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Organic carbon burial rates in the Baltic Sea sediments

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ABSTRACT

Recent studies indicate the important role of the marine environment in the circulation of CO2. This is due to the occurrence of the so called "biological pump" mechanism. A special role in this process is played by the shelf seas. The paper presents estimates of organic carbon burial rates in the Baltic Sea sediments. Quantification of the burial rate required the determination of organic carbon accumulation rate to the Baltic sediments and the carbon return flux from sediments to the water column. Results of both sediment and mass accumulation rates as well as profiles of dissolved inorganic carbon (DIC) and dissolved organic carbon (DOC) were used. Sediment accumulation rates were based on ^{210}Pb method validated by ^{137}Cs measurements and ranged from 66 g m^{-2} yr^{-1} to 744 g m^{-2} yr^{-1} as regards mass accumulation rates and from 0.07 cm yr^{-1} to 0.25 cm yr^{-1} as regards linear accumulation rates. Carbon deposition to the Baltic sediments amounts to 1.955 ± 0.585 Tg m^{-2} yr^{-1}, while 0.759 ± 0.020 g m^{-2} yr^{-1} of carbon returns from sediments to the water column. Thus the organic carbon burial rate in the Baltic Sea sediments is equal to 1.197 ± 0.584 Tg C m^{-2} yr^{-1}.

1. Introduction

Shelf seas extend between shores and continental shelf breaks, including estuaries (Borges, 2005). Another definition says that they are the coastal waters which link the terrestrial environment, the open ocean and the atmosphere (Gattuso et al., 1998; Thomas et al., 2009). They are quite shallow (depth less than 200 m), and account for only 7% of the total area of all marine and oceanic waters, as well as less than 0.5% of their total volume. Despite all this, they play an important role in the global carbon cycle (Walsh, 1991; Chen and Borges, 2009). It has been estimated that they are responsible for approximately 20% of marine organic matter production, about 80% of the total organic matter load deposited to marine sediments, and 90% of the total mineralization of organic matter in the sediments of the world ocean (de Haas et al., 2002; Borges, 2005; Bozec et al., 2005).

The role of the shelf seas, including the Baltic Sea, as regards CO_2 absorption from the atmosphere, has not been recognized fully so far. This is attributed to the dynamics of shelf seas. They represent, most often, nutrient-rich areas with abundant biological activity (Gattuso et al., 1998). It is believed that due to an effectively functioning "biological pump" shelf seas contribute to the reduction of CO_2 concentrations in the atmosphere by absorbing this greenhouse gas (Chen and Borges, 2009; Laruelle et al., 2010). On the other hand both the earlier (Smith and Hollibaugh, 1993) and the recent (Kuliński and Pempkowiak, 2011) estimates show their slightly heterothropic (Smith and Mackenzie, 1987; Smith and Hollibaugh, 1993), or close to neutral (Kuliński and Pempkowiak, 2011) role in the global carbon cycle. It is noteworthy that in the paper by Smith and Hollibaugh (1993) burial in sediments was indicated as an important sink of organic matter in the coastal ocean, and quantification of the flux to- and burial in- sediments were suggested to be the important topics for further studies. Wei-Jun Cai et al. (2010) investigated mechanism of carbon return flux from organic rich sediments. They concluded that transport of CO_2 evolving in the process of organic matter mineralization is responsible for the flux (Wei-Jun Cai et al., 2010).

The Baltic Sea is characterized by intensive phytoplankton blooms lasting from early spring (April) to autumn (October). High primary production in the Baltic Sea is induced by high concentrations of biogenic substances which are provided from land (Wasmund and Uhlig, 2003; Dippner et al., 2008; HELCOM, 2009). In the context of these reports it would appear that the Baltic Sea effectively absorbs atmospheric CO_2 (Thomas et al., 2010). However, mineralization of the organic matter from river run-off contributes to the production of CO_2 (Kuliński and Pempkowiak, 2012). There are contrasting reports regarding CO_2 exchange between the Baltic Sea and the atmosphere. According to Thomas and Schneider (1999) the Baltic Proper, together with the Gulf of Finland and the Gulf of Riga, absorbs atmospheric CO_2 at the level of

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10.8 g C m^{-2} yr^{-1}. While Kuss et al. (2006) suggest that the Arkona Basin absorbs 36.0 g C m^{-2} yr^{-1}. On the other hand, Algesten et al. (2004, 2006) present results indicating net emissions of CO_2 from the Gulf of Bothnia to the atmosphere. These are in the range of −37.2 g C m^{-2} yr^{-1} (Algesten et al., 2004) and −35.4 g C m^{-2} yr^{-1} (Algesten et al., 2006). The results obtained by Kuliński and Pempkowiak (2011) also present the Baltic Sea as a net source of CO_2 to the atmosphere, although a marginal one. The estimates are based on the quantification of major sources and sinks of carbon to the Baltic. These include: primary production, river run-off, water exchange with the North Sea, and burial of carbon in sediments (Wasmund and Uhlig, 2003; Kuliński and Pempkowiak, 2011). Among these carbon fluxes we can distinguish the ones that play a key role, and others whose role is minor. Carbon burial rate is one of the most important, but insufficiently recognized, elements of the carbon budget in the Baltic Sea. Existing data are mostly out-of-date, and do not take into account the carbon return flux from sediments to the water column that originates from organic matter mineralization (Leipe et al., 2011), and might be supplemented by thermo-genic methane oxidation in the surface sediments (Brodecka et al., 2013). Furthermore, the data which does take into account of the carbon return flux are based on the analysis of a limited number of sediment cores (Kuliński and Pempkowiak, 2011; Szczepańska et al., 2012). Determining the role of sediments in the carbon cycle, as well as the status of the Baltic Sea regarding the sequestration of carbon dioxide requires that carbon budget is better defined. Burial rates of organic matter in the Baltic sediments are a key factor here.

The main aim of this study was to determine the carbon burial rates within the Baltic Sea sediments. This required the calculation of the organic carbon accumulation rate in the Baltic Sea sediments and the carbon return flux from the sediments to the water column. The former was established using mass sediment accumulation rates, derived from ^{210}Pb and ^{137}Cs vertical profiles in sediments, and organic carbon concentrations in sediments. The carbon return flux from the sediments to the water column was calculated using First Fick's Law of Diffusion and concentrations of dissolved inorganic (DIC) and organic (DOC) carbon in sediment pore water. The study was carried out on sediment cores collected from depositional areas of the sea.

2. Experimental

2.1. Study area

The Baltic Sea with a surface area of 415,000 km^2 (including the Kattegat) is the second largest brackish water body in the world. It extends between 10–30°E and 54–64°N. The Baltic Sea is connected with the North Sea via narrow straits: the Sound, the Little Belt, the Great Belt, and the Kattegat. Inflows of saline water lead to a stable stratification in the basinal water columns (Łomniewski et al., 1975; Leipe et al., 2011). Surface water salinity ranges from 1 to 4 in the Gulf of Bothnia, and in the eastern part of the Gulf of Finland, to about 6–8 in the Baltic Proper. The salinity of the sub-halocline water layer of the Baltic Proper ranges from 11 to 15. The halocline is located at a depth of 60–80 m, while the summer thermocline – at a depth of 25–30 m. Limited vertical mixing, and rare inflows of water masses through the Danish Straits accompanied by eutrophication are the causes of oxygen deficits in the sub-halocline water layer (Voipio, 1981; Björck, 1995; Heino et al., 2008).

The Baltic Sea is one of the most productive marine ecosystems (HELCOM, 2002). This is due to a considerable amount of nutrients being discharged to the sea from agriculture and industry via river runoff.

The major sub-basins of the Baltic Sea are: the Gulf of Bothnia, the Gulf of Finland, Baltic Proper (the Arkona Deep – maximum depth of 53 m, the Bornholm Deep – 105 m, the Gdansk Deep – 118 m, the Gotland Deep – 249 m), and the Danish Straits (the Belt Sea, the Kattegat, the Skagerrak) (HELCOM, 2009).

The Baltic Proper is characterized by a permanent halocline located at a depth of 50–70 m, which is the result of the freshening of the surface water layer by river run-off and inflows of saline water from the North Sea that form a dense water layer below the halocline at 50–70 m (Voipio, 1981; Christiansen et al., 2002). The salinity of the surface water layer is between 7 and 8. In the sub-halocline water layers, it is between 10 and 17. The bottom of the depositional basin is flat, mostly covered by clay and muddy sediments (Leipe et al., 2011).

The hydrography of the Gulf of Finland is typical to estuaries. It is characterized by high vertical and horizontal variability. This is a result of saline water inflows from the Baltic Proper and freshwater inflows from rivers, mostly the Neva (Alenius et al., 1998; Omstedt and Axell, 2003; Almroth et al., 2009). The salinity of the Gulf of Finland increases from east to west, and from north to south (Vallius, 2006). Surface water salinity ranges from 5 to 7 in the western part of the Gulf to 0–3 in the eastern part. The deeper water layer is characterized by a salinity of 8–9. The halocline in the western part of the Gulf is formed at a depth of 60–80 m, in contrast to the eastern and south-eastern part of the Gulf where it does not form at all.

The restricted connection that the Gulf of Bothnia has with the Baltic Proper results in a limited exchange and the retention time of water as long as 5 years (Häkannson et al., 1996; Samuelsson, 1996; Marmefelt and Omstedt, 1999). The halocline is located at a depth of 50–60 m and it separates low saline surface water (salinity 3–5) from the deeper waters (salinity 6–7). The low salinity of surface water is a result of large river run-off.

2.2. Materials and methods

Twenty two sediment cores were collected using a GEMAX corer (equipped with two 50 cm long, 10 cm diameter core tubes) during research excursions on r/v Oceania and r/v Aranda (Table 1, Fig. 1). Immediately after being collected the cores were sliced into 10 mm thick layers and the resulting sediment samples were frozen

Table 1
Location of core sampling sites and sediment bulk properties.

Station	Latitude	Longitude	Depth [m]	Core length [cm]	Porosity
I	54°49′N	19°28′E	105	28	0.87–0.95
II	54°48′N	19°06′E	101	30	0.87–0.95
III	54°44′N	19°07′E	102	30	0.83–0.93
IV	54°47′N	19°19′E	103	30	0.83–0.93
V	57°17′N	19°51′E	217	37	0.87–0.99
VI	57°21′N	20°10′E	238	30	0.89–0.98
VII	57°13′N	19°48′E	213	30	0.85–0.98
VIII	57°19′N	19°55′E	218	30	0.85–0.97
IX	55°38′N	19°13′E	105	30	0.85–0.98
X	55°01′N	15°41′E	81	30	0.77–0.92
XI	55°05′N	15°53′E	84,5	30	0.85–0.93
XII	64°18′N	22°22′E	109	30	0.87–0.97
XIII	62°51′N	18°53′E	204	30	0.85–0.91
XIV	63°19′N	20°16′E	105	30	0.83–0.90
XV	62°25′N	23°30′E	90	20	0.73–0.96
XVI	59°50′N	24°50′E	100	30	0.85–0.98
XVII	59°02′N	21°05′E	171	30	0.85–0.98
XVIII	56°37′N	19°20′E	135	30	0.82–0.98
XIX	56°57′N	19°30′E	172	29	0.84–0.94
XX	57°19′N	19°54′E	230	23	0.81–0.98
XXI	56°19′N	18°36′E	85	32	0.71–0.94
P1	54°50′N	19°20′E	112	30	0.88–0.99