Estuarine, Coastal and Shelf Science 100 (2012) 38–57

Contents lists available at SciVerse ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

Interannual variability of carbon fluxes in the North Sea from 1970 to 2006 – Competing effects of abiotic and biotic drivers on the gas-exchange of CO_2

Ina Lorkowski*, Johannes Pätsch, Andreas Moll, Wilfried Kühn

Universität Hamburg (CEN-ZMAW), Institut für Meereskunde (IfM), Bundesstr. 53, 20146 Hamburg, Germany

ARTICLE INFO

Article history:
Received 19 October 2010
Accepted 21 November 2011
Available online 3 December 2011

Keywords:
North Sea
carbon budget
biological carbon pump
solubility carbon pump
shelf pump
ECOHAM

ABSTRACT

The three-dimensional biogeochemical model ECOHAM was applied to the Northwest European Continental Shelf (NECS) (47° 41′ – 63° 53′ N, 15° 5′ W – 13° 55′ E) for the years 1970–2006. The development of annual carbon fluxes was analysed for the North Sea as the inner shelf region. We divided the North Sea into several regions, the northern North Sea, the southern North Sea, the German Bight and the Southern Bight for a more detailed analysis. To separate the effect of physical and biological processes a second simulation without biology was performed. The results of our method for calculating the biological pCO_2 were in good agreement with the biological pCO_2 calculated after the method of Takahashi et al. (2002). While in the standard run the North Sea acted as sink for atmospheric CO_2, in the run without biology the North Sea was a continuous source for atmospheric CO_2.

The main drivers of the air-sea flux variability were identified as being temperature, net ecosystem production and pH. The eutrophication due to high riverine nutrient inputs during the 1980s had no significant effect on the air-sea flux of CO_2 because in contrast to net primary production, net ecosystem production did not respond to the period of higher phosphate input. The increase of sea surface temperature of 0.027 $^\circ C\ yr^{-1}$ over the simulation period and the pH decline of 0.002 yr^{-1} led to a decline of the uptake of atmospheric CO_2 by the North Sea of about 30% in the last decade of the simulation period. A special feature occurred in the year 1996, where a cold sea surface temperature anomaly led to an additional (physical) uptake of atmospheric CO_2 and corresponded with a low primary and net ecosystem production, which on the other hand led to less biologically induced uptake of CO_2.

Our results indicate an ongoing decline of the uptake capacity for atmospheric carbon dioxide of the North Sea for future scenarios.

1. Introduction

The detailed understanding of the global carbon cycle is of great importance in times of rising atmospheric CO_2 concentrations (IPCC, 2001). There has been increasing interest in understanding and quantifying the carbon fluxes in continental shelf seas and coastal areas (Borges and Gypens, 2010; Kühn et al., 2010; Liu et al., 2010; Omar et al., 2010) and their contribution to the oceanic uptake of atmospheric carbon dioxide. The effects of anthropogenic activities and the reaction of the marine ecosystem are more pronounced in shelf seas than in the open sea. Additionally, systematic observation-surveys (Thomas et al., 2004) and the establishment of long time series of measurements (Shadwick et al., 2011) are logistically easier in nearshore regions. Such efforts become globally relevant because one component of the carbon budgets is the CO_2 air-sea flux which may potentially result in the uptake of atmospheric CO_2 in shelf seas (Omar et al., 2010). The physically induced uptake, the biological fixation of inorganic carbon and the effective export of carbon into the adjacent deep ocean is called "continental shelf pump", a term firstly introduced by Tsunogai et al. (1999). The continental shelf pump mechanism has been applied to the South China Sea (Tsunogai et al., 1999) and the North Sea (Thomas et al., 2004; Bozec et al., 2005). Furthermore global estimates of the magnitude of the continental shelf pump have been carried out (Yool and Fasham, 2001; Thomas et al., 2004).

Our area of interest is the North Sea (NS) (511724 km^2) (Fig. 1), as part of the Northwest European Continental Shelf sea, constrained by the coastlines of Germany, the Netherlands and Belgium in the south, the United Kingdom in the west, and Norway and Denmark in the east. It is connected to the North Atlantic via the open north-western boundary and the English Channel and to the Baltic Sea via the Skagerrak. The North Sea can be divided into two parts, the permanently

---

* Corresponding author.
E-mail address: ina.lorkowski@zmaw.de (I. Lorkowski).

0272-7714/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ecss.2011.11.037

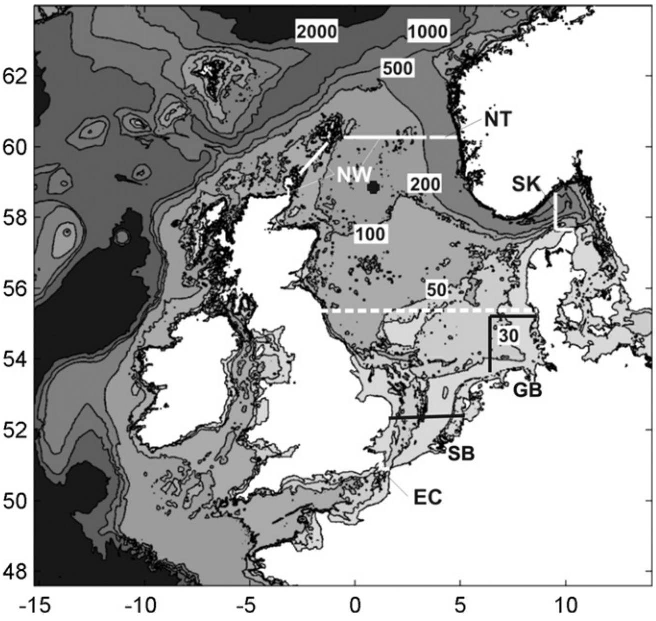

Fig. 1. Model area with bottom topography and boundaries of the North Sea which we used for budgeting (bold line). EC: English Chanel, SK: Skagerrak, NT: Norwegian Trench, NW: North-Western boundary. The boundary between southern and northern North Sea is indicated by the dashed line. The black lines indicate the subregions of the southern North Sea; GB: German Bight, SB: Southern Bight. The FLEX position is indicated by the black dot.

mixed shallow southern North Sea (SNS) (190760 km^2) which is strongly influenced by the coast and the adjacent river systems, and the deeper – seasonally stratified – northern North Sea (NNS) (320960 km^2), which is more strongly influenced by the North Atlantic Ocean. For this study, in the southern North Sea two subregions have been additionally separated: the German Bight (GB) (12563 km^2) and the Southern Bight (SB) (28099 km^2).

For the North Sea Thomas et al. (2005a) established a complete observation-based carbon budget resolving the seasonal cycle of the year 2001/2002. The variability of DIC and the partial pressure of CO_2 was discussed (Thomas et al., 2005b). Using a model approach Kühn et al. (2010) investigated the seasonal and interannual variability of the North Sea-wide carbon fluxes for the years 1995 and 1996. Though the techniques differed, all these studies focussed on distinguishing biologically and physically driven carbon fluxes. The main goal of these efforts was to understand the impact of the variability of different drivers on the carbon fluxes and their possible feedbacks.

Within this study we deepen the investigations of Kühn et al. (2010) and widen the temporal range of simulations to the period 1970–2006. The years from 1977 to 1989 were characterised by a strong eutrophication of the southern North Sea (Peeters and Peperzak, 1990; van der Zee and Chou, 2005) mainly induced by high riverine phosphate loads. The nutrient-enrichment of the southern North Sea had a significant impact on the marine ecosystem (Vermaat et al., 2008), particularly on the primary production (Skogen and Moll, 2005). The hydrodynamic properties of the northern North Sea are mainly governed by the influence of the North Atlantic. We investigate the interplay between the overall (climate-induced) trend of increasing SST (Wiltshire and Manly, 2004; Wiltshire, 2008; Wiltshire et al., 2010) and acidification due to ongoing uptake of anthropogenic atmospheric CO_2 (Blackford et al., 2008) in the shelf pump mechanism. For the continuous simulation from 1970 to 2006 the ecosystem model ECOHAM4 together with the hydrodynamic model HAMSOM (Backhaus, 1985; Pohlmann, 2006) were used. Thomas et al. (2005b), and later also Omar et al. (2010) have shown that biology and temperature effects are responsible for most of the variations in pCO_2 in the North Sea on an interannual and seasonal scale. We therefore conducted two simulations, one with biology and one without biology to identify the main drivers of air-sea flux variability in the North Sea.

In the present work we analyse the different components of the organic and inorganic carbon budgets and subsequently identify the main drivers of their variability.

2. Material and methods – the model

2.1. Model setup

The three-dimensional model ECOHAM4 (ECOlogical model, HAMburg, version 4) consists of two components: first, the hydrodynamic module HAMSOM (Hamburg Shelf Ocean Model) (Backhaus, 1985), which simulates the three-dimensional advective flow field, the turbulent mixing, temperature and salinity. See Backhaus and Hainbucher (1987) and Pohlmann (1996) for a detailed description of the model. The second part is the biogeochemical module (Kühn et al., 2010) which was used to calculate nitrogen and carbon budgets for the North Sea. The newer version of ECOHAM used for this study has an advanced phytoplankton module. The model includes 4 nutrients (nitrate, ammonium, phosphate, silicate), two phytoplankton groups (diatoms and flagellates), two zooplankton groups (micro- and mesozooplankton), bacteria, two fractions of detritus (fast and slowly sinking), labile dissolved organic matter, semi-labile organic carbon, oxygen, calcite, dissolved inorganic carbon, total alkalinity and the benthic state variables calcite and particulate organic matter (C, N, P, Si). The C:N:P ratio is fixed for both phytoplankton groups ($C{:}N_p = 6.625$, $N{:}P_p = 20$) (Quigg et al., 2003), both zooplankton compartments ($C{:}N_z = 5.5$; $N{:}P_z = 20$) and bacteria ($C{:}N_b = 4.0$; $N{:}P_b = 10$); for diatoms a C:Si ratio of 5.76 has been applied. In order to maintain the prescribed molar C:N:P ratios within the zooplankton and bacteria compartments additional carbon, nitrogen and phosphorus fluxes were introduced (see Appendix).

The two detritus fractions and dissolved organic matter have freely varying elemental ratios. Calcite and ‘large’ detritus have a sinking velocity of 10 m d^{-1}, ‘small’ detritus sinks with a velocity of 0.4 m d^{-1}. Phytoplankton and zooplankton mortality (including mortality due to grazing by higher predators) and fecal pellet production are the sources for the two detritus fractions; 85% of the detritus produced is directed into the slowly sinking detritus pool, 15% feeds the faster sinking fraction. Together with the corresponding decay rates (see Appendix) the sinking velocities mainly determine the ratio between pelagic and benthic remineralisation.

A special feature of the model is that it allows for ‘excess’ or ‘overflow’ (Fogg, 1983) production (NPP_{exc}) or ‘carbon overconsumption’ as specified by Toggweiler (1993). Carbon overconsumption is defined as carbon fixation by photosynthesis when the surface layers are depleted in bioavailable nutrients (Toggweiler, 1993; Thomas et al., 1999). This fixed excess carbon is released in the form of dissolved or colloidal extracellular carbohydrates which tend to coagulate forming transparent exopolymer particles (TEP) (Engel, 2002; Schartau et al., 2007). In the model the excess carbon is immediately channelled into the pool of slowly degradable semi-labile dissolved organic carbon, which is eventually metabolized by the bacteria (on a time scale of 9 months). Thus, the model differentiates between ‘normal’ exudation by phytoplankton, the result of which is labile dissolved organic matter with Redfield composition (Fogg, 1983), and an excess exudation of semi-labile organic carbon.