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Mechanisms controlling the air–sea CO_2 flux in the North Sea

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ABSTRACT

The mechanisms driving the air–sea exchange of carbon dioxide (CO_2) in the North Sea are investigated using the three-dimensional coupled physical–biogeochemical model ECOHAM (ECOlogical-model, HAMburg). We validate our simulations using field data for the years 2001–2002 and identify the controls of the air–sea CO_2 flux for two locations representative for the North Sea's biogeochemical provinces. In the seasonally stratified northern region, net CO_2 uptake is high (2.06 mol m^{-2} a^{-1}) due to high net community production (NCP) in the surface water. Overflow production releasing semi-labile dissolved organic carbon needs to be considered for a realistic simulation of the low dissolved inorganic carbon (DIC) concentrations observed during summer. This biologically driven carbon drawdown outcompetes the temperature-driven rise in CO_2 partial pressure (pCO_2) during the productive season. In contrast, the permanently mixed southern region is a weak net CO_2 source (0.78 mol m^{-2} a^{-1}). NCP is generally low except for the spring bloom because remineralization parallels primary production. Here, the pCO_2 appears to be controlled by temperature.

1. Introduction

The role of coastal shelf seas in the exchange of CO_2 between atmosphere and ocean has been in the focus of many investigations over the past few years (Borges, 2005). Despite evidence of the shelf seas' significant contribution, global estimates of current and future ocean carbon uptake often neglect shelf areas (e.g. Takahashi et al., 2009). The North Sea and other shelf seas have been identified as continental shelf pumps, transferring atmospheric CO_2 into the ocean interior via physical and/or biological mechanisms (e.g. Tsunogai et al., 1999; Thomas et al., 2004; Borges et al., 2005). The mechanisms of this CO_2 uptake and their seasonality, however, are still poorly understood.

The North Sea constitutes of two biogeochemical provinces (Thomas et al., 2004): In the shallow southern North Sea, biological uptake and release of dissolved inorganic carbon (DIC) occur in a single compartment with a mixed water column throughout the year. As a result, after the initial DIC drawdown during the spring phytoplankton bloom the DIC remains at intermediate levels throughout the mixed water column (Fig. 1). In the seasonally stratified northern part, primary production draws down DIC in the surface mixed layer. Organic material sinks into the subsurface layer where remineralization releases DIC with no contact to the atmosphere. Low DIC levels prevail in the surface layer, while the DIC-enriched deeper waters are exported to the adjacent North Atlantic. In fall, mixing and remineralization restore uniform high winter DIC levels in both regions (Bozec et al., 2006). Weak annual net air–sea CO_2 fluxes have been reported for the southern regions, while the North has been identified as a strong sink for atmospheric CO_2 (Thomas et al., 2004).

In this study, we unravel the biogeochemical dynamics controlling the air–sea CO_2 fluxes in detail for two representative locations in the North Sea employing a three-dimensional coupled physical–biogeochemical ecosystem model.

2. Methods

2.1. The model

We use the three-dimensional ecosystem model ECOHAM (ECOlogical-model, HAMburg; Pätsch and Kühn, 2008), consisting of a biogeochemical model coupled to the hydrodynamical

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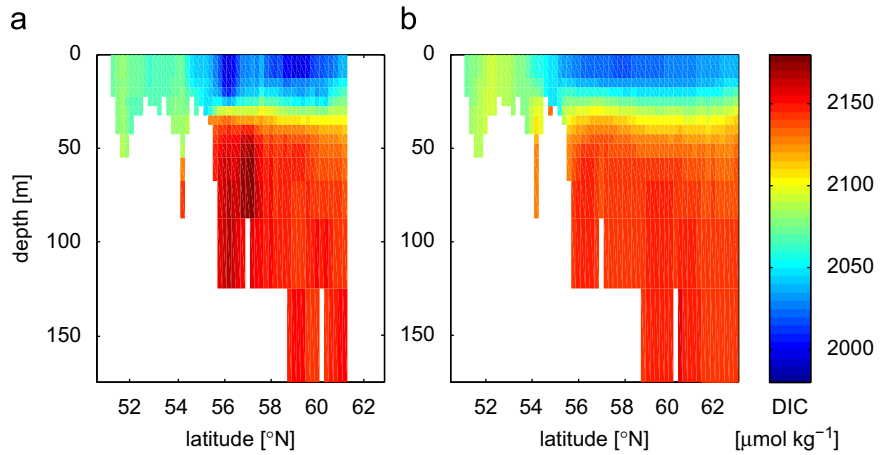

Fig. 1. Observed (a) and simulated (b) monthly mean DIC (µmol kg^{-1}) along a section at 2°E in August/September 2001.

HAMburg Shelf Ocean Model (HAMSOM; Backhaus, 1985; Pohlmann, 1996). Simulations for the years 2001–2002 comprise carbon (C), nitrogen (N) and oxygen cycles including state variables DIC, total alkalinity (TA), bulk phytoplankton, bulk zooplankton, bacteria, detritus and dissolved organic matter (DOM).

DIC is calculated prognostically while TA is restored to yield daily values. A relaxation time of 14 days allows for short-term variability. Restoring (TA) and initial values (DIC and TA) within the North Sea are taken from observational data (Thomas et al., 2005, 2009) obtained during four cruises in August/September 2001, November 2001, February 2002 and May 2002 at 97 stations on a $1^\circ \times 1^\circ$ grid (see Thomas, 2002 for details). For the adjacent regions of the North Atlantic, DIC initial and boundary conditions are taken from CDIAC (Carbon Dioxide Information Analysis Center: www.cdiac.ornl.gov; data from NDP 076). Here, above 100 m water depth DIC values are derived using the *T*–*S*–nitrate correlation proposed by Lee et al. (1999) with *T*, *S* and nitrate data from Conkright et al. (2002). The latter data are also used as boundary conditions for nitrate. TA initial and restoring values for the adjacent North Atlantic are taken from CDIAC NDP 076. For all other state variables, reflecting boundary conditions are used because of the lack of sufficient data. The model is forced by six-hourly wind stress, air pressure and temperature, humidity, cloudiness and six-hourly short wave radiation recalculated to two-hourly resolution. Data stem from the ERA-40 reanalysis data provided by the European Centre for Medium-Range Weather Forecasts with a spatial resolution of 1.125° (ECMWF, 2005). River inputs of DIC, particulate organic C and N, nitrate and ammonium are taken from Pätsch and Lenhart (2004) as daily data for the German, Dutch and Belgian rivers. For the Scandinavian and British river loads, data from Heath et al. (2005) representing annual loads of the year 1990 are used.

In the model, C- and N-cycles are coupled via several fixed C/N-ratios for phytoplankton, zooplankton and bacteria. Detritus and DOM have flexible C/N-ratios, since the C and N contents are simulated independent from each other.

2.2. Overflow production

Shifts in environmental factors such as light and nutrients can cause the excretion of organic carbon from phytoplankton cells (Mague et al., 1980). This extracellular release of organic carbon leads to the formation of high molecular dissolved organic matter with a negligible content of nitrogen ("overflow production", Fogg, 1983). This enhanced exudation of DOC is often observed when inorganic nutrients become depleted but photosynthesis continues. The excess DIC uptake without corresponding nutrient uptake is therefore also referred to as "carbon overconsumption" (Toggweiler, 1993), and facilitates a non-Redfield pathway for carbon fixation. As physiological basis, e.g. Geider and MacIntyre (2002) discuss the glycolate metabolism as a means of reducing oxidative stress at high irradiance (Kozaki and Takeba, 1996) due to photorespiration.

For the fate of the extracellular DOC from overflow production two pathways are discussed (Schartau et al., 2007). The excess DIC can be transferred to the labile DOC pool which is taken up by bacteria (e.g. Kähler and Koeve, 2001). Alternatively, a fraction of the exuded DOC consisting of polysaccharides can fuel the formation of transparent exopolymer particles (TEP; Mopper et al., 1995; Zhou et al., 1998). For *Phaeocystis* colonies, for instance, fixation of carbon well above the Redfield ratio is linked to increased production of mainly polysaccharidic mucilaginous matrix under low nutrient, high light conditions (see Bozec et al., 2006 and references therein), which again may lead to enhanced TEP formation (Mari et al., 2005). Field observations in various areas including the Northeast Atlantic and the English Channel show that the increase of DOC during the productive season significantly exceeds the corresponding DON increase multiplied by the Redfield ratio (Williams, 1990; Kähler and Koeve, 2001). The two pathways have different implications for export of carbon from the upper ocean depending on which form of carbon, DOC vs. POC, is finally produced.

This study intends to elucidate whether non-Redfield processes need to be taken into account for (future) modelling studies in highly dynamic ocean regions like shelf seas. Consequently, for this application C and N uptake by phytoplankton are decoupled to permit overflow production of C-rich, N-deplete DOM, while the formulation is deliberately kept simple.

Total net primary production (flux *dic_phc*) consists of a Redfield-based portion (NPP_{red}; flux dic_phc_{red}) and the overflow production (flux dic_phc_{exc})

$$dic\_phc = dic\_phc_{red} + dic\_phc_{exc}. \quad (1)$$

Nutrient-limited primary production is applied in both the phytoplankton C and N equations of state, applying the Redfield ratio for conversion between C and N units. It is formulated as Michaelis–Menten equation for two nutrients

$$dic\_phc_{red} = T_{fac} \cdot F_{light} \cdot v_P \cdot (Q1 + Q2) \cdot phc, \quad (2)$$