



ORIGINAL RESEARCH ARTICLE

Comparison of the burial rate estimation methods of organic and inorganic carbon and quantification of carbon burial in two high Arctic fjords

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Summary Quantifying the burial of organic carbon (OC) and inorganic carbon (IC) species in marine sediments contribute to a better understanding of carbon cycle. This is especially important in the Arctic, where carbon deposition is relatively high and expected to change with climate warming. This study aimed to quantify the burial rates of OC and IC in the sediments of two high-latitude fjords – Hornsund and Kongsfjorden (European Arctic). Comparison of the results from three methods quantifying carbon burial in marine sediments was carried out.

Sediment cores, pore water, and over-bottom water samples were analyzed for OC and IC. The burial rates were established by considering: carbon deposition to sediments minus carbon return flux, carbon deposited to sediments 80–100 years ago and carbon deposited to sediments recently. The radiolead method was employed for sediment dating. Carbon return flux was obtained using dissolved carbon species concentrations in pore water and over-bottom water.

Sediment linear and mass accumulation rates in the fjords were 0.12–0.20 cm y⁻¹ and 1160–2330 g m⁻² y⁻¹. The OC burial rates were 19.3–30.3 g OC m⁻² y⁻¹ in Hornsund and 5.7–10.0 g OC m⁻² y⁻¹ in Kongsfjorden. IC burial was taken as equal to IC deposition and ranged from 10.7 to 20.8 g IC m⁻² y⁻¹ in Hornsund and 19.4–45.7 g IC m⁻² y⁻¹ in Kongsfjorden. The “return flux” model seems most appropriate for carbon burial rate studies. The data demonstrated that OC burial dominates in Hornsund, while in Kongsfjorden, IC burial is more important. © 2018 Institute of Oceanology of the Polish Academy of Sciences. Production and hosting by Elsevier Sp. z o.o. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

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1. Introduction

Carbon dioxide is a trace component of the atmosphere that has a major role in the greenhouse effect (IPCC, 2013). As carbon dioxide is an important component of carbon cycling, the quantification of sinks, sources, and fluxes that influence its concentration in the atmosphere is important, especially in the context of future CO₂ concentrations in the atmosphere and predictions of future climate.

Marine sediments constitute the most important long-term sink of carbon worldwide, while Arctic sediments preserve much of the deposited carbon (Smith et al., 2015). This is apparently facilitated by large loads of carbon delivered from land (Smeaton et al., 2016) and integrated in a short time period primary production (Stein and Macdonald, 2004), which supports organic carbon (OC) and inorganic carbon (IC) deposition to sediments (Koziarowska et al., 2017). It has recently been postulated that the sediments of the high-latitude fjords serve as a sink of OC to an extent that greatly exceeds the fjords' contribution to the Arctic area (Smith et al., 2015). Moreover, recent reports indicate that high loads of IC (carbon in carbonates) are deposited in fjord sediments (Smeaton et al., 2016), while significant part of the loads can be attributed to biogenic carbonates (Koziarowska et al., 2017).

Both OC and IC species that originate either from primary production or are delivered from land are readily deposited to the bottom sediments (Teske et al., 2011). The former are intensively mineralized in the water column and at the sediment–water interface (Holding et al., 2017; Teske et al., 2011), where the redox conditions determine the efficiency of mineralization and biogenic element exchange between sediments and the overlying water (Ingall et al., 2005; Jorgensen et al., 2005). The load of biogenic carbonates originating from numerous carbonate-secreting organisms, such as coccolithophores, barnacles, echinoids, and bivalves, reaches the sediments and is largely unaffected when buried there (Andrulleit et al., 1996; Freiwald, 1998).

Recently, a major effort has been directed toward establishing the rate of OC deposition and its burial in surface sediments (Smeaton et al., 2016; Smith et al., 2015). To calculate OC burial in sediments, most often, the product of the sediment mass accumulation rate (MAR) and the concentration of OC in sediments have been used. OC mineralization in sediments has been either neglected or estimated based on the difference between contemporary and preindustrial OC delivery to surface sediments (Kuliński et al., 2014; Zaborska et al., 2016); in practice, the OC load in a sediment layer deposited 80–100 years ago is taken as equal to the burial rate. The former approach (ignoring mineralization) is valid for short-term carbon preservation in sediments, while the latter is subject to uncertainties caused by the unspecified effects of glacier surges and the primary production changes caused by the recent warming of the Arctic. Due to the global warming, and, in the consequence, substantially increased primary production (Arrigo et al., 2008; Fernandez-Mendez et al., 2015), the surface sediments have been enriched with autochthonous labile OC that is eventually mineralized and/or decomposed, while the dissolved IC (DIC) and dissolved OC (DOC) species resulting from those processes return to the seawater overlying the sediments.

The problem concerning quantifying burial rates in view of the recent increase of OC in marine surface sediments has been resolved by measuring the return flux of OC and IC species from sediments to the overlying seawater (Arndt et al., 2013; Kuliński and Pempkowiak, 2012; Winogradow and Pempkowiak, 2018). The actual burial of carbon is obtained by subtracting the carbon return flux from the carbon deposition to sediments. Burial of carbonates is much easier to quantify, as they do not undergo any microbial processes in the surface sediments. The only way to reduce the concentration of carbonates in sediments would involve a significant pH decrease; pH, although low, is relatively constant in pore waters (Mucci et al., 2000). Despite the straightforward measurement technique, the sedimentary carbonate deposition and burial in sediments of the Arctic fjords have seldom been quantified (Freiwald, 1998; Koziarowska et al., 2017; Smeaton et al., 2016). Thus, the burial of both OC and IC in the fjords' sediments remains to be assessed.

The purpose of this study was to quantify the OC and IC burial rates in the subsurface sediments of the two high-latitude fjords – Hornsund and Kongsfjorden – localized on the western shores of Spitsbergen, the main island of the Svalbard archipelago, European Arctic. OC and IC concentrations were measured in the subsequent layers of sediment cores collected at two sampling stations along each fjord axis, in pore water separated from the surface core layers and seawater overlying sediments. Carbon deposition was equal to the product of the sediment MAR and carbon concentration in sediments. The sediment accumulation rate (SAR) and age of the sediment layers, required for assessing carbon deposition, were obtained using the ²¹⁰Pb method, which was validated with the distribution of ¹³⁷Cs. The return fluxes of both DOC and DIC were calculated as diffusion flows from pore water of the uppermost sediment layer to water overlying sediments using Fick's first law of diffusion. The carbon burial rates were calculated based on all three available approaches, as follows: (I) the difference between carbon deposition to sediments and the carbon return flux; (II) carbon deposited to sediments approximately 80–100 years ago, as this is considered enough time for mineralization of the labile OC in sediments (for further calculations, we took samples from about 1930 AD); and (III) carbon deposited to sediments recently.

2. Study area

The study was carried out in Hornsund and Kongsfjorden on the west coast of Spitsbergen. *Hornsund* is the southernmost fjord; it is a medium-sized fjord characterized by a complex coastline including 14 tidewater glaciers entering it directly. The fjord is influenced by two main current systems. The first, the coastal Sørkapp Current, carries less saline and cold Arctic-type waters, while the other, the West Spitsbergen Current (WSC), carries relatively warm and saline Atlantic water (Piechura et al., 2001; Swerpel, 1985). In Hornsund, however, the influence of WSC is less pronounced, due to strong pressure from waters of the Sørkapp Current. The SARs vary significantly, with a decreasing trend toward the mouth of the fjord. In the inner part (Brepollen), the rate is about 0.7 cm y⁻¹ (Szczuciński et al., 2006; Zaborska et al., 2016); in the central part, it ranges from 0.2 cm y⁻¹ (Pawłowska et al.,

2017; Zaborska et al., 2016, 2017) to 0.5 cm y^{-1} (Szczeniński et al., 2006); and it is 0.17 cm y^{-1} in the outer part (Zaborska et al., 2017). The sediments are mainly composed of sandy mud in the inner part (close to the glacier fronts) and mud in the outer part of the fjord (Gorlich, 1986). The highest concentration of sedimentary OC is about 20 mg g^{-1} at the innermost part of the fjord and 14 mg g^{-1} at the fjord mouth (Koziarowska et al., 2016; Zaborska et al., 2016). Hornsund is characterized by a relatively high primary production – from 120 to $220 \text{ g C m}^{-2} \text{ y}^{-1}$ (Piwoż et al., 2009; Smoła et al., 2017).

Kongsfjorden is a relatively small fjord with a wide opening to the open ocean. The area is divided into two parts by a sill – an outer part strongly affected by the WSC and an inner part under the influence of five tidewater glaciers (Promińska et al., 2017). Due to the large supply of mineral material with freshwater from melting glaciers in the inner part, the SARs differ significantly along the fjord axis. In the inner part, the SAR is estimated at $6\text{--}8 \text{ cm y}^{-1}$ (Elverhoi et al., 1983); in the central part, SARs of 0.1 cm y^{-1} (Elverhoi et al., 1983), 0.20 cm y^{-1} (Koziarowska et al., 2017), 0.24 cm y^{-1} (Kuliński et al., 2014), and $0.38\text{--}0.41 \text{ cm y}^{-1}$ (Zaborska et al., 2016) have been reported; and in the outer part of the fjord, the rate ranges from 0.04 cm y^{-1} (Elverhoi et al., 1983) to 0.13 cm y^{-1} (Koziarowska et al., 2017; Kuliński et al., 2014). Large differences in the reported SAR values arise from the different distances of sampling stations from the glacier front. Surface sediments are dominated by silt fractions (Bijoy Nandan et al., 2016), silts, and silty clays (Zaborska et al., 2006), while below a water depth of $30\text{--}40 \text{ m}$, sediments are composed of fairly uniform mud (Włodarska-Kowalczyk and Pearson, 2004). The total carbon (TC) concentration is relatively constant across the fjord, as it ranges between 30 and 40 mg g^{-1} (Bijoy Nandan et al., 2016; Koziarowska et al., 2017). The amount of OC in the surface sediments increases along the fjord axis from less than 1 mg g^{-1} close to the glacier front to over 20 mg g^{-1} at the fjord mouth (Bijoy Nandan et al., 2016; Kędra et al., 2010; Koziarowska et al., 2017; Kuliński et al., 2014; Włodarska-Kowalczyk and Pearson, 2004). Primary production is much lower than it is in Hornsund, as it ranges between $20 \text{ g C m}^{-2} \text{ y}^{-1}$ (Piwoż et al., 2009) and $50 \text{ g C m}^{-2} \text{ y}^{-1}$ (Hop et al., 2002).

3. Experimental

3.1. Sampling and general flow of analyses

Sediment cores were collected using a Nemisto gravity corer at two stations in each fjord (H1, H2 in Hornsund and Kb1, Kb2 in Kongsfjorden), located in the outer and central parts of the fjords (Fig. 1). Locations of sampling stations were carefully selected to reduce the impact of land – namely a direct discharge of freshwater and mineral material, and consequently, a rapid and/or irregular accumulation of sediments.

At each sampling station, a sediment core with undisturbed overlying bottom water was collected and prepared for the analyses, as shown in Fig. 2. Briefly, bottom water overlying the sediment was sampled for DIC and DOC analyses 5 cm above the sediment surface. Following this, the core was sliced into 10-mm -thick layers, and the obtained sediment samples were frozen (-20°C). In the laboratory, sediment samples were centrifuged (15 min , 5000G), and pore

water from the uppermost layers was used for DIC and DOC measurements. The moisture-deprived sediment samples were used for analyses of OC and IC concentrations and ^{210}Pb and ^{137}Cs activity concentrations. All the analyses were carried out in the Marine Biogeochemistry Laboratory of the Institute of Oceanology of the Polish Academy of Sciences, in Sopot, using the methods described concisely below. In the case of Kongsfjorden, the same stations were sampled previously by Koziarowska et al. (2017) for studies related to sediment accumulation rates, OC and IC provenience.

3.2. ^{210}Pb and ^{137}Cs activity concentrations analyses

Measurements of ^{210}Pb activity concentration were performed following the procedure developed by Flynn (1968) and adopted by Pempkowiak (1991) and Zaborska et al. (2007). Here, 200 mg of dry and homogenous material was spiked with a ^{209}Po chemical yield tracer with known activity and digested using 12 M hydrofluoric acid (3 mL) and concentrated perchloric acid (2 mL). Isotopes of polonium were spontaneously deposited on a silver disk. After deposition, the disks were analyzed for ^{210}Po and ^{209}Po in a multichannel analyzer (Canberra, United States) equipped with a Si/Li detector. The activity concentrations of ^{210}Po in the sediment samples were calculated based on chemical recovery by comparing the measured and spiked activities of ^{209}Po . Quality control was based on measurements of blanks and standards (IAEA-300 and IAEA-326) and spiked samples to verify the chemical recovery and the efficiency of detection.

The ^{137}Cs activity concentrations were measured in a γ -spectrometer (Canberra, United States) equipped with a high-purity Ge detector. Sediment samples were packed in a vessel of standard geometry ($65 \text{ mm } \varphi \times 10 \text{ mm}$) and counted for at least 24 h . The counting error was lower than 10% . Calibration of the counter was performed based on the reference materials obtained from IAEA (IAEA-300 and IAEA-385).

3.2.1. Linear sediment accumulation rates [cm y^{-1}]

Linear SARs were determined from profiles of excess ^{210}Pb activity concentration ($^{210}\text{Pb}_{\text{ex}} = ^{210}\text{Pb}_{\text{total}} - ^{210}\text{Pb}_{\text{supported}}$) vs. porosity-corrected sediment depth. The rates were calculated from the sections of profiles with exponential decreases in $^{210}\text{Pb}_{\text{ex}}$ vs. sediment depth (Zaborska et al., 2007).

3.2.2. Sediment mass accumulation rates [$\text{g m}^{-2} \text{ y}^{-1}$]

Sediment MARs were determined from the activity concentrations of the $^{210}\text{Pb}_{\text{ex}}$ profiles after earlier transformation of the linear depth in sediments to the “mass” depth using the consecutive layers' specific mass and linear depth in sediments (Robbins, 1978; Zaborska et al., 2008).

3.3. Total carbon (TC), organic carbon (OC), and inorganic carbon (IC) analyses in sediment samples

The analyses of TC and OC concentrations were performed using an Elemental Analyzer Flash EA 1112 Series combined with a Delta V Advantage (Thermo Electron Corp., Germany) isotopic ratio mass spectrometer (IRMS). Measurements were

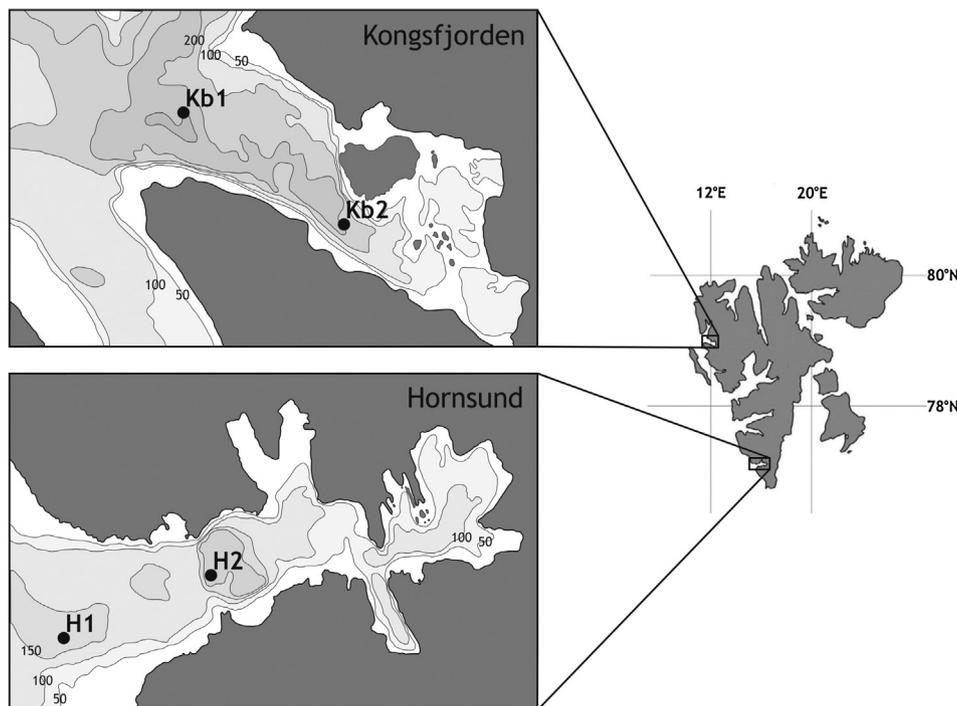


Figure 1 Locations of sampling stations in the Hornsund and the Kongsfjorden.

performed according to the method described by Kuliński et al. (2014). Briefly, about 30 mg (10- μ g accuracy) of freeze-dried and homogenized sediments were weighed into silver capsules. For OC concentration measurements, samples were acidified with 2 M hydrochloric acid to remove carbonates and dried at 60°C for 24 h (the procedure was repeated until a constant sample weight was achieved). The OC and IC measurements were calibrated against certified reference materials consisting of environmental samples (marine sediments; Flußsediment) provided by HEKatech GmbH (Germany). The precisions of the TC and OC measurements, given as relative

standard deviations, were better than $\pm 1.6\%$ and $\pm 1.4\%$ ($n = 5$), respectively. Concentrations of IC were measured as differences between TC and OC concentrations.

3.4. Dissolved inorganic carbon (DIC), dissolved organic carbon (DOC), and light absorption spectra analyses in water samples

The DIC and DOC concentrations were measured in a TOC-L analyzer (Shimadzu Corp., Japan). The DOC analyses were conducted using a high-temperature (680°C) oxidation

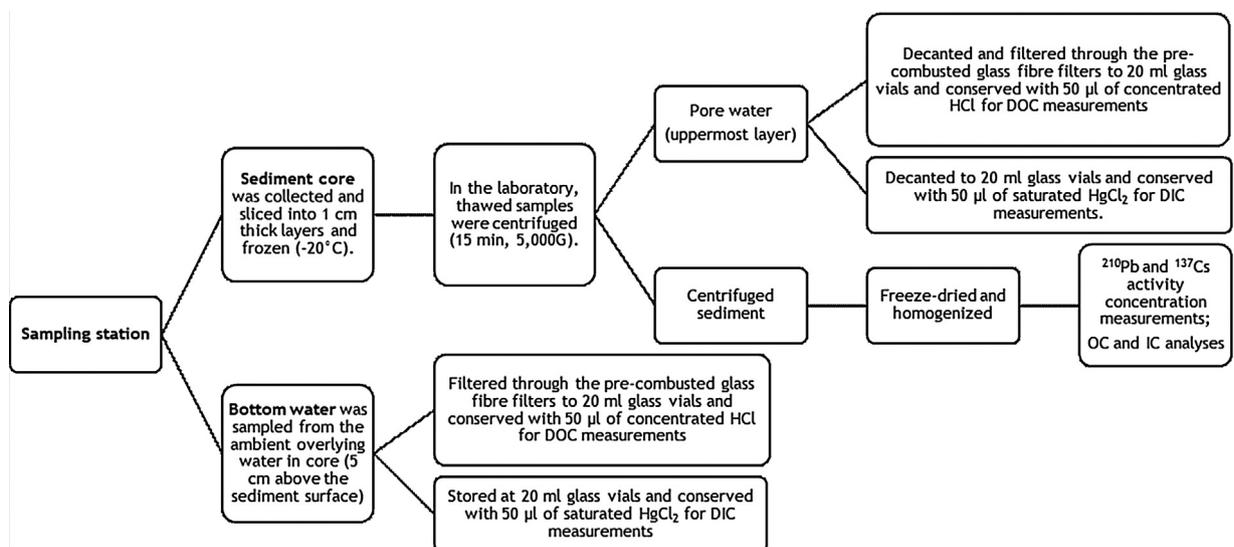


Figure 2 Flowchart of the analyses.

method and Pt catalyst. Quality control consisted of the regular analysis of blanks, as well as accuracy and precision checks based on comparisons with the reference material – North Atlantic water obtained from the Hansell Laboratory (recovery: 95%, precision characterized by relative standard deviation [RSD]: $\pm 0.8\%$; $n = 5$). The DIC concentrations were measured using a method based on sample acidification and detection of the evolving CO_2 in a nondispersive infrared (NDIR) detector. The accuracy and precision were based on the analyses of the reference material – natural seawater obtained from the Marine Physical Laboratory, University of California, San Diego (recovery: 98.5%, RSD: $\pm 1.3\%$; $n = 5$).

To assess quality of organic matter (OM) dissolved in the pore water, absorption spectra of pore water in the visible (Vis) and ultraviolet (UV) spectrum range were recorded with a UV–Vis Spectrophotometer (Hitachi, Japan) in the range of 200–800 nm. The measurements were performed in a 10-mm-length quartz cuvette against distilled water.

3.5. Calculations

3.5.1. Carbon deposition to sediments

Carbon deposition to sediments was calculated as a product of sediment MAR and OC and/or IC concentrations in the subsequent sediment layers.

3.5.2. Carbon return flux

Diffusion of dissolved carbon species from sediments into the over-bottom seawater was estimated based on Fick's first law of diffusion (Ullman and Aller, 1982):

$$J = -\phi \cdot D_{\text{sed}} \cdot \frac{\Delta c}{\Delta x},$$

where J is the diffusion flux of DIC or DOC [$\mu\text{g cm}^{-2} \text{s}^{-1}$], ϕ is the porosity of the sediment (%), D_{sed} is the sediment diffusion coefficient DIC or DOC [$\text{cm}^2 \text{s}^{-1}$], and $\Delta c/\Delta x$ is the DIC or DOC concentration gradient between pore water of the surface-most sediment layer and seawater overlying sediments [$\mu\text{g cm}^{-3}/\text{cm}$].

The sediment diffusion coefficients derived from the literature were $6.32 \times 10^{-6} \text{ cm}^2 \text{ s}^{-1}$ for DIC (Martin and McCorkle, 1993) and $1.22 \times 10^{-6} \text{ cm}^2 \text{ s}^{-1}$ for DOC (Holcombe et al., 2001).

3.5.3. Carbon burial rate

Three approaches were used to establish the carbon burial rate ($C_{\text{BR(I); II; III}}$) in bottom sediments, as follows:

- I. $C_{\text{BR(I)}}$ was determined as the difference between the OC accumulation in the surface-most sediments and the sum of return fluxes of both DIC and DOC; for IC, we assumed that its accumulation was equal to burial;
- II. $C_{\text{BR(II)}}$ was taken as the IC and OC accumulated in sediments of the approximately 80–100-year-old core layer (for further calculations, we took samples from about 1930 AD; depending on the SAR, the layer is found at a depth of 15–30 cm below the sediment water interface); this approach assumes that after this time from deposition, carbon no longer undergoes quantitative changes; and
- III. $C_{\text{BR(III)}}$ was taken as carbon deposition to the surface-most sediment layer.

4. Results

4.1. Sediment dating

The linear SAR at station H1 was 0.12 cm y^{-1} , while it was 0.19 cm y^{-1} at station H2. At the sediment depths of 15–16 cm and 17–18 cm, respectively, the activity concentration of $^{210}\text{Pb}_{\text{total}}$ reached the values assigned to the supported radiolead (Fig. 3). The linear SAR obtained in this study was in the range reported previously by Pawłowska et al. (2017). The vertical profiles of ^{210}Pb indicated that the uppermost 6 cm of sediments in the outer part of the fjord and the uppermost 5 cm in the fjord central part were mixed. The respective values for Kongsfjorden were 0.13 cm y^{-1} at station Kb1 and 0.20 cm y^{-1} at station Kb2, representing faster sedimentation. These rates were in the range reported by Elverhoi et al. (1983) and Kuliński et al. (2014). The SAR results were also positively validated by radiocesium measurements. The depth of the ^{137}Cs appearance in the cores layers dated to about 1950 AD was taken as a proof that sediment mass accumulation rates are sufficiently accurate. The measured ^{137}Cs activity concentrations ranged from <0.1 to 6.4 Bq kg^{-1} and were comparable to results reported previously by Zaborska (2017) (Fig. 3). The MAR calculation in Hornsund indicated that 1310 g, at station H1, and 2330 g, at station H2, of sedimentary material is annually deposited in every square meter of this region of the fjord. In the case of Kongsfjorden, the sediment MAR results amounted to $1160 \text{ g m}^{-2} \text{ y}^{-1}$ in the outer part of the fjord and $1950 \text{ g m}^{-2} \text{ y}^{-1}$ in the central part. The differences of mass SAR in the fjords indicate different loads of the suspended matter reaching the sea floor, and they can, most likely, be assigned to different levels of proximity to, and activity of, glaciers.

4.2. Carbon concentrations in sediments, pore water, and over-bottom water

4.2.1. Sedimentary carbon concentrations

The OC concentrations in sediments ranged between 5.0 mg g^{-1} and 19.0 mg g^{-1} (0.5% and 1.9%, respectively; Fig. 4a) – values close to the concentrations previously reported for sediments of the Svalbard fjords (Koziarowska et al., 2016; Kuliński et al., 2014; Szczuciński et al., 2009; Winkelmann and Knies, 2005; Zaborska et al., 2006). There were no significant differences between the two stations in Hornsund. However, in Kongsfjorden, the Kb2 station was characterized by significantly lower sedimentary OC concentrations. All vertical profiles, especially those from the central parts of the fjords, indicated increasing OC concentrations in the upper sections of the cores.

There were significant differences between fjords concerning IC concentrations. These were lower in Hornsund (8.0 – 13.8 mg g^{-1}) and higher in Kongsfjorden (16.8 – 29.5 mg g^{-1} ; Fig. 4b; Koziarowska et al., 2017).

4.2.2. DIC and DOC concentrations

DOC concentrations in pore water of the surface sediment layers varied between 84.0 and 243.8 mg L^{-1} (Table 1). DOC concentrations differed significantly between the fjords: the lowest were measured at station H1, while the highest were found at Kb2. The obtained results are much higher than

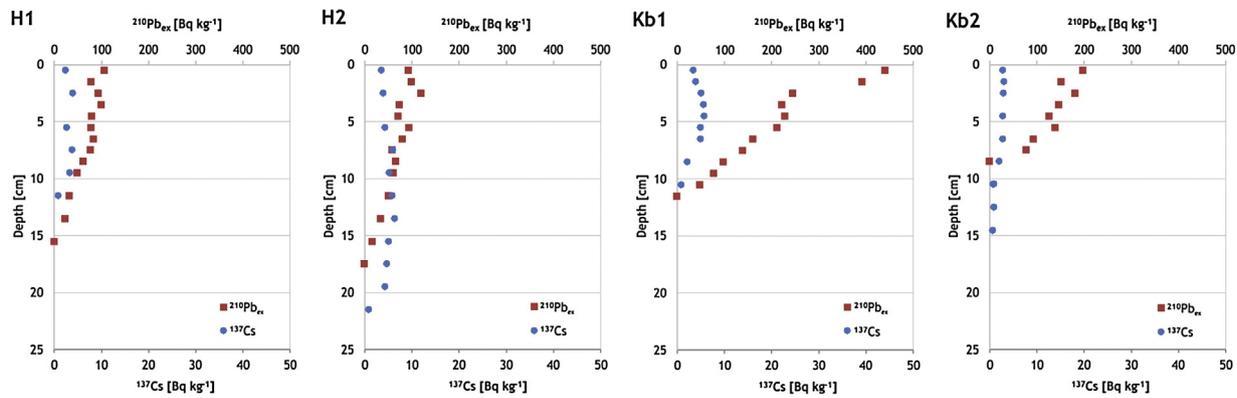


Figure 3 Vertical profiles of $^{210}\text{Pb}_{\text{ex}}$ (scale – upper X-axis) and ^{137}Cs (scale – lower X-axis) activity concentrations plotted against depth below sediment-water interface.

those reported previously in high latitude marine sediments – Hulth et al. (1996) reported a range of 5–100 mg L^{-1} , while Mucci et al. (2000) results were 5–30 mg L^{-1} . DIC concentrations were much lower than those of DOC, as they varied in the range of 26.5–37.5 mg L^{-1} in Kongsfjorden and 30.2–32.3 mg L^{-1} in Hornsund (Table 1). Concentrations measured in the Svalbard fjords in this study are close to the concentrations previously measured in the pore water of Arctic sediments, for example, 22–38 mg L^{-1} (Glud et al., 1998).

4.3. Accumulation rates of organic (OC_{AR}) and inorganic (IC_{AR}) carbon

The results of sediment MARs were lower in the central parts of the fjords (1310 and 1160 $\text{g m}^{-2} \text{y}^{-1}$ in Hornsund and Kongsfjorden, respectively) than at the mouth of the fjords (2330 and 1950 $\text{g m}^{-2} \text{y}^{-1}$). The combination of MAR

distribution and OC concentration profiles caused OC_{AR} to be different along the Hornsund axis; it ranged from 20.6 to 24.3 $\text{g OC m}^{-2} \text{y}^{-1}$ at H1 and from 32.4 to 40.5 $\text{g OC m}^{-2} \text{y}^{-1}$ at H2. In Kongsfjorden, despite differences in these two features (MARs and OC concentrations), OC_{AR} was quite similar and ranged from 15.4 to 20.8 $\text{g OC m}^{-2} \text{y}^{-1}$ at Kb1 and from 9.7 to 20.3 $\text{g OC m}^{-2} \text{y}^{-1}$ at Kb2 (Fig. 5a). These values are in the range of previously reported results for the Svalbard fjords (Kuliński et al., 2014; Winkelmann and Knies, 2005; Zaborska et al., 2016).

The IC_{AR} results differed significantly between the fjords and sampling stations; higher loads of IC were accumulated in Kongsfjorden sediments (19.4–23.0 $\text{g IC m}^{-2} \text{y}^{-1}$ and 41.4–57.5 $\text{g IC m}^{-2} \text{y}^{-1}$ at Kb1 and Kb2, respectively) and lower in Hornsund (10.7–13.1 and 20.8–32.1 $\text{g IC m}^{-2} \text{y}^{-1}$ at H1 and H2, respectively; Fig. 5b). Significant variations in the carbon accumulation rates could also be observed in the vertical

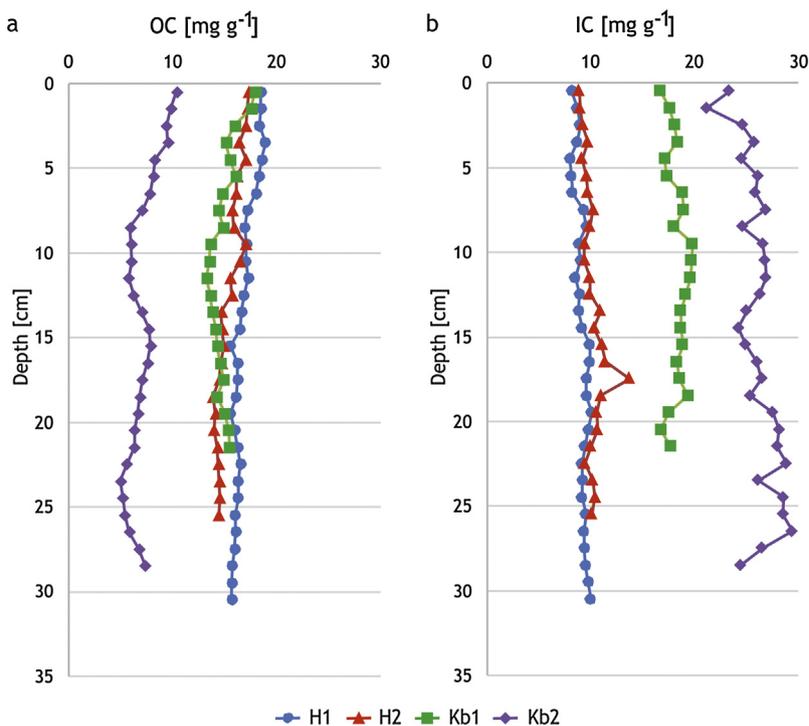


Figure 4 Sedimentary organic carbon (OC) (a) and sedimentary inorganic carbon (IC) (b) versus depth in the investigated sediment cores.

Table 1 Concentrations of dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC) in pore water of the surface-most sediment layer and seawater overlying sediments in the investigated cores.

Stations	Pore water [mg L^{-1}]		Sea water [mg L^{-1}]	
	DOC	DIC	DOC	DIC
H1	84.0	30.2	1.9	25.4
H2	192.6	32.3	0.8	25.2
Kb1	231.3	26.5	1.1	25.3
Kb2	243.8	37.5	2.3	25.4

profiles. Both OC_{AR} and IC_{AR} showed larger variations in the sampling stations located in the central parts of the fjords (H2 and Kb2) than these in the fjords' mouths.

It is characteristic for OC_{AR} to increase toward the sediment surface, while IC_{AR} decreases. The stations located in the outer parts of the fjords (H1 and Kb1) were characterized by a relatively constant amount of deposited carbon over the last century. This was not the case for the central parts in the two fjords. This indicates a much higher dynamics of processes in the central regions than in the open parts of the fjords.

4.4. Carbon return flux (C_{RF})

Carbon return flux from bottom sediments to the water column was determined as the amount of carbon species diffusing from sediment pore water to the over-bottom seawater based on Fick's first law of diffusion. The porosity was equal to 0.76–0.81 and these are typical values for muddy

sediments (Robbins, 1978). The obtained C_{RF} results were in the range of 5.0–10.2 $\text{g m}^{-2} \text{y}^{-1}$ in Hornsund (stations H1 and H2) and 10.9–14.6 $\text{g m}^{-2} \text{y}^{-1}$ in Kongsfjorden (stations Kb1 and Kb2; Table 2). The results showed that lower contribution in the TC return flux had DIC, only 3–24% (0.3–3.0 $\text{g m}^{-2} \text{y}^{-1}$). More significant were the OC return fluxes, which were 3.8 $\text{g m}^{-2} \text{y}^{-1}$ and 8.6 $\text{g m}^{-2} \text{y}^{-1}$ at stations H1 and H2 and 10.6 $\text{g m}^{-2} \text{y}^{-1}$ and 11.6 $\text{g m}^{-2} \text{y}^{-1}$ at stations Kb1 and Kb2, respectively. This is contrary to findings from the Baltic Sea, where the DIC return flux predominates (Kuliński and Pempkowiak, 2012).

4.5. Carbon burial in sediments (C_{BR})

4.5.1. $\text{C}_{\text{BR(I)}}$ based on deposition and return flux

The OC burial rates are presented in Tables 3 and 4. The values differed significantly for both fjords, as they were in the range of 19.3–30.3 $\text{g OC m}^{-2} \text{y}^{-1}$ in Hornsund and 5.7–10.0 $\text{g OC m}^{-2} \text{y}^{-1}$ in Kongsfjorden (Table 3). In addition, the $\text{IC}_{\text{BR(I)}}$ varied in both fjords and stations (10.7 $\text{g IC m}^{-2} \text{y}^{-1}$, 20.8 $\text{g IC m}^{-2} \text{y}^{-1}$, 19.4 $\text{g IC m}^{-2} \text{y}^{-1}$, and 45.7 $\text{g IC m}^{-2} \text{y}^{-1}$ at H1, H2, Kb1, and Kb2, respectively).

Despite differences in the MARs and both OC and IC concentrations, the values of $\text{C}_{\text{BR(I)}}$, defined as the sum of the organic and inorganic fractions buried in the outer and central parts of both fjords, were surprisingly similar. They were 29.4–30.0 $\text{g m}^{-2} \text{y}^{-1}$ at the outer parts and 51.1–51.4 $\text{g m}^{-2} \text{y}^{-1}$ in the central parts of the investigated fjords (Table 3).

4.5.2. $\text{C}_{\text{BR(II)}}$ based on the concentrations in subsurface sediments

The OC burial rate, determined by multiplying MAR by the OC concentration in sediment layers accumulated about

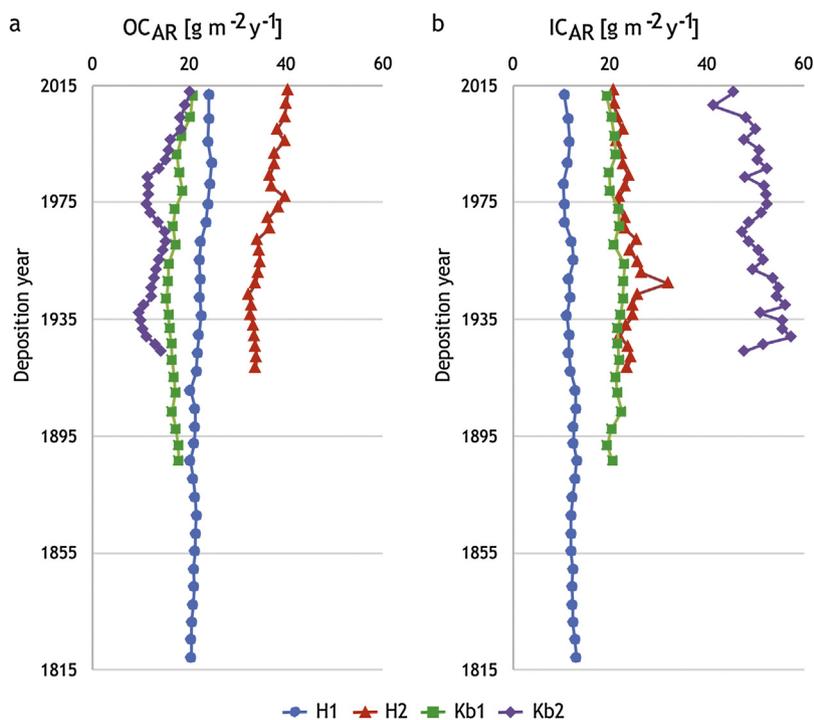


Figure 5 Vertical profiles of organic (OC_{AR}) (a) and inorganic (IC_{AR}) (b) carbon accumulation rates in the investigated sediment cores plotted against the sediment layer deposition.

Table 2 Results of porosity, diffusion flux (J) of dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC), carbon return flux (C_{RF}).

Station	Porosity	J_{DOC} [$g\ m^{-2}\ y^{-1}$]	J_{DIC} [$g\ m^{-2}\ y^{-1}$]	C_{RF} [$g\ m^{-2}\ y^{-1}$]
H1	0.78	3.8	1.2	5.05
H2	0.76	8.6	1.6	10.2
Kb1	0.78	10.6	0.3	10.9
Kb2	0.81	11.6	3.0	14.6

Table 3 Results of the mass accumulation rate (MAR), organic carbon accumulation rate (OC_{AR}), carbon return flux (C_{RF}), organic carbon burial rate ($OC_{BR(I)}$), efficiency of $OC_{BR(I)}$, inorganic carbon burial rate ($IC_{BR(I)}$), and total carbon burial rate ($TC_{BR(I)}$) in the investigated cores.

Station	MAR [$g\ m^{-2}\ y^{-1}$]	OC_{AR} [$g\ m^{-2}\ y^{-1}$]	C_{RF} [$g\ m^{-2}\ y^{-1}$]	$OC_{BR(I)}$ [$g\ m^{-2}\ y^{-1}$]	Efficiency of $OC_{BR(I)}$ [%]	$IC_{BR(I)}$ [$g\ m^{-2}\ y^{-1}$]	$TC_{BR(I)}$ [$g\ m^{-2}\ y^{-1}$]
H1	1310	24.3	5.0	19.3	79.5	10.7	30.0
H2	2330	40.5	10.2	30.3	74.7	20.8	51.1
Kb1	1160	20.8	10.9	10.0	47.8	19.4	29.4
Kb2	1950	20.3	14.6	5.7	27.9	45.7	51.4

Table 4 Burial rates of total carbon (TC), organic carbon (OC) and inorganic carbon (IC) in the investigated sediments assessed by methods: I (carbon deposition minus carbon return flux), II (carbon deposition in the sediment layer dated 1930 AD), and III (contemporary carbon deposition).

Station	OC_{BR} [$g\ m^{-2}\ y^{-1}$]			IC_{BR} [$g\ m^{-2}\ y^{-1}$]			TC_{BR} [$g\ m^{-2}\ y^{-1}$]		
	I	II	III	I	II	III	I	II	III
H1	19.3	22.1	24.3	10.7	11.7	10.7	30.0	33.8	35.0
H2	30.3	33.4	40.5	20.8	23.4	20.8	51.1	56.8	61.3
Kb1	10.0	16.1	20.8	19.4	21.7	19.4	29.4	37.8	40.2
Kb2	5.7	10.6	20.3	45.7	55.8	45.7	51.4	66.4	66.0

1930 AD, ranged from 22.1 to 33.4 $g\ OC\ m^{-2}\ y^{-1}$ in Hornsund and 10.6 to 16.1 $g\ OC\ m^{-2}\ y^{-1}$ in Kongsfjorden. The results differ from those obtained using carbon return flux (method I, see Section 4.5.1), as they are slightly higher in Hornsund and significantly higher in Kongsfjorden. In the case of $IC_{BR(II)}$, the obtained results were higher than those calculated using methods I and III. In Hornsund, the values varied from 11.7 to 23.4 $g\ IC\ m^{-2}\ y^{-1}$, while they were in the range of 21.7–55.8 $g\ IC\ m^{-2}\ y^{-1}$ in Kongsfjorden. The values of $TC_{BR(II)}$ (sum of $IC_{BR(II)}$ and $OC_{BR(II)}$) were comparable in the outer and central parts of both fjords and varied between 33.8 and 37.8 $g\ m^{-2}\ y^{-1}$ in the outer parts and 56.8 and 66.4 $g\ m^{-2}\ y^{-1}$ in the central parts of Hornsund and Kongsfjorden, respectively.

4.5.3. $C_{BR(III)}$ based on the contemporary carbon deposition

The results of $OC_{BR(III)}$, assessed as carbon deposition at the top-most sediment layers, were 24.3–40.5 $g\ OC\ m^{-2}\ y^{-1}$ in Hornsund and 20.3–20.8 $g\ OC\ m^{-2}\ y^{-1}$ in Kongsfjorden. These values are larger than the results obtained using the two methods described above (methods I and II, see Sections 4.5.1 and 4.5.2), especially at station Kb2 in Kongsfjorden, where the return flux was the highest. The results are also

larger than the OC burial rate obtained by Zaborska et al. (2016) and Kuliński et al. (2014). In the case of $IC_{BR(III)}$, the obtained results were the same as those calculated using method I. This is due to the assumption that sedimentary IC is stable and not subject to removal processes. The values of $TC_{BR(III)}$ were higher than those calculated using methods I and II, as they varied from 35.0 to 61.3 $g\ m^{-2}\ y^{-1}$ in Hornsund and 40.2 to 66.0 $g\ m^{-2}\ y^{-1}$ in Kongsfjorden. The results of the OC, IC, and TC burial rates obtained using the three methods are presented in Table 4.

4.6. Absorption spectra in the visible (Vis) and ultraviolet (UV) ranges

Absorption spectra of pore waters from the surface-most sediment layers (0–1 cm) from Kongsfjorden are presented in Fig. 6. In the 260–300 nm range, a clear absorption peak can be seen (Fig. 6a). The shapes of the absorption spectra resemble those of humic substances (Schnitzer and Khan, 1972), including those recorded for humic substances from marine sediments (Pempkowiak and Szponar, 1993).

Based on the measured pore water absorbances and mass absorption coefficients (MAC) of the aquatic humic acids separated from seawater (4.3 and 7.8 $cm^2\ mg^{-1}$ at wavelengths

260 and 300 nm; Stoumer and Harvey, 1974), it was calculated that concentration of humic substances in pore water range from 12 to 32 mg L⁻¹ at station Kb1 and from 11 to 22 mg L⁻¹ at Kb2. As no MACs for humic substances from the fjords, or even Arctic, pore waters are available, the reported humic substances concentration ranges should be regarded as preliminary. However even these preliminary calculations suggest that humic substances can play an important role in the DOC return flux from sediments.

Unfortunately, corresponding pore water samples from Hornsund were lost during transportation.

5. Discussion

Studies suggest that climate warming, and consequently, the reduction of sea ice in summer together with an increase of the annual availability of light, may cause an expansion of the area favorable for phytoplankton growth and may enhance the pelagic primary production in the Arctic (Fernandez-Mendez et al., 2015). Arrigo et al. (2008) reported that annual primary production in the Arctic Ocean in 2007 was 23% higher than in 1998–2002, therefore an export of particulate OC is likely to have increased (Lalande et al., 2009).

Assessment of the consequences of those processes for both historical and present-day equilibriums is under way (Cochrane et al., 2009; Renaud et al., 2007, 2008). Due to the influence of warm Atlantic waters, Kongsfjorden can be considered a “warm fjord,” while Hornsund is a “cold” one; thus, the different intensities of the processes in the two fjords may represent possible effects of the climate change in the Arctic.

5.1. Efficiency of carbon burial in bottom sediments

The terms *OC deposition rate* and *OC burial rate* are often used interchangeably (St-Onge and Hillaire-Marcel, 2001), but these are terms that describe two separate phenomena, as a fraction of the deposited OM is mineralized. To establish the OC burial rate, it is necessary to determine the amount of OC deposited to sediments and subtract from it the amount of carbon that is mineralized and/or hydrolyzed in surface sediments and diffuses back to seawater overlying sediments, as a dissolved carbon species return flux.

It is worth emphasizing that there are different approaches to determining the OC burial rate in sediments. St-Onge and Hillaire-Marcel (2001) identified carbon burial as equal to carbon deposition to sediments, while Kuliński et al. (2014) and Zaborska et al. (2016) defined burial as a deposition in subsurface sediments (e.g. deposition in the sediment layer dated as about 80–100 years old – the time believed to be long enough for mineralization of the labile OC in sediments). The former approach is valid for short-term carbon preservation in sediments, while the latter considers mineralization and hydrolysis but is subject to possible serious errors caused by an unspecified effect of glacier surges and the primary production changes caused by the recent climate warming. Recently, the burial rate has been defined as a difference between the carbon deposited to sediments and the return flux of dissolved carbon species from sediments to the overlying water (Kuliński and Pempkowiak, 2012). Thus, the comparison of carbon burial rates from different publications and calculated in different ways must be treated with caution. The burial rates are likely sensitive and susceptible to environmental changes related to global alterations, such as a decrease in ice cover, increase in freshwater supplies, or changes in the functioning of fjords' ecosystems (Węstawski et al., 2017).

In this study, carbon burial rates were evaluated using three different approaches, as described above. The data presented in Table 4 demonstrate that the values obtained by the three methods are often comparable. The biggest differences in the obtained values were seen in the case of the OC burial rate (especially in sampling stations from Kongsfjorden), probably due to a much higher dynamics of the processes associated with OC (mineralization and/or hydrolysis) in surface sediments than with IC. In addition, methods II and III are vulnerable to OC concentration changes caused by factors other than sedimentary OM mineralization, such as inflow changes of the mineral material and/or fluctuation of OM deposition to sediments. Therefore, we think that the most accurate calculations are those using the carbon return flux method (I), and below, we only discuss and interpret the data calculated using the first method.

Substantial differences of $OC_{BR(I)}$ are characteristic of the study area. Differences in the $OC_{BR(I)}$ in Hornsund and Kongsfjorden may be due to the different intensities of primary production in the two areas – which is much higher in Hornsund and lower in Kongsfjorden (Hop et al., 2002; Piewosz

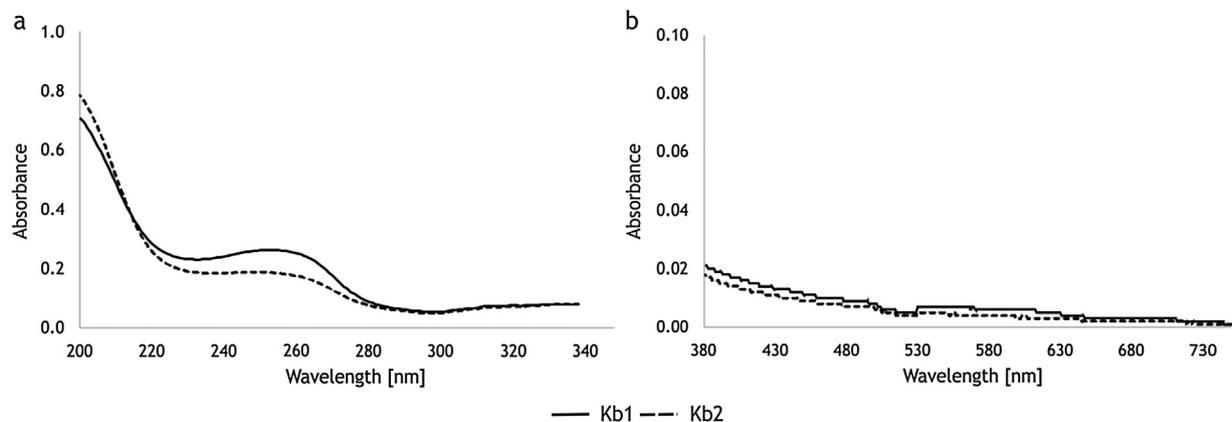


Figure 6 Absorption spectra of pore-water from the top-most sediment layers: (a) ultraviolet (UV), (b) visible (Vis).

et al., 2009). Another reason for this may be the provenience of OM. Zaborska et al. (2016) reported that sediments in Hornsund contain twice as much terrestrial carbon as Kongsfjorden sediments. Furthermore, Koziarowska et al. (2016) estimated that 69–75% of sedimentary OM in the central and outer parts of Hornsund is of terrestrial origin. This high contribution of land-derived OM in Hornsund sediments (Koziarowska et al., 2016) is especially important, if its high resistance to mineralization is taken into account (Antonio et al., 2010). Consequently, the mineralization rate in Hornsund sediments is lower (low carbon return flux), and the efficiency of $OC_{BR(I)}$ is higher. This suggests that it is not only the quantity of OM deposited into sediments that influences the OC burial rate, but also the OM source (marine vs. terrestrial). Thus, the efficiency of carbon burial rates is different in the investigated fjords; higher values were found in Hornsund – 79.5% at H1 and 74.7% at H2 – while lower rates were observed in Kongsfjorden – 47.8% at Kb1 and 27.9% at Kb2 (Table 3). In addition, the difference in $OC_{BR(I)}$ between the fjords may be due to other environmental conditions, like: water depth, water temperature, activity of benthic organisms, and/or oxygen availability (Promińska et al., 2017). Interestingly, lower burial efficiencies and higher return fluxes were found at stations located in the central parts of both fjords. This may confirm the hypothesis that the observed increase of OC_{AR} toward the sediment surface in the vertical profiles at stations H2 and Kb2 is caused by an increasing contribution of labile OM.

The IC burial rates were calculated by assuming that the amount of IC deposited to the sediments is equal to its burial rate, as carbonates can be removed from sediments only due to a pH decrease, and the pH, although low, is relatively constant in near bottom waters (Mucci et al., 2000). The lower IC concentrations in Hornsund indicate a low carbonate supply from the mainland and/or small in situ production by calcareous organisms. In Kongsfjorden, high IC concentrations in the central part (Kb2) are likely the effect of land-derived carbonates supplied by glaciers that, when moving, scratch the land surface rich in limestone in that region. The problem has already been discussed in detail by Koziarowska et al. (2017). In Hornsund, the differences of $TC_{BR(I)}$ between stations are caused mainly by different MARs, while in Kongsfjorden, the differences are due to both different MARs and different IC concentrations.

To conclude, OC burial dominates in the Hornsund sediments, while IC burial is more intensive in Kongsfjorden.

5.2. Carbon burial – the global perspective

As scarce reports on IC deposition to fjord sediments are available, in this section, just the OC burial rate established by considering the return flux is compared ($OC_{BR(I)}$). The obtained results are comparable, yet not identical, to those reported earlier in the Svalbard region (Kuliński et al., 2014; Winkelmann and Knies, 2005; Zaborska et al., 2016) (Table 5). Minor differences in $OC_{BR(I)}$ are likely due to slightly different location of the sampling stations – closer or farther from the shore and/or glacier front; however, the general pattern is similar, with higher OC burial rate values in Hornsund than in Kongsfjorden. For other Arctic regions, variation of OC burial is more visible; in the cases of the Barents Sea (Carroll et al., 2008), Young Sund in the Greenland Sea (Rysgaard and Nielsen,

2006), and Gulf of St. Lawrence (Silverberg et al., 2000), the OC burial rates are comparable to those for Kongsfjorden reported in this study. The results from glaciated and non-glaciated fjords in Southeast Alaska (Cui et al., 2016) and the Saguenay Fjord, Canada (St-Onge and Hillaire-Marcel, 2001) were characterized by much higher and more varied rates ($13–1113 \text{ g OC m}^{-2} \text{ y}^{-1}$). In other regions (mid-latitude fjords), the OC burial rate was slightly lower due to the smaller MAR (Knudson et al., 2011; Muller, 2001; Muzuka and Hillaire-Marcel, 1999; Pickrill, 1993; Smeaton et al., 2016; Smith et al., 2015), as MARs strongly influence the amount of carbon deposited to the seafloor. Most of the Patagonia (Chile) fjords are characterized by OC_{AR} and OC_{BR} in similar ranges to those measured in the frame of the present study. For example, the Jacaf Fjord ($OC_{AR} = 33.4–40.8 \text{ g m}^{-2} \text{ y}^{-1}$; $OC_{BR} = 21.0–25.7 \text{ g m}^{-2} \text{ y}^{-1}$) is characterized by rates similar to those in Hornsund, while the OC_{BR} in the Aisén Fjord ($OC_{AR} = 10.5–20.7 \text{ g m}^{-2} \text{ y}^{-1}$; $OC_{BR} = 6.6–13.1 \text{ g m}^{-2} \text{ y}^{-1}$) resembles Kongsfjorden in this respect (Sepulveda et al., 2011).

Reported carbon burial rates often lack definitions. In addition, the methodology used to calculate the rates is not included or lacking detail; thus, direct comparisons of data originating from recent reports may be misleading. Nevertheless, it may be concluded that the OC_{BR} values in the Svalbard fjords sediments vary in the range of $5–40 \text{ g m}^{-2} \text{ y}^{-1}$. The actual rate depends on the number of glaciers and their activity in the watershed, proximity of sampling locations to glacier fronts, water depth, and intensity of both primary production and OM mineralization.

5.3. Sources of DIC and DOC in pore water

It is generally accepted that DIC in bottom waters is composed of carbon dioxide and bicarbonate ions. Carbon dioxide is produced during OM mineralization. Then, it reacts with carbonates, giving bicarbonate ions. The relatively small concentrations of DIC measured in the pore water of the studied fjords indicate that mineralization processes in the sediments are weak. In contrast, the DOC concentrations measured in pore water of the studied area sediments are larger than the DOC concentrations in the pore water of the Baltic sediments by nearly an order of magnitude (Kuliński and Pempkowiak, 2012). A plausible explanation for this is that the dissolved organic substances originate as products of sedimentary OM hydrolysis and/or desorption from the solid phase. It is further argued that the dissolved organic substances released from sediments are refractory in nature.

The absorption curves of pore water, presented in Fig. 6, can be interpreted as resulting from the presence of dissolved fulvic acids – the water-soluble fraction of humic substances. Thus, such high concentrations of DOC in pore waters may be explained by, for example, the presence of large amounts of fulvic substances, which are relatively resistant to biological degradation (Schnitzer, 1991). Both humic acids and fulvic acids are refractory, as they result from a prolonged biochemical stabilization. This explanation agrees well with the previously mentioned high contribution of the land-derived OM in the Hornsund sediments (Koziarowska et al., 2016). This fraction of sedimentary OM is apparently brought to sediments as a part of soil particles. Thus, it is possible that dissolved organic substances present

Table 5 Sediment accumulation rate (SAR), mass accumulation rate (MAR), organic carbon accumulation rate (OC_{AR}), OC burial rate (OC_{BR}) and OC_{BR} efficiency in this study compared with global fjords.

Region	SAR [cm y ⁻¹]	MAR [g m ⁻² y ⁻¹]	OC _{AR} [g m ⁻² y ⁻¹]	OC _{BR} [g m ⁻² y ⁻¹]	OC _{BR} efficiency [%]	Reference
Svalbard						
Kongsfjorden	0.13–0.20	1160–1950	20.3–20.8	5.7–10.0	28–48	This study
	0.13–0.23	1350–3200	16.6–16.8	9–13	54–69 ^a	Kuliński et al. (2014)
	0.38–0.41	5491–6279	29.5–35.3	15.4–15.9	45–53 ^a	Zaborska et al. (2016)
Hornsund	0.12–0.19	1310–2330	24.3–40.5	19.3–30.3	75–79	This study
	0.22–0.24	2916–3299	38–42	35.5–38.6	84–98 ^a	Zaborska et al. (2016)
Storfjorden	0.18	570–2240	11–46	–	–	Winkelmann and Knies (2005)
Arctic region						
Barents Sea	0.03–0.4	320–650	–	3.7–8.5	5–7 ^d	Carroll et al. (2008)
Young Sund (Greenland Sea)	0.04–0.23	–	–	7.2	–	Rysgaard and Nielsen (2006)
Glaciated fiord (SE Alaska)	–	90,000–3,300,000	–	30–1113	–	Cui et al. (2016)
Non-glaciated fiord (SE Alaska)	–	–	–	13–82	–	Cui et al. (2016)
Saguenay fjord (Canada)	0.2–1.5	–	24–291	24–291	–	St-Onge and Hillaire-Marcel (2001)
Gulf of St. Lawrence (Canada)	0.08	~285	–	5.5–6.4	3.5 ^d	Silverberg et al. (2000)
Gulf of St. Lawrence (Canada)	1.0–1.5	–	0.7–2.5	–	–	Muzuka and Hillaire-Marcel (1999)
Labrador Sea	0.2–2.8	–	0.02–1.5	–	–	Muzuka and Hillaire-Marcel (1999)
Other regions						
Nordåsvannet fjord (Norway)	0.04–0.22	44.6–261.5	1.9–19.5	–	–	Muller (2001)
Loch Sunart (Scotland)	0.02–0.09	–	3.0–32.1	1.9–25.7 ^b	–	Smeaton et al. (2016)
Patagonia fjords (Chile)	0.14–0.47	–	1.9–40.8	1.2–34.8	63	Sepulveda et al. (2011)
Fiorland (New Zealand)	0.06–0.38	51–1140	2.3–23.2	1.8–18.6 ^c	–	Smith et al. (2015), Knudson et al. (2011), Pickrill (1993)

^a Difference in OC concentration between the surface layer and deepest layer.

^b Burial rate calculated assuming a burial efficiency of 63% (Sepulveda et al., 2011).

^c Burial rate calculated assuming a burial efficiency of 80% (Bernier, 1980).

^d Share of primary production buried in sediments.

in pore water are fulvic acids – products of desorption and/or hydrolyzation of terrestrial OM brought to the fjord sediments as a suspension, as well as residues of the autochthonous OM mineralization and humification.

5.4. Future challenges

This research quantified OC and IC burial in bottom sediments of two high Arctic fjords, Hornsund and Kongsfjorden, which differ significantly in terms of their hydrological features, activity, and number of surrounding glaciers, as well as primary production. At the same time, this study organized the knowledge on the meaning of carbon burial. It clearly defined carbon burial as the difference between carbon deposition and carbon return flux. This is especially important for quantifying burial of OC that undergoes mineralization, decomposition, and/or hydrolysis during early diagenesis.

Since it was shown that Arctic fjords are important regions in the global carbon cycle (Smith et al., 2015), quantification of carbon burial in sediments of these regions is of key

importance. There are different environmental consequences of burial for different carbon species (organic vs. inorganic) and origins (marine vs. terrestrial). Thus, it is important for the accurate quantification of carbon burial performed in this study to be followed by detailed study on the provenience of both IC and OC. It is well known that burial of marine OC, as the last link of the biological pump, contributes significantly to the reduction of atmospheric CO₂. In the case of terrestrial OC burial, carbon only changes the location from the terrestrial (soils) to the marine (sediments). Supply, transformations, and burial of carbonates, depending on their sources, may generate contrary mechanisms. The discharge of carbonates from land may lead to their partial dissolution in seawater, and consequently, to an increase in total alkalinity. This increases the uptake or lowers emission of CO₂ from/to the atmosphere. In contrast, the formation of biogenic carbonates reduces alkalinity and leads to the opposite effects.

It is not clear how to distinguish between terrestrial and biogenic IC. Recently an effort to do this for Kongsfjorden sediments was carried out by Koziarowska et al. (2017). In the

case of the organic fraction ratio of carbon stable isotopes represent a tool commonly used for distinguishing between marine and terrigenous sources. However, numerous studies report limitations of this method for high latitudes (Bourgeois et al., 2016; Kuliński et al., 2014; Kumar et al., 2016). Thus, separate quantification of marine and terrestrial OC and IC burial is still a challenge for high Arctic regions.

6. Conclusions

In this study, surface sediments of two high-latitude Arctic fjords, Hornsund and Kongsfjorden, were assessed as a sink of both IC and OC. The burial rate of carbon was taken as a measure of the actual carbon sink. Moreover, comparison of the results from three methods quantifying carbon burial in marine sediments was carried out.

The $OC_{BR(I)}$ differed significantly in the two investigated fjords, as it equaled 19.3–30.3 g OC $m^{-2} y^{-1}$ in Hornsund and 5.7–10.0 g OC $m^{-2} y^{-1}$ in Kongsfjorden. This was accompanied with a higher efficiency of OC burial in Hornsund (75–80%) than in Kongsfjorden (30–50%). The higher carbon burial efficiency in the former indicates that more OC reaching sediments is permanently buried in sediments, a feature attributed to the higher contribution of land-delivered OM there. The burial rate of IC was much smaller in Hornsund and much higher in Kongsfjorden than OC burial was, a feature attributed to both varying SARs and concentrations of carbonates in sediments. The latter reason may result from the larger activity of calciferous organisms and spread of carbonates in the Kongsfjorden catchment area than in Hornsund. The study showed that the values obtained by the three tested methods in separate cores may differ and/or be comparable. On the other hand, by definition, just the 'return flux' method simultaneously takes into account processes that likely affect carbon concentration in sediments: diffusion, mineralization and/or hydrolysis, while it is not vulnerable to OC concentration changes caused by e.g. dynamics of mineral material and/or OC deposition to sediments.

The DOC occurrence in pore water was attributed to hydrolysis and the desorption of biochemically refractory, possibly high-molecular substances, from sediment mineral particles. The absorption spectra indicated that the organic substances released from sediments are likely fulvic acids. This implies that organic substances are delivered to sediments and accumulated in the sediments already as refractory carbon species adsorbed to mineral particles.

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