

## ***Interactive comment on “Carbon dynamics and CO<sub>2</sub> 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.**

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We are grateful to A. Lerman and F.T. Mackenzie for their interests and their constructive comments on our manuscript.

We agree with A. Lerman and F.T. Mackenzie that the surface area of inner estuaries is relatively small ( $0.94 \cdot 10^6 \text{ km}^2$ , Woodwell et al. 1973) compared to the remaining continental shelf ( $26 \cdot 10^6 \text{ km}^2$ , Gattuso et al. 1998), however, the air-water CO<sub>2</sub> fluxes are usually one order of magnitude higher than over continental shelves (refer to review by Abril & Borges 2004), whether the latter are sources or sinks of CO<sub>2</sub>. Thus, the overall emission of CO<sub>2</sub> from estuaries could be significant for the overall budget of CO<sub>2</sub> in the Coastal Ocean. Also, the surface area of outer estuaries (or river plumes) is usually higher than the one of inner estuaries. For instance in the Scheldt whole estuarine system, the surface area of the outer estuary is about 2000 km<sup>2</sup> (Borges & Frankignoulle 2002) while the one of the inner estuary is about 200 km<sup>2</sup> (e.g. Abril et al. 2000). Also, Körtzinger (2003) estimates that the surface area of the Amazon

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outer estuary alone is about  $2.4 \cdot 10^6$  km<sup>2</sup> extending into the open oceanic waters and thus efficiently links the Coastal Ocean to the Open Ocean. This confirms that (inner and outer) estuaries are important features of the carbon cycling of the Coastal Ocean. Also, it has been suggested and fairly well argued that biologically available organic carbon delivered by the terrestrial realm is degraded in rivers and estuaries and does not reach the distal continental shelf nor the deep ocean (refer to review by Richey 2004). This would imply that degradation of organic matter and ventilation of the corresponding CO<sub>2</sub> occurs in near-shore systems, in particular estuaries.

Concerning the role of CaCO<sub>3</sub> in CO<sub>2</sub> cycling in the Coastal Ocean, there is an ample literature on the link between calcification and CO<sub>2</sub> fluxes in coral reef ecosystems, that clearly highlight the importance of this process in carbon cycling at tropical and subtropical latitudes of the Coastal Ocean (Gattuso et al. 1993; Kayanne et al. 1995; Frankignoulle et al. 1996; Gattuso et al. 1997; Kawahata et al. 1999; Bates et al. 2001; Suzuki et al. 2001; Bates 2002; Suzuki and Kawahata 2003).

We agree with A. Lerman and F.T. Mackenzie that CaCO<sub>3</sub> dynamics have been to some extent overlooked at temperate latitudes, although Borges & Frankignoulle (2003) show that in the English Channel the amount of CO<sub>2</sub> fixed annually by pelagic new production is equivalent to the amount of CO<sub>2</sub> released by calcification from extensive brittle star populations. This can explain why the English Channel is neutral from the point of view of air-water CO<sub>2</sub> annual exchange and is not a significant sink for CO<sub>2</sub> as other temperate marginal non-upwelling seas (East China Sea - Tsunogai et al. 1999; North Sea - Thomas et al. 2004; Baltic Sea - Thomas and Schneider 1999, Gulf of Biscay - Frankignoulle and Borges 2001; Middle Atlantic Bight - DeGrandpre et al. 2002). Note that the English Channel is very shallow and characterized by a low new primary production, unlike the two adjacent systems (Gulf of Biscay and Southern Bight of the North Sea). Also, Abril et al. (2003) have recently shown the importance of CaCO<sub>3</sub> dynamics in CO<sub>2</sub> cycling in a temperate estuary (the Loire). Hence, there evidence based on field data that in some temperate systems CaCO<sub>3</sub> dynamics are important

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in the overall CO<sub>2</sub> atmospheric exchanges.

Moreover, this certainly requires further research in particular in relation to role of pelagic calcification and CO<sub>2</sub> fluxes, although pelagic blooms of calcifying organisms are transient events and highly heterogeneous in space, making the acquisition of field data difficult, but probably highly significant.

Recently, mesocosm experiments have also shown that the predicted increase of atmospheric CO<sub>2</sub> in the next 100 years will have some very interesting and highly complex implications (and feedbacks) on both CaCO<sub>3</sub> and organic carbon dynamics of coccolithophorids. These experiments clearly show that the future increase CO<sub>2</sub> in water column will have a much more complex effect than “simply” decreasing the CaCO<sub>3</sub> saturation level and decreasing calcification rates as described to-date in some prognostic models (refer to the publications of the PEECE (Pelagic Ecosystem CO<sub>2</sub> Enrichment Study) project at <http://spectrum.ifm.uni-kiel.de/peece/references.htm>).

Concerning our own study site, we did not explicitly include CaCO<sub>3</sub> dynamics in the model simply because the data do not suggest that this process is significant. The Chemical Oceanography Unit of the University of Liège has carried out more than 30 cruises (to be honest we lost count!) in the Scheldt outer estuary, and a conservative behavior of total alkalinity against salinity has been observed in the very large majority of cruises. When exceptionally non-conservative behavior was observed, the total alkalinity versus DIC slope shows that it is related to aerobic respiration processes due to the release of nutrients, as confirmed by nutrient data when available (note that this reasonably well simulated in the model, refer to Figure 3b).

We can conclude that the rates of CaCO<sub>3</sub> precipitation or dissolution are too slow or the water residence time is too short or the overall volume of water is too large (or a combination of the latter three), for CaCO<sub>3</sub> dynamics to significantly affect the water column DIC chemistry. However, we do not deny the importance of CaCO<sub>3</sub> dynamics in coastal ecosystems but we simply do not “see” it in the data of our study site. Thus,

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it would have been impossible to validate a CaCO<sub>3</sub> module in the model.

Reply to specific comments:

1. The definition of the partial pressure of CO<sub>2</sub> (pCO<sub>2</sub>) is the classical one:  $p\text{CO}_2 = [\text{CO}_2^*]/a$  where  $[\text{CO}_2^*]$  is the concentration of CO<sub>2</sub>\* (CO<sub>2</sub> + H<sub>2</sub>CO<sub>3</sub>) in seawater and  $a$  is the solubility coefficient and pCO<sub>2</sub> is expressed in parts per million by volume.

By assumption, the model boxes are thermo-hydrodynamically homogeneous. A constant salinity of 33.5 is attributed to the BCZ box. This salinity corresponds to the long-term mean salinity measured at the reference station 330 located in the central BCZ. In order to take into consideration the discrepancy between field salinity and that imposed in the model, field data of DIC and Alk were normalized to the model salinity. The normalized DIC and Alk are written DIC<sub>33.5</sub> and Alk<sub>33.5</sub>. This will be more explicitly described in the revised version.

2. The discussion will be improved to explicit the dual effect of temperature on the solubility CO<sub>2</sub> coefficient and the biological rates

3. In Fig 5 we explore separately and compare the impact of carbon river inputs and biological and thermodynamical processes on the modelled pCO<sub>2</sub>. For instances, in order to evidence the impact of the only biological activity, all physiological processes are suppressed, and the computed seasonal evolution of pCO<sub>2</sub> is then influenced by the only river inputs and thermodynamical process. In the same way, in order to evidence the impact of organic and inorganic carbon river loads, these inputs are closed, and modelled pCO<sub>2</sub> results from temperature variability and biological processes sustained by Atlantic and benthic inputs. When both river input and biological processes are suppressed, the modelled pCO<sub>2</sub> seasonal evolution is mainly driven by the seasonal temperature variability.

4. Water temperature, wind speed and river inputs are the forcing functions of the

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model. There are derived from either meteorological station (wind) or calculated from time-series (weekly seawater temperature at station 330; monthly river inputs). Model results shown in Fig 5 and 6 were obtained making use of river loads, temperature and wind speed forcing averaged for the period 1996-1999. These results constitute the reference run of the paper. The effect of the year-to-year variability of the different forcing functions on the modelled pCO<sub>2</sub> is appraised by comparison with this reference run. Fig. 7 shows the seasonal cycle of (a) Scheldt fresh water discharge, (b) water temperature and (c) wind speed for specific 1996 and 1999 years. These years were contrasted with respect to temperature and river loads. In order to test and compare the impact of the interannual variability of each of these forcing of this forcing on the model response, different model runs were conducted making use of the 1996 and 1999 value for one of these forcing (Fig. 8). The other forcing is maintained equal to the reference 1996-1999 mean value. The sub-titles river carbon input, temperature and wind speed correspond to simulations where the respective forcing is modified. We will try to make it more clear in the revised version

5. A carbon budget table will be added in the revised version.

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