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Nitrogen and carbon cycling in the North Sea and exchange with the North Atlantic—A model study. Part I. Nitrogen budget and fluxes

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Abstract

The three-dimensional biogeochemical model ECOHAM was applied to the Northwest European Shelf (47°41′–63°53′N, 15°5′W–13°55′E) for the years 1993–1996. Nitrogen budgets were calculated for the years 1995 and 1996 for the inner shelf region, the North Sea (511,725 km^2). Simulated temperatures as well as nitrate, oxygen, and chlorophyll concentrations are compared with observations.

The mid-1990s were chosen because they exhibit a shift from a very high North Atlantic Oscillation Index (NAOI) in winter, 1994/1995, to an extremely low one in winter, 1995/1996, with consequences for the North Sea system: During the first-half of 1996, the observed mean sea surface temperature (SST) was about 1 °C lower than in 1995; in the southern part of the North Sea the difference was even larger. These observations could be reproduced by the model. Due to a different wind regime, the normally prevailing anti-clockwise circulation, also found in winter 1995, was replaced by more complicated patterns in winter 1996. Decreased precipitation over the drainage area of the continental rivers led to a reduction in the total riverine nitrogen loads to the North Sea from 76 Gmol N yr^{-1} in 1995 to 52 Gmol N yr^{-1} in 1996. In addition to these high loadings (additionally, atmospheric deposition supplied 27 Gmol N yr^{-1} of inorganic nitrogen), the system imported from the adjacent seas a net amount of 28 and 13 Gmol yr^{-1} of TN, in 1995 and 1996, respectively. As the main sink for nitrogen, we identified the coupled benthic nitrification/denitrification, which released 118 and 119 Gmol N yr^{-1} of molecular nitrogen into the atmosphere in the two years, respectively. This would account for the removal of the total amount of terrigenous (riverine and atmospheric) nitrogen inputs by denitrification in these two years. Additionally, allochthonous organic nitrogen, imported across the northern boundary, was transformed to inorganic nitrogen, part of which was also denitrified, the rest being exported as DIN to the North Atlantic.

Keywords: Ecosystem modeling; ECOHAM; North Sea; Nitrogen budget; NAO

1. Introduction

Continental shelves play a key role in the global cycling of biogeochemically essential elements. From observations in the East China Sea, Tsunogai et al. (1999) speculated that the global shelves act as a sink for atmospheric carbon dioxide and as a source of carbon for the ocean. Whereas the pathways of carbon onto and out of the East China Sea has been discussed (Chen, 2005), the process of "nitrogen onwelling" has been established as a general mechanism that transports nitrogen from the deep ocean onto the shelves. Galloway et al. (1996) compiled a North Atlantic-wide nitrogen budget in which the shelves were explicitly resolved. According to this study, the shelves take up 600 Gmol N yr^{-1} from land and more than 800 Gmol N yr^{-1} from the open ocean. This material (1400 Gmol N yr^{-1}) is released into the atmosphere as molecular nitrogen by denitrification.

The North Sea, as part of the Northwest-European shelf, has been characterized as a sink for atmospheric CO_2 (Thomas et al., 2005). However, it remains unclear whether the North Sea acts as a source or a sink of nitrogen for the adjacent North Atlantic waters. Investigations focusing on North Sea nitrogen or other macronutrients like phosphorus have a long tradition (van Bennekom et al., 1975;

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Weichart, 1986; Radach et al., 1990). The main focus of these studies was eutrophication, i.e. the increased level of nutrients due to human activities, and the consequences for the marine ecosystem, especially in coastal waters (Jickells, 1998). Whereas phosphorus concentrations in the marine environment of the Northwest European Shelf peaked in the early 1980s of the 20th century and declined drastically afterwards (Pätsch and Radach, 1997), a concomitant reduction in nitrogen inputs via rivers (Radach and Pätsch, 2007), from diffusive sources, and via the atmosphere was not observed.

Denitrification and burial are the possible internal sinks of nitrogen in such an environment. For the North Sea, the burial of organic carbon was estimated at less than 1% of the primary production (de Haas et al., 2002). We assume that the corresponding burial of organic nitrogen is even smaller. Under low oxygen conditions, denitrification, which produces molecular nitrogen or N_2O, is the dominant sink (Middelburg et al., 1996).

Total nitrogen (TN) inputs into the North Sea via the continental rivers exhibit large interannual variation. For the years 1977–2000, inputs varied between 33 Gmol N yr^{-1} in 1996 and 76 Gmol N yr^{-1} in 1981 (Radach and Pätsch, 2007). This variability was strongly correlated with the precipitation over the drainage areas but was not correlated with the NAOI, which is usually defined as the normalized pressure difference between the Azores and Iceland. Jones et al. (1997) calculated the NAOI by using stations on Gibraltar and southwest of Iceland. They found an extremely strong transition from a high winter NAOI to a very low one: $NAOI_{94/95} = 3.1$, $NAOI_{95/96} = -2.1$ for the years 1995 and 1996.

This shift influenced the physical environment of the Northwest European Shelf. According to Dippner (1997), the mean winter sea surface temperature (SST) in NAOI-low years is generally lower than in years with high NAOI. Indeed, Loewe (1996) observed an extremely low SST in the North Sea during the first-half of the year 1996. In NAOI-high years westerly winter winds dominate, whereas in NAOI-low years winds from easterly directions prevail.

2. The North Sea system

The North Sea, as part of the Northwest European Continental Shelf, has a large open boundary to the North Atlantic (Fig. 1 — model area). Depths greater than 100 m prevail in the north, where seasonal stratification has a strong impact on the biological components. The southern shallow part, south of the Dogger Bank (~55°N, 2°E), is influenced by continental rivers and the English Channel (EC), which is the other connection to the North Atlantic. These topographical features, together with the tidal system and the wind field, determine the hydrodynamic and biological features of the North Sea (Thomas et al., 2005).

The mean annual cycle of water transport is determined by these two different geographical regimes. The water masses entering the northern North Sea from the North Atlantic via the northwestern boundaries (NW, see Fig. 1) turn eastward in the central North Sea and generally do not influence the southern part. According to Lenhart and Pohlmann (1997), only about 5% of the North Atlantic water entering via the NW reaches the continental coastal region. The tidally induced transport processes of advection and mixing are more vigorous in the southern, shallow parts than in the northern, deep parts. In winter, the whole North Sea is vertically mixed due to strong winds and surface cooling (Elliott et al., 1991). The sections Skagerrak (SK), Norwegian Trench (NT), NW, and EC separate the North Sea area from the adjacent seas.

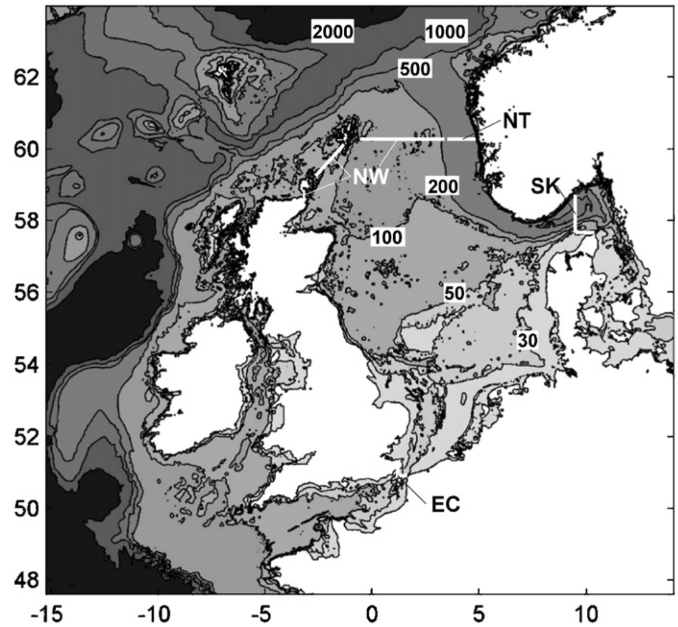

Fig. 1. Model area and bottom topography with depth contours (m). The transects confining the North Sea area are: Skagerrak (SK: [58.7°N, 9.6°E], [57.9°N, 9.9°E]), Norwegian Trench (NT: [60.2°N, 3.75°E], [60.2°N, 5.4°E]), Northwestern Boundary (NW: [58.7°N, 3.1°W], [60.2°N, 5.4°E]) and the English Channel (EC: [50.8°N, 0.7°E], [50.6°N, 1.1°E]).

3. Model setup

The three-dimensional (3D) model ECOHAM (ECOlogical model, HAMburg) consists of two components: the hydrodynamic module Hamburg Shelf Ocean Model-HAMSOM (Backhaus, 1985), which simulates the 3D advective flow field, the turbulent mixing, temperature, and salinity. Details were described by Backhaus and Hainbucher (1987), Pohlmann (1996a), and Pohlmann (1996b). The biogeochemical part of ECOHAM describes the carbon, nitrogen and oxygen cycles. It is based on the one-dimensional (1D) models by Kühn and Radach (1997) and Pätsch et al. (2002). The latter was applied to the deep North Atlantic. The model includes the pelagic state variables phytoplankton, zooplankton, bacteria, two fractions of detritus (with different sinking velocities), and