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Interactive Comment

Interactive comment on "The carbon budget of the North Sea" *by* H. Thomas et al.

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General comments

The authors' study of the present-day carbon budget in the North Sea is an excellent work that clearly identifies the external and internal carbon flows within a major body of water of the coastal ocean and addresses the dynamics of the interacting organic and inorganic carbon cycles. It is particularly significant that the authors analyze the carbon budget both as affected by the strong water exchange with the Atlantic as well as without the Atlantic influence, enabling them to quantify regional contributions such as those from the rivers and the Baltic Sea. The discussion of the relative roles played by salinity-stratification of the water column and by sea-floor topography in the overall carbon budget are significant aspects of cycle-analysis in a coastal environment.

The authors make a striking demonstration of how air-sea exchange of CO_2 changes both in magnitude and direction over relatively short distances within the North Sea basin. This makes one wonder how far away can CO_2 air-sea exchange fluxes be extrapolated from a measurement area, as reported by numerous investigators, including some of the co-authors of this paper (data compilation in Mackenzie et al., 2004)?

The variation in the atmosphere-seawater CO_2 flows either from or to the water reflects the global picture of such reversals on a bigger scale, where some oceanic regions emit CO_2 to the atmosphere and some are sinks of atmospheric CO_2. For example, the tropical oceanic region between about 15° S and 15° N emits CO_2 at a rate of 1 mol C m^{-2} yr^{-1}, whereas the global ocean as a whole is a CO_2 net sink of 0.6 mol C m^{-2} yr^{-1} (Takahashi et al., 2002). The sink strength of the North Sea, as reported by Thomas et al., is greater, 1.3 mol C m^{-2} yr^{-1}.

Heterotrophy and CO_2 air-sea flux

The authors point out that the North Sea is a heterotrophic system, where the organic carbon (DOC and POC) inputs of 4.35×10^{12} mol C yr^{-1} or 7.6 mol C m^{-2} yr^{-1} are greater than the outputs, 3.71×10^{12} mol C yr^{-1} or 6.5 mol C m^{-2} yr^{-1} (their Table 1). However, this trophic state does not in principle preclude seawater from being a CO_2 sink if the increase in atmospheric CO_2 is sufficiently strong and the air-sea flux is controlled not by simple mass-balance, but by such processes as, for example, an equilibrium partitioning of CO_2 (Bacastow and Keeling, 1973; Revelle and Munk, 1977; Ver et al., 1999; Andersson and Mackenzie, 2004; Mackenzie et al., 2004). As the authors state, the trophic status cannot by itself be used as an indicator of the direction of the air-sea exchange because the physics and biogeochemistry of the region also have to be considered. Furthermore, based on observations from the HOTs (HOTs, 2003; Winn et al., 1998) and BATS (Bates et al., 1996, 2001, 2002) programs, we know that surface water DIC is in fact not constant because of the rapid increase of atmospheric CO_2 owing to human activities, although this increase probably can be neglected on an annual basis.

The carbon balance based on Eqs. (1) and (2) in the Thomas et al. paper, as the authors point out, is a steady-state balance from which the CO_2 flux (F_A) between the water and atmosphere is calculated. Consequently, the input and output fluxes of carbon are assumed to be in balance. In addition, a steady state assumption implies that the total inorganic and organic carbon pools have remained steady and unchanged during the course of study. It is probably reasonable to assume that the hydrological budget of the North Sea is in fact in a steady state on annual and decadal time scales. However, if the similar assumption of Thomas et al. about the carbon budget were not true, the conclusions could be significantly different. Although it is admittedly very difficult, if not impossible, to distinguish between a steady and non-steady state of a shelf area without a long time-series of measurements, a more general formulation of the carbon budget should be considered (Mackenzie et al., 1998; Andersson and Mackenzie, 2004; Mackenzie et al., 2004). The main inputs to a shelf section of the ocean include dissolved inorganic and organic (DIC and DOC) and particulate organic carbon (POC) that are supplied by water flows, and the same components are also exported by water flows from the shelf area. Sedimentation removes inorganic carbon in the form of $CaCO_3$ that is produced in the water (assuming that no carbonate minerals are supplied by inflow) and POC that is in part brought from the land and in part produced in situ. The direction of the air-sea exchange would then depend on the algebraic sum of the input and output fluxes and any change in the carbon content of the system, as shown by the following equation for a non-steady state system:

$$F_A = (F_{dic} + F_{doc} + F_{poc})_{in} - (F_{dic} + F_{doc} + F_{poc})_{out} - (F_{carb} + F_{poc})_S - dC_T/dt \quad (1)$$

where F_A is the CO_2 flux across the air-sea interface (either positive or negative; in the above notation, F_A is positive for CO_2 evasion from sea water and all the other F terms are positive); C_T = C_{dic} + C_{doc} + C_{poc} is total carbon mass in seawater consisting of DIC, DOC, and POC; dC_T/dt is the change in total carbon within the system, and it is 0 at a steady state; subscripts in and out are inputs and outputs by inflows and outflows, respectively, and subscript S denotes sedimentation (in the Thomas et al. paper, F_S is used both for the carbon input via the Shetland Channel and for the

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output of organic carbon by sedimentation); and F_{carb} is a net rate of $CaCO_3$ deposition. Although carbonate sedimentation is not part of the North Sea carbon budget, it should be emphasized that $CaCO_3$ formation increases dissolved CO_2 concentration in seawater that in turn affects the conditions of the air-sea exchange. Net primary production, consisting of gross primary production minus autorespiration, and remineralization of DOC and POC are internal parts of the total carbon cycle, and these terms mutually cancel out in the derivation of the preceding Eq. (1). The preceding Eq. (1) with the term dC_T/dt = 0 is the carbon balance equation used by Thomas et al. Conceivably, it could lead to spurious conclusions regarding the carbon budget and the air-sea exchange of the North Sea if the steady state assumption were not correct. Hypothetically, if the organic carbon pool actually was increasing during the time of the Thomas et al. study, incorporating inorganic carbon and nutrients into the organic carbon pool, the North Sea could turn out being characterized as autotrophic rather than heterotrophic, depending on the relative magnitude of this increase.

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