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The carbon budget of the Baltic Sea

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Abstract

The paper presents the results of a detailed study of the Baltic Sea's carbon budget. The Baltic is very much influenced by terrestrial carbon input. Import from the land from rivers is the largest carbon source, amounting to 10.90 Tg C yr^{-1} with a 37.5 % contribution from organic carbon. On the other hand, carbon is effectively exported from the Baltic to the North Sea (7.67 Tg C yr^{-1}) and is also buried in bottom sediments (2.73 Tg C yr^{-1}). The other sources and sinks of carbon are of minor importance. The net CO_2 emission (1.05 Tg C yr^{-1}) from the Baltic to the atmosphere was calculated as the closing term of the carbon budget presented here. There is a net loss of organic carbon, which indicates that the Baltic Sea is heterotrophic.

1 Introduction

Shelf seas play a key role in the global fluxes of matter and energy between the land, ocean and atmosphere (Thomas et al., 2009). Although they make up a little over 7 % of the global sea surface and less than 0.5 % of the ocean volume, shelf seas are responsible for 15–30 % of marine primary production and as much as 80 % of organic matter burial (Walsh, 1991; Borges, 2005; Bozec et al., 2005; Chen and Borges, 2009). These features of shelf seas are due to the high biological activity they support, which is driven by nutrient inputs from all of the adjacent environments (Gattuso et al., 1998; Pätsch and Kühn, 2008; Thomas, 2009).

As a consequence of this high biological productivity, most global shelf seas are believed to act as net sinks for anthropogenic CO_2 (e.g. Chen et al., 2003; Borges et al., 2005; Chen and Borges, 2009). Moreover, the CO_2 loads absorbed by shelf seas exceed those reported from the open ocean (Chen and Borges, 2009; Takahashi et al., 2009). It has recently been suggested that in contrast to open shelf seas, some near-shore zones are identified as sources of CO_2 to the atmosphere (Chen and Borges, 2009; Liu et al., 2010b). Consequently, detailed studies of the carbon cycle in shelf seas are still required in order to clarify their role in the global carbon cycle . Although several attempts have been made to quantify the role of shelf seas in global CO_2 fluxes (Tsunogai et al., 1999; Andersson and Mackenzie, 2004; Thomas et al., 2004), validation of the outcome of these studies must be based on compilations of the results of local studies. These enable the multifarious locally specific processes influencing CO_2 exchange between seawater and the atmosphere to be taken into consideration (Borges, 2005; Borges et al., 2005; Chen and Borges, 2009).

The Baltic Sea is a spatially and temporally highly diverse ecosystem (Dippner et al., 2008; HELCOM, 2009). This is the reason behind the significant discrepancies in the CO_2 air-sea exchange results reported in the literature (Ohlson, 1990; Thomas and Schneider, 1999; Thomas et al., 2003; Algesten et al., 2004, 2006; Kuss et al., 2006; Wesslander et al., 2010). On the one hand the Gulf of Bothnia is believed to be a CO_2 source to the atmosphere (Algesten et al., 2004, 2006). On the other, the southern Baltic acts as an effective sink for atmospheric CO_2 (Ohlson, 1990; Thomas and Schneider, 1999; Thomas et al., 2003; Kuss et al., 2006; Chen and Borges, 2009). This geographical distribution is comparable to the magnitude of the biological activity. Primary production in the northern Baltic is less than in the southern Baltic because of the insufficient light and temperature conditions and the lower terrestrial nutrient input (Wasmund and Uhlig, 2003; Wasmund and Siegel, 2008; HELCOM, 2009). However, recent data (Wesslander et al., 2010) have identified the southern and central Baltic as a significant source of CO_2 to the atmosphere as well.

The results reported above are based on pCO_2 measurements made at stations located in the open waters of the Baltic Sea. The near-shore zones and areas adjacent to river mouths are often omitted from pCO_2 measurements. However, these regions of the Baltic Sea could be of special importance for CO_2 cycling, since it has been demonstrated worldwide that near-shore zones and river mouths are important sources of CO_2 to the atmosphere (Frankignoulle et al., 1998; Borges, 2005; Chen and Borges, 2009; Liu et al., 2010a). This is due to the significant input of terrestrial carbon. The rivers flowing into the Baltic Sea drain an area that is more than four times larger than that of the sea itself. Moreover, the water volume the rivers supply annually to the Baltic Sea amounts to almost 2 % of the total water volume of the Baltic (Lass and Matthäus, 2008).

Although numerous measurements of $p\mathrm{CO_2}$ have been performed in the Baltic Sea in comparison with other shelf seas, there is no straightforward understanding of the part played by the entire Baltic Sea in CO_2 air-sea exchange. There are discrepancies between reported results, even though they relate to the same area (Thomas and Schneider, 1999; Wesslander et al., 2010). Similarly, the other carbon inputs and outputs to and from the Baltic Sea, reported in the literature, are incomplete or require revision (Thomas et al., 2003, 2010). The recent studies by Kuliński et al. (2011) and by Kuliński and Pempkowiak (2011) respectively redefine the results of carbon exchange between the Baltic and the North Sea, and quantify carbon burial in Baltic bottom sediments. Moreover, although the Baltic Sea carbon cycle is significantly influenced by the input of terrestrial carbon, calculations of carbon supply from land are still based on annual averages of water flow and carbon concentrations obtained as extrapolations of marine carbon concentrations against salinity (Thomas et al., 2003, 2010).

These aspects were the motivation for the present study. The aim was to develop a state-of-the-art carbon budget for the entire Baltic Sea that would provide a comprehensive description of the boundary carbon fluxes. Based on both experimental and literature data (Pempkowiak and Kupryszewski, 1980; Granskog et al., 2005; Thomas et al., 2005; Algesten et al., 2006; Kuliński and Pempkowiak, 2008; Dzierzbicka-Głowacka et al., 2010; Kowalczuk et al., 2010; Thomas et al., 2010), major carbon fluxes were selected for the present investigation. They include carbon exchange between the Baltic and North Sea, river input, organic carbon burial in bottom sediments, atmospheric deposition, point sources (all terrestrial carbon loads other than those entering the Baltic Sea from rivers), fisheries, and net CO_2 exchange between sea water and the atmosphere (Fig. 1). Since the net CO_2 exchange is temporally and spatially highly variable, and the results reported in the literature are ambiguous (Thomas and Schneider, 1999; Algesten et al., 2006; Kuss et al., 2006; Wesslander et al., 2010), it was calculated using the mass balance approach. The mass balance is based on the assumption that a steady state occurs, as a result of which all carbon sinks and sources in the Baltic Sea balance one another. The mass balance approach is a minimal requirement to obtain a reliable, quantitative description of the carbon cycle in highly diverse ecosystems (Liu et al., 2010a). A similar method for quantifying CO_2 exchange between the Baltic Sea and the atmosphere was used a decade ago and described by Thomas et al. (2010). Those authors identified the Baltic Sea as a sink for atmospheric CO_2 amounting to 2.28 Tg C yr^{-1}. Since then, however, revised carbon fluxes in the Baltic Sea have been reported (Kuliński et al., 2011; Kuliński and Pempkowiak, 2011), and other corrected fluxes are reported here.

2 Material and methods

2.1 Study area

The Baltic Sea is a landlocked shelf sea connected to the North Sea only via the shallow and narrow Danish Straits. Moreover, there are two sills at the entrance to the Baltic, the Drogden Sill and the Darss Sill, with respective maximum depths of 8 and 18 m. These features restrict the exchange of water between the Baltic and the North Sea and permit the inflow of only large, episodic volumes (in excess of 100 km^3) of highly saline and well oxygenated North Sea water. On the other hand there is a larger volume of river runoff (428 km^3 yr^{-1} on average). Almost 70 % of this runoff enters the north-eastern Baltic, i.e. the Gulfs of Bothnia, Finland and Riga. This gives rise to horizontal and vertical gradients of the sea's physical, chemical and ecological properties. There is a permanent halocline at 60–80 m depth separating the brackish surface water from the deep, more saline, water of North Sea origin. This natural density barrier hinders the ventilation of deep water, resulting in conditions of permanent hypoxia or even anoxia at the sediment surface of the Baltic Sea deeps (Elken and Matthäus, 2008; Lass and Matthäus, 2008).

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2.2 Quantification of carbon fluxes

All the investigated carbon fluxes were quantified on an annual timescale, irrespective of the temporal resolution used for the assessment. This was essential to balance the carbon inputs and outputs and to construct the carbon budget.

2.3 Carbon exchange between the Baltic Sea and North Sea

Carbon exchange between the Baltic Sea and North Sea (F_e and F_i) was calculated as the product of water volume and carbon concentration (Eqs. 1 and 2). On the basis of experimental work performed at the Institute of Oceanology PAS (Kuliński, 2010) and literature data (Thomas and Schneider, 1999; Omstedt et al., 2004; Lass and Matthäus, 2008; Prowe et al., 2009), it was found that temporal resolutions of the variables should be no worse than one week for concentrations of carbon species, and one day for water volumes and directions. Hence, three latitudinal transects in the Danish Straits were selected, for which hydrological data were supplied from the DMI-BSHcmod three-dimensional (3-D) ocean circulation model, which is the Danish Meteorological Institute's (DMI) operational model. The "end members" method was used to separate the Baltic Sea and the North Sea water masses (V_B and V_N, respectively) in the bulk of water flowing across the transects. Simultaneously, the seasonal variabilities in inorganic (DIC) and organic (DOC) carbon concentrations were assessed separately for the Baltic Sea ($\mathrm{DIC_B}$ and $\mathrm{DOC_B}$) and North Sea ($\mathrm{DIC_N}$ and $\mathrm{DOC_N}$) water masses. The details of the methods used for quantifying carbon exchange between the Baltic and North Seas and of the results used in this study are described in Kuliński et al. (2011).

$$F_e = V_B \cdot (\mathrm{DIC_B} + \mathrm{DOC_B}) \tag{1}$$

$$F_i = V_N \cdot (\mathrm{DIC_N} + \mathrm{DOC_N}) \tag{2}$$

2.4 Organic carbon burial in the bottom sediments

Organic carbon burial (F_b) in the bottom sediments of the Baltic Sea was calculated as the difference between the organic carbon accumulated in the deep depositional areas of the Baltic Sea (F_s) and the organic matter losses due to long-term mineralization (F_m) (Eq. 3). The former was assessed from sediment accumulation rates (ϖ) obtained using the ^{210}Pb method and validated against the ^{137}Cs distribution (Joshi and Shukla, 1991; Pempkowiak, 1991) and organic carbon concentrations in the sediments (C_{org}) (Eq. 4). Carbon losses caused by long-term mineralization were calculated from the dissolved inorganic carbon and dissolved organic carbon diffusive fluxes (F_{DIC} and F_{DOC}, respectively) from the sediment surface to the water column (Eq. 5). The details of organic carbon burial quantification in Baltic Sea sediments are presented in Kuliński and Pempkowiak (2011).

$$F_b = F_s - F_m \tag{3}$$

$$F_s = \varpi \cdot C_{org} \tag{4}$$

$$F_m = F_{DIC} + F_{DOC} \tag{5}$$

2.5 Riverine input

The terrestrial carbon load entering the Baltic Sea from rivers (F_r) was calculated as the product of individual river discharges (R_d) and carbon concentrations in river water – both total inorganic carbon and total organic carbon (TIC_r and TOC_r, respectively) – for the 63 largest Baltic Sea rivers (Eq. 6). The relevant data (monthly means of R_d, TIC_r and TOC_r) were taken from the database created and provided by Baltic-C – a BONUS funded project. This database contains the results obtained by national monitoring programmes carried out by the Baltic Sea countries. Because of the lack of up-to-date data, the mean annual carbon loads for 6 rivers – the Koskenkyla, Kuivajoki, Lestijoki, Paimionjoki, Perhojoki and Sirrpujoki – were assessed for the period 1995–2000. In the case of the Rivers Göta, Narva, Daugava and Neva, water flows were taken from the paper by Kuusisto et al. (2008). Moreover, the TIC and TOC concentrations data for the Rivers Daugava and Neva were assumed to be similar to those found in adjacent rivers whose drainage basins have a similar geological structure (Voipio, 1981). In the case of Daugava they were adapted from the River Neman, whereas for the River Neva, the mean TIC and TOC concentrations used were the average of the concentrations measured in the Narew and Virajoki.

$$F_\mathrm{r} = \sum R_\mathrm{d} \cdot (\mathrm{TIC_r} + \mathrm{TOC_r}) \tag{6}$$

Atmospheric deposition

Atmospheric deposition (F_o) consists of two terms: dry deposition (F_od) and wet deposition (F_ow) (Eq. 7).

$$F_\mathrm{o} = F_\mathrm{od} + F_\mathrm{ow} \tag{7}$$

The literature data do not supply straightforward information relating to the dry deposition of carbon to the Baltic Sea. Even so, the dry deposition of carbon from the atmosphere is significantly lower than that attributed to wet deposition (Jurado et al., 2008). It was assumed that marine aerosols emitted from the Baltic Sea surface are redeposited in the same amounts on the water surface. Hence, only the wet deposition of carbon to the Baltic Sea is considered in the present study (Eq. 8):

$$F_\mathrm{o} = F_\mathrm{ow} = P \cdot (\mathrm{C_o} + \mathrm{C_i} + \mathrm{C_b}) \tag{8}$$

where P is the mean precipitation over the Baltic Sea, and $\mathrm{C_o}$, $\mathrm{C_i}$ and $\mathrm{C_b}$ are the respective concentrations of organic, inorganic and black carbon in rain water.

The organic carbon load entering the Baltic Sea with wet atmospheric deposition was calculated by scaling up the values reported by Algesten et al. (2006) to the entire Baltic Sea surface area. Kuśmierczyk-Michulec et al. (2001) noted that black carbon concentrations were eight times lower than organic carbon concentrations in the aerosol samples collected over the Baltic. Since aerosols are a major source of organic carbon in rain water (Jurado et al., 2008), the same rate was used to calculate the black carbon load to the Baltic Sea derived from wet deposition.

Rainwater saturated with atmospheric CO_2 was identified as a source of inorganic carbon entering the Baltic Sea with wet deposition. Henry's Law (Eq. 9) was used to calculate the CO_2 concentration in rainwater (Ibanez et al., 2007):

$$\mathrm{C} = K_\mathrm{H} \cdot p \tag{9}$$

where C is a CO_2 concentration in rainwater, K_H is a Henry's constant ($T = 10\,^\circ\mathrm{C}$ and 1013 hPa) and p is a CO_2 partial pressure in the atmosphere.

2.6 Point sources

The amount of carbon entering the Baltic Sea from point sources (F_p) was assessed on the basis of HELCOM (2004) data. Since it was expressed in terms of BOD_7 (biological oxygen demand), the conversion rate (k) was applied according to HELCOM (1983) to calculate the carbon mass (Eq. 10).

$$F_\mathrm{p} = \mathrm{BOD}_7 \cdot k \quad (k = 2.27) \tag{10}$$

2.6.1 Fisheries

Fish landings are assumed to be a carbon sink. Recent data describing total fish landings in the Baltic Sea (F_l) were adapted from the ICES report of 2008. In accordance with Crabtree's (1995) results, a mean organic carbon concentration in the fish biomass ($\mathrm{C_f}$) amounting to 8.2 % of the wet weight was used to recalculate fish landings as carbon mass removed from the Baltic Sea (F_f) (Eq. 11):

$$F_\mathrm{f} = F_\mathrm{l} \cdot \mathrm{C_f} \tag{11}$$

2.6.2 CO_2 exchange between the Baltic Sea and the atmosphere

The net CO_2 exchange between the Baltic Sea and the atmosphere (FCO_2) was calculated using the mass balance approach on the assumption that an equilibrium exists between carbon sources and sinks (Eq. 12). Hence, when carbon sources in the Baltic Sea are presented as positive values and carbon sinks as negative ones, the sum of the carbon fluxes should balance one another (Eq. 13). This enables the FCO_2 direction and strength between the Baltic Sea and the atmosphere to be calculated (Eq. 14).

$$\sum \text{carbon sources} = \sum \text{carbon sinks} \tag{12}$$

$$F_\mathrm{e} + F_\mathrm{i} + F_\mathrm{o} + FCO_2 + F_\mathrm{f} + F_\mathrm{p} + F_\mathrm{r} + F_\mathrm{m} + F_\mathrm{s} = 0 \tag{13}$$

$$FCO_2 = F_\mathrm{e} + F_\mathrm{i} + F_\mathrm{o} + F_\mathrm{f} + F_\mathrm{p} + F_\mathrm{r} + F_\mathrm{m} + F_\mathrm{s} \tag{14}$$

The uncertainty of the FCO_2 (X) flux was calculated as the total uncertainties of all the carbon sources and sinks (x_i) (Eq. 15). The uncertainties of the individual carbon fluxes take into account both the representativeness of water flows and the seasonality of carbon concentrations.

$$X = \sum x_i \tag{15}$$

3 Results

All the results obtained in this study are presented according to the following scheme: positive values indicate carbon sources, negative ones indicate carbon sinks.

The carbon loads entering the Baltic Sea from the 63 rivers investigated are listed in Table 1. These results exhibit a distinct discrepancy in carbon loads and water flows between the Scandinavian (Sweden, Finland) and continental rivers (Poland, Lithuania, Latvia, Estonia and Russia). The former have higher TOC than TIC loads, in contrast to the results obtained for the continental rivers. TOC fluxes in the Scandinavian rivers range from 0.5 Gg yr^{-1} to 102.4 Gg yr^{-1} (the Rivers Ljusnan and Torne, respectively), and TIC loads range from 0.1 Gg yr^{-1} to 63.8 Gg yr^{-1} (the Rivers Sirppujoki and Göta, respectively). In the case of the continental rivers the ranges are from 75.5 Gg yr^{-1} (Odra) to 1209.5 Gg yr^{-1} (Neva) and from 384.5 Gg yr^{-1} (Narwa) to 1295.2 Gg yr^{-1} (Neva) for TOC and TIC loads respectively. The fact that both TOC and TIC loads are higher in the continental rivers than in the Scandinavian ones is the result of the higher water flows in the former. The annual freshwater volume entering from the continental rivers to the Baltic Sea fluctuate between 11.9 km^3 and 77.6 km^3 for the Neman and Neva respectively. The same range for the Scandinavian rivers is between 0.1 km^3 (the Sirppujoki and the Virojoki) and 18.1 km^3 (the Göta).

The freshwater supply from all 63 rivers amounts to 345 $\text{km}^3\,\text{yr}^{-1}$, some 80 % of the total river runoff to the Baltic Sea (428 $\text{km}^3\,\text{yr}^{-1}$) (Lass and Matthäus, 2008). Thus, assuming the results obtained to be representative of the entire Baltic Sea, total loads of 6.81 Tg TIC yr^{-1} and 4.09 Tg TOC yr^{-1} were calculated (Table 2) – the highest carbon source (10.90 Tg yr^{-1}) in the carbon budget of the Baltic Sea (Fig. 2).

The second largest source of carbon to the Baltic Sea is the input from the North Sea (3.91 Tg yr^{-1}; see Fig. 2 and Table 2). Almost 95 % of this amount is inorganic carbon. However, carbon exchange between the Baltic and North Sea is dominated by an export to the North Sea of −9.70 Tg yr^{-1} of inorganic carbon and −1.88 Tg yr^{-1} of organic carbon (Fig. 2; Table 2). The Baltic Sea is thus a net source of carbon (−7.67 Tg yr^{-1}) for the North Sea. The bottom sediments are yet another crucial carbon sink in the Baltic Sea (Fig. 2; Table 2), annually receiving −3.87 Tg of organic carbon. This amount needs to be corrected by the return carbon flux (1.14 Tg yr^{-1}) originating from the long-term mineralization and hydrolysis of the organic matter deposited in the sediments. The bulk of the carbon returning to the water column (91 %) is dissolved inorganic carbon (DIC), indicating that the rate of mineralization exceeds that of hydrolysis of organic carbon in the sediments. The contributions of atmospheric deposition, point sources and fisheries are less significant (0.57, 0.04 and −0.06 Tg C yr^{-1}, respectively; see Fig. 2 and Table 2).

The unbalanced amount of carbon, according to the definition given in Sect. 2.2.7, is attributed to the net CO_2 exchange between the seawater and the atmosphere. The results (Fig. 2; Table 2) show that the Baltic Sea acts as a small source of CO_2 to the atmosphere. On average, 1.05 Tg of carbon are emitted annually to the atmosphere in the form of CO_2, a result that is encumbered with an uncertainty of ±2.47 Tg yr^{-1}. Although this uncertainty exceeds the value of FCO_2, one should remember that it makes up as little as 7.7 % of the total carbon sources and sinks summed as absolute values.

4 Discussion

The carbon budget obtained in this work identifies the Baltic Sea as a region very much influenced by the surrounding drainage area. The total terrestrial carbon input is 10.94 Tg C yr^{-1} (Fig. 2; Table 2), of which only 0.04 Tg C $\text{yr}^{-1}$is attributable to point sources; the remaining 10.90 Tg C yr^{-1} enter the Baltic Sea from rivers. This amount is comparable to the results reported by Thomas et al. (2010), who estimated the riverine carbon load to be 10.27 Tg C yr^{-1}. However, we see a remarkable difference when the organic carbon contribution is considered in the total carbon load supplied from rivers: riverine TOC is 37.5 % in our study but only 20.5 % in Thomas et al. (2010).

On the other hand the results obtained in the present study point unequivocally to two crucial carbon sinks in the Baltic Sea: net export to the North Sea (–7.67 Tg C yr^{-1}; Kuliński et al., 2011) and burial in the bottom sediments (2.73 Tg C yr^{-1}; Kuliński and Pempkowiak, 2011) (Fig. 2; Table 2). The former amounts to 56 % and 77 %, respectively, of the estimates reported by Thomas et al. (2003, 2010). When the individual carbon fluxes are analysed in detail, the reasons for these discrepancies become clear. Carbon fluxes through the Danish Straits are highly dependent on the water flows. In both previous estimates (Thomas et al., 2003, 2010), the water export from and import to the Baltic Sea were higher than the flows calculated in our study (Kuliński and Pempkowiak, 2011). Moreover, in contrast to previous papers (Thomas et al., 2003, 2010), we considered the seasonality of both water flows and carbon concentrations (Kuliński and Pempkowiak, 2011).

The other important carbon sink in the Baltic Sea is the export of organic matter to the bottom sediments. According to the results obtained by Kuliński and Pempkowiak (2011), $-2.73\,\mathrm{Tg\,C\,yr^{-1}}$ are buried in the deep depositional basins of the Baltic Sea (Fig. 2; Table 2). This is comparable to the results of Thomas et al. (2010), who reported $-2.64\,\mathrm{Tg\,C\,yr^{-1}}$. However, since the data of these latter authors are based on sediment accumulation rates and carbon concentrations in the sediments, they do not take into account carbon loss during early diagenesis. Kuliński and Pempkowiak (2011) demonstrated that almost 30 % of recently accumulated organic matter in Baltic Sea bottom sediments is released back to the water column as dissolved carbon species. Moreover, it is suggested that mineralization and hydrolysis of the organic matter accumulated in sediments goes on for as long as 60 yr after deposition. Thus, the return carbon flux should be quantified when the carbon budget is assessed.

Although the other carbon sources and sinks are of minor importance (Fig. 2; Table 2), their quantification may be decisive for the quality of the whole carbon budget. We assessed the carbon source from atmospheric deposition as a product of precipitation and carbon concentration in rain water. We find this approach more accurate than that suggested by Thomas et al. (2010), where the precipitation used for the calculations was reduced by evaporation. Consequently, our result is higher ($0.57\,\mathrm{Tg\,C\,yr^{-1}}$) than the $0.24\,\mathrm{Tg\,C\,yr^{-1}}$ reported by Thomas et al. (2010).

Apart from the sources and sinks of total carbon, our carbon budget provides a detailed description of the organic and inorganic carbon fluxes. These data are significant since the trophic status of marine areas can be assessed using the organic carbon balance. Autotrophic areas are net producers of organic carbon, whereas heterotrophic areas are net consumers (Gattuso, 1998; Thomas et al., 2005). Thus, on the basis of the organic and inorganic carbon balance (Table 2), the Baltic Sea can be characterized as a heterotrophic marine system. However, it needs to be borne in mind that this is the net state of the entire sea. Generally, in stratified systems like the Baltic Sea, autotrophic processes dominate in the upper, euphotic zone, whereas heterotrophic ones are dominant in the subsurface layer (Thomas et al., 2005; Bozec et al., 2005). Moreover, the spatial inconstancy of the Baltic Sea's trophic state is evident, a feature related to the diverse intensity of biological activity.

The results obtained in the present study identify the entire Baltic Sea as a source of CO_2 to the atmosphere. When the calculated FCO_2 ($-1.05\,\mathrm{Tg\,C\,yr^{-1}}$) is divided by the Baltic's surface area of $3.85 \times 10^5\,\mathrm{km}^2$ (excluding the Kattegat), we obtain a mean CO_2 emission of $-2.7\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ ($-9.9\,\mathrm{g\,CO_2\,m^{-2}\,yr^{-1}}$). This finding is significant, since none of the data reported so far have yielded such a simple result (Table 3; Ohlson; 1990; Thomas and Schneider, 1999; Algesten et al., 2004, 2006; Kuss et al., 2006; Wesslander et al., 2010; Thomas et al., 2010). The biggest discrepancy concerns the status of the Baltic Proper, where the mean FCO_2 ranges from $36.0\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ (Kuss et al., 2006) to $-28.1\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ (Wesslander et al., 2010), values respectively identifying these areas as a sink for atmospheric CO_2 and a source of CO_2 to the atmosphere. More coherent data are reported for the Gulf of Bothnia, defining this region as an evident CO_2 source (Table 3; Algesten et al., 2004, 2006). On the basis of these reports and taking into consideration the results of this study, the Baltic Proper together with the Gulfs of Finland and Riga act as a CO_2 sink. When the most recent FCO_2data for the entire Gulf of Bothnia ($-3.61\,\mathrm{Tg\,C\,yr^{-1}}$) (Algesten et al., 2006) is used in this calculation, the mean FCO_2 in the remaining part of the Baltic Sea area amounts to $2.56\,\mathrm{Tg\,C\,yr^{-1}}$ or $9.0\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$. This result is close to that reported by Thomas and Schneider (1999) but more than 30 % lower than the one reported by Ohlson (1990) (Table 3). Moreover, it is contrary to the findings by Wesslander et al. (2010), who report respective emissions of CO_2 to the atmosphere from both the East Gotland Sea and the Bornholm Sea of -19.7 and $-28.1\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ (Table 3). However, these results become questionable when they are compared to the carbon budget obtained in this study. Assuming FCO_2 values of $-35.4\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ (Algesten et al., 2006) and $-19.7\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ (Wesslander et al., 2010) to be representative of the Gulf of Bothnia and the Baltic Proper together with the Gulfs of Finland and Riga, the entire carbon budget would be unbalanced with 9.18 Tg C yr^{-1}. This corresponds to more than 84 % of the river input, which is the largest source of carbon for the Baltic Sea reported in this study. In other words, an additional carbon source of 9.18 Tg C yr^{-1} would need to be supplied to the Baltic Sea if the average carbon concentration in the Baltic Sea water did not change. Otherwise the carbon concentration of the Baltic Sea water would increase by an average of 0.4 mg dm^{-3} yr^{-1} in the total water volume of the Baltic Sea (22 000 km^3). This concentration change would correspond to about 10 % of the DOC concentration or to almost 2 % of the DIC concentration recorded in the surface water of the southern Baltic Sea (Thomas and Schneider, 1999; Schneider et al., 2003; Kuliński and Pempkowiak, 2008; Beldowski et al., 2010).

It is unlikely that this carbon budget for the Baltic Sea will not evolve in the next few decades. Several studies report on the changes that may occur within the Baltic Sea region, most of them are induced by global climate changes (e.g. Graham, 2004; Meier, 2006; Graham et al., 2007, 2008). The expected total runoff change to 2100 ranges from −2 % to 15 % of the present flow according to the different climate scenarios (Graham, 2004; Graham et al., 2008). Studies performed on Swedish rivers (Smith et al., 2008) indicate that 71–97 % of the carbon load is explained by the water volume. Thus, it is very likely that the change in river runoff to the Baltic Sea will result in a change of terrestrial carbon input. Since the carbon entering the Baltic Sea from rivers is the largest source of carbon to the Baltic Sea, such changes may significantly contribute to the functioning of the entire Baltic Sea carbon system. However, the greatest unknown factor still remains the future input of nutrients to the Baltic Sea, which is the basic force driving the biological pump.

Simultaneously, as a consequence of the river runoff increase, outflows of Baltic Sea water to the North Sea will increase and inflows of highly saline North Sea water will decrease (Cyberski and Wróblewski, 2000). Thus, some part of the additional terrestrial carbon load will be compensated for the increased carbon export to the North Sea and the reduced carbon import from the North Sea. There is still much debate on the consequences of the predicted lower frequency of the North Sea water inflows (Gerlach, 1994; Meier, 2006; Graham et al., 2008). On the one hand a salinity decrease in the whole water column together with the simultaneous maintenance of vertical stratification is expected (Meier, 2006; Graham et al., 2008). On the other hand it is suggested that the halocline will drop to a lower depth (Gerlach, 1994; Graham et al., 2008). This may change the near-bottom redox conditions in parts of the depositional areas, with the consequent liberation of buried carbon resulting from increased mineralization.

Comparison of the results obtained in this study with the findings reported for other shelf seas identifies the Baltic Sea as a basin with a close to neutral balance of CO_2 exchange between seawater and the atmosphere (Table 4). Worldwide investigations show that FCO_2 may be highly diverse in time and space within the same shelf sea. Some parts of the basin may act as efficient sinks for atmospheric CO_2, whilst others are simultaneously a source of CO_2 to the atmosphere. This feature justifies the use of the mass balance method for determining FCO_2 for entire seas or at least for the verification of assessments based on local measurements of pCO_2. This becomes crucial since the latter are very sensitive to the transfer velocity parameterization, which may be locally specific. Although the mass balance approach is not a direct method of quantitatively assessing the CO_2 exchange between the marine environment and the atmosphere, and such FCO_2 results are burdened with a relatively high uncertainty, it should be taken into account as a basis for describing the average state of the environment. The carbon budget calculated for the North Sea (Thomas et al., 2005) shows that calculated carbon inputs and outputs are well balanced, so that it is possible to calculate one missing carbon flux when all the others have been calculated correctly, especially in enclosed or semi-enclosed shelf seas where the hydrological conditions are easier to define. Moreover, the carbon budget provides a qualitative and quantitative assessment of boundary conditions, which become crucial for understanding the carbon cycle in enclosed ecosystems like the Baltic Sea.

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Table 1. Water flows, TIC and TOC loads for the 63 largest rivers entering the Baltic Sea.

	River	Country	Water flow [$km^3 yr^{-1}$]	TIC [$Gg\,yr^{-1}$]	TOC [$Gg\,yr^{-1}$]
1	Ahtava	Finland	0.5	1.2	6.9
2	Ångermanälven	Sweden	16.3	37.5	84.6
3	Ätran	Sweden	1.8	7.0	19.3
4	Aura	Finland	0.2	1.7	4.1
5	Botorpström	Sweden	0.2	1.1	2.6
6	Daugava	Latvia	20.8	1068.9	210.7
7	Delångersån	Sweden	0.4	1.0	2.6
8	Emån	Sweden	1.1	4.3	16.8
9	Eura	Finland	0.2	0.9	2.7
10	Gide	Sweden	0.9	1.0	9.2
11	Göta	Sweden	18.1	63.8	80.5
12	Helgeån	Sweden	1.5	7.3	27.0
13	Iijoki	Finland	5.7	12.9	66.5
14	Indalsälven	Sweden	13.9	61.1	57.0
15	Kalajoki	Finland	1.1	2.6	26.9
16	Kalix	Sweden	10.1	20.5	59.0
17	Kemijoki	Finland	0.3	1.3	2.1
18	Kiiminki	Finland	1.5	2.9	25.8
19	Kiskonjoki	Finland	0.2	0.7	2.7
20	Kokemaenjoki	Finland	7.0	28.0	75.0
21	Koskenkyla	Finland	0.2	1.0	1.9
22	Kuivajoki	Finland	0.5	1.3	7.5
23	Kymi Ahven	Finland	5.8	21.9	46.2
24	Kymi Kokon	Finland	5.1	17.9	38.5
25	Lagan	Sweden	2.8	4.8	37.9
26	Lapuanjoki	Finland	0.9	1.7	19.1
27	Lestijoki	Finland	0.3	0.5	6.2
28	Ljungan	Sweden	3.2	15.2	19.2
29	Ljungbyån	Sweden	0.2	0.3	3.4
30	Ljusnan	Sweden	0.2	0.9	0.5
31	Lule	Sweden	16.1	31.6	44.4
32	Lyckebyån	Sweden	0.2	0.4	3.8

Table 1. Continued.

	River	Country	Water flow [km^3 yr^{-1}]	TIC [Gg yr^{-1}]	TOC [Gg yr^{-1}]
33	Merikarvia	Finland	0.6	0.9	11.7
34	Mörrumsån	Sweden	0.9	1.7	12.8
35	Motala	Sweden	3.2	33.0	24.3
36	Mustijoki	Finland	0.2	1.3	3.6
37	Narpionjoki	Finland	0.3	0.5	7.2
38	Narwa	Estonia	12.7	384.5	190.9
39	Nemen	Lithuania	11.9	609.1	123.4
40	Neva	Russia	77.6	1295.2	1209.5
41	Nissan	Sweden	1.6	3.0	24.5
42	Nyköpingsån	Sweden	0.6	5.5	6.4
43	Odra	Poland	13.1	431.8	75.5
44	Öre	Sweden	1.1	1.2	13.7
45	Oulujoki	Finland	8.9	17.4	87.3
46	Paimionjoki	Finland	0.2	2.4	2.3
47	Perhojoki	Finland	0.6	0.6	10.1
48	Pite	Sweden	5.5	8.9	22.4
49	Porvoonjoki	Finland	0.4	3.6	5.5
50	Pyhajoki	Finland	1.0	2.3	20.0
51	Råne	Sweden	1.4	2.1	11.7
52	Rickleån	Sweden	0.5	0.7	5.8
53	Rönneån	Sweden	0.4	5.4	4.1
54	Siikajoki	Finland	1.4	3.1	29.3
55	Simojoki	Finland	1.5	3.6	20.3
56	Sirppujoki	Finland	0.1	0.1	1.1
57	Skellefte	Sweden	3.4	6.0	8.2
58	Torne	Sweden	14.2	28.9	102.4
59	Ume	Sweden	14.9	35.9	63.8
60	Uskela	Finland	0.2	1.4	2.6
61	Vantaa	Finland	0.6	4.7	8.9
62	Virojoki	Finland	0.1	0.4	2.5
63	Vistula	Poland	28.5	1168.1	175.6
	Total		344.9	5486.6	3297.9

Table 2. Sources and sinks of inorganic (IC) and organic carbon (OC) expressed in $\mathrm{Tg\,yr^{-1}}$. Positive values indicate carbon sources, negative ones indicate carbon sinks.

Carbon flux	Sources		Sinks		Sum		Total
	IC	OC	IC	OC	IC	OC	
Rivers	6.81	4.09			6.81	4.09	10.90
Baltic Sea/North Sea	3.70	0.21	−9.70	−1.88	−6.00	−1.67	−7.67
Sediments	1.04	0.10		−3.87	1.04	−3.77	−2.73
Atmospheric deposition	0.06	0.51*			0.06	0.51*	0.57
Point sources		0.04				0.04	0.04
Fisheries				−0.06		−0.06	−0.06
Net CO_2 exchange			−1.05		−1.05		−1.05
Total	11.61	4.95	−10.75	−5.81	0.86	−0.86	0.00

* – the sum of organic carbon ($0.45\,\mathrm{Tg\,C\,yr^{-1}}$) and black carbon ($0.06\,\mathrm{Tg\,C\,yr^{-1}}$) loads.

Table 3. Comparison of the FCO_2 results obtained with the literature data reported for the Baltic Sea. Positive values of FCO_2 indicate CO_2 sequestration in seawater, whereas negative ones indicate emission of CO_2 to the atmosphere.

Region	FCO_2 [$\mathrm{g\,C\,m^{-2}\,yr^{-1}}$]	Reference
Baltic Sea	−2.7	Present study
Baltic Proper + Gulf of Finland + Gulf of Riga	9.0	Present study based on the results of Algesten et al. (2006)
Baltic Sea	2.3	Thomas et al. (2010)
Baltic Proper + Gulf of Finland + Gulf of Riga	13.2	Ohlson (1990)
Baltic Proper + Gulf of Finland + Gulf of Riga	10.8	Thomas and Schneider (1999)
Arkona Basin	36.0	Kuss et al. (2006)
East Gotland Sea	−19.7	Wesslander et al. (2010)
Bornholm Sea	−28.1	Wesslander et al. (2010)
Gulf of Bothnia	−37.2	Algesten et al. (2004)
Gulf of Bothnia	−35.4	Algesten et al. (2006)

Table 4. Comparison of the FCO_2 results calculated for the Baltic Sea with the literature data for other shelf seas. Positive values of the FCO_2 indicate CO_2 sequestration in seawater, whereas negative ones indicate emission of CO_2 to the atmosphere.

Region	FCO_2 $[\mathrm{g\,C\,m^{-2}\,yr^{-1}}]$	Reference
Baltic Sea	−2.7	Present study
Baltic Proper + Gulf of Finland + Gulf of Riga	9.0	Present study based on the results by Algesten et al. (2006)
North Sea	18.0–26.4	Bozec et al. (2005)
North Sea	16.5	Thomas et al. (2005)
North Sea	−9.4	Prowe et al. (2009)
North Sea	24.7	Prowe et al. (2009)
Barents Sea	6.6	Fransson et al. (2001)
Barents Sea	43.2	Borges et al. (2005)
Bering Sea	51.6	Walsh and Dieterle (1994)
Bering Sea	−56.4	Fransson et al. (2006)
Chukchi Sea	57.6	Bates, 2006
Chukchi Sea	37.2	Kaltin and Anderson (2005)
Sea of Okhotsk	10.0	Wakita et al. (2003)
Arabian Sea	−10.8	Goyet et al. (1998)
Sea of Japan	45.6	Cai et al. (2006)
South China Sea	−15.6	Zhai et al. (2005)
South China Sea	12.0	Chen et al. (2003)
Yellow Sea	24.0	Chen and Borges (2009)

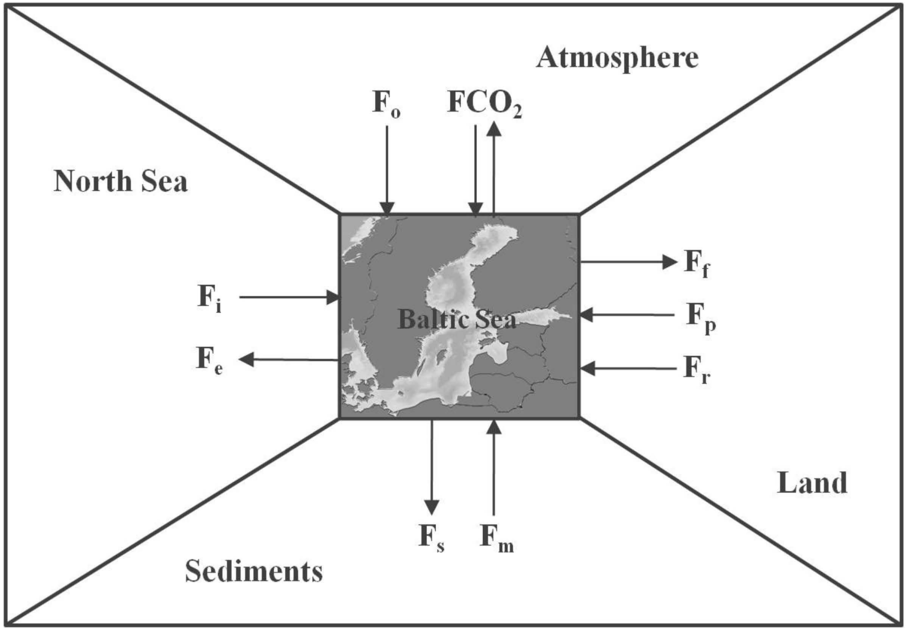

Fig. 1. Carbon sources and sinks in the Baltic Sea. Symbols: F_e – export to the North Sea, F_i – import from the North Sea, F_o – atmospheric deposition, FCO_2 – net CO_2 exchange between seawater and the atmosphere, F_f – fisheries, F_p – point sources, F_r – river input, F_s – accumulation in sediments, F_m – return flux from sediments to the water column.

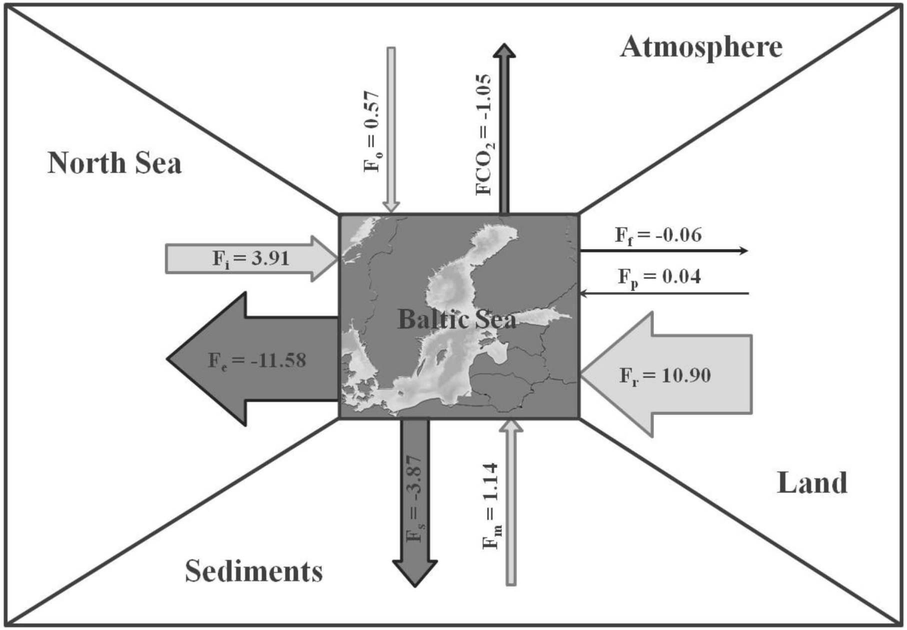

Fig. 2. Carbon budget of the Baltic Sea. Sources are marked in green (positive values), whereas sinks are marked in blue (negative values). Symbols: F_e – export to the North Sea, F_i – import from the North Sea, F_o – atmospheric deposition, FCO_2 – net CO_2 exchange between seawater and the atmosphere, F_f – fisheries, F_p – point sources, F_r – river input, F_s – accumulation in sediments, F_m – return flux from sediments to the water column.