Nitrogen cycling in the Middle Atlantic Bight: Results from a three-dimensional model and implications for the North Atlantic nitrogen budget

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[1] The biogeochemistry of continental shelf systems plays an important role in the global elemental cycling of nitrogen and carbon, but remains poorly quantified. We have developed a high-resolution physical-biological model for the U.S. east coast continental shelf and adjacent deep ocean that is nested within a basin-wide North Atlantic circulation model in order to estimate nitrogen fluxes in the shelf area of the Middle Atlantic Bight (MAB). Our biological model is a relatively simple representation of nitrogen cycling processes in the water column and organic matter remineralization at the water-sediment interface that explicitly accounts for sediment denitrification. Climatological and regionally integrated means of nitrate, ammonium, and surface chlorophyll are compared with its model equivalents and were found to agree within 1 standard deviation. We also present regional means of primary production and denitrification, and statistical measures of chlorophyll pattern variability. A nitrogen budget for the MAB shows that the sediment denitrification flux is quantitatively important in determining the availability of fixed nitrogen and shelf primary production (it was found to remove 90% of all the nitrogen entering the MAB). Extrapolation of nitrogen fluxes estimated for the MAB to the North Atlantic basin suggests that shelf denitrification removes 2.3×10^{12} mol N annually; this estimate exceeds estimates of N_2 fixation by up to an order of magnitude. Our results emphasize the importance of representing shelf processes in biogeochemical models.

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1. Introduction

[2] Continental shelves play a key role in the global cycling of biologically essential elements such as nitrogen and carbon. The shelves are known to be highly productive [*Longhurst et al.*, 1995], the majority of the oceanic burial of organic carbon occurs on continental shelves and the adjacent slope [*Premuzic et al.*, 1982; *Hedges and Keil*, 1995], and shelf sediments are important sites for denitrification [*Christensen et al.*, 1987; *Christensen*, 1994]. The loss of fixed nitrogen from the global ocean through denitrification is estimated to exceed the known inputs [*Codispoti et al.*, 2001, and references therein] and more than half of this removal occurs in sediments, mostly on continental shelves [*Christensen et al.*, 1987]. The exact role of continental shelf processes in global biogeochemical cycling remains, however, poorly quantified. For example,

it is still not clear whether the continental shelves presently represent a source or sink of CO_2 to the atmosphere. It has been hypothesized that continental shelves act as a sink for atmospheric CO_2 owing to export of particulate or dissolved organic carbon to the adjacent slope and open ocean [e.g., *Walsh et al.*, 1981; *Smith and MacKenzie*, 1987]. This hypothesis was investigated for the Middle Atlantic Bight (MAB) in the interdisciplinary Shelf Edge Exchange Processes (SEEP) programs I and II [*Walsh et al.*, 1988; *Biscaye et al.*, 1994], which concluded that only a small fraction of particulate carbon (<5%) is exported [*Falkowski et al.*, 1988]. The subsequent Ocean Margins Program (OMP [*Verity et al.*, 2002]) explicitly considered the dissolved and suspended forms of organic carbon in the MAB. OMP results suggest that export of dissolved and suspended organic carbon to the open ocean's interior could be significant provided that advective and eddy diffusive transports are large enough. Another mechanism for the sequestration of inorganic carbon could be the winter production of cold, dense shelf water with high inorganic carbon content that is subsequently exported through isopycnal mixing processes [*Tsunogai et al.*, 1999]. This mechanism may represent a globally important carbon flux [*Yool and Fasham*, 2001]. Further investigation and quantification of shelf denitrification in basin-wide and global nitrogen cycling and its potential effect on the carbon balance of shelf systems is also required.

[3] The quantification of elemental exchange fluxes at the ocean margins is in part hindered by their large variability.

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Exchange processes between the margins and the open ocean occur at mesoscales and within boundary layers, and are highly dynamic. Steady state approximations that are conveniently used for the open oceans (e.g., the concept of new production) are hence problematic. The quantification of biogeochemical processes at the ocean margins will have to rely on a combination of models and observations. In an effort to quantify the elemental fluxes of nitrogen across the shelf boundaries for the MAB, we have constructed a high-resolution, coupled physical-biogeochemical model of the continental shelf of the U.S. east coast and the adjacent deep ocean.

5. Discussion and Conclusions

[34] The high spatial resolution necessary to capture the small-scale features of margin topography, as well as mesoscale and small-scale currents and the resulting fluxes of nutrients and organic matter represent a challenge to resolving biogeochemical processes at ocean margins. In our approach a high-resolution coupled model of the continental shelves is nested within a larger-scale circulation model of the NA. In the nesting procedure open boundary information for currents, temperature and salinity is provided from the large-scale circulation model to the regional model, but boundary information for the biochemical variables has to be prescribed. We used a simple approach to prescribing the biochemical variables where nitrate concentrations are determined from temperature using approximations that were derived from the NODC data set, and all other variables

Table 2. North Atlantic Flux Estimates

Data Source	Estimate
N Sink: Sediment Denitrification, mol N yr^{-1}	
Model (this study)	2.3×10^{12}
	(MAB only: 5.3×10^{10})
Seitzinger and Giblin [1996]	1.43×10^{12}
N Sources: N$_2$ Fixation, mol N yr^{-1}	
Michaels et al. [1996]	$3.7–6.4 \times 10^{12}$
Gruber and Sarmiento [1997]	2.3×10^{12}
Hansell et al. [2004]	0.3×10^{12}
Capone et al. [2005]	1.6×10^{12}
N Sources: Atmospheric Deposition, mol N yr^{-1}	
Nixon et al. [1996]	0.13×10^{12}
CO$_2$ Flux	
Model (this study)	0.18 Pg C yr^{-1}
	(MAB only: 4.2×10^{12} g C yr^{-1})
Takahashi et al. [2002]	−0.6 Pg C yr^{-1}

are set to a small positive number. Analysis of our model results suggests this approach to work well. Boundary artifacts, in particular, elevated chlorophyll levels and elevated primary production, are limited to the immediate vicinity of open boundaries and do not affect the continental shelf area of the MAB.

[35] Further challenges in capturing continental shelf processes arise from the pronounced benthic-pelagic coupling and the input of nutrients and organic matter from land. In contrast to open ocean regions, steady state assumptions can hardly be made and benthic processes cannot be ignored. On the one hand, it becomes possible to assess the effects of variability on coastal ecosystems and elemental fluxes through the use of coupled models. On the other hand, model validation is difficult because there are few permanent features and the variability on sub-seasonal

scales is dominated by sporadic events (e.g., wind-induced upwelling events and frontal shifts). We chose to compare climatological and regionally integrated means of surface chlorophyll, nutrients, primary production and denitrification, and statistical measures of pattern variability (the correlation and centered RMS difference of simulated and SeaWiFS chlorophyll).

[36] Denitrification in shelf sediment is known to be a quantitatively important sink in the global nitrogen cycle [*Hattori*, 1983; *Codispoti and Christensen*, 1985; *Christensen et al.*, 1987]. Our model suggests this flux to be important in reducing primary production on the shelf as well. Accurate prediction of sediment denitrification is hence crucial in simulating shelf production, but currently dependent on only few direct measurements. It would be costly to measure denitrification rates at high spatial and temporal resolution; hence, the development of well-constrained models (e.g., *Seitzinger and Giblin* [1996], *Middelburg et al.* [1996], and this study) may be more practical. Our model is based on *Seitzinger and Giblin*'s [1996] approximation of denitrification with sediment oxygen consumption, and our estimates hence hinge on the validity of this relationship.

[37] In our analysis, denitrification removes the majority of nitrogen entering the MAB in dissolved or particulate form, significantly more than enters from rivers, and thus makes the shelf system a net sink in the NA nitrogen cycle. This result is consistent with the observational-based estimates of *Seitzinger and Giblin* [1996], who suggested that denitrification on the NA shelves exceeds nitrogen inputs from land and must be sustained by fixed nitrogen that is imported from the open ocean. Assuming that the MAB shelf is representative of the NA shelves we can extrapolate the denitrification flux to the whole NA. Using the model-predicted mean denitrification flux for the MAB of 1.13 mmol N m^{-2} d^{-1} and a shelf area of 5.66×10^{12} m^2 [*Pilson and Seitzinger*, 1996] the extrapolation yields 2.3×10^{12} mol N yr^{-1}. Estimates of N$_2$ fixation for the NA vary by an order of magnitude (Table 2). Our denitrification estimate is 35% of the largest N$_2$ fixation estimate by *Michaels et al.* [1996], but 7 times higher than the most conservative estimate by *Hansell et al.* [2004]. Onwelling of inorganic nitrogen onto the continental shelves and subsequent denitrification are consequently key components of the NA nitrogen cycle, emphasizing the need to better represent margin processes in basin-wide and global models.

[38] A large nitrogen sink on the continental shelves is likely to have implications for carbon cycling. Since the nitrogen import to the MAB is likely to be accompanied by an influx of inorganic carbon, the denitrification flux should be associated with an outgassing of CO$_2$. For the sake of simplicity we assume here that carbon and nitrogen import occur in Redfield ratio and can then estimate the outgassing of CO$_2$ at 0.19 PgC yr^{-1} (1 Pg = 10^{15}g) (Loss of fixed nitrogen from the North Atlantic shelf area determined as follows: 2.3×10^{12} mol N yr^{-1} × 106/16 = 15.2×10^{12} mol C yr^{-1} multiplied by the molar mass of C (12 g) yields 0.18×10^{15} gC yr^{-1}). In comparison, *Takahashi et al.*'s [2002] estimate of the NA uptake of CO$_2$ is 0.6 PgC yr^{-1}. However, our estimate should not be mistaken for a carbon budget of the shelves. We did not address the transformation of river and estuarine dissolved organic matter, oxidation of which could result in an inorganic carbon source [*Borges and Frankignoulle*, 1999], and the possibility of inorganic carbon export through isopycnal export of CO$_2$-supersaturated shelf water in winter [*Tsunogai et al.*, 1999; *Yool and Fasham*, 2001].