eutrophication started to increase the nutrient pools. The high ratios of CO_2 uptake to N and P accumulation, respectively (CO_2-uptake/N-accum. = 30; CO_2-uptake/P-accum. 2000), might imply that the Baltic Sea has been autotrophic earlier and the efficient nutrient recycling mechanisms (Thomas et al., 1999; Osterroht and Thomas, 2000) would still have enabled CO_2 drawdown from the atmosphere.

7.3 The North Sea

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7.3.1 Introduction

The North Sea (Fig. 7.3.1) is located on the northwestern European continental shelf with an open northern boundary to the Atlantic Ocean. In the west and southwest the North Sea is enclosed by the British Islands, whereas the south-eastern and eastern boundary is constituted by the European continent (France, Belgium, Netherlands, Germany and Denmark) and the Norwegian west coast. In the south the English Channel is a further open boundary to the Atlantic Ocean. Via the Skagerrak between Denmark and Norway the Baltic Sea waters enter the North Sea.

The bottom topography constitutes a major control of the conditions for the hydrodynamic circulation patterns as well as for biogeochemical cycling in the North Sea. The deeper northern part reveals depths down to approximately 150 m on the shelf, down to 400 m in the Norwegian Channel and 700 m in the Skagerrak. South of the Dogger Bank (~55°N, 2°E) the water depths are less than 50 m, near the coasts even less than 20 m.

The continuous water exchange across the northern boundary (Fig. 7.3.1) dominates the water budget. All other water fluxes, e.g. the Baltic Sea or the riverine freshwater inflows, are of minor relevance on a quantitative basis (Table 7.3.1). There are two different hydrographical regimes in the North Sea. The north can be seen as an oceanic basin with continuous Atlantic Ocean water inflow, of which a high amount recirculates into the North Atlantic again. Only a fraction of this North Atlantic inflow reaches the second system south of the Doggerbank.

Wind, tidal motion and density variations are the main drivers for the circulation in the North Sea. As depicted in Fig. 7.3.1 the dominant feature is an anticlockwise circulation entering the North Sea west and east of the Shetland Islands. The current turns north-eastward in the central North Sea finally leaving the North Sea through the Norwegian trench. In the southern part the inflow from the English Channel moves along the southern and eastern continental coast toward the Norwegian coast, where it joins the Baltic Sea outflow and enters the outflow current to the North Atlantic Ocean (Otto et al., 1990; OSPAR Commission, 2000). As a consequence of the circulation pattern, the most prevailing feature of the semi-enclosed North Sea is the short residence time of its water, which is in the order of 6–12 months (Lenhart and Pohlmann, 1997; OSPAR, 2000). While different water budget calculations (ICES, 1983; Eisma and Kalf, 1987; Otto et al., 1990; Lenhart et al., 1995; Smith et al., 1996; Lenhart and Pohlmann, 1997; OSPAR Commission, 2000) represent the main features in the hydrodynamic circulation well, they are difficult to compare between each other, since they are obtained from model simulations with different model structure or forcing. In addition, the natural variability of the flows across different transects is rather large causing uncertainties in the derived water budgets.

The seasonal variations in temperature show lowest amplitudes near the northern boundaries to the North Atlantic Ocean and increase in south-easterly direction because of the increasing influence of coastal waters and the decreasing water depths (Becker and Schulz, 2000). Accordingly, warmest and coldest waters can be observed in the German Bight and the Skagerrak area, whereas the English Channel area

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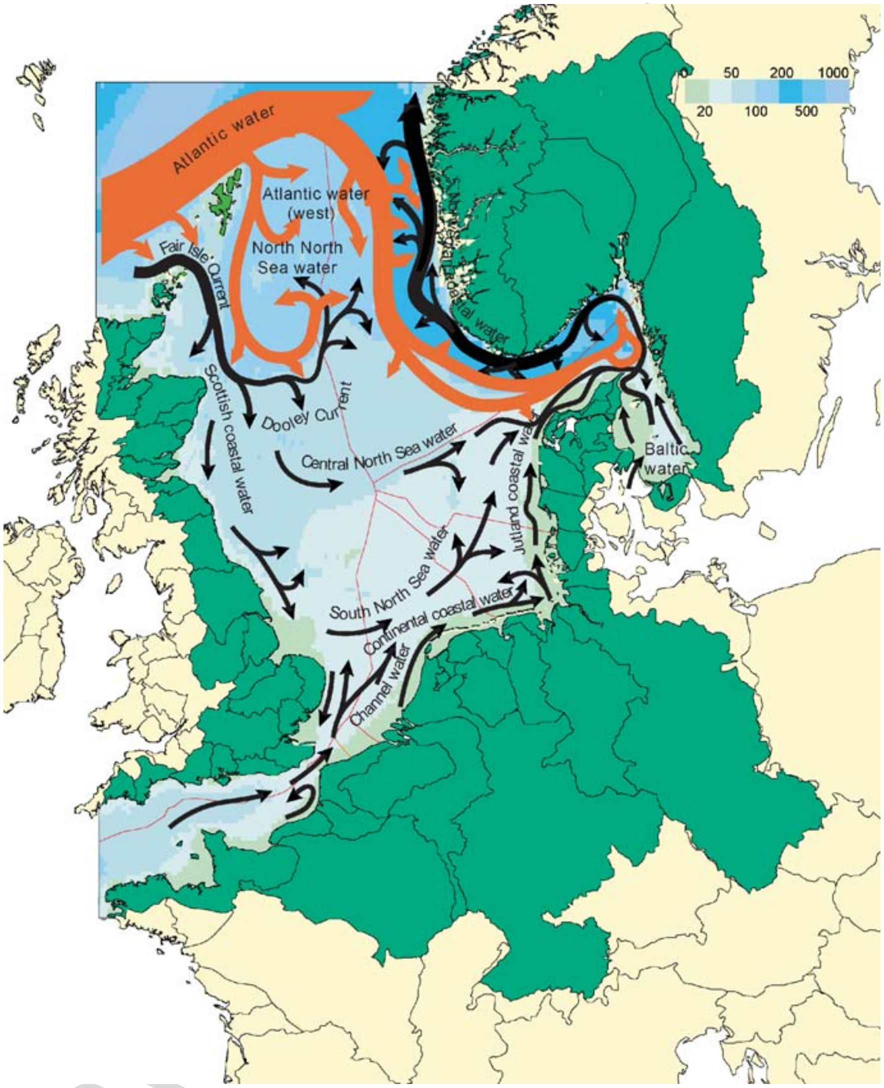

Fig. 7.3.1 The location of the North Sea and main water masses redrawn after OSPAR Commission (2002). The *dark green colour* indicates the drainage area and the arrows the main circulation scheme. The orange arrows indicate relatively pure North Atlantic Ocean water within the North Sea. The colour scale indicates approximate water depths of the North Sea

shows the highest annual mean temperature because of the inflow of warmer Atlantic Water from the south. A similar feature shows the surface salinity with lowest values during summer and lowest amplitudes at the northern boundaries to the Atlantic Ocean. In the shallow areas in the south, the water column is mixed permanently throughout the year. On the other hand, there is a thermal stratification in the northern part during summer. In addition, the continental southern part receives most of the freshwaters inputs notably from the rivers Rhine, Scheldt, Thames, Elbe and Weser (Radach and Pätsch, 2007). Comparing the surface areas of the North Sea and the Baltic Sea, the North Sea receives approximately 50% less freshwater per m^2 from its drainage area, which is approximately 1.5 times larger than the surface area of the North Sea itself (OSPAR Commission, 2000). However, except for a small band along the coast the freshwater is mixed rapidly with Atlantic Ocean water finally leading to the almost oceanic salinity observed in the entire North Sea. Haline stratification is an exception in the North Sea only occurring in the Norwegian Trench area during the whole year and as a local phenomenon in the vicinity of rivers inlets with strong freshwater input.

In the northern North Sea the stratification enables net export of carbon and nutrient to the deeper layers via sinking of particulate organic matter (POM). In contrast, the south is strongly affected by terrestrial and

Table 7.3.1 One-box carbon budget of the North Sea (acc. Thomas et al., 2005a). The budgeting area is 575, 300 km^2, and the water volume is 42, 294 km^3. The water budget is according to Eisma and Kalf (1987). The Baltic Sea inputs are taken from Thomas et al. (2003). The inflow and outflows were separated into upper and lower water column and the corresponding contributions to the entire flux have been given in parenthesis ([ ]) (Pätsch and Radach, 1997). The overall flux across these boundaries has been calculated accordingly. Sedimentation of organic carbon is according to De Haas et al. (2002). DIC and DOC data are taken from Thomas (2002), riverine inputs from Borges (unpublished). Positive flows indicate inputs into the North Sea and negative ones export out of the North Sea. The CO_2 air–sea exchange is adopted from Thomas et al. (2004). The uncertainty of the DIC and DOC concentrations is approximately ±1 μM (0.05%) and ±1 μM (1.25%), respectively. A 10% error of both the air–sea flux and the sedimentation estimates has been assumed. The errors given in the last three parts are due to the analytical errors in the DIC and DOC measurements as well as due to the assumed errors in the estimates of the air–sea fluxes and of sedimentation. The unbalanced term is within the range of uncertainty. The heterotrophy increases the DIC pool at the expense of the DOC pool. It does not constitute a net carbon flux across the North Sea boundaries

		Carbon				
		Input/output concentration		Input/output fluxes		
	Water input/ output (km^3 a^{-1})	DIC (μmol l^{-1})	DOC/POC (μmol l^{-1})	DIC/ (10^{12} mol a^{-1})	DOC/POC (10^{12} mol a^{-1})	Total C (10^{12} mol a^{-1})
Baltic Sea	500	2118	78	1.059 (±0.05%)	0.039 (±1.5%)	1.098 (±0.08%)
Atlantic Ocean:						
Via English Channel	4900	2100	80.5	10.290 (±0.05%)	0.395 (±1.5%)	10.685 (±0.08%)
Via Fair Island and Pentland Firth	9000	Upper: 2094 (58%) Lower: 2108 (42%)	Upper: 71.2 (58%) Lower: 66.0 (42%)	18.898 (±0.05%)	0.621 (±1.5%)	19.520 (±0.07%)
Via Shetland Channel	42000	Upper: 2102 (53%) Lower: 2126 (47%)	Upper: 73.9 (53%) Lower: 71.6 (47%)	88.758 (±0.05%)	3.058 (±1.5%)	91.812 (±0.07%)
Rivers	300			0.778 (±0.05%)	0.088 (±1.5%)	0.866 (±0.16%)
Outflow to the North Atlantic Ocean via Norwegian Trench	−56700	Upper: 2075 (14%) Lower: 2142 (86%)	Upper: 93.4 (14%) Lower: 63.4 (86%)	−120.92 (±0.05%)	−3.831 (±1.5%)	−124.751 (±0.07%)
Atmosphere		1.38 mol C m^{-2} a^{-1}		0.794 (±10%)		0.794 (±10%)
Sedimentation (marine part. Organic Carbon)			−0.13 mol C m^{-2} a^{-1}		Shelf: 0.007 Deep basins: 0.067	−0.073 (±10%)
Subtotals						
Input				120.577 (±0.08%)	4.201 (±1.13%)	124.779 (±0.09%)
Output				−120.92 (±0.05%)	−3.904 (±1.5%)	−124.824 (±0.07%)
Heterotrophy signal		0.59 (±32%) mol C m^{-2}	−0.52 (±26%) mol C m^{-2}	0.34 (±32%)	−0.30 (±26%)	
Unbalanced: (0.04% of total input)						0.045 (±236%)

anthropogenic nutrient inputs (organic and inorganic) and the mixed water column does not enable export of POM to any deeper layers. The POM is mineralised in the surface layer causing high turnover of carbon and nutrients and avoiding burial of POM. Only in the deeper basins of the Skagerrak and the Norwegian Trench final burial of POM can be observed, whereas on the more shallow areas of the North Sea almost no burial occurs. The overall burial can be considered as insignificant on an annual timescale and amounts to less than 1% of the annual primary production (Radach and Lenhart, 1995; de Haas et al., 2002).

7.3.2 Carbon and Nutrient Budgets

The North Sea is amongst the best-studied areas worldwide with respect to its physical, chemical and biological conditions. We have established a budget for the entire North Sea (as one-box). The boundaries of the budget area are the Strait of Dover in the south, the Skagerrak, the section along 61°N and across the Shetland and Orkney Islands (Fig. 7.3.2). Observations of the concentrations of the carbon species (DIC, DOC) are the basis for the budget calculation in combination with water fluxes from the literature. The nutrient budget covers the same area, but has been obtained from a specific application (Heath et al., 2002) of the ecosystem model ERSEM. The corresponding simulation is based on circulation data from a hydrodynamic model (Pohlmann, 1996). The features of the ecosystem simulation are described in Table 7.3.2 and Pätsch and Radach (1997) have discussed its possibilities and limitations.

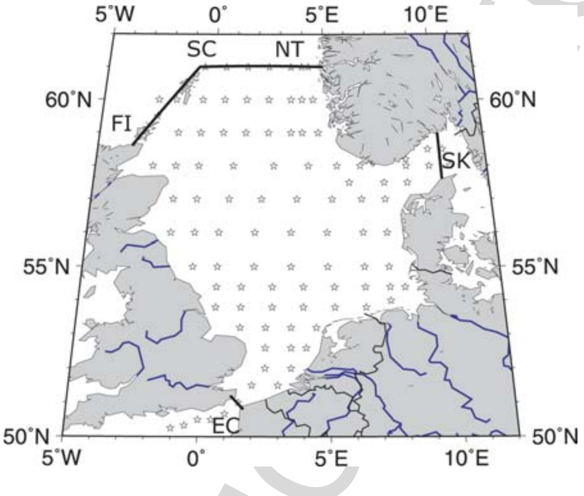

Fig. 7.3.2 The budgeting area for the North Sea. The various input/output pathways are indicated: English Channel (EC), Skagerrak (SK), Fair Isle Current (FI), Shetland Current (SC), and Norwegian Trench (NT). The stars indicate the stations occupied during the recent field program in 2001/2002 (e.g. Thomas, 2002; Bozec et al., 2006). All relevant parameters for budgeting carbon and nutrients were determined at each station during all four seasons. Between the stations pCO_2 as well as hydrographic parameters were measured continuously

Table 7.3.2 The ERSEM model application to the Northwest European Continental Shelf (NECS)

Overall references in the special issues	Netherlands Journal of Sea Research, 33(3/4), 1995 Journal of Sea Research, 38, 1997
Specific reference for the NECS application	Heath et al. (2002)
Simulation year	1990
Meteorological forcing	NCEP reanalysis for 1990
Hydrodynamic forcing	HAMSOM (semi-baroclinic mode)
River loads	Radach and Pätsch (2007)
Nutrient boundary values	Climatological values (ICES)
Underlying ERSEM version	V11
ERSEM spatial and temporal resolutions	Horizontal: 60–120 km vertical: two layers: 0–30 m; 30 m – bottom temporal: daily

7.3.2.1 The Carbon Budget of the North Sea

The carbon budget relies on a recent intense basin-wide carbon cycle study has been carried out in the North Sea (Thomas et al., 2002, 2004, 2005a,b; Bozec et al., 2005, 2006, Fig. 7.3.2) as well as on investigations in the southern bight of the North Sea (e.g. Borges and Frankignoulle, 1999, 2002, 2003; Schiettecatte et al., 2006, 2007). The carbon budget has been established according to Thomas et al. (2005a) considering one homogeneous box for the entire North Sea and we refer to reader to the latter work for details. Cross boundary carbon fluxes have been computed referring to the water budget by Eisma and Kalf (1987), since it is in agreement with the water budget of the Baltic Sea (see for details: Thomas et al., 2003) and with the riverine inputs to the North Sea (OSPAR

Commission 2000, see also Thomas et al. [2005a] for critical discussion of the water budgets applied here). According to Lenhart et al. (1995) and Pätsch and Radach (1997) the water transports across the northern boundaries can be subdivided into upper and lower transports (see also Table 7.3.1). The information on this subdivision has been applied, since this allows considering the observed high-resolution DIC and DOC data recently obtained.

In order to establish a carbon budget for the North Sea, one box was defined with the following boundaries: the Strait of Dover in the South, the Faire Island Channel in the Northwest, the Shetland Channel and the Norwegian Trench in the North along 61°N and the Skagerrak in the east (Fig. 7.3.2). The carbon fluxes across these boundaries have been computed using the water transports and the corresponding DIC and DOC concentrations. Although POC plays a key role in the carbon metabolism, it only plays a negligible role in importing or exporting carbon across the North Sea boundaries (De Haas et al., 2002; Thomas et al., 2005a). The fluxes of POC thus have been neglected in the present budget except for the final burial of POC in the North Sea. Riverine inputs and carbon burial have been considered as further sinks or sources to the North Sea box. We assume the system to be in a steady state, i.e. the fluxes into and out of the box balance each other Eq. (7.3.1). Accordingly, the following components of the North Sea carbon fluxes were considered (Eq. 7.3.2): inflow with river run-off (F_R), inflow from the Baltic (F_B), inflow from the Atlantic Ocean via the Shetland Channel (F_S), via the Faire Island Channel (F_F), via the English Channel (F_E), sedimentation (F_S), outflow to the Atlantic Ocean (F_O) and net exchange with the atmosphere (F_A). Carbon flows into the box are denoted by a positive sign increasing the carbon content within the box. Carbon flows out of the box are denoted by a negative sign decreasing the carbon content within the box.

$$\Sigma\left(F_{\text{into the box}}\right) = \Sigma\left(F_{\text{out of the box}}\right) \qquad (7.3.1)$$

or

$$F_R + F_B + F_S + F_F + F_E + F_S + F_O + F_A = 0 \qquad (7.3.2)$$

For each station the average of the observations has been used as an annual average for the budget calculation. Riverine freshwater inputs to the North Sea amount to 300 km^3 per year (OSPARCOM, 2000). The riverine DIC and DOC data were compiled from various sources, notably the EU BIOGEST program applying the "apparent zero end member" method (Kaul and Froelich, 1984) and upscaled using the "rate curve estimation" method (Cooper and Watts, 2002). The inorganic carbon inputs from the Baltic Sea have been taken from Thomas et al. (2003). The sedimentation of organic carbon has been estimated according to De Haas et al. (2002) considering only the sedimentation of marine material. The uncertainty of the calculations has been estimated with regard to the analytical uncertainty of the DIC and DOC concentration values as well as with regard to an assumed 10% uncertainty of each the air–sea flux and sedimentation estimates (Table 7.3.1). The errors have been propagated using the formula:

$$X = \left(\sum_i x_i^2\right)^{0.5} \qquad (7.3.3)$$

where X denotes the combined error and x_i the partial errors. The unbalanced term of the budget (0.04% of the total inputs) is within the range of uncertainty (0.09% of the total inputs) and the budget thus can be considered as a closed budget.

Results

Table 7.3.1 and Fig. 7.3.3 comprise the results of the carbon budget of the North Sea. As already indicated the water and thus the carbon exchange across the northern North Sea boundaries dominate the budget (Fig. 7.3.3a). The Atlantic Ocean supplies more than 98% of the carbon: 74% via the Shetland Channel, 16% via the Fair Island Channel and 8% via the English Channel. The Baltic Sea supplies approximately 1% of the carbon. Finally, the rivers provide 0.7% and the atmosphere 0.6% of the overall carbon import, respectively. Inorganic species including atmospheric CO_2 are the major vehicles accounting for 96% of the inputs. A similar feature is obtained for the export of carbon: less than 1% is exported to the sediments and the major amount of the carbon is exported to the North Atlantic as inorganic (97%) and organic (<3%) carbon. The uptake of atmospheric CO_2 of approximately 800 Gmol C a^{-1} corresponds to a flux of 1.4 mol C m^{-2} a^{-1} into the North

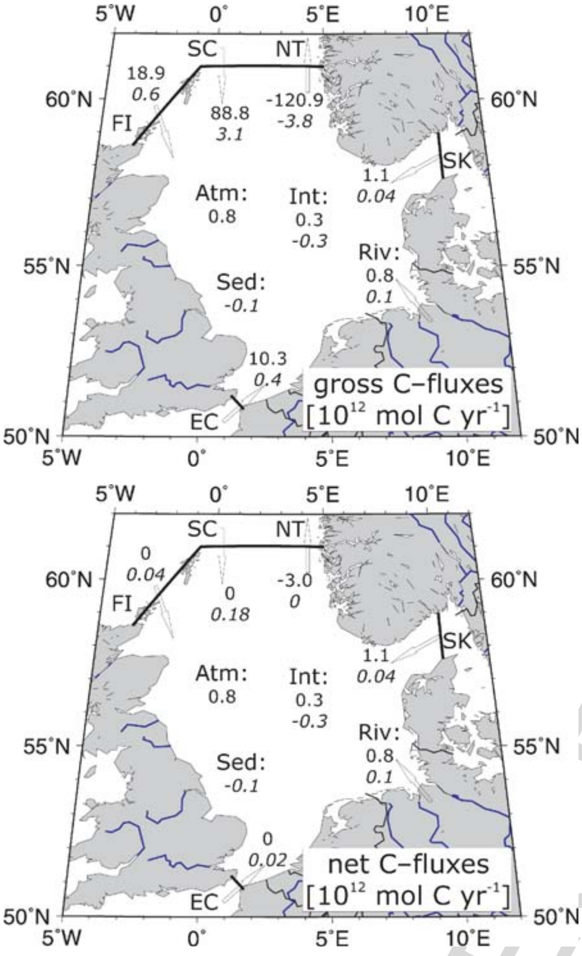

Fig. 7.3.3 The 1-box carbon budget for the North Sea. Positive values denote transports into the North Sea water body, negative ones out of it. Organic carbon fluxes and given in italics, inorganic fluxes in standard font. (**a**) Shows the gross carbon fluxes and (**b**) the net carbon fluxes respectively

Sea (Thomas et al., 2004), whereof 10% are transferred to the sediments and 90% to the North Atlantic Ocean with primary production being the engine for the uptake of atmospheric CO_2. This export of atmospheric CO_2 constitutes the continental shelf pump function of the North Sea. Considering the North Sea as carbon enrichment pump for Atlantic Ocean water, which circulates through the North Sea, the initial carbon content is increased by three suppliers: the atmosphere, the Baltic Sea and the rivers. The overall enrichment of the carbon content of the Atlantic Ocean water amounts to $2626\,\mathrm{Gmol\,C\,a^{-1}}$ corresponding to approximately 2% of the initial content or – related to the North Sea surface – to $4.6\,\mathrm{mol\,C\,a^{-1}\,m^{-2}}$. The atmosphere covers 25% of this enrichment, the Baltic Sea 42% and the riverine input 33%, respectively.

Despite the obvious predominance of the carbon transports to and from the Atlantic Ocean the minor contributors such as the inputs from the Baltic Sea balance the net transport terms of the budget (Fig. 7.3.3b). Because of the relevance of the inputs from the Baltic Sea and the rivers, the water budget by Eisma and Kalf (1987) has been referred to, since it considers both the inputs from rivers (OSPAR Commission, 2000) and from the Baltic Sea (see for details Thomas et al., 2003, 2005a) reliably. The current discussion describes the North Sea as a steady-state system in order to provide an initial assessment of the carbon cycling, necessarily considering processes as constant at annual timescales. Recent findings, however, imply that interannual difference might be evident either as part of long term trends or as interannual variability (Schiettecatte et al., 2007; Thomas et al., 2007). Both the long-term trends and interannual variability might be influenced by anthropogenic activities or climate change processes. Ongoing and future studies will focus on understanding and unravelling such effects on the North Sea ecosystem.

7.3.2.2 The Nutrient Budgets of the North Sea

The nutrient budgets have been established using an ERSEM model application for the year 1990 covering the whole Northwest European Continental Shelf (NECS). Compared to earlier ERSEM versions (Radach and Lenhart, 1995), this set-up (Heath et al., 2002) is less dependent on the boundary conditions, since the budgeting area of the North Sea (Fig. 7.3.2) comprises only the inner part of the model area. The details of the model set-up are given in Table 7.3.2. External sources as riverine and atmospheric input are derived from literature. The river input consists of inorganic and organic material, while the atmospheric deposition supplies only inorganic nitrogen. The daily riverine inputs are realised as point sources at the coast (Heath et al., 2002; Radach and Pätsch, 2007), while the atmospheric deposition is introduced as a constant load over the whole model area (Pätsch and Radach, 1997). To estimate nutrient fluxes, the corresponding ERSEM state variables are denoted as inorganic nitrogen (sum of nitrate and ammonium), phosphorus (phosphate) and silicon

Table 7.3.3 North Sea nutrient fluxes ($\mathrm{Gmol\,a^{-1}}$) obtained by the ERSEM model application NECS for the year 1990. The water transports ($\mathrm{km^3\,a^{-1}}$) are described by Pätsch and Radach (1997) and the water fluxes aggregated from the hydrodynamic simulation for the same transects as for the carbon budget (see Table 7.3.1). Atmospheric inputs are according to Pätsch and Radach (1997) and river loads according to Heath et al. (2002)

	Water	N_{inorg}	N_{org}	N_{tot}	P_{inorg}	P_{org}	P_{tot}	Si_{inorg}	Si_{org}	Si_{tot}
FI	24700	261.1	64.9	326.0	16.4	4.7	21.1	118.5	25.3	143.8
SC	10548	113.6	25.1	138.7	7.4	1.8	9.2	53.8	13.9	67.7
NT	−39130	−505.4	−70.0	−575.4	−29.1	−5.0	−34.1	−231.3	−30.8	−262.1
SK	1817	23.5	−4.9	18.6	1.8	−0.3	1.5	13.2	1.0	14.2
EC	2063	13.6	4.9	18.5	0.8	0.4	1.2	9.1	0.2	9.3
SUM	**2**	**−93.6**	**20.0**	**−73.6**	**−2.7**	**1.6**	**−1.1**	**−36.7**	**9.6**	**−27.1**
RIV		43.6	10.5	54.1	0.9	0.6	1.5	23.1	0.8	23.9
ATM		33.9		33.9						
Org → inorg		15.4	−15.4		1.8	−1.8		12.6	−12.6	
Δ	2	−0.7	15.1	14.4	0.0	0.4	0.4	−1.0	−2.2	−3.2
UPTA		−1248.1			−82.8			−358.0		
PREMI		672.9			51.2			0.0		
BREMI		590.6			33.4			370.6		

N_{inorg}, flux of inorganic nitrogen; N_{org}, flux of organic nitrogen; N_{tot}, sum of both; for P and Si correspondingly; FI, Fair Isle Current; SC, Shetland Current; NT, Norwegian Trench; SK, Skagerrak; EC, English Channel; RIV, riverine input; ATM, atmospheric input; org → inorg, net biological transfer from the organic into the inorganic pool; Δ, biological net storage; UPTA, nutrient uptake by phytoplankton; PREMI, pelagic remineralisation; BREMI, benthic remineralisation.

(silicate). The organic pools for N and P comprise the ERSEM state variables phytoplankton, zooplankton, bacteria and detritus. To maintain this nomenclature we used the term organic silicon for the silica shells and opal. The transport of both inorganic and organic matter into and out of the North Sea is considered. Furthermore, the budgeting accounts for nutrient uptake, pelagic and benthic remineralisation, which mediate the transfer between the inorganic and the organic pools. A limitation of this application arises from the relatively simple benthic module which does not include the benthic denitrification explicitly, i.e. the production of molecular nitrogen (Seitzinger and Giblin, 1996).

The general pattern is clearly visible from the nutrient budgets given in Table 7.3.3: the North Sea obtains a net amount of organic material via the external boundaries (open ocean boundaries and continent via river input) which is used by the biological system and partly converted into inorganic material. These inorganic nutrients together with the nutrients delivered by rivers and atmosphere are ultimately exported to the open North Atlantic.

The Nitrogen Budget

The exchange with the North Atlantic Ocean plays a dominant role in governing the nitrogen budget (Table 7.3.3, Fig. 7.3.4). About 80% of the total nitrogen gain ($590\,\mathrm{Gmol\,N\,a^{-1}}$) is imported from the Atlantic Ocean across the northern boundary, 9% is delivered by the rivers, 6% by the atmosphere and 3% is imported from the Baltic Sea. The total nitrogen export to the Atlantic Ocean through the Norwegian Trench ($575\,\mathrm{Gmol\,N\,a^{-1}}$) is responsible for about 98% of the nitrogen loss. The biological net storage (Δ) is identified as minor sink of organic nitrogen.

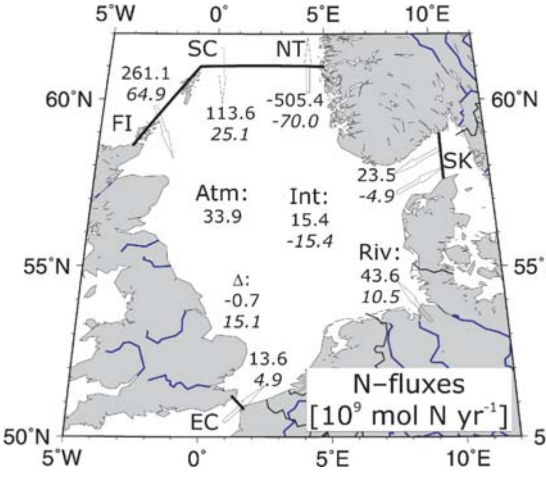

Fig. 7.3.4 The 1-box nitrogen budget for the North Sea. Positive values denote transports into the North Sea water body, negative ones out of it. Organic nitrogen fluxes and given in italics, inorganic fluxes in standard font. Further notations: see Table 7.3.3

Interestingly, the North Sea gets relatively large amounts of organic nitrogen through the Fair Isle Current and the Shetland Current. This is the result of high biological activity on the outer part of the shelf in combination with the prevailing circulation pattern.

According to the model results (Table 7.3.3) about half of the produced organic nitrogen is remineralised in the water column, the other half is sinking to the sediment, where it is remineralised again. The rivers and the atmosphere supply relevant amounts of nitrogen to the North Sea, however, these inputs into the North Sea are less important as they are for the Baltic Sea; this is because of the above-mentioned dominance of the nitrogen exchange with the Atlantic Ocean. The inorganic species constitute the major vehicle for the nitrogen transport covering approximately 80% for both input and output. The internal, i.e. biological, processes indicate a high turnover of nitrogen in relation to the North Sea winter content (~0.3 a^{-1}), although their net contribution to the budget is negligible. Atmospheric and riverine inputs are of similar order of magnitude, each of them is larger than the nitrogen input from the Baltic Sea.

The Phosphorus Budget

Similar to the nitrogen budget, the phosphorus budget of the North Sea (Table 7.3.3, Fig. 7.3.5) is controlled by the exchange with the Atlantic Ocean across the northern boundaries. According to the model results about 90% of the incoming total phosphorus (34.5 Gmol P a^{-1}) is imported from the Atlantic Ocean, approximately 5% from the Baltic Sea and 5% from rivers. The largest part (99%) of the obtained phosphorus is exported to the North Atlantic via the Norwegian Trench. A small amount of organic phosphorus is exported into the Skagerrak. The biological processes result in a net transfer from the organic into the inorganic pool. The latter net flux is compared to the net phytoplankton uptake of phosphate very small (2%). In accordance with the nitrogen budget the phosphorus budget shows a net import of organic material and a larger net export of dissolved inorganic material over the external boundaries of the North Sea. The remineralisation fluxes of phosphorus are divided into a smaller benthic (40%) and a larger pelagic (60%) one. A small part (0.4 Gmol P a^{-1}) of the organic material accumulated during the simulation year.

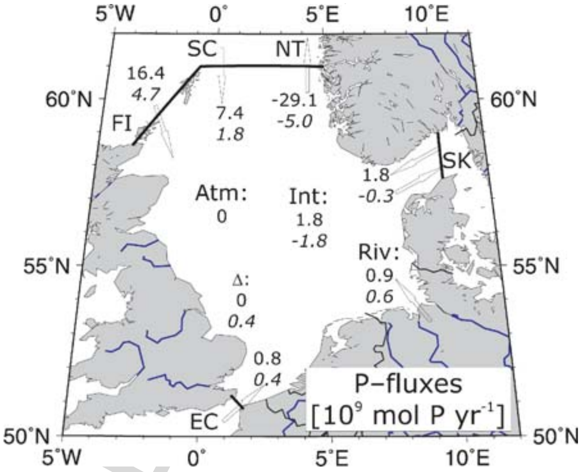

Fig. 7.3.5 The 1-box phosphorus budget for the North Sea. Positive values denote transports into the North Sea water body, negative ones out of it. Organic phosphorus fluxes and given in italics, inorganic fluxes in standard font. Further notations: see Table 7.3.3

Whereas total nitrogen inputs from the rivers were about three times higher than the import from the Baltic, the corresponding phosphorus inputs were of the same magnitude.

The Silicon Budget

Despite the high relevance of the silicon exchange (Table 7.3.3, Fig. 7.3.6) between the North Sea and the Atlantic Ocean, the sum of inputs from the rivers and from the Baltic Sea are more relevant for Si than for N and P and notably also than for carbon. Still, the Atlantic Ocean provides 84% of the Si input (259 Gmol Si a^{-1}) via the northern boundaries and the English Channel; however, the rivers contribute approximately 9% and the Baltic Sea 5%, respectively. As also shown for the other nutrients, the inorganic species constitute the major transport vehicle; it is directed out of the North Sea, while a smaller fraction is entering the North as organic silicon. The export to the North Atlantic Ocean through the Norwegian Trench can be identified as the only sink for silicon. This sink is larger than all sources together, consequently after one-simulation year the silicon content has declined. Degradation of opal (in the sediment) is higher than the silicate uptake resulting in a net gain of inorganic silicon by biological activities.

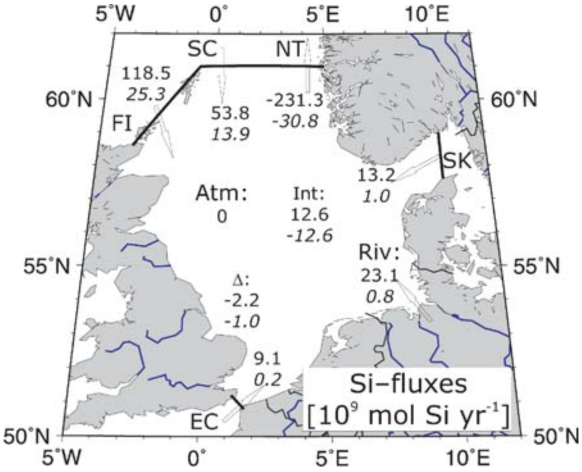

Fig. 7.3.6 The 1-box silicon budget for the North Sea. Positive values denote transports into the North Sea water body, negative ones out of it. Organic silicon fluxes and given in italics, inorganic fluxes in standard font. Further notations: see Table 7.3.3

7.3.3 Discussion (Combining Carbon and Nutrient Budgets)

The carbon budget describes the North Sea as an overall heterotrophic semi-enclosed sea. The main feature is the circulation of Atlantic Ocean water through the North Sea, the carbon content of which is increased during this transport. Major sources increasing the carbon contents of the Atlantic Ocean water are the Baltic Sea, the rivers and moreover the atmosphere. The uptake of atmospheric CO_2 by the North Sea amounts to 1.4 mol C m^{-2} a^{-1}, of which 90% are transferred to the Atlantic Ocean. The continental shelf pump is thus more effective than in the Baltic Sea, which exports approximately 43% of the CO_2 air–sea flux to the North Sea and the remaining 57% to the sediments (Thomas et al., 2003). This can be explained by different modes of operation of the continental shelf pump: The brackish Baltic Sea rather serves as a collecting basin for freshwater, which finally is transported following a "one-way road" via the Skagerrak to the North Sea. The permanent halocline and the deeper basins enable effective export of organic matter from the surface layer which is equivalent to CO_2 drawdown from the atmosphere. Once this carbon has escaped from the surface layer it hardly can be exported to the North Sea and only the remaining part in the surface layers is available to the continental shelf pump. In contrast, the North Sea reveals almost no sedimentation, which ultimately implies that the entire CO_2 drawdown caused mainly by biological activity is available for export to the Atlantic Ocean. The North Sea's circulation with its short flushing times and the bottom topography play major roles in avoiding sedimentation (de Haas et al., 2002). Once the CO_2 has been taken up by the North Sea, it is rapidly exported to the Atlantic Ocean. The North Sea thus can be seen as a bypass pump (Fig. 7.3.7a), which increases the carbon content of Atlantic water while it is circulated through the North Sea. In contrast, the Baltic Sea rather acts as an injection pump (Fig. 7.3.7b), which injects "new" water and corresponding carbon loads to the adjacent open ocean, which is in this case the North Sea.

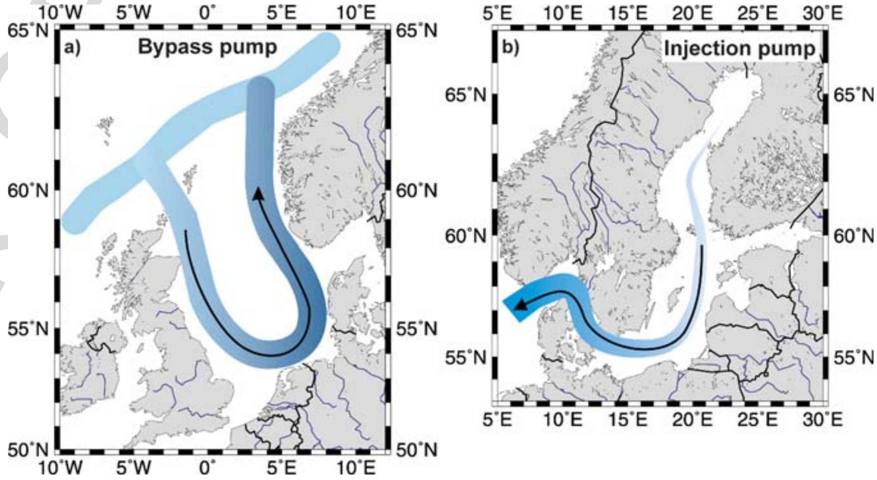

Fig. 7.3.7 Different modes of operation of the continental shelf pump: (**a**) the bypass pump as active in the North Sea and (**b**) the injection pump as active in the Baltic Sea (reprinted from Thomas et al., 2005a)

From the nutrient budgets it is evident that the contributions of inorganic and organic species to input and output are in a similar order of magnitude for all nutrients. However, the North Sea gets a net excess amount of organic material from the external sources, i.e. the open boundaries with the Atlantic Ocean and the Baltic, the atmosphere and the continents (due to river runoff). This material is converted into inorganic material and exported into the open North Atlantic Ocean. This feature is mainly caused by the input of near-surface organic material from the northwest and the export of deep inorganic material through the Norwegian Trench (Pätsch and Kühn, 2008). According to the simulation with ERSEM which neglects benthic denitrification the North Sea is a source of total nitrogen for the North Atlantic (74 Gmol N a^{-1}).

Concerning nitrogen, 30.5 Gmol N a^{-1} are imported into the North Sea in the form of organic matter, of which 50% are converted into dissolved inorganic nitrogen and exported into the North Atlantic, the other 50% are stored in the different biological compartments.

With phosphorus the situation is somewhat different: approximately 82% of the net import of organic phosphorus (2.2 Gmol P a^{-1}) is converted into dissolved inorganic phosphorus and exported, whereas only 18% are stored and/or buried as particulate organic phosphorus.

All budgets given and especially the direct comparison between the carbon and the nutrient budgets should be interpreted carefully. The main critical items are

- For the carbon budget the underlying water budget stems from climatological estimates, it does not correspond directly with the values used for the nutrient budgets.
- The nitrogen budget suffers from the lack of simulated benthic denitrification.
- The budgets are mean budgets, and the variability of the atmospheric, hydrodynamic and riverine forcing is not considered.

The variability of the driving forces is large and so is the variability of the resulting budgets (Pätsch and Radach, 1997; Radach and Pätsch, 2007). Therefore a 3D physical – biogeochemical coupled model including the carbon chemistry, the biological interactions of carbon, nitrogen, phosphorus and silicon, and the benthic denitrification will be established. In combination with observations this tool will allow to calculate simultaneously time-dependent budget for the relevant elements of the marine ecosystem.

7.4 The Black Sea and the Turkish Straits System

Temel Oguz and Suleyman Tugrul

7.4.1 Introduction

The Black Sea, located between latitudes of 41° to 46°N and longitudes of 28° to 41.5°E, is an elongated, elliptic, nearly enclosed basin with a narrow opening to the Aegean basin of the Eastern Mediterranean through the Bosphorus and Dardanelles Straits and the Sea of Marmara (Fig. 7.4.1). Together with the Sea of Marmara, it is characterized by eutrophication-induced strong and extended phytoplankton blooms and complex ecosystem structure as compared to the mesotrophic Aegean Sea and the oligotrophic Mediterranean Sea. The surface chlorophyll concentration distribution, depicted in Fig. 7.4.1, increases by an order of magnitude from the saltier Eastern Mediterranean to the brackish Black Sea, which receives large nutrient input from rivers discharging into the northwestern shelf (hereinafter referred to as NWS) of the basin. The underflow through the Bosphorus also introduces some nutrients available in the salty waters of Mediterranean into the Black Sea. The presence of a permanent pycnocline between the brackish upper layer and the saltier deep waters prevents ventilation of deep layer below 100–150 m depth. Within the last ∼7000 years, the Black Sea therefore developed distinctly different chemical features in the water column, the most significant of which were the oxic/anoxic transition zone between the upper oxygenated layer and sulfide-bearing deep layer and a series of complicated oxidation–reduction processes mediated by bacterial activities. Long-term observations have shown that the Black Sea ecosystem has been drastically modified

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