton (Lancelot et al., 2004).

- Seasonal evolution of DIC and total alkalinity

We agree with the referee that our model is unable to accurately capture the magnitude of DIC and total alkalinity in winter and late fall. The revised version now includes a sensitivity test with changing initial conditions as an attempt to explain the discrepancy between model results and data. However, these discrepancies have no influence on the magnitude and seasonal evolution of the modelled pCO₂ which is mainly driven by biological processes in this coastal area (see Figs. 5a,b).

“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. 4 a,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 contribute to 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 are due to the structure of the model since initial conditions are not forced in the BCZ but result from the transformations of chemical water properties from the WCH (model initial conditions) due to river inputs and biological activity during transport through the FCZ and BCZ boxes. Altogether, these discrepancies between observed and modelled DIC and TA have no influence on the magnitude and seasonal evolution of the modelled pCO₂.”

- Interannual variability

In section 3.5, our objective was to explore separately the effect of changing one forcing

(either the river discharge or the water temperature or the wind field) in the reference MIRO-CO2 simulations run with a climatological forcing calculated for the 1996-1999 period. In order to be realistic we choose to compare the effect of extreme events that occurred in the region during the simulated period. For this reason we choose years 1996 and 1999. This section has been carefully revised in order to improve understanding

We are grateful to reviewer 3 for his/her constructive comments on the manuscript and we hope we answered most of his/her questions.

References

Abril G. and Frankignoulle M. Nitrogen-alkalinity interactions in the highly polluted Scheldt basin (Belgium). *Water Research*, 35(3), 844-850, 2001.

Borges A.V. Do we have enough pieces of the jigsaw to integrate CO2 fluxes in the Coastal Ocean ? submitted to *Estuaries*, 2004

Cai, W.-J., Z. H. A. Wang, and Y. C. Wang. 2003. The role of marsh-dominated heterotrophic continental margins in transport of CO2 between the atmosphere, the land-sea interface and the ocean. *Geophysical Research Letters* 30(16): 1849-
doi:10.1029/2003GL017633.

Cai, W.-J. and Dai, M. Comment on “Enhanced Open Ocean Storage of CO2 from Shelf Sea pumping”. *Science* 306 (5701):1477c, 2004.

Ducklow, H. W. and S. L. McAllister. The biogeochemistry of carbon dioxide in the coastal oceans, in press, In K. H. Brink and A. R. Robinson (eds.) *The Global Coastal Ocean - Multiscale Interdisciplinary Processes*. Harvard University Press, 2004.

Lacroix G., Ruddick K., Ozer J. and Lancelot C. Modelling the impact of the Scheldt and Rhine/Meuse plumes on the salinity distribution in Belgian waters (southern North Sea). *J. Sea Res.*, 52(3):149-163, 2004.

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Lancelot C., Y. Spitz, N. Gypens, K. Ruddick, S. Becquevort, V. Rousseau, G. Lacroix, G. Billen. Modelling diatom-Phaeocystis blooms and nutrient cycles in the Southern Bight of the North Sea with focus on the Belgian coastal zone: the MIRO model., accepted for publication in Mar. Ecol. Prog. Ser., 2004.

Schoemann V, Becquevort S, Stefels J, Rousseau V, Lancelot C. Phaeocystis blooms in the global ocean and their controlling mechanisms: a review. J Sea Res in press, 2004

Interactive comment on Biogeosciences Discussions, 1, 561, 2004.

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1, S411–S424, 2004

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