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The carbon budget of the North Sea

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Abstract

A carbon budget has been established for the North Sea, a shelf sea of the NW European continental shelf. The air-sea exchange of CO_2 has been assessed as closing term of the budget. The carbon exchange fluxes with the North Atlantic Ocean dominate the gross carbon budget. The net carbon budget – more relevant to the issue of the contribution of the coastal ocean to the marine carbon cycle – is dominated by the carbon inputs from rivers, the Baltic Sea and the atmosphere. The dominant carbon sink is the final export to the North Atlantic Ocean. The North Sea acts as a sink for organic carbon. More than 90% of the CO_2 taken up from the atmosphere is exported to the North Atlantic Ocean making the North Sea a highly efficient continental shelf pump for carbon.

1 Introduction

During the last decade many efforts have been made to investigate, understand and quantify the global carbon cycle, since the greenhouse gas carbon dioxide (CO_2) plays a key role in controlling climate on Earth. It has also been realised that the CO_2 released by human activities is in part responsible for global warming by affecting the heat balance on Earth (IPCC, 2001). Large international projects such as the World Ocean Circulation Experiment (WOCE) or the Joint Global Ocean Flux Study (JGOFS) as well as many national programs have been devoted to understand and assess the ocean's role in the global carbon cycle. Evidence has been provided that the atmosphere and the ocean absorb major amounts of the anthropogenic CO_2, whereas the role of the terrestrial biosphere, which is commonly assessed as a closing term of the global carbon balance, still remains unclear. This in part is caused by the uncertainty in the assessment of the oceanic uptake of anthropogenic CO_2 (Sarmiento et al., 2000; Gruber and Keeling, 2001; IPCC, 2001; Orr et al., 2001; Thomas et al., 2001; Takahashi et al., 2002; Sabine et al., 2004). One of the reasons for this uncertainty is the lack of reliable information on the coastal oceans, which hitherto have only barely been considered in the oceanic and global carbon budgets.

Coastal and marginal seas reveal strong biological activity, in part triggered by terrestrial and human impacts, and play an important role in the global carbon cycle by linking the terrestrial, oceanic and atmospheric carbon reservoirs (Gattuso et al., 1998). The high biological activity causes high CO_2 fluxes between the coastal and marginal seas and the atmosphere and the adjacent open oceans, respectively. Considering the surface area, coastal seas thus might have a contribution disproportionately high to the open ocean storage of CO_2 (Thomas et al., 2004a) via a mechanism called the "continental shelf pump" (Tsunogai et al., 1999). High biological activity enables CO_2 drawdown from the atmosphere and subsequent export to the subsurface layer. The outflow of these CO_2-enriched subsurface waters ultimately transfers the atmospheric CO_2 into the intermediate layers of the open ocean. During the last years detailed field studies have been initiated in a few areas such as the East China Sea, the NW European shelf, the Baltic Sea and the North Sea (Chen and Wang, 1999; Thomas et al., 1999; Thomas and Schneider, 1999; Frankignoulle and Borges, 2001; Borges and Frankignoulle, 2002; Borges and Frankignoulle, 2003; Thomas et al., 2003b; 2004a). However, there is only limited information available on a global scale about these CO_2 fluxes (Liu et al., 2000a, 2000b; Cai et al., 2003; Chen et al., 2003).

The North Sea is amongst the best-studied coastal areas world-wide with respect to its physical, chemical and biological conditions, since it has been subject to detailed investigations for many decades. Earlier carbon cycle studies in the North Sea were confined to certain near-shore coastal areas such as the German Bight, the Wadden Sea or the Belgian coast (Hoppema, 1991; Frankignoulle et al., 1996; Borges and Frankignoulle, 1999, 2002; Brasse et al., 1999). An early basin-wide pioneer study relied on total alkalinity, dissolved inorganic carbon (DIC) and pH observations during late spring and provided first insights in the North Sea carbon cycle (Pegler and Kempe, 1988; Kempe and Pegler, 1991). Recently, an intense field study has been carried out covering all seasons with high spatial resolution in order to comprehensively investigate

the carbon cycle and its controlling processes in the North Sea (Thomas, 2002; Bozec et al., 2004; Thomas et al., 2004a). Here we establish for the first time ever a full carbon budget for the North Sea considering the CO_2 air-sea exchange as the closing term. We rely our study on data from the above program, data from the European Union project BIOGEST, as well as further complementary data.

2 Site description and methods

2.1 Hydrography

The North Sea (Fig. 1) is located on the north-western European continental shelf with an open northern boundary to the North Atlantic Ocean. In the west and south the North Sea is enclosed by the British Islands, and the European continent (France, Belgium, Netherlands, Germany and Denmark) and the Norwegian West Coast constitute the south-eastern and eastern boundary. The Baltic Sea waters enter the North Sea via the Skagerrak between Denmark and Norway. In the south the English Channel constitutes a further connection to the North Atlantic Ocean. The continuous water exchange across the northern boundary dominates the water budget (OSPARCOM, 2000). Only a minor fraction of this North Atlantic inflow reaches the region south of the Dogger Bank (approx. 55° N/3° E; Fig. 1), which is controlled by the inputs via the English Channel. As a consequence, the most prevailing feature of the semi-enclosed North Sea is an anticlockwise "u-shaped" circulation of North Atlantic Ocean water entering at the north-western boundaries via the Shetland Channel and the Faire Island Channel and leaving along the Norwegian Trench at the eastern boundary (Fig. 1) with residence times of less than one year (Lenhart and Pohlmann, 1997; Thomas et al., 2003a). For details refer to OSPARCOM (2000).

2.2 Bottom topography and carbon cycling

The bottom topography constitutes a major control of the conditions for the hydrodynamical conditions as well as for biogeochemical cycling in the North Sea (Frankignoulle and Borges, 2001; Bozec et al., 2004; Thomas et al., 2004a). The deeper northern part reveals depths down to approx. 150 m on the shelf, down to 400 m in the Norwegian Channel and 700 m in the Skagerrak. This seasonally stratified part of the North Sea is a rather oceanic system, dominated by the influence of North Atlantic Ocean water. Terrestrial influences play a minor role, riverine inputs from the Scandinavian peninsula and the Baltic Sea inputs "dilute" the North Atlantic Ocean water only in a narrow band along the Norwegian coast. In the northern North Sea stratification enables net export of carbon and nutrient to the deeper layers via sinking of particulate organic matter (POM). In contrast, the water depths south of the Dogger Bank are less than 50 m deep, and even less than 20 m deep near the coasts. This much smaller, shallow and continuously mixed southern region receives the vast majority of the riverine fresh water supplied to the North Sea. Together with the inputs from the Wadden Sea (Brasse et al., 1999), these inputs exert a significant control of the biogeochemical cycles. The southern region is strongly affected by terrestrial and anthropogenic nutrient inputs (organic and inorganic) and the permanentely mixed water column does not enable export of POM to any deeper layers. The POM is mineralised in the whole water column, causing high turnover of the carbon and nutrients and preventing final burial of POM.

Final burial of POM can be observed only in the deeper basins of the Skagerrak and the Norwegian Channel, whereas in the remaining parts of the North Sea almost no POM burial occurs. The overall POM burial can be considered as insignificant on an annual time scale and amounts to less than 1% of the annual primary production (Radach and Lenhart, 1995; De Haas et al., 2002). The lack of ultimate POM burial in both regions of the North Sea has different consequences for the carbon cycling: 1) In the southern part, most of the carbon, fixed as POM by photosynthetic activity,

is recycled within the mixed water column. On an annual time scale the net CO_2 exchange with the atmosphere is small, since the net removal of DIC by photosynthetic activity is negligible except for the period of the spring bloom. 2) In the northern part the stratification enables net removal of CO_2 by the export of POM to the sub-surface layer and finally DIC export to the North Atlantic Ocean (Bozec et al., 2004; Thomas et al., 2004a).

2.3 The water budget

One of the most critical terms in establishing a carbon budget of entire coastal seas or marine areas in general is the water budget, since the gross and net carbon fluxes related to water mass transport usually dominate the budget. Information available on the various components of the water budget of the North Sea (ICES, 1983; Eisma and Kalf, 1987; Otto et al., 1990; Lenhart et al., 1995; Smith et al., 1996; Lenhart and Pohlmann, 1997) adequately describes the main features of the hydrodynamical circulation, but exhibit some discrepancies regarding the net water flows from rivers and the Baltic Sea. Notably the exchange flows between the North Atlantic Ocean and the North Sea from the different simulations are difficult to compare, since they rely on different model structures or forcing conditions. In order to overcome this problem, our carbon budget calculations rely on the water budget by Eisma and Kalf (1987), which describes reliably the influx from the Baltic Sea (Stigebrandt, 2001; Thomas et al., 2003b) as well as the magnitude of the riverine inputs (OSPARCOM, 2000). There is notable evidence that the water transports across the northern boundaries can be subdivided into transports in the upper and lower parts of the water column (Lenhart et al., 1995; Pätsch and Radach, 1997). The relative information on this subdivision has been applied (Table 1), since this allows us to consider the recently obtained high resolution DIC and dissolved organic carbon (DOC) data.

2.4 The carbon budget for the North Sea

In order to establish a carbon budget for the North Sea, the North Sea was defined as one box 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. 1). The carbon fluxes across these boundaries have been computed using the water transports and the corresponding DIC and DOC concentrations. Realising the essential role of POM in the carbon metabolism, POM plays a negligible role in importing or exporting carbon (De Haas et al., 2002; Thomas et al., 2004b). Riverine inputs, carbon burial have been considered as further sinks or sources to the North Sea box. The CO_2 air-sea exchange (F_A) has been obtained as closing term of the budget. We assume the system to be in a steady state, i.e. the fluxes into and out of the box balance each other (Eq. 1). Accordingly, the following components of the North Sea carbon fluxes were considered (Eq. 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) and via the English Channel (F_E), sedimentation (F_S), outflow to the Atlantic Ocean (F_O), net exchange with the atmosphere (F_A). Carbon flows into the box are denoted by a positive sign. Carbon flows out of the box are denoted by a negative sign.

$$\Sigma(F_{\text{into the box}}) = \Sigma(F_{\text{out of the box}}) \tag{1}$$

or

$$F_R + F_B + F_S + F_F + F_E + F_S + F_O + F_A = 0. \tag{2}$$

Since the carbon fluxes F into and out of the box balance each other, F_A can be obtained as:

$$F_A = -(F_R + F_B + F_S + F_F + F_E + F_S + F_O). \tag{3}$$

If the resulting F_A value is positive, i.e. the output is larger than the input, the North Sea absorbs CO_2 and acts as a sink for atmospheric CO_2. If F_A is negative, the North Sea releases CO_2 to the atmosphere.

The required DIC and DOC data (Tab. 1) have been obtained during the recent North Sea carbon cycle study (Thomas, 2002). 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 (Borges et al., in preparation). The final inputs were compiled applying the “apparent zero end member” method (Kaul and Froelich, 1984) and upscaled using the “rate curve estimation” method (Cooper and Watts, 2002). The carbon inputs from the Baltic Sea have been taken from Thomas et al. (2003b). The sedimentation of organic carbon has been estimated according to (De Haas et al., 2002) considering only the sedimentation of marine material.

3 Results

3.1 Carbon fluxes in the North Sea

The carbon budget of the North Sea is clearly dominated by the carbon exchange across the northern North Sea boundaries (Fig. 2a, Table 1). The Atlantic Ocean supplies more than 98% of the carbon: 74% via the Shetland Channel, 16% via the Faire Island Channel and 8% via the English Channel. Moreover, the Baltic Sea supplies approximately 1% of the carbon. Finally, rivers provide 0.7% and the atmosphere 0.6% of the overall carbon import. The dominant role of the North Atlantic Ocean is even more pronounced in exporting carbon from the North Sea. More than 99% of all carbon is exported to the North Atlantic Ocean via the Norwegian Trench, which constitutes the only notable carbon sink of the North Sea over an annual scale. Only less than 1% of primary production is exported to sediment for burial, which still might play a relevant role over geological time scales. The separation of the gross carbon fluxes into its inorganic (Fig. 2b) and organic (Fig. 2c) fractions shows that inorganic species including (DIC and CO_2 including atmospheric CO_2) are the major vehicles for the carbon transport. Inorganic species account for 96% of the inputs and for 97% of the exports respectively. 4% of the carbon is imported to the North Sea as organic carbon and 3% of the carbon exports leaves the North Sea as DOC and less than 1% is exported to the sediments. Moreover, the North Sea acts as a sink for organic carbon, i.e. in the view of the budget a part of the organic carbon imported to the North Sea is converted to DIC and thus leave the North Sea as inorganic carbon.

The main features relevant for carbon budgets for coastal areas are more evident when considering the net carbon fluxes, in our case when ignoring the gross fluxes of carbon because of the exchange with the North Atlantic Ocean. For this purpose, the carbon fluxes entering the North Sea via the Faire Island Channel, the Shetland Channel and the English Channel have been subtracted from the carbon outflow via the Norwegian Trench. The riverine inputs, the uptake of atmospheric CO_2 and the carbon import from the Baltic Sea can now be identified as the major carbon sources controlling the carbon cycling (Fig. 3a). All are of the same order of magnitude (Table 1). It is evident that the carbon content of the North Atlantic Ocean is enriched, while it circulates through the North Sea, by the three suppliers (the atmosphere, the Baltic Sea and the rivers). The overall enrichment of the carbon content of the Atlantic Ocean water amounts to $2.69\cdot10^{12}\,\mathrm{mol\,C\,yr^{-1}}$. This represents approximately 2% of the initial carbon content or, related to the North Sea surface, $-4.6\,\mathrm{mol\,C\,yr^{-1}\,m^{-2}}$. The atmosphere represents 29% of this enrichment, the Baltic Sea 40% and the riverine input 31%.

A closer look to the net fluxes of the inorganic and organic species shows that the inorganic carbon pool is increased not only by the atmosphere, the Baltic Sea and the rivers, but also from the North Sea DOC pool (Fig. 3b). Considering the observed increase of DIC between the inflowing and outflowing waters, it has been shown that the uptake of atmospheric CO_2 and the "internal" conversion of DOC to DIC contribute almost equally to the DIC increase. Approx. 13.5% of the entire DOC inputs are transferred to the inorganic pool, which is equivalent to 6.5 times the riverine organic carbon inputs. The major difference between both DIC sources is that the conversion of DOC to DIC does not constitute a net carbon flux, whereas the uptake of atmospheric CO_2

constitutes a net import of carbon. About 10% of the latter are transferred to the sediments and 90% to the North Atlantic Ocean by the continental shelf pump (Bozec et al., 2004; Thomas et al., 2004a; Table 1). The North Sea thus acts as a highly efficient continental shelf pump. For the organic carbon pool (Fig. 3c) the situation is different. The Atlantic Ocean acts as the major source of DOC in the North Sea, while rivers and the Baltic Sea play a rather modest role in the organic carbon budget of the North Sea. Still, these inputs are biogeochemically significant, especially in the southern part, which receives the largest part of the river runoff. Final POM burial acts as a minor sink of organic carbon and the loss of DOC to the DIC pool constitutes the major sink for DOC.

The trophic status of marine areas is often determined by assessing whether the area is a net sink or source of organic carbon or nutrients. The CO_2 air-sea flux is then predicted by this assessment. A heterotrophic area, characterised by a net consumption of organic carbon and a net release of inorganic nutrients is thought to be a source of atmospheric CO_2. An autotrophic region – an exporter of organic carbon and a net sink for inorganic nutrients – is thought to be a sink of atmospheric CO_2. From the carbon budget of the North Sea discussed here as well as from the detailed air –sea CO_2 flux study (Thomas et al., 2004a) it is evident that the trophic status cannot be used to reliably predict the direction of the CO_2 air-sea flux. According to the carbon and nutrient budgets (Table 1, this work; Lenhart et al., this issue; Thomas et al., 2004c) the North Sea would be characterised as a heterotrophic sea. Still, the North Sea acts as a sink for atmospheric CO_2. A similar feature has been observed in the Baltic Sea (Thomas et al., 2003b). It appears that the trophic state might only be used as an indicator for the direction of CO_2 air-sea fluxes in homogenous (real 1-box) systems, but not in stratified systems like the North Sea or the Baltic Sea. The relationship at ecosystem level between the trophic status and the air-water CO_2 fluxes is modulated by at least two factors: hydrographic features and the spatial extent of continental shelves. Permanently well-mixed systems like the English Channel (Borges and Frankignoulle, 2003) and the Southern Bight of the North Sea (Bozec et al., 2004; Thomas et al., 2004a) tend to be weak sources of CO_2 to the atmosphere in contrast with seasonally stratified regions such as the northern North Sea (Thomas et al., 2004a) and the Gulf of Biscay (Frankignoulle and Borges, 2001), or permanently stratified regions such as the Baltic Sea (Thomas and Schneider, 1999). Stratification enables net removal of CO_2 by the export of POM to the surface layer and finally DIC export to adjacent aquatic systems. In a permanently well-mixed water column, CO_2 fixed by photosynthesis during the bloom period is released to the water column during the heterotrophic post-bloom period and ventilated back to the atmosphere. Also, near-shore coastal regions influenced by anthropogenic and/or terrestrial organic and inorganic carbon inputs such as estuaries and estuarine plumes are sources of CO_2 (Frankignoulle et al., 1998; Borges and Frankignoulle, 2002; Borges et al., 2003). In wide continental shelves like the North Sea, these CO_2 source regions have a local and overall small effect of the air-water CO_2 flux budget. However, in narrow continental shelves like the South Atlantic Middle Bight these near-shore regions influenced by terrestrial inputs have a more important weight in the budget and the overall continental shelf tends to release part of the CO_2 to the atmosphere, which has been imported from the adjacent near coast area (Cai et al., 2003).

3.2 Discussion of the budget

As already indicated in section two, the carbon budget is closely related to the water budget of the North Sea. Despite the fact that the water exchange with the North Atlantic Ocean dominates both the carbon and the water budget, the carbon budget is highly sensitive to the net water fluxes from the land and the Baltic Sea. While the water import from the Baltic Sea is well established e.g. Stigebrandt (2001), available information on the riverine inputs has to be carefully evaluated. For example the runoff of the major rivers amounts to approximately 130 $km^3\,yr^{-1}$, whereas the total river runoff to the North Sea amounts to 300 $km^3\,yr^{-1}$ (OSPARCOM, 2000). Given the comparable magnitude of the net players of the carbon budget (Fig. 3), a reliable knowledge is required on these fluxes is essential. This also holds true for the inflow from the Baltic

Sea, which has been overestimated in all modelling studies (see Sect. 2.2). In order to establish the net carbon fluxes, a reliable knowledge on the gross fluxes, i.e. on the carbon exchange between North Sea and North Atlantic Ocean. The assessment of the gross flows benefited from the high resolution carbon cycle data set (Thomas, 2002) and allowed to unravel the net flows from the much larger gross flows. The resulting assessment of the CO_2 air-sea exchange is in very good agreement with the recent results from a direct air-sea flux study, which reports a CO_2 uptake of 1.38 $mol\,C\,m^{-2}\,yr^{-1}$ by the North Sea (Thomas et al., 2004a). These results thus underpin the carbon budget presented here.

4 The continental shelf pump: operational modes in the North Sea and the adjacent Baltic Sea

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, of which carbon content is increased during this transport. Major sources increasing the carbon contents of the Atlantic Ocean water are the Baltic Sea, the rivers and the atmosphere. The uptake of atmospheric CO_2 by the North Sea amounts to 1.38 $mol\,C\,m^{-2}\,yr^{-1}$, of which more than 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., 2003b). This can be explained by different bottom topographic and hydrographic conditions, which cause different operational modes for the continental shelf pump. The brackish Baltic Sea rather serves as a collecting basin for fresh water, 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 draw-down from the atmosphere. Once this carbon escapes the surface layer it can hardly 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 carbon preservation in sediments, which ultimately implies that the entire CO_2 draw-down caused by biological activity is available for export to the Atlantic Ocean. The relatively short flushing time of the North Sea and its bottom topography play a major role in preventing sedimentation and accumulation of POM (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. 4a), which increases the carbon content of Atlantic Ocean water while it is circulated through the North Sea. In contrast, the Baltic Sea rather acts as an injection pump (Fig. 4b), which injects "new" water and corresponding carbon loads to the adjacent aquatic system, which is in this case the North Sea.

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Table 1. One-box carbon budget of the North Sea. The budgetting area is 575 300 km^2, and the water volume 42 294 km^3. The water budget is according to Eisma and Kalf (1987). The Baltic Sea inputs are taken from Thomas et al. (2003b). The inflow and outflows were separated into upper and lower water column (Pätsch and Radach, 1997). 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 et al. (in preparation). Positive flows indicate inputs into the North Sea and negative ones flows out of the North Sea. The CO_2 air-sea exchange is computed from the difference between carbon output and input.

	Flow [km^3 yr^{-1}]	Carbon				
		Input/Output concentrations		Input/Output fluxes		
		DIC [µmol l^{-1}]	DOC/POC [µmol l^{-1}]	DIC/ [10^{12} mol yr^{-1}]	DOC/POC [10^{12} mol yr^{-1}]	Total C 10^{12} mol yr^{-1}]
Water input into box from:						
Baltic Sea	500	2118	100	1.059	0.050	1.109
Atlantic Ocean:						
Via English Channel	4900	2100	60	10.290	0.294	10.584
Via Faire Island and Pentland Firth	9000	Upper: 2094 (58%) Lower: 2108 (42%)	76.8	18.898	0.691	19.590
Via Shetland Channel	42000	Upper: 2102 (53%) Lower: 2166 (47%)	76.8	88.758	3.226	91.983
Rivers	300			0.778	0.088	0.866
Outflow to the North Sea via Norwegian Trench	-56700	Upper: 2075 (10%) Lower: 2142 (90%)	Upper: 56 (14%) Lower: 67 (86%)	-121.071	-3.712	-124.783
Sedimentation (marine part. Organic Carbon)			-0.13mol C m^{-2} yr^{-1}		Shelf: 80kt C yr^{-1} Deep basins: 800ktC yr^{-1}	-0.073
Subtotals:						
Input:						124.132
Output:						-124.856
Difference (-output-input): (air-sea flux)		**1.3 mol CO_2 m^{-2} yr^{-1}**				0.724

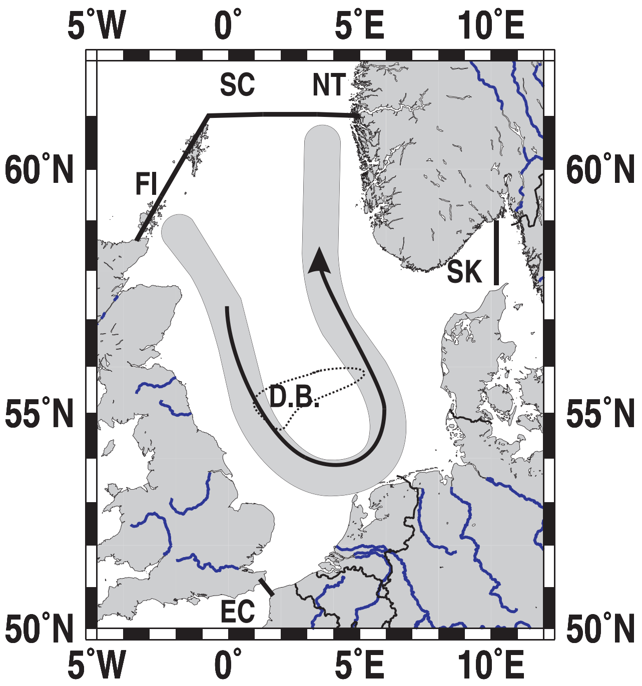


Fig. 1. The Budgeting area for the North Sea. The boundaries of the budgeting area are: English Channel (EC), Skagerrak (SK), Faire Island Channel (FI), Shetland Channel (SC), Norwegian Trench (NT). The arrow indicates the dominant anticlockwise circulation of North Atlantic Ocean water through the North Sea. The location of the Dogger Bank (D.B.) is indicated.

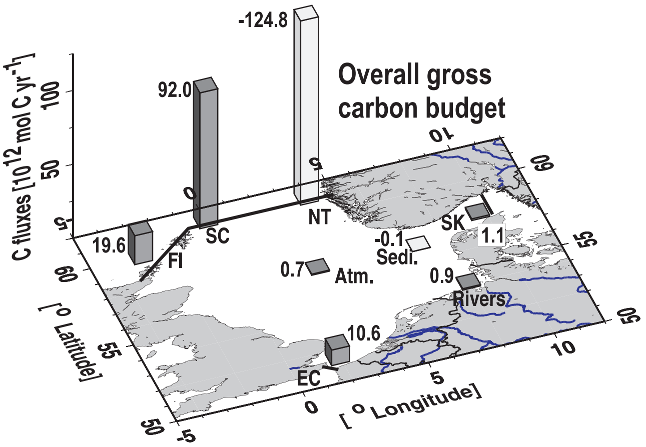


Fig. 2. Gross carbon budgets of the North Sea. The gross carbon fluxes across the boundaries (see Fig. 1) as well as the fluxes across the air-sea and sediment water interfaces are shown. **(a)** shows the total (inorganic and organic) gross carbon fluxes and **(b)** and **(c)** the gross inorganic and organic carbon fluxes, respectively. The lighter columns denote carbon sinks (negative values) and the darker columns carbon sources (positive values), respectively. Note the different scales of the plots.

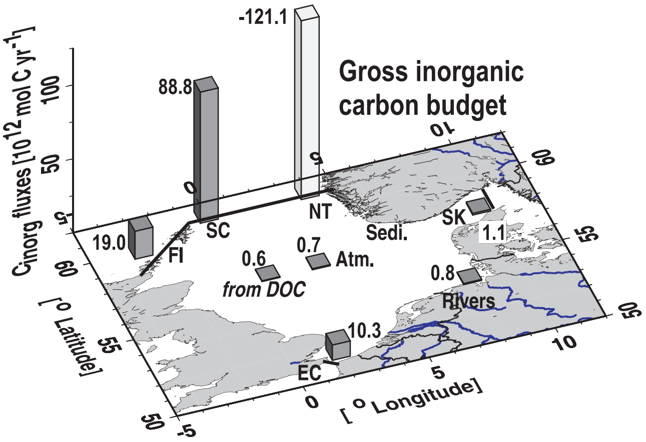
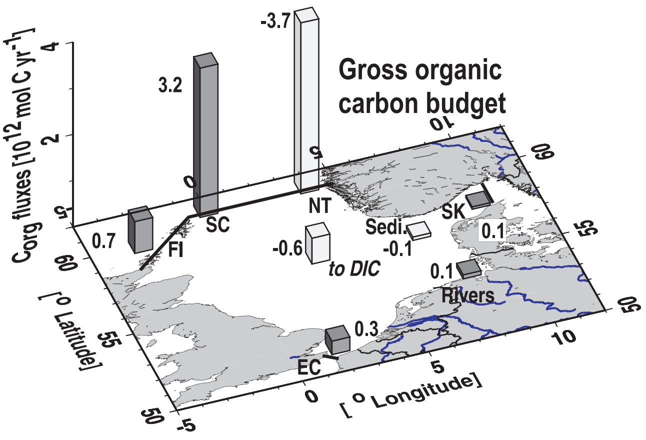


Fig. 2. Continued.



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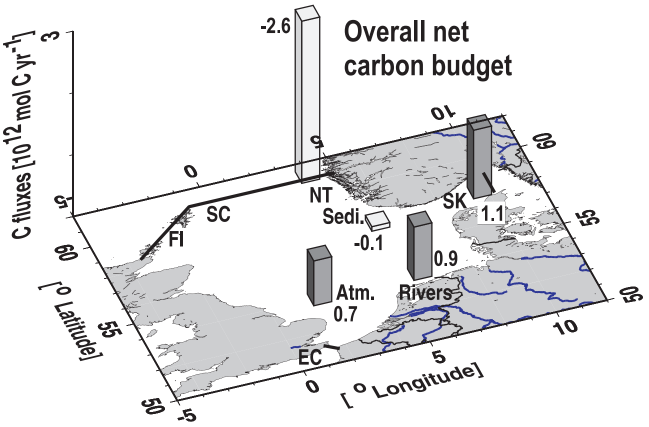
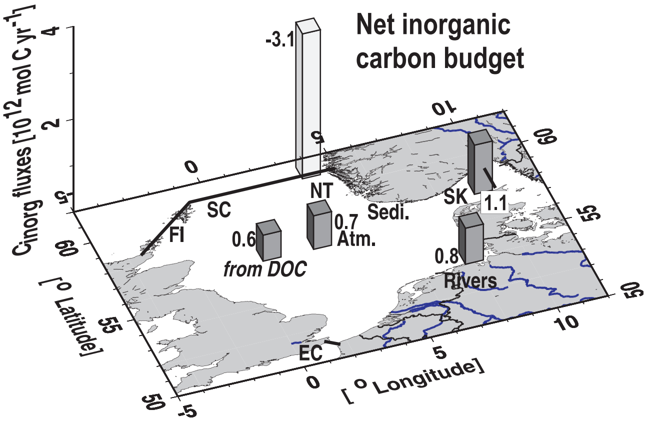


Fig. 3. Net carbon budgets of the North Sea. The net fluxes are calculated from the gross fluxes minus the carbon imports via Faire Island Channel, Shetland Channel and English Channel representing the circulation of Atlantic Ocean water through the North Sea. The net (residual) carbon fluxes across the boundaries as well as the fluxes across the air-sea and sediment water interfaces are shown. **(a)** overall net carbon budget; **(b)** the net budget of inorganic carbon: **(c)** net budget of organic carbon. The lighter columns denote carbon sinks (negative values) and the darker columns carbon sources (positive values), respectively. Note the different scales of the plots.



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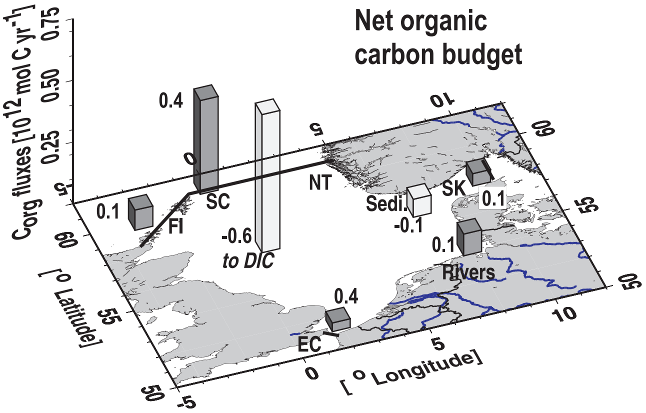

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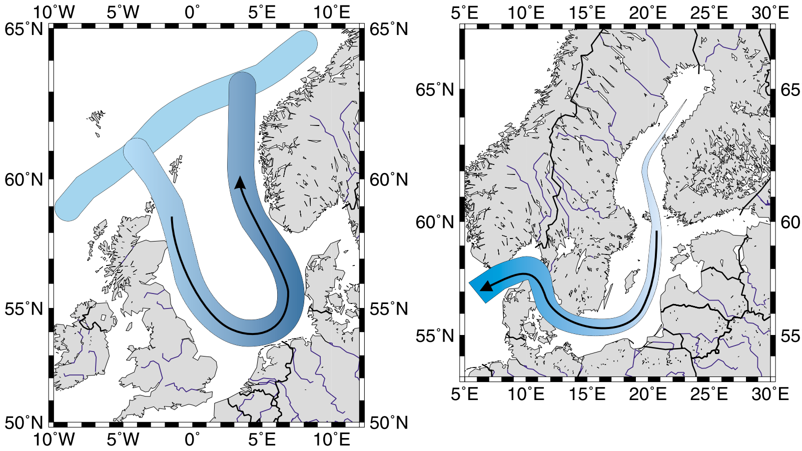

Fig. 4. Different operational modes of the continental shelf pump: the bypass pump in the North Sea **(a)** and the injection pump in the Baltic Sea **(b)**.