

**Particulate organic matter fluxes and carbon cycling
at cold-water coral reefs –
A three years study at the Tisler Reef, Norway**

by

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I declare that this thesis represents original and independently conducted research that has not been submitted to any other university for the conferral of a degree.

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Abstract

Cold-water corals (CWC) occur throughout the world's oceans, with the reef building coral *Lophelia pertusa* forming giant reefs and mounds in the Northeast Atlantic. CWC reefs are hotspots of biomass and biodiversity, economically important as breeding and nursing grounds for many commercial fish species, and valuable paleoclimatic archives. Furthermore, recent research suggests that CWC reefs may play an important role in the marine carbon cycle, as they might be hotspots of carbon cycling along continental margins. Fundamental issues regarding CWC reef functioning remain not well understood. These include the relative contribution of different food sources to CWC ecosystem nutrition, the influence of hydrodynamic processes on reef nutrition, as well as the contribution of CWC ecosystems to benthic carbon turnover along continental margins.

Within this PhD project, these issues were addressed at the Tisler cold-water coral reef in a succession of field campaigns between 2007 and 2009. The reef is centred on a sill peak in the Norwegian Skagerrak. A variety of methodological approaches were used. These consisted of the collection of CTD and chlorophyll profiles, the deployments of sediment traps, current meters, temperature sensors and oxygen sensors for time-series measurements in the benthic boundary layer (BBL), the sampling of particulate organic matter (POM) across the reef with subsequent chemical analyses, and the chemical analysis of freshly released *L. pertusa* mucus.

The environmental conditions at the Tisler Reef were found to be highly dynamic, with an overall water temperature range of 8.3 °C (min 5.6 °C; max 13.9 °C) and occasional temperature jumps of up to 4 °C in less than one hour. Flow velocity was also highly variable, with maximum velocities of $>80 \text{ cm s}^{-1}$. Vertical particle fluxes were in the ranges of $1\text{--}125 \text{ g m}^{-2} \text{ d}^{-1}$ (mass) and $35\text{--}2643 \text{ mg m}^{-2} \text{ d}^{-1}$ (POC). CTD and chlorophyll profiles indicated that downstream of the sill crest, downwelling delivered warmer, fresher and chlorophyll richer water masses down to the BBL. Both sides of the reef received downwelling nutrition delivery, as flow direction over the reef reversed periodically. Several chemical composition indicators revealed that suspended POM was significantly fresher on the downstream side of the reef than on the upstream side. *L. pertusa* mucus from the Tisler Reef was labile in composition, as indicated by a low C/N ratio and a high amino acid degradation index (DI) value. The combination of fresh, downwelling POM with mucus released from the reef is proposed as the cause of the greater lability of the downstream POM.

Particulate organic carbon (POC) content in the BBL was significantly depleted across the reef. Biodeposition was calculated to be $459 \text{ mg POC m}^{-2} \text{ d}^{-1}$ on average. Dissolved oxygen concentration within the reef structure was $\sim 6 \text{ ml l}^{-1}$ ($\sim 270 \text{ } \mu\text{mol l}^{-1}$) and decreased rapidly during short phases of stagnant or near stagnant flow. The maximum rate of O_2 decrease was $20.04 \text{ } \mu\text{mol l}^{-1} \text{ h}^{-1}$. This decrease led to an estimate of the coral community respiration rate of $981 \text{ mg C m}^{-2} \text{ d}^{-1}$, which suggests that CWC reefs are hotspots of carbon cycling along continental margins. The vertical POC fluxes measured with sediment traps supplied only $\sim 25\%$ of the total community respiration, indicating the presence of other carbon supplying mechanisms to the coral community such as biodeposition and feeding on zooplankton. The coral community respiration rates reported here at Tisler and from the literature on Rockall Bank indicate that these are a factor 10 to 15 higher than those of shelf and slope sediments. These high respiration rates suggest that though the areal extent of CWC reefs on the central Norwegian shelf is limited to $\sim 0.5\%$, their carbon processing may represent about 3.2% to 10.9% of the total benthic carbon processing of this region.

In order to improve the accuracy of vertical flux measurements in future studies, a new approach to quantify vertical particle fluxes was developed and tested in a pilot study. This approach is based on a modification of the IRSC-trap technology and is capable of determining settling velocity specific fluxes. Results of the pilot study indicate that particles with slow settling velocities are generally undertrapped, whereas particles with fast settling velocities are overtrapped, confirming earlier results from the literature. The new approach can serve as an improvement of vertical flux quantification in future studies on CWC reefs and in the world's oceans in general.

An additional chapter of this thesis, which is a co-author contribution, deals with the influence of 'drill cuttings' - drilling waste material - on the physical characteristics of phytodetritus. In the vicinity of drilling rigs used by the oil and gas industry, the concentration of drill cuttings in the water column may at times be enriched as a result of discharge. As many drilling rigs are located in close vicinity to CWC reefs, it is important to know how these drill cuttings alter the vertical carbon flux towards nearby located CWC reef ecosystems. Laboratory produced phytoplankton aggregates were exposed to drill cuttings of various composition. Results indicate that settling velocities are greater in aggregates exposed to drill cuttings than in aggregates not exposed to them.

CHAPTER 1

Introduction

1 Cold-water coral reefs and particulate organic matter fluxes

Cold-water coral (CWC) reefs occur throughout the world's oceans (Freiwald and Roberts 2005, Roberts et al. 2006, 2009). In the Northeast Atlantic the main reef-building coral species *Lophelia pertusa* (Scleractinia) has formed giant reefs (Mortensen et al. 2001, Freiwald et al. 2004, Fossa et al. 2005) and carbonate mounds (Henriet et al. 1998, De Mol et al. 2002, Kenyon et al. 2003, Wheeler et al. 2007). CWC ecosystems are characterized by a high biodiversity and biomass as compared to adjacent slope sediments (Jonsson et al. 2004, Roberts et al. 2008), with the dead skeletal material of the reef structure providing a useful substrate for numerous sessile and mobile suspension and filter feeders (Henry and Roberts 2007, van Oevelen et al. 2009). Knowledge on the composition and functioning of CWC ecosystems has grown rapidly over the last two decades, as they have become a focus of research within large international programs, such as ACES, MoundForce, HERMES, CORAMM, CoralFish, HERMIONE and TRACES.

Aquarium studies (Mortensen 2001, Purser et al. 2010) and in situ observations (Freiwald et al. 2002) have shown that *L. pertusa* can feed on zooplankton, with higher capture rates observed when higher concentrations of zooplankton were available (Purser et al. 2010). Studies using $\delta^{15}\text{N}$ values suggested that *L. pertusa* utilise a mixed diet of zooplankton and phytodetritus (Duineveld et al. 2004, 2007, Kiriakoulakis et al. 2005). High nutritional values of particulate organic matter (POM) observed in the vicinity of some reefs indicate the potential importance of POM as a food source for coral communities (Kiriakoulakis et al. 2004, 2007). Nevertheless, vertical POM fluxes to CWC reefs can be highly variable (Duineveld et al. 2004, Mienis et al. 2009). Recent studies based on $\delta^{15}\text{N}$ values also suggested that bacterial sources might complement *L. pertusa* nutrition (Wild et al. 2008). From these studies, it is clear that corals, and associated communities, are able to ingest

various food sources. Physical phenomena, such as internal waves (Frederiksen et al. 1992) with their respective flow acceleration and subsequent resuspension (Mienis et al. 2007, 2009), Taylor column development (White et al. 2005, White 2007), and downwelling (Davies et al. 2009) have been reported and are likely important food supply mechanisms to the various CWC communities, indicating the importance of the environmental settings on food availability.

Vertical POM fluxes are commonly measured with sediment traps. Potential biases and limitations of sediment traps have been identified, of which the most important are hydrodynamic biases, zooplankton “swimmer” retention and sample solubilisation in the sample cups (see review papers by Gardner 2000 and Buesseler et al. 2007). Whereas the latter two issues can be addressed quite satisfactorily, hydrodynamic biases are harder to assess (Gust et al. 1992, 1994, 1996, Gardner et al. 1997), but are on the way to be better understood (Gust and Kozerski 2000).

In addition to utilizing POM from vertical fluxes, suspension feeding fauna (such as corals) living within the benthic boundary layer (BBL) are able to actively capture suspended (phyto)detrital carbon sources from the water column, which would otherwise not settle on the seafloor, a process called “direct biodeposition” (Graf 1992, Thomsen et al. 1995, Graf and Rosenberg 1997). Additionally, as benthic organisms (especially reef building ones) indirectly change the hydrodynamic properties of the BBL by their vertical growth, they can indirectly increase the flux towards the seafloor, a process called “indirect biodeposition” (Graf and Rosenberg 1997). Biodeposition, which is the sum of both direct and indirect biodeposition, is an additional “lateral depositional flux” (additional to the carbon supply from passive vertical settling of POM onto the seabed) and is influenced by flow velocity (Thomsen 2002). Flow velocity at CWC reefs can be highly variable (Duineveld et al. 2004, 2007, Davies et al. 2009, 2010, Mienis et al. 2009, Lavaleye et al. 2009). Biodeposition was suggested to play a major role in coral community nutrition at the Rockall Bank (van Oevelen et al. 2009).

Though food availability evidently impacts carbon cycling in coral communities, also environmental conditions such as temperature may play an important role. However, information on respiration of *L. pertusa* as well as of the whole CWC ecosystem is very scarce, with only two published papers focusing on respiration. The first (Dodds et al. 2007) indicates that *L. pertusa* respiration is very sensitive to temperature changes, with a nearly three-fold increase in respiration with temperature increase from 6.5 to 11 °C. This study

suggests that temperature as a process-regulating parameter is important to record within CWC reef monitoring programs. Fluctuations in temperature were shown to be high (Duineveld et al. 2007, Davies et al. 2009, 2010, Mienis et al. 2009), with maximum diurnal differences of up to 2.6 °C (Mienis et al. 2009). The second study on respiration (van Oevelen et al. 2009) assessed the coral community as a whole and showed that coral respiration was only 9% of the whole community respiration at a site on Rockall Bank (~800 m depth). They measured community respiration to be 688 mg C m⁻² d⁻¹ and suggested that CWC ecosystems are hotspots of biomass and carbon cycling along continental margins.

As important hotspots of biodiversity and biomass, it is imperative to study the environmental conditions in which these coral communities flourish and to understand their role on a large spatial scale. The complex interplay between environmental drivers requires long-term monitoring and an integrative approach in studying CWC reef ecosystems, but such studies are scarce to date.

2 Framework, aim and approaches of this thesis

This PhD work was carried out within the Coral Risk Assessment, Monitoring and Modelling (CORAMM) and the Hotspot Ecosystem Research on the Margins of European Seas (HERMES) projects. Within these two projects, the Tisler cold-water coral reef was investigated as one study site. The Tisler Reef, principally formed from the calcium carbonate skeleton secreted by *Lophelia pertusa* during coral growth, is located in the NE Skagerrak at water depths between 70-150 m. It is situated on a sill in the deepest connection between the Kosterfjord and Skagerrak, forming a structure approximately 1.0-1.2 km in length (live reef), and several hundred metres in width, orientated in a NW-SE direction. The bathymetric situation forces the near-bottom currents in a NW or SE direction, which makes the reef an ideal place to study biodeposition of a CWC reef. The reef was first discovered in 2002 and was protected against bottom-impacting fishing techniques by Norwegian fishery regulations in late 2003 (Fossa and Skjoldal, 2010). It is one of the largest and shallowest inshore CWC reefs discovered to date. Additionally the reef is located close to the Sven Lovén Centre for Marine Sciences in Tjärnö, Sweden, making it accessible for research cruises on a daily basis.

Given these advantages and given the chance to work on the Tisler Reef within the CORAMM and HERMES projects, I therefore chose it as the main study site within my PhD project.

The aim of this thesis was to answer the following questions:

- How high are the vertical and lateral fluxes of particulate organic matter in the BBL at the Tisler Reef?
- What is the quality of the organic matter in the BBL at the Tisler Reef?
- What role do physical factors play in determining the fluxes and quality of organic matter at the Tisler Reef?
- Which carbon sources do the reef community utilise and how high are the contributions of vertical fluxes and biodeposition to total nutrition?
- Do CWC reefs play a significant role in benthic carbon turnover along continental margins?

To answer these questions, the reef community as a whole was investigated, rather than *Lophelia pertusa* in particular. Though the corals themselves are the main catalysts for high biodiversity within the reef ecosystem (Freiwald and Roberts 2005, Roberts et al. 2009), they were recently shown to be responsible for only 9% of the total coral community respiration (van Oevelen et al. 2009). Thus, to evaluate the role of the reef in the marine carbon cycle, the reef ecosystem as a whole should be considered.

The following approaches were used to answer the above questions.

Identification of hydrodynamic forcing on fluxes

To identify possible physical mechanisms influencing vertical fluxes, to calculate lateral fluxes, and to get general information on variability of flow, CTD transects across the reef as well as ADCP measurements (time-series) at different positions within and at the edges of the reef were carried out.

Quantification of lateral (POM) fluxes and biodeposition

To quantify the amount, quality and variability of lateral fluxes in the BBL above the Tisler Reef, water samples on the upstream and downstream sides of the reef were taken, with subsequent chemical analyses, and together with flow velocity determination. No studies on biodeposition at CWC reefs have been published in the literature to date.

Quantification of vertical (POM) fluxes

To quantify the amount, quality and variability of vertical fluxes towards the coral community, sediment traps were deployed for time-series measurements at different locations within the reef, at different times. Furthermore, a new method to further improve the quantification of vertical particle fluxes towards the coral community and in the ocean in general was developed and tested in a pilot study.

Quantification of respiration

To quantify coral community respiration, an oxygen sensor was deployed close to the seabed and parallel temperature measurements were collected.

Compilation of a carbon budget and assessment on carbon cycling along continental margins

To draw a carbon budget at the Tisler Reef, measured data on vertical fluxes, lateral fluxes and respiration were compiled. They were furthermore complemented by data from the literature on respiration and on reef extent on the Norwegian shelf, to make a first estimate of the contribution of Norwegian CWC reefs to benthic carbon cycling along the Norwegian continental margin.

As an additional topic, the impact of drill cuttings on the physical characteristics of phytodetritus were studied to identify possible delivery pathways of these potentially toxic rock fragments to reef ecosystems, following drilling operation on continental margins.

The following hypotheses were investigated:

- H1) The Tisler Reef produces a measurable signal of biodeposition.
- H2) POM is more degraded on the downstream side of the Tisler Reef than on the upstream side.
- H3) Near shore CWC reefs are able to thrive in highly dynamic environments.
- H4) CWC reefs can be considered as hotspots of carbon cycling along continental margins.

The thesis research is presented in four manuscripts, with the first two manuscripts (Chapter 2 and Chapter 3) comprising the core of this thesis.

The first manuscript (Chapter 2) summarizes the work on the influence of hydrodynamic forcing on particle fluxes and on the quantification of lateral (POM) fluxes and biodeposition. CTD and chlorophyll measurements as well as data on the amount and quality of POM and coral mucus in the BBL are presented and discussed.

The second manuscript (Chapter 3) complements the first manuscript by presenting the work on vertical flux measurements and on time series measurements of temperature, flow and oxygen. A respiration estimate is compiled from the oxygen measurements. At the end of the second manuscript, data on carbon fluxes from the first and second manuscript are taken together to draw a carbon budget of the Tisler Reef.

The third manuscript (Chapter 4), which is a co-author contribution, investigates how drill cuttings impact on the sedimentation process through aggregation with phytodetritus. As many oil rigs are located in close vicinity to CWC reefs, it is important to know how drill cuttings alter the vertical carbon fluxes towards reef communities.

Because vertical flux measurements determined with sediment traps have known accuracy problems (e.g. Buesseler et al. 2007 and references therein), a new approach for vertical flux measurement is presented in the fourth manuscript (Chapter 5). This approach could in the future help to more accurately determine vertical carbon fluxes at CWC reefs, as well as in the world's oceans in general.

Chapter 6 summarizes the thesis work and addresses the hypotheses. Finally, Chapter 7 gives a short outlook.

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CHAPTER 2

Particulate organic matter fluxes and hydrodynamics at the Tisler cold-water coral reef

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ABSTRACT

Cold-water coral reefs occur in many regions of the world's oceans. Fundamental questions regarding their functioning remain unanswered. These include the biogeochemical influence of reefs on their environment ("reef effects") and the influence of hydrodynamic processes on reef nutrition. In a succession of field campaigns in 2007 and 2008, these questions were addressed at the Tisler cold-water coral reef, which is centered on a sill peak in the Norwegian Skagerrak. A variety of methodological approaches were used. These consisted of the collection of CTD and chlorophyll profiles, current measurements, sampling of particulate organic matter (POM) in the benthic boundary layer (BBL) across the reef with subsequent chemical analyses, and the chemical analysis of freshly released *Lophelia pertusa* mucus.

CTD and chlorophyll profiles indicated that downstream of the sill crest, downwelling delivered warmer, fresher and chlorophyll richer water masses down to the BBL. Both sides of the reef received downwelling nutrition delivery, as flow direction over the reef reversed periodically. Several chemical composition indicators revealed that suspended POM was significantly fresher on the downstream side of the reef than on the upstream side. *L. pertusa* mucus from the Tisler Reef was labile in composition, as indicated by a low C/N ratio and a high amino acid degradation index (DI) value. Particulate organic carbon (POC) content in the BBL was significantly depleted across the reef. Lateral depositional fluxes were calculated to be 18–1485 mg POC m⁻² d⁻¹, with a mean of 459 mg POC m⁻² d⁻¹.

We propose that the combination of fresh, downwelling POM with mucus released from the reef was the cause of the greater lability of the downstream POM. Our data on POC depletion across the reef suggest that cold-water coral reefs could play an important role in carbon cycling along continental margins.

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1. Introduction

Cold-water corals occur in many parts of the world's oceans. Numerous species and growth forms can lead to a variety of colony morphologies, such as scattered individuals, isolated thickets, carbonate mounds and complex reef structures (Roberts et al., 2006).

As the research regarding cold-water corals is a relatively new field in interdisciplinary ocean science, many important aspects of reef functioning have to date been poorly investigated. These include the biogeochemical influence of reefs and mounds on their surrounding environment ("reef effects") and the role they may play in the global carbon cycle. The diet of cold-water corals and the food supply to reefs and mounds have been a focus of study over the last decade, but are

still a topic of ongoing research and debate. Many questions regarding the role of hydrodynamic influences on reef and mound nutrition remain open.

Aquaria and *in-situ* observations have shown that cold-water corals can selectively feed on live zooplankton or suspended particles (Mortensen, 2001; Freiwald et al., 2002; Tsounis et al., 2010). Isotope studies suggest that corals utilise a mixed diet of zooplankton and phytodetritus (Kiriakoulakis et al., 2005; Duineveld et al., 2007; Dodds et al., 2009). The high nutritional values of particulate organic matter (POM) observed in the vicinity of some reefs indicate the potential importance of POM as a food source for reef ecosystems (Kiriakoulakis et al., 2004, 2007). Nevertheless, POM fluxes to cold-water coral reefs can be highly variable (Duineveld et al., 2004).

Certain physical processes have been identified that favour the nutrition and growth of reefs. A seafloor relief which accelerates near-bed currents and enhances food supply is believed to be essential for coral development (Genin et al., 1986; Thiem et al., 2006). Along the Atlantic European continental margin, living cold-water coral reefs occur within a seawater density envelope of sigma-theta (σ_θ) between 27.35 and 27.65 kg m⁻³, highlighting the importance of

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physical boundary conditions for cold-water coral growth and distribution (Dullo et al., 2008). Internal waves do play a role in particle supply to some cold-water coral communities. Frederiksen et al. (1992) found the highest *Lophelia pertusa* abundance around the Faroe Islands where the bottom slope was critical to internal waves of semi-diurnal frequency. They suggested that breaking internal waves enhance local food availability for cold-water corals by redistribution of suspended particles in the bottom mixed layer. On the southeast flank of Rockall Bank, internal waves force the formation of intermediate and bottom nepheloid layers and deliver fresh phytodetritus to the cold-water coral communities covering the giant carbonate mounds (Mienis et al., 2007). White et al. (2005) showed that Taylor columns develop around the Porcupine and Rockall banks and suggested that their retentive action can trap POM. This trapped material is subsequently transported downslope through the benthic boundary layer (BBL) towards coral communities by resulting Ekman drainage. A recent study by Davies et al. (2009) showed that tidally induced downwelling of fresher, warmer and chlorophyll richer water from surface layers is important for the reef nutrition of the Mingulay Reef complex, a reef located on a sill in the Sea of Hebrides.

These studies are also of increasing importance for the development of strategies for the sustainable management of continental margins, primarily because of the extensive oil and gas reservoirs located in the vicinity of cold water coral reefs. The drilling activities associated with the exploitation of these reservoirs can discharge large amounts of drill cuttings to the ocean. These drill cuttings consist predominantly of ground up rock fragments and barite (added in the drilling process). Following release to the ocean, these particles can accumulate around oil and gas installations and increase the levels of particle exposure experienced by the surrounding benthic ecosystems (Lepland and Mortensen, 2008; Trannum et al., 2010). Therefore, *in-situ* studies of natural particle modification across the reef environment ("reef effects") will also aid in determining the level of threat posed by such drilling activity.

To date, studies on the biogeochemical influence of reefs on their environment ("reef effects") are scarce. Benthic ecosystems with suspension-feeding fauna are known to actively remove particles from the water column and deposit them as faeces either within or on top of the sediment, a process known as biodeposition (Graf and Rosenberg 1997). *In-situ* experiments on biodeposition of suspension feeders at the Norwegian continental margin were carried out by Thomsen et al. (1995). The authors followed a watermass in the downstream direction to quantify the particle modification. Kiriakoulakis et al. (2004) showed for the Darwin mounds, a cold-water coral ecosystem on the NE Atlantic margin, that the action of certain benthic faunal elements associated with the corals (e.g. echinuran worms) can lead to the subduction of fresh organic material into the sediments. In a recent study on Tisler Reef, Norway, Lavaleye et al. (2009) showed the preferential removal of nitrogen rich compounds from suspension as water masses flowed over the reef, suggesting that the reef serves as a filter for high-quality POM. They also suggest that, globally, cold-water coral reefs are hotspots of remineralization activity in the ocean. Another recent study by Van Oevelen et al. (2009) came to a similar conclusion. Their quantitative food-web analysis of the cold-water coral community at Rockall Bank (~800 m water depth) revealed that coral communities are hotspots of carbon cycling along continental margins. Wild et al. (2008, 2009) showed a release of organic matter by cold-water corals, in particular mucus, that influenced the surrounding ecosystem by enhancing microbial activity in the overlying water column. The corals released mucus mainly in the dissolved phase, so POM uptake by the corals and subsequent dissolved organic matter (DOM) release can be seen as a POM–DOM transformation process (Wild et al., 2009).

Our study had two main aims. The first aim was to further investigate food supply mechanisms to cold-water coral reefs, with special emphasis on hydrodynamic forcing. The second aim was to

investigate the biogeochemical influence of cold-water coral reefs on their environment ("reef effects"). As components of the second aim we wanted:

- 1) To assess the degree to which a reef imposes chemical transformation processes on POM passing through it,
- 2) To answer the question, if mucus is occasionally released by the corals and whether it is transported in a downstream direction or not,
- 3) To investigate the capacity of a medium-sized cold-water coral reef for biodeposition and carbon remineralization.

2. Methods

2.1. Study site

As a study site, we choose the Tisler cold-water coral reef, Norway. The reef, principally formed from the calcium carbonate skeleton secreted by *Lophelia pertusa* (Scleractinia) during coral growth, is located in the NE Skagerrak at water depth between 70 and 150 m. It is situated on a sill in the deepest connection between the Kosterfjord and Skagerrak, forming a structure approximately 1.2 km in length (live reef), and several hundred meters in width, orientated in a NW–SE direction (Fig. 1A). The bathymetric situation forces the near-bottom currents in a NW or SE direction, which makes the reef an ideal place to study the possible reef effect on passing water masses. The main component of the flow are usually residual currents, whereas the tidal component is weak, ranging from 5 to 10 cm s⁻¹ (Lavaleye et al., 2009). The reef was first discovered in 2002 and was protected against bottom-impacting fishing techniques by Norwegian fishery regulations in late 2003 (Fosså and Skjoldal, 2010). It is one of the largest and shallowest inshore cold-water coral reefs. Additionally the reef is located close to the Sven Lovén Centre for Marine Sciences in Tjärnö, Sweden, making it accessible for research cruises on a daily basis.

2.2. Flow measurements

To gain information on hydrodynamic conditions at the reef, flow measurements were conducted using two Acoustic Doppler Current Profilers (ADCP), a RDCP 600 (Aanderaa) and an Aquadopp current profiler (Nortek). Three deployments of between 7 days and 3 months duration were conducted using RV *Lophelia* and a Remotely Operated Vehicle (ROV; Sperre SUB-fighter 7500 DC) for underwater deployment, positioning and recovery (Table 1). Additionally, daily deployments from research boat *Norppa* were conducted, using a small tripod with the RDCP 600 as payload and a surface buoy. Regular ferry crossings above the reef required periodic retrieval of the RDCP 600, and thus the flow data from these days vary in duration and sample location (Table 1).

2.3. CTD and chlorophyll profiles

For further hydrodynamic investigations, on 26 September 2007, 15 August 2008 and 26 September 2008 three CTD transects were made across the reef (transect shown in Fig. 1A). A DR-Mini Probe CTD (ADM) was used, with a chlorophyll fluorometer (Seapoint) attached as auxiliary sensor. The first two transects consisted of stations at the NW edge of the reef, the middle and SE edge of the reef. The distance between the stations was ~500 m. The third transect consisted of two additional stations positioned approximately 350 m NW and SE of the edges of the reef. During each transect, measurements were taken from each station in quick succession. Only the downcast data were analysed. For cross sectional visualisation, the CTD and chlorophyll profiles were interpolated with the Surfer 8 (Golden Software) application using kriging interpolation after Davies et al. (2009).

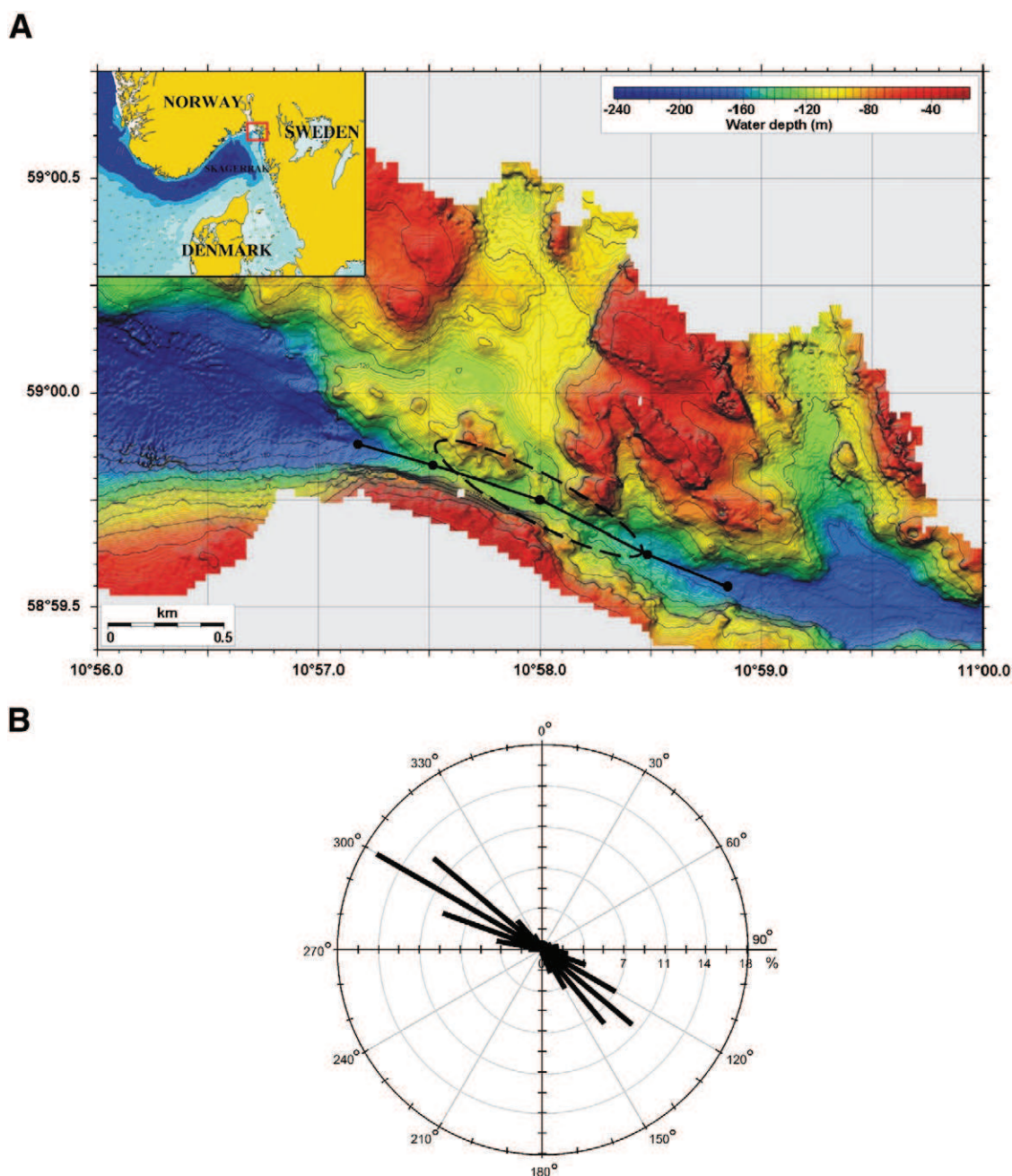


Fig. 1. A.) Location of Tisler Reef in the northeast Skagerrak and bathymetry of the reef area. The approximate extent of the live reef is marked. The black line shows the CTD transect. B.) Frequency distribution of current direction 20 m above Tisler Reef, recorded during long-term RCDP 600 deployment at the centre of the reef (# 2).

2.4. POM sampling

To investigate changes in POM composition and particulate organic carbon (POC) concentration across the reef, water samples were taken in the BBL at 2–3 m above the seafloor with a 5 l Niskin bottle. This sampling was conducted at the NW and SE edges of the reef (same locations as CTD profiles) on 3 days in early fall 2007 and on 3 days in summer 2008 (Table 2). Water samples were additionally taken from the middle of the reef on one of these days in 2007 and on two of these days in 2008. On each sampling day, 1–3 replicate 5 l samples were collected per location in quick succession (for details on replication see Supplementary Table 1). The Niskin bottle was lowered from the research boat *Norppa* and was equipped with a 2 m rope and groundweight, which automatically closed the bottle at 2.5 m above the seabed, guaranteeing accurate sampling depth. The water samples were subsequently filtered onto 47 mm GF/F filters

(Whatman, 0.7 μm nominal pore size). After filtration, the filters were freeze dried and stored frozen until analysis. According to the flow direction given by the ADCP data, the samples were later classified into upstream, middle and downstream samples.

2.5. Mucus sampling

For investigation of mucus chemical composition and later comparison with suspended POM composition, 10 *Lophelia pertusa* colony branches (~150 live polyps) were used to produce “fresh” mucus in the laboratory. These branches were collected by ROV from the middle reef station in summer 2008. The coral pieces were maintained at the Sven Lovén Centre for Marine Sciences for two weeks prior to mucus sampling. They were kept in 40 l flow-through aquaria supplied with sand filtered seawater pumped from a depth of 40 m from the adjacent Koster fjord. A constant temperature of 8 °C

Table 1
Description of ADCP deployments.

Depl. no.	Instrument	Lat (N)	Lon (E)	Location	Depth (m)	Period/day/time
#1	Aquadopp	58°59.685	10°58.028	Near middle station	115	05.09.2007–12.09.2007
#2	RDCP 600	58°59.822	10°57.953	Near middle station	120	11.09.2007–28.10.2007
#3	Aquadopp	58°59.820	10°57.546	NW station	134	27.09.2007–11.01.2008
#4	RDCP 600	58°59.820	10°57.546	NW station	132	09.08.2008 10:24–11:44
#5	RDCP 600	58°59.705	10°58.020	Near middle station	111	09.08.2008 12:09–13:09
#6	RDCP 600	58°59.610	10°58.470	SE station	148	12.08.2008 14:12–14:57
#7	RDCP 600	58°59.610	10°58.470	SE station	148	12.08.2008 15:12–15:37
#8	RDCP 600	58°59.610	10°58.470	SE station	148	15.08.2008 10:12–10:57
#9	RDCP 600	58°59.610	10°58.470	SE station	148	15.08.2008 15:39–16:09
#10	RDCP 600	58°59.610	10°58.470	SE station	148	26.09.2008 9:05–16:40

was maintained in the aquaria prior to mucus sampling. To stress the coral branches into producing mucus the fragments were briefly exposed to air. Latex gloves were then used to stroke the mucus from the branches into a glass beaker. This process was repeated with each coral branch several times to produce a sufficient quantity of mucus for analysis. Aliquots of 5–10 ml mucus were filtered onto four 25 mm GF/F filters (Whatman, 0.7 μm nominal pore size). After filtration, the filters were freeze dried and stored frozen until analysis. Two filters were used for C/N analysis and 2 filters for amino acid analysis.

2.6. Laboratory analysis

To assess the degradation state and bioavailability of the POM and mucus, carbon content, nitrogen content and amino acid composition were chosen as biochemical indicator parameters. All POM-filters were cut in half. One half was used for carbon and nitrogen analyses, with the other half used for amino acid determination. For C/N analysis of POM and mucus, filters were acidified after the method of Pike and Moran (1997) to remove particulate inorganic carbon. Acidification of dried samples prior to C/N analysis was conducted in a desiccator using fuming reagent grade 12 M HCl for 24 h. After acidification, samples were dried in a 60 °C oven and subsequently analysed in a EURO EA Elemental Analyser. Amino acid analysis of POM and mucus was carried out by reverse-phase HPLC using a slightly modified method of Cowie and Hedges (1992) and Van Mooy et al. (2002), as described in Garcia and Thomsen (2008). From the amino acid composition, the degradation index (DI) was calculated after Dauwe et al. (1999). The ratios of aspartic acid (asp) and glutamic acid (glu) to their decompositional products β -alanine

(bala) and γ -aminobutyric acid (gaba), as well as the joint percentage of bala and gaba (%[bala + gaba]) on all amino acids were calculated. These indicators have been widely used to verify variations in organic matter decomposition stage, both within the water column and in marine sediments (Lee and Cronin, 1982; Cowie and Hedges, 1994; Dauwe and Middelburg, 1998).

2.7. Statistical analysis

To investigate whether POM composition and concentration differed between the downstream and upstream sides of the reef, statistical analyses were carried out. For the overall period 2007–2008, the Wilcoxon signed-rank test was used for all measured parameters (POC, C/N, DI, asp:bala, glu:gaba and %[bala + gaba]), comparing the downstream daily mean values against the upstream daily mean values. Additionally, Mann–Whitney U tests were carried out to compare variations in all measured parameters across the reef for each individual sampling day and for each survey season (2007 and 2008). Mann–Whitney U tests were also used to detect seasonal variations (2007 vs. 2008) and daily variations within each season for all parameters in incoming waters (upstream samples).

2.8. Calculation of POC fluxes

Lateral POC fluxes and depletion of suspended POC across the reef in $\text{mg m}^{-2} \text{d}^{-1}$ (“lateral depositional fluxes”) were calculated for each sampling day assuming a uniform POC content throughout the first 3 m above the seabed. The mean POC content from upstream, middle and downstream stations on each sampling day was taken, as well as

Table 2
POC concentration and POM composition across Tisler Reef at upstream (U), middle (M) and downstream (D) edge in September 2007 and August 2008 (daily mean values). For values of each replicate measurement see Supplementary Table 1.

Date	Location	Current direction	Velocity (cm s^{-1})		Site	POC ($\mu\text{g l}^{-1}$)	C/N (molar)	DI (index)	asp:bala	glu:gaba	%[bala + gaba]
			5 mab	20 mab*							
06.09.2007	SE	NW	29	33	U	106.3	10.7	n.a.	n.a.	n.a.	n.a.
06.09.2007	NW	NW	29	33	D	95.1	11.5	0.28	63.9	42.6	0.47
09.09.2007	NW	SE	37	34	U	80.7	8.7	0.20	46.3	43.2	0.56
09.09.2007	SE	SE	37	34	D	61.9	7.2	0.09	53.2	35.0	0.55
26.09.2007	SE	NW	14	36	U	71.6	11.2	0.31	41.7	21.6	0.78
26.09.2007	M	NW	14	36	M	56.6	10.7	0.27	59.7	20.9	0.78
26.09.2007	NW	NW	14	36	D	63.0	10.1	0.17	76.4	21.0	0.75
09.08.2008	SE	NW	17	19	U	50.9	8.4	−0.38	37.1	12.1	1.27
09.08.2008	M	NW	17	19	M	46.9	7.9	−0.03	39.6	14.5	1.11
09.08.2008	NW	NW	17	19	D	43.5	8.1	0.09	37.2	13.4	1.14
12.08.2008	SE	NW	3	11	U	48.9	7.7	−0.31	31.0	13.1	1.22
12.08.2008	M	NW	3	11	M	44.0	8.6	−0.24	45.2	12.9	1.12
12.08.2008	NW	NW	3	11	D	46.3	7.6	0.02	33.1	12.9	1.14
15.08.2008	SE	NW	11	10	U	56.7	8.8	−0.36	18.4	9.8	1.66
15.08.2008	NW	NW	11	10	D	55.9	8.4	0.01	31.0	12.5	1.24
Mucus							6.2	0.29	33.1	6.9	2.15

* 20 m above bottom (mab) velocities on 06.09.2007 and 09.09.2007 were taken from 7 mab (uppermost cell of Aquadopp current profiler, deployed on these two days).

the mean flow velocity in the BBL at time of sampling. A reef length of 1200 m, with a cross-sectional area of 3 m² (1 m width, 3 m height) was assumed for the calculations. The lateral depositional fluxes were calculated for the reef as a whole, and additionally for the initial, upstream 600 m of reef structure.

3. Results

3.1. Flow data and CTD transects

The main current over the Tisler Reef was forced in a NW–SE direction by the bathymetry of the region (Fig. 1B). Data indicated that a prevailing flow direction over the reef typically lasted for several days (sometimes up to two weeks) before reversing direction, therefore rendering each side of the reef ‘upstream’ and ‘downstream’ in turn. Flow was in a NW direction for approximately 60% of the measurement period, and SE for the remaining 40% (Fig. 1B). Current velocities were mostly in the range of 10–50 cm s^{−1}, with peaks occasionally in excess of 70 cm s^{−1}. The current direction (NW or SE) and velocity during POM sampling is shown in Table 2 (and Supplementary Table 1).

All CTD transects showed a clear depression of isotherms and isohalines downstream of the reef crest (Fig. 2, and Supplementary

Figs. 1 and 2). On the downstream side (either the NW or the SE edge of the reef, depending on the current direction) the water was in all cases observed to be warmer and less saline than on the upstream side at comparable depths. The chlorophyll profiles also showed that chlorophyll was transported down to deeper water layers on the downstream side than on the upstream side (Fig. 2, and Supplementary Figs. 1 and 2). The CTD and chlorophyll profiles correlated with flow direction, with downwelling and mixing on the NW side of the reef when flow was towards the NW, and downwelling and mixing on the SE side when the flow was towards the SE.

A further indication of a downwelling process was presented by the vertical flow velocities recorded by the Aquadopp current profiler during the three month deployment (# 3) at the NW edge of the reef (Fig. 3). Vertical flow velocities recorded by the instrument from 6 m above the seabed showed a net downwelling when flow was in a NW direction (at which time the instrument was at the downstream edge of the reef). During periods of flow towards the SE (when the instrument was therefore at the upstream edge of the reef) a net upwelling was recorded, but weaker in intensity than the downwelling. As indicated by linear regression, these vertical downwelling and upwelling flow velocity components were greater during periods of elevated horizontal current flow. Based on this regression, average downwelling was 1.4 cm s^{−1} for a 40 cm s^{−1} horizontal velocity.

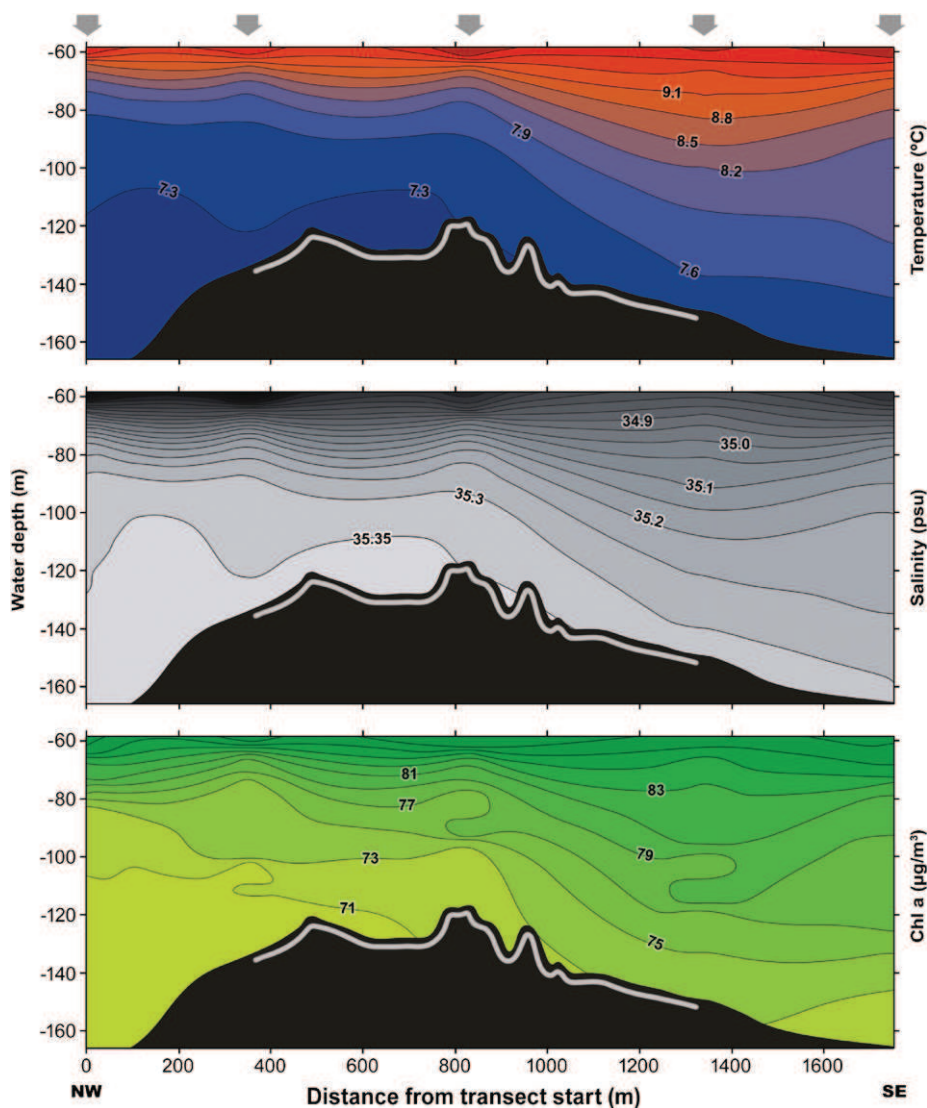


Fig. 2. CTD transect across Tisler Reef (for transect position see Fig. 1) on 26 September 2008. The white bar represents the live reef; grey arrows in the upper panel are individual CTD locations. The values along the x-axis represent the distance from the northwest end of the transect. Flow on 26 September 2008 was towards SE.

3.2. POM composition gradients across the reef

The results from the POM composition analysis are listed in Table 2 and shown in Fig. 4 (for values of each replicate measurement see Supplementary Table 1). Only the statistically significant findings are described in the following.

In the overall period 2007–2008, the ratio of aspartic acid to β -alanine (asp:bala) was significantly higher in POM samples from the downstream side of the reef than from the upstream side (Wilcoxon signed-rank test; $p < 0.05$). This indicated a fresher POM composition downstream than upstream. Furthermore, the joint percentage of β -alanine and γ -aminobutyric acid (%[bala + gaba]) of the whole amino acid content of POM was significantly lower in POM samples from the downstream side of the reef than from the upstream side in the overall period 2007–2008 (Wilcoxon signed-rank test; $p < 0.05$). This result also indicated a fresher POM composition downstream than upstream. Degradation index (DI) was significantly higher in downstream POM samples than in upstream samples only in August 2008 (Mann–Whitney U test; $p < 0.01$), again indicating a fresher POM composition downstream than upstream. In contrast to that, on 09 September 2007 DI was significantly lower in downstream samples than in upstream samples (Mann–Whitney U test; $p < 0.05$), an indication that the POM was more degraded on the downstream side than on the upstream side on that particular day. This was the only significant exception to the general finding that POM was more labile on the downstream side than on the upstream side of the reef.

A short additional look at seasonal and daily variations in composition of material in incoming waters (upstream samples) revealed that the C/N ratio of the POM on the upstream side was significantly lower in August 2008 than in September 2007 (Mann–Whitney U test; $p < 0.05$). This indicated a fresher POM incoming source in August 2008 compared to September 2007 or a higher proportion of terrigenous POM in September 2007 compared to August 2008. In contrast to that, DI, glu:gaba and % [bala + gaba] indicated a significantly more degraded POM in incoming waters in August 2008 compared to September 2007 (for all three parameters: Mann–Whitney U test; $p < 0.01$).

3.3. Mucus composition and comparison with POM

Lophelia pertusa mucus from the Tisler Reef samples was found to have a molar C/N ratio of 6.0–6.3. The amino acid (AA) composition of

the mucus in Mol% is given in Fig. 5 (black bars). The degradation index (DI) was 0.29 (Table 2).

We compared the AA composition of the mucus with the mean AA compositions of the upstream and downstream POM samples for each individual sampling day. By doing so, we wanted to assess if the downstream AA composition was more similar to that of mucus than the upstream. This was observed on 26 September 2007, when 15 of the 18 analysed amino acids were more similar in concentration, with only 3 amino acids (Ala, Lys, and bala) were more dissimilar (Fig. 5). Based on binomial probabilities, the probability of getting such a result (15 vs. 3) randomly is only 0.4%. On the other sampling days, no significant results were found.

3.4. POC depletion across the reef and fluxes

POC content across the reef is listed in Table 2 and shown in Fig. 4 (for values of each replicate measurement see Supplementary Table 1). In the overall period 2007–2008, POC content was significantly lower on the downstream side of the reef than on the upstream side (Wilcoxon signed-rank test; $p < 0.05$). Table 3 summarizes this depletion across the reef in absolute values and in percent. Calculations on lateral POC fluxes determined an influx on the upstream side of the reef of 416–7849 g POC per 3 m² d^{−1}, with an outflux of 395–7025 g POC per 3 m² d^{−1} on the downstream side (after passing 1200 m of reef). This corresponds to lateral depositional fluxes of 18–1485 mg POC m^{−2} d^{−1}, with a mean of 459 mg POC m^{−2} d^{−1} (Table 3). To determine the total depositional flux, addition of the vertical particle flux to the lateral depositional flux would be required. This was not possible as sediment trap data quantifying vertical fluxes were not determined within this study.

A short additional look at seasonal and daily variations in POC content in incoming waters (upstream samples) revealed that the POC content on the upstream side was significantly higher in September 2007 than in August 2008 (Mann–Whitney U test; $p < 0.05$).

4. Discussion

4.1. Downwelling and reef nutrition

Our CTD and chlorophyll profiles from Tisler Reef indicated that downwelling occurred at the downstream side of the sill crest. Several phenomena associated with mixing and downwelling are described in

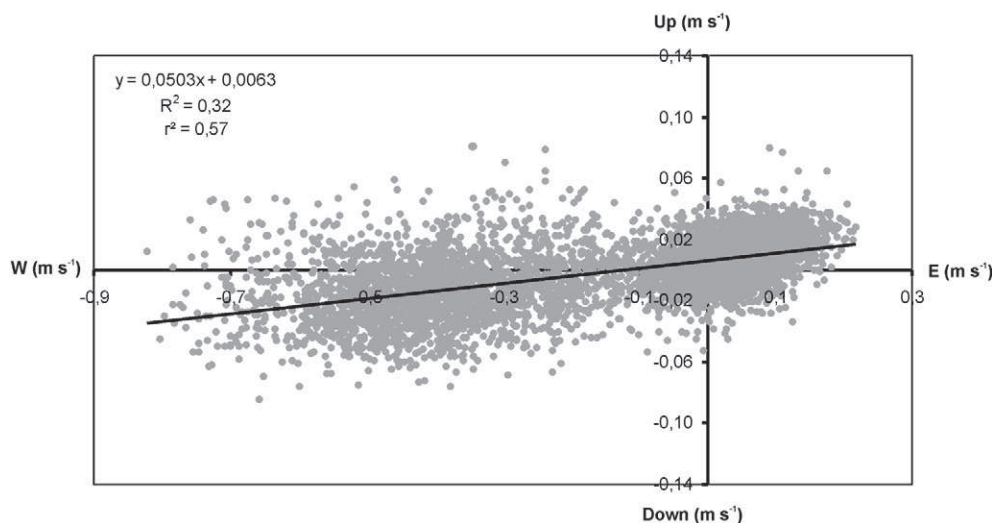


Fig. 3. Record of vertical water movement (y-axis) plotted against W–E current speed component (x-axis) at 6 m above seafloor at the NW side of the reef (128 m water depth), measured by Aquadopp current profiler during long-term deployment (# 3). Units are in m s^{−1}. Negative values represent current velocities towards W (x-axis) and downwelling (y-axis), positive values represent current velocities towards E (x-axis) and upwelling (y-axis). Each dot is one measurement (15 min interval).

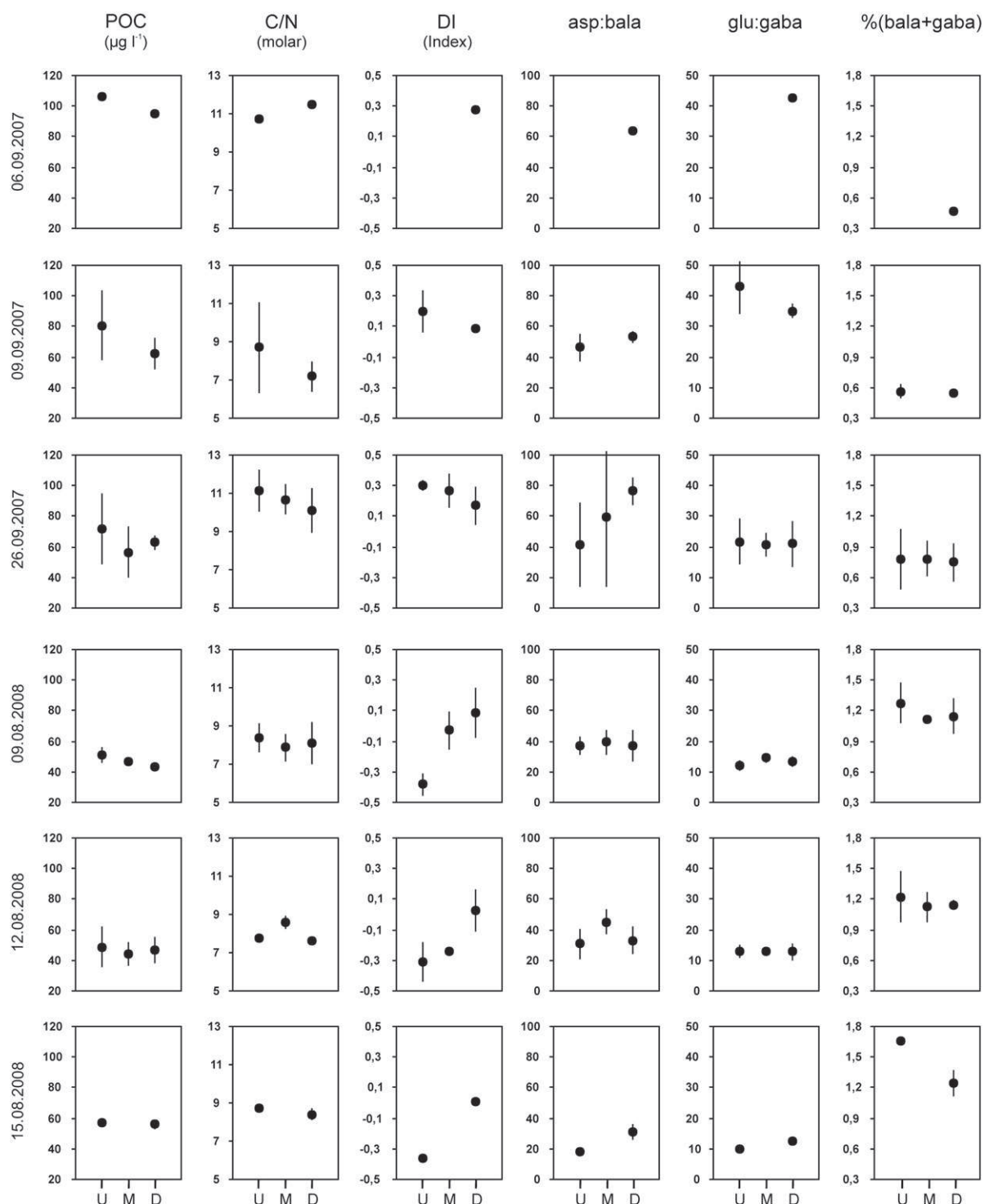


Fig. 4. POC concentration and POM composition across Tisler Reef in September 2007 and August 2008. In each diagram from left to right: Upstream (U), middle (M), downstream (D). Values are means $\pm$ SD ($n = 1$ to 3).

the literature when water masses flow over sill like structures. Flow over banks generates increased mixing downstream (Nash and Moum, 2001). The depression of isotherms, -halines and -bars, together with downwelling and lee wave generation are general phenomena occurring downstream of sills (Farmer and Armi, 1999; Vlasenko et al., 2002; Klymak and Gregg, 2004; Lamb, 2004; Xing and Davies, 2009). At the Mingulay cold-water coral reef complex, downwelling was observed to bring chlorophyll rich water masses down to the BBL of the reef downstream of a sill crest (Davies et al., 2009). Our observations indicate a similar effect at Tisler Reef.

Through downwelling, organisms on the downstream side of the reef benefit from having more labile POM as a food source available. This study and that by Davies et al. (2009) both show the importance of downwelling as a potential reef nutrition supply mechanism. The difference between the two reef locations is that at Mingulay the downwelling is tidally induced and hence the downwelling direction changes with a tidal frequency. At Tisler the main component of the flow are usually residual currents, with a lower tidal component, ranging from 5 to 10 cm s^{-1} (Lavaleye et al., 2009). The prevailing current (and hence the downwelling direction) above Tisler Reef

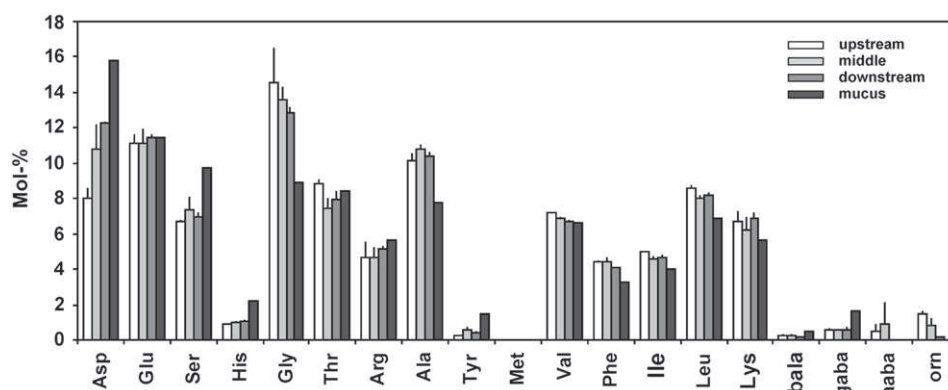


Fig. 5. Amino acid (AA) composition of *Lophelia pertusa* mucus in Mol% (black bars) compared to the mean AA composition of the upstream (white bars), middle (light grey) and downstream (dark grey) POM samples from 26 September 2007. Error bars denote $\pm$ SD ($n = 2$ (upstream), 3 (middle) and 3 (downstream)).

typically lasts for several days (sometimes up to two weeks) before reversing direction.

The importance of accelerated currents on cold-water coral nutrition has been highlighted, as the food flux per time unit is higher when flow velocity is higher, given a constant particle concentration (Genin et al., 1986). At Tisler Reef, the current is accelerated by forcing of the water masses through the channel between the Tisler Islands and the Hvaler Islands. Furthermore, a comparison between flow velocities measured during parallel long term deployments (Table 1) of Aquadopp current profiler (NW edge of reef; # 3) and RDCP 600 (middle of reef; # 2) revealed that the flow velocity was accelerated downstream and food flux per time unit was therefore increased. Thus, the reef ecosystem on the downstream side benefited from both the delivery of fresher particles via downwelling and from the increase in food flux associated with current acceleration. This situation was similar to that at Mingulay Reef (Davies et al., 2009).

Downwelling, mixing and the associated increased vertical nutrition delivery could help explain why cold-water coral reefs develop at certain locations that favour the development of these processes, such as on sills, ridges, moraines, iceberg ploughmarks and banks. In Norwegian waters many reefs are found on fjord sills and on ridges and ploughmarks on the continental shelf (Freiwald et al., 1999; Mortensen et al., 2001; Fosså et al., 2002; Fosså et al., 2005). On the local scale, the exact location of the downwelling could help explain the spatial extent and growth morphology of reefs. At the Mingulay Reef complex downwelling mainly occurred on one side of the Mingulay sill, with the live corals only covering that side of the sill (Davies et al., 2009), whereas at Tisler Reef downwelling can occur in both directions, depending on prevailing flow direction, and so reef growth and development has taken place on both sides of the sill.

Prior to damage from bottom trawling, the Tisler Reef was more extensive in coverage. It covered roughly twice its current area, with smashed and dislodged coral blocks evident from ROV investigations conducted by the authors. The reef extended down to depths of approximately 150 m at the NW side and 170 m at the SE side. The

observation that the reef was historically more extensive tallies with our findings presented here that both sides of the sill are delivered fresh labile material by the downwelling process over a greater area than is currently covered by living reef (see Fig. 2 for SE flow direction).

4.2. POM composition gradients across the reef

POM composition in the BBL was significantly different between the two sides of the reef, with in general the downstream POM sampled being fresher in composition than that sampled upstream. We identify two possible causes for this difference in composition. Firstly we assume that the reef effect shown by Lavaleye et al. (2009) for Tisler Reef (the preferential removal of nitrogen rich compounds by the reef ecosystem), takes place at the same time as the influx of fresh material on the downstream side as a result of downwelling. We hypothesize that the POM composition signature of this fresh downwelling material outweighs the degraded signature of the material which has passed through the reef structure. Secondly, mucus was released from the corals and transported in the downstream direction. Increased mucus production is an observed stress response in scleractinians (Reitner, 2005), and in *Lophelia pertusa* mucus production can be induced by particle exposure (Brooke et al., 2009). Our data on comparison of POM and mucus composition suggest that mucus was a significant component of the downstream POM on 26 September 2007. We hypothesize that mucus was released from the corals into suspension and transported with the prevailing current through and above the reef structure, this mucus enriching the POM in suspension throughout and downstream of the reef. Wild et al. (2009) also observed that mucus was released by *L. pertusa* colonies at the Tisler Reef. The results from this study, in combination with the observations of Wild et al., indicate that mucus release occurs periodically at cold-water reefs. *L. pertusa* mucus was found to have C/N ratios of 5.5–6.0 (Wild et al., 2008), resp. 5.7 ± 0.3 (Wild et al., 2009), resp. 6.0–6.3 (our study) and a degradation index

Table 3
POC depletion and calculated POC fluxes.

Date	Depletion ($\mu\text{g l}^{-1}$)		Depletion (%)		Flux (g per $3 \text{ m}^2 \text{ d}^{-1}$)			Lat. dep. flux ($\text{mg m}^{-2} \text{ d}^{-1}$)	
	Until middle	Whole reef	Until middle	Whole reef	Upstream	Middle	Downstream	First half	Whole reef
06.09.2007	n.a.	11.2	n.a.	10.5	7849	n.a.	7025	n.a.	687
09.09.2007	n.a.	18.8	n.a.	23.2	7669	n.a.	5887	n.a.	1485
26.09.2007	15.0	8.7	21.0	12.1	2641	2087	2322	924	266
09.08.2008	4.0	7.4	7.9	14.5	2280	2099	1949	302	276
12.08.2008	4.9	2.6	10.0	5.2	416	374	395	70	18
15.08.2008	n.a.	0.8	n.a.	1.4	1616	n.a.	1593	n.a.	19
Mean		8.2		11.2	3745		3195		459

(DI) of 0.29 (our study). Thus, release and transport of mucus towards the downstream side could additionally explain why certain POM degradation indicators revealed a significantly fresher downstream POM composition than upstream.

Lophelia pertusa mucus with C/N ratios around 6 has a high nutritional value and is an attractive organic substrate for planktonic microbial assemblages, as was shown by clearly increased microbial activity in the water column above the Rost Reef and Tisler Reef (Wild et al., 2008, 2009). The question arises as to whether or not mucus in cold-water coral reefs plays a similar role in ecosystem functioning as it does in tropical coral ecosystems. Tropical corals release mucus in huge amounts which is then transported to the surrounding seabed, providing a fresh labile food source for surrounding benthic ecosystems (Wild et al., 2004, 2005). As in the water column above the Tisler cold-water coral reef, planktonic heterotrophic bacteria can convert coral-derived DOC back to POC, thereby making it again available for higher trophic levels (Wild et al., 2009). This observation combined with our hypothesis of mucus transport in the downstream direction by currents suggests, that higher trophic levels of the seabed ecosystems surrounding cold-water coral reefs could benefit from mucus export out of the reef.

An exception to the POM composition gradient trend across the reef discussed above was observed for 09 September 2007. On this date the DI indicated a significantly more degraded downstream POM composition than upstream. A likely cause of this exception was the high current speeds ($35\text{--}39\text{ cm s}^{-1}$) observed on that day. This high flow may well have led to resuspension of degraded, refractory material from within the reef structure (Thomsen and Gust, 2000). The large volume of such material could have provided a POM composition signature sufficiently large to outweigh the fresh POM signature delivered downstream by downwelling and mucus transport.

In addition to the main focus on gauging the influence of the reef on POM composition, we also investigated the temporal variability in the composition of the upstream material reaching the reef. Most amino acid indicators revealed a significantly more degraded upstream POM composition in August 2008 than in September 2007. In contrast to that, upstream C/N ratios were significantly lower in August 2008 compared to September 2007, principally indicating a fresher upstream POM composition in August 2008. As the reef is located in close proximity to the Swedish/Norwegian mainland and terrestrial input to the reef is very likely, the observed differences in the C/N ratios most likely indicate a higher proportion of terrigenous organic matter delivery in 2007. Terrigenous organic matter in general has a much higher C/N ratio than marine derived organic matter (e.g. Meyers 1994, 1997 and references therein). From the ratios observed in this study a fresher terrigenous input was suggested for the 2007 sampling days, with a more degraded marine input for the 2008 sampling days.

4.3. POC depletion across the reef

POC concentrations observed in this study were in the range of $44\text{--}106\text{ }\mu\text{g l}^{-1}$ (Table 2). Other results from the Tisler Reef report $22\text{--}80\text{ }\mu\text{g l}^{-1}$ for the BBL ($<1\text{--}5$ meters above bottom (mab)) in May 2008 (Wild et al., 2009) and $10\text{--}50\text{ }\mu\text{g l}^{-1}$ for the BBL (1 mab) in April 2007 (Lavaleye et al., 2009). These differences could reflect either difference in sampling technique (bottle collecting and lab filtration in this study and that by Wild et al. versus *in-situ* large volume pump filtration by Lavaleye et al.) or difference due to seasonality. Small scale hydrographic differences that arise due to placement of equipment could also be an explanatory factor. Differences in filter retention due to sampling techniques are documented and could have led to these differences (Moran et al., 1999; Turnewitsch et al., 2007). However, as we always used the same methodology for our sample

collection, they can be compared among each other, in order to reveal changes in POC content in the BBL across the reef.

Our data showed that suspended POC was significantly depleted across the reef, with a mean depletion of $8.2\text{ }\mu\text{g l}^{-1}$ and a mean lateral depositional flux of $459\text{ mg POC m}^{-2}\text{ d}^{-1}$. The calculated lateral depositional fluxes should be considered as minimum values, as we have not assumed the depletion of POC to reach further up in the water column. We only took the depletion in the first 3 m above the seabed (up to our sampling height) into account. We also did not assume an increasing depletion with decreasing distance to the reef.

The POC depletion in $\mu\text{g l}^{-1}$ and the lateral depositional fluxes (across the reef) were greater when there was more POC available, as in September 2007 compared to August 2008 (Table 2). A possible explanation for the higher depletion of POC observed in September 2007 was the greater food supply (higher POC content) available in that year. In a recent laboratory study of *Lophelia pertusa* net capture rates, higher capture rates were observed when larger concentrations of food were available (Purser et al., 2010).

We want to address the implications of the general depletion of POC observed in this study. If feeding and subsequent respiration of the corals and the associated reef community is the main cause for the observed POC depletion, then cold-water coral reefs could be considered as hotspots of carbon remineralization activity in the ocean, as was also suggested by Lavaleye et al. (2009) and Van Oevelen et al. (2009). However, several other explanations for the observed POC depletion are conceivable. One such explanation is biodeposition without immediate respiration. Kiriakoulakis et al. (2004) showed for the Darwin mounds, a cold-water coral ecosystem at the NE Atlantic margin, that the action of certain benthic faunal elements that are associated with the corals (e.g. echinuran worms) leads to the subduction of fresh organic material into the sediments. Another explanation is given in a situation when the POC content of the BBL-overlying water mass (middle water column) is lower, as was observed by Wild et al. (2009) for a sampling day in May 2008. In this situation the “original” (upstream) BBL POC content is mixed across the reef with the lower POC content from overlying waters (middle water column) through downwelling and mixing. The result then is a lower POC content in the BBL at the downstream side. However, as we do not have time series data on the vertical POC concentrations through the water column above the Tisler Reef, we do not yet know if the POC content of the BBL-overlying water (middle water column) is lower in general. It could have been also higher during the sampling days which would have led to an underestimation of POC depletion. The POC content of the middle water column could potentially change due to bloom successions in surface waters and subsequent mixing with these surface waters etc. A further possible explanation for the observed POC depletion across the reef is the already mentioned POC–DOC transformation by the corals, which was suggested by Wild et al. (2009). The different possible explanations for reef induced POC depletion highlights that further research is needed to understand the role of cold-water coral reefs in the global carbon cycle.

5. Conclusions

1. Downwelling and mixing play an important role for reef nutrition of cold-water coral reefs located on sills, as the process delivers fresh particles to the downstream side of the sill. Accordingly, reefs located in similar settings (e.g. on ridges on the Norwegian continental shelf) may well also benefit from this effect, and the exact location of downwelling occurrence could help explain the spatial extent and morphology of reefs.
2. *Lophelia pertusa* mucus is a labile organic substrate. Released mucus can be transported by currents towards the downstream side of a reef. It is likely that the reef surrounding environment benefits from the export of this labile substrate.

3. It was shown that POM at the downstream side of a reef can be more labile than at the upstream side. The combination of fresh, downwelling POM with mucus released from the reef is the most likely cause of the higher lability.
4. It has to be further investigated, if the observed POC-depletion originates from the metabolic activity of the corals and associated fauna, from biodeposition, from POC–DOC transformation by the corals, or from mixing with overlying water masses. If the first of these processes is the most significant, then globally cold-water coral reefs could be hotspots of carbon remineralization.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.jmarsys.2010.11.003.

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CHAPTER 3

Environmental variability, organic matter fluxes and carbon cycling at the Tisler cold-water coral reef

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Abstract

Cold-water corals (CWC) occur throughout the world's oceans, with the reef building coral *Lophelia pertusa* forming giant reefs and mounds in the Northeast Atlantic. The relative contribution of different food sources to CWC ecosystem nutrition and the respective food supply mechanisms, as well as the contribution of CWC ecosystems to benthic carbon turnover along continental margins are to date not well understood. In a succession of field campaigns at the Tisler Reef, Norway, we deployed sediment traps, current meters and sensors for temperature and dissolved oxygen for time-series measurements. The environmental conditions at the Tisler Reef were found to be highly dynamic, with an overall water temperature range of 8.3 °C (min 5.6 °C; max 13.9 °C) and occasional temperature jumps of up to 4 °C in less than one hour. Flow velocity was also highly

variable, with maximum velocities of $>80 \text{ cm s}^{-1}$. Vertical particle fluxes were in the ranges of $1\text{--}125 \text{ g m}^{-2} \text{ d}^{-1}$ (mass) and $35\text{--}2643 \text{ mg m}^{-2} \text{ d}^{-1}$ (POC). Dissolved oxygen concentration within the reef structure was $\sim 6 \text{ ml l}^{-1}$ ($\sim 270 \text{ } \mu\text{mol l}^{-1}$) and decreased rapidly during short phases of stagnant or near stagnant flow. The maximum rate of O_2 decrease was $20.04 \text{ } \mu\text{mol l}^{-1} \text{ h}^{-1}$, which translates into a community respiration rate of $981 \text{ mg C m}^{-2} \text{ d}^{-1}$ and confirms that CWC reefs are hotspots of carbon cycling along continental margins. The vertical POC fluxes measured with sediment traps supplied $\sim 25\%$ of the total community respiration, indicating the presence of other carbon supplying mechanisms to the coral community such as biodeposition and feeding on zooplankton. The coral community respiration rates reported here at Tisler and from the literature on Rockall Bank indicate that these are a factor 10 to 15 higher than those of shelf and slope sediments. These high respiration rates suggest that though the areal extent of CWC reefs on the central Norwegian shelf is limited to $\sim 0.5\%$, their carbon processing may represent about 3.2% to 10.9% of the total benthic carbon processing of this region.

Key words: cold-water corals, carbon cycle, respiration, vertical fluxes, lateral fluxes, food sources, environmental variability

1 Introduction

Cold-water coral (CWC) reefs occur throughout the world's oceans (Freiwald and Roberts 2005, Roberts et al. 2006, 2009). In the Northeast Atlantic the main reef-building coral species *Lophelia pertusa* (Scleractinia) has formed giant reefs (Mortensen et al. 2001, Freiwald et al. 2004, Fossa et al. 2005) and carbonate mounds (Henriet et al. 1998, De Mol et al. 2002, Kenyon et al. 2003, Wheeler et al. 2007). CWC ecosystems are characterized by a high biodiversity and biomass as compared to slope sediments (Jonsson et al. 2004, Roberts et al. 2008), with the dead skeletal material of the reef structure providing a useful substrate for numerous sessile and mobile suspension and filter feeders (Henry and Roberts 2007, van Oevelen et al. 2009). Knowledge on the composition and functioning of CWC ecosystems has grown rapidly over the last two decades, as they have become a focus of research within large international research programs.

Aquarium studies (Mortensen 2001, Purser et al. 2010) and in situ observations (Freiwald et al. 2002) have shown that *L. pertusa* can feed on zooplankton, with higher capture rates observed when higher concentrations of zooplankton were available (Purser et al. 2010). Studies using $\delta^{15}\text{N}$ values suggested that *L. pertusa* utilises a mixed diet of zooplankton and phytodetritus (Duineveld et al. 2004, 2007, Kiriakoulakis et al. 2005). High nutritional values of particulate organic matter (POM) observed in the vicinity of some reefs indicate the potential importance of POM as a food source for coral communities (Kiriakoulakis et al. 2004, 2007). Nevertheless, vertical POM fluxes to CWC reefs can be highly variable (Duineveld et al. 2004, Mienis et al. 2009). Recent studies based on $\delta^{15}\text{N}$ values also suggested that bacterial sources might complement *L. pertusa* nutrition (Wild et al. 2008). From these studies, it is clear that corals, and associated communities, are able to ingest various food sources. Physical phenomena, such as internal waves (Frederiksen et al. 1992) with their respective flow acceleration and subsequent resuspension (Mienis et al. 2007, 2009), Taylor column development (White et al. 2005, White 2007), and downwelling (Davies et al. 2009, Wagner et al. 2011) have been reported and are probably important food supply mechanisms to CWC communities, indicating the importance of the environmental settings on food availability.

In addition to physical mechanisms, suspension feeding fauna (such as corals) in the benthic boundary layer (BBL) are able to actively capture suspended (phyto)detrital carbon sources from the water column, which would otherwise not settle on the seafloor, a process called “direct biodeposition” (Graf 1992, Thomsen et al. 1995, Graf and Rosenberg 1997). Additionally, as benthic organisms (especially reef building ones) indirectly change the hydrodynamic properties of the BBL by their vertical growth, they can indirectly increase the flux towards the seafloor, a process called “indirect biodeposition” (Graf and Rosenberg 1997). Biodeposition, which is the sum of both direct and indirect biodeposition, is an additional “lateral depositional flux” (additional to the carbon supply from passive vertical settling of POM onto the seabed) and is influenced by flow velocity (Thomsen 2002). Flow velocity at CWC reefs can be highly variable (Duineveld et al. 2004, 2007, Davies et al. 2009, 2010, Mienis et al. 2009, Lavaleye et al. 2009). Biodeposition was estimated to be $459 \text{ mg POC m}^{-2} \text{ d}^{-1}$ for the Tisler Reef (Wagner et al. 2011) and was also suggested to play a major role in coral community nutrition at the Rockall Bank (van Oevelen et al. 2009).

Though food availability evidently impacts carbon cycling in coral communities, also environmental conditions such as temperature may play an important role. However, information on respiration of *L. pertusa* as well as of the whole CWC ecosystem is very

scarce to date. We are only aware of two studies to date which report on respiration. The first (Dodds et al. 2007) indicates that *L. pertusa* respiration is very sensitive to temperature changes, with a nearly three-fold increase in respiration with temperature increase from 6.5 to 11 °C. This study suggests that temperature as a process-regulating parameter is important to record within CWC reef monitoring programs. Fluctuations in temperature were shown to be high (Duineveld et al. 2007, Davies et al. 2009, 2010, Mienis et al. 2009), with maximum diurnal differences of up to 2.6 °C (Mienis et al. 2009). The second study on respiration (van Oevelen et al. 2009) assessed the coral community as a whole and showed that coral respiration was only 9% of the whole community respiration at a site on Rockall Bank (~800 m depth). They measured community respiration to be 688 mg C m⁻² d⁻¹ and concluded that CWC ecosystems are hotspots of biomass and carbon cycling along continental margins.

Being important hotspots of biodiversity and biomass, it is imperative to study the environmental conditions in which these coral communities flourish and to understand their role on a large spatial scale. The complex interplay between environmental drivers requires long-term monitoring and an integrative approach in studying CWC reef ecosystems, but such studies are however scarce to date. Here, measurements on organic matter fluxes, respiration and environmental variability taken at various periods in the year are combined to study the Tisler Reef ecosystem (Norway). Sediment traps were deployed to determine vertical fluxes and their variability, an oxygen optode for *in situ* respiration calculation, and sensors to measure variability in flow and temperature at the Tisler Reef. We upscale these results with data on biodeposition at Tisler (Wagner et al. 2011) and with other data from the literature, to obtain a first estimate of the contribution of CWC reefs to benthic carbon cycling along the central Norwegian continental margin.

2 Methods

2.1 Study site

The Tisler Reef, principally formed from the calcium carbonate skeleton secreted by *L. pertusa* during coral growth, is located in the NE Skagerrak at water depths between 70-150 m. It is situated on a sill in the deepest connection between the Kosterfjord and Skagerrak, forming a structure approximately 1.0-1.2 km in length (live reef), and several hundred

metres in width, orientated in a NW-SE direction. The bathymetric situation forces the near-bottom currents in a NW or SE direction, which makes the reef an ideal place to study biodeposition of a CWC reef (Wagner et al. 2011). The main component of the flow are usually residual currents, whereas the tidal component is weak, ranging from 5 to 10 cm s⁻¹ (Lavaleye et al. 2009). The reef was first discovered in 2002 and was protected against bottom-impacting fishing techniques by Norwegian fishery regulations in late 2003 (Fossa and Skjoldal 2010). It is one of the largest and shallowest inshore CWC reefs known to date.

2.2 Lander deployments

Five deployments of small benthic landers at different locations within and at the edge of the reef took place between September 2007 and June 2009. The landers carried a variety of different instruments and were deployed and recovered via a Remotely Operated Vehicle (ROV; Sperre SUB-fighter 7500 DC) from RV *Lophelia* operated by the Sven Lovén Centre for Marine Sciences. Instruments consisted of a sediment trap (Hydro-Bios; 13 cm inner diameter, aspect ratio 6:1), two different Acoustic Doppler Current Profilers (ADCPs; Aanderaa RDCP 600 and Nortek Aquadopp current profiler), three different temperature sensors (Aanderaa, Nortek and Sequoia), a salinity sensor (Aanderaa), an oxygen sensor (Aanderaa optode), a turbidity sensor (Aanderaa), and a Laser In Situ Scattering and Transmissometry particle sizer (LISST; Sequoia). An overview of the combination of instruments carried by each lander, as well as the location, water depth, measurement height above bottom (hab), sampling time and sampling interval is given in Table 1. For the sediment trap deployments, sample cups were filled with a 5% formalin solution (salinity 40‰).

2.3 Laboratory analysis

Sediment trap samples were stored at 4 °C after retrieval of landers. They were picked for swimmers under a stereomicroscope (following Buesseler et al. 2007a) and were subsequently split with a rotor splitter. Aliquots of ¼ to ½ of each sample were filtered onto pre-weighed 0.4-µm Nuclepore filters, gently rinsed with ~5 ml DI water to remove salt and formalin, dried overnight at 60 °C, desiccated and weighed for mass using a semi-micro balance (following Lee et al. 2009). The material collected on the filters was then carefully

scraped from the filters and homogenized in a mortar mill (following Bonnin et al. 2002). Aliquots of 7-20 mg (in duplicate) were weighed into silver cartridges, decarbonated with 2N HCl, dried at 60 °C for ~90 min and acidified again until termination of bubbling (following Garcia et al. 2010). Silver cartridges were subsequently closed and processed for organic carbon and nitrogen content in an EURO EA Elemental Analyser using an acetanilide standard for calibration.

Table 1. Description of lander deployments. M = middle of reef; NW = northwest side of reef; hab = height above bottom; dir = direction

Deploy-ment no.	Position	Lat °N	Lon °E	Water depth (m)	measured parameters	Measure-ment hab (m)	Sampling time	Sampling interval
1	M	58°59.685	10°58.028	115	Vertical flux Flow speed + dir Temperature	1 2 – 7 1	05.09.07 – 09.09.07 05.09.07 – 12.09.07 05.09.07 – 21.09.07	8 h 10 min 10 min
2	M	58°59.822	10°57.953	120	Flow speed + dir Temperature Salinity Turbidity	4 – 30 1 1 1	11.09.07 – 28.10.07 11.09.07 – 28.10.07 11.09.07 – 28.10.07 11.09.07 – 28.10.07	15 min 15 min 15 min 15 min
3	NW	58°59.820	10°57.546	134	Vertical flux Flow speed + dir Temperature Particle size Temperature	1 2 – 7 1 1 1	27.09.07 – 28.12.07 27.09.07 – 11.01.08 27.09.07 – 18.01.08 27.09.07 – 11.01.08 27.09.07 – 11.04.08	96 h 15 min 15 min 15 min 15 min
4	NW	58°59.864	10°57.454	131	Vertical flux Flow speed + dir Temperature	1 2 – 7 1	30.09.08 – 04.10.08 29.09.08 – 05.10.08 29.09.08 – 23.11.08	36 h 10 min 10 min
5	M	58°59.767	10°58.005	109	Flow speed + dir Temperature Salinity Turbidity Oxygen	4 – 34 1 1 1 0.2	28.03.09 – 17.06.09 28.03.09 – 16.06.09 28.03.09 – 16.06.09 28.03.09 – 17.06.09 28.03.09 – 17.06.09	30 min 30 min 30 min 30 min 30 min

3 Results

3.1 Temperature and flow

Water temperature in the BBL of the Tisler Reef covered a wide range, from 5.6 °C in spring to 13.9 °C in autumn (Fig. 1).

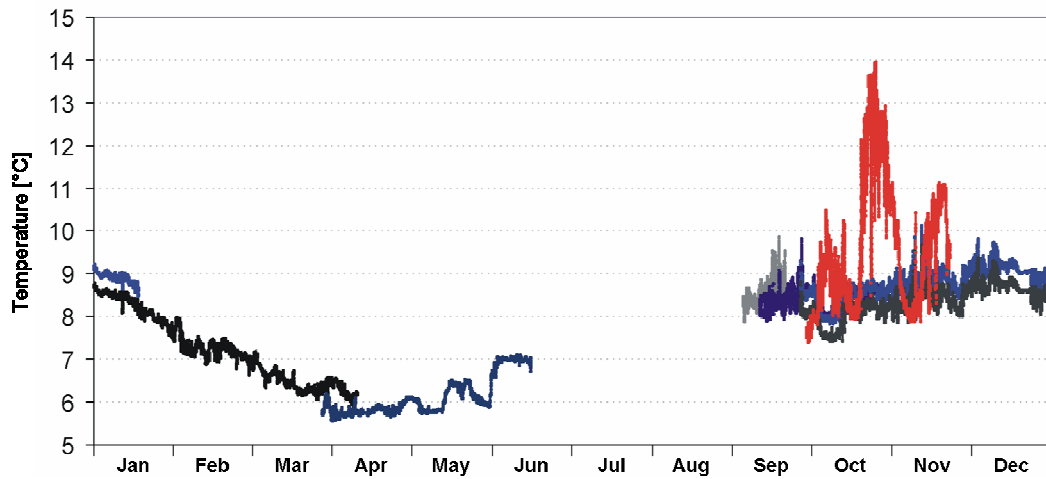


Fig. 1 Water temperature in the BBL as measured by different sensors at different locations within the reef in different years. Grey: Depl. no. 1; Dark blue: Depl. no. 2; Light blue: Depl. no. 3a; Black: Depl. no. 3b; Red: Depl. no. 4; Bluegreen: Depl. no. 5. For deployment numbers see Table 1.

The characteristic features at Tisler are the non-regularity and the presence of extreme events, rather than regular forcing of currents and temperature by tides, as seen in some other reefs. We will therefore in the following concentrate on observed extreme values and sudden fluctuations in temperature and flow.

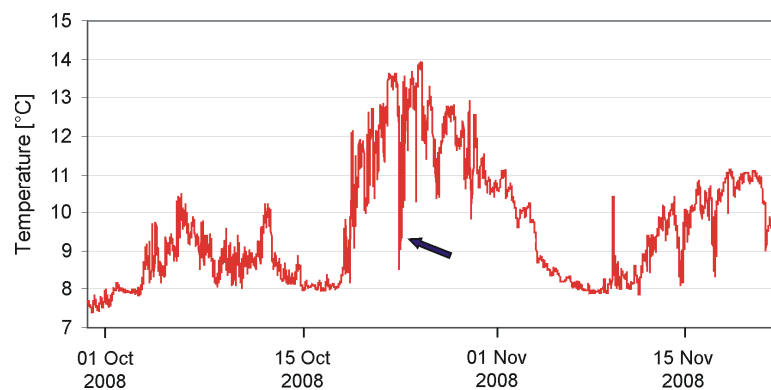


Fig. 2 Extreme temperature event in autumn 2008, recorded at the NW side of the reef (deployment no. 4).

In autumn 2008, an extreme temperature event took place (Fig. 1 red line; Fig. 2) during which temperature stayed above 10 °C for more than 10 days, with only one short very abrupt interruption (blue arrow in Fig. 2). During this interruption, temperature dropped by more than 4 °C within 40 min, with a rate of decrease of 2.9 °C in the initial 10 min (Table 2). The decrease was followed by a comprehensive increase. A maximum recorded diurnal difference was 5.2 °C. Further large temperature drops and jumps were recorded during autumn 2008, although of smaller intensity.

Table 2. Overall maximum and minimum temperature, overall temperature amplitude, and maximum temperature amplitude measured within a given interval.

T max	13.9 °C
T min	5.6 °C
ΔT max	8.3 °C
ΔT max 10 min	2.9 °C
ΔT max 40 min	4.2 °C
ΔT max 8.5 h	5.2 °C
ΔT max 24 h	5.2 °C

Flow velocity was also highly variable, with maximum values of 86 cm s⁻¹ at 2 meters above bottom (mab) (Fig. 3) and 122 cm s⁻¹ at 7 mab, both measured at the NW edge of the reef. Fig. 3 shows the flow regime at the NW edge of the reef, with the bathymetry there governing slow currents towards the SE (mostly 0-10 cm s⁻¹; ~50% of the time) or fast currents towards the NW (~40-50 cm s⁻¹; ~50% of the time). This observation is also apparent in the frequency distribution of current velocities for the same deployment (Fig. 4).

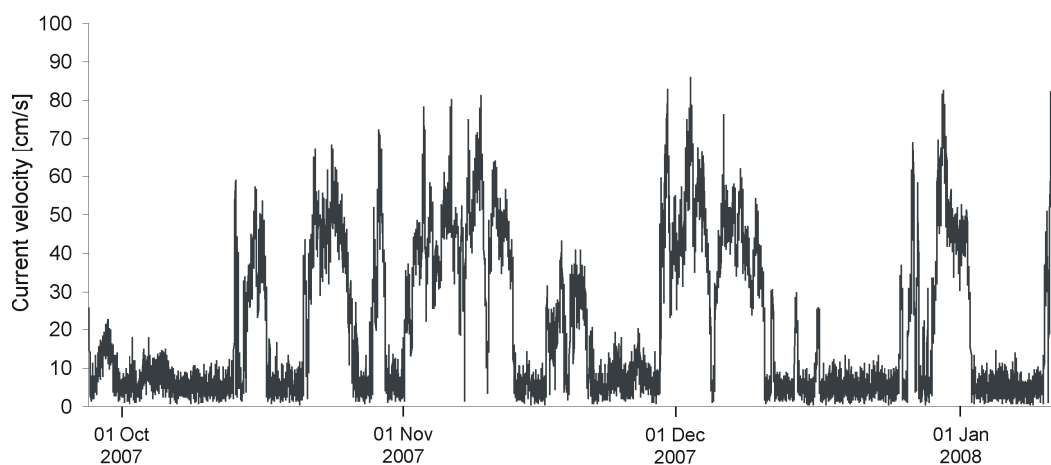


Fig. 3 Current velocity measured at the NW side of the reef at 2 mab (deployment no. 3).

When switching from one mode to the other, sudden increases or decreases in flow velocity (at 2 mab) of up to 34 cm s^{-1} within 10 min and up to 46 cm s^{-1} within 20 min occurred. The mean flow velocity at the NW reef edge in autumn 2007 at 2 mab was as high as 21 cm s^{-1} , with a median of 9.8 cm s^{-1} . All other deployments had lower mean velocities of $\sim 12\text{-}13 \text{ cm s}^{-1}$, but with comparable median velocities.

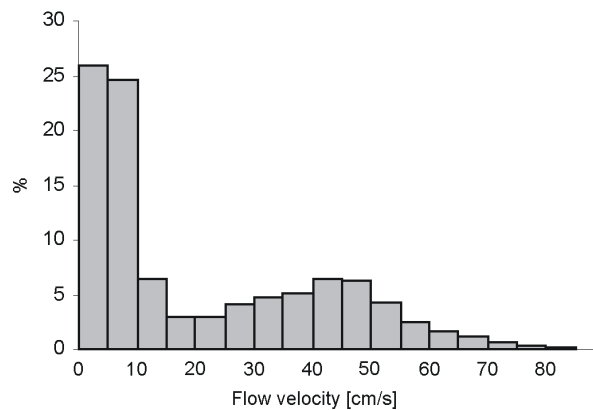


Fig. 4 Frequency distribution of current velocities for deployment no. 3, NW reef side, 2 mab.

3.2 Vertical particle and carbon fluxes

Mass fluxes were highly variable, ranging from $0.9 \text{ g m}^{-2} \text{ d}^{-1}$ to $125.2 \text{ g m}^{-2} \text{ d}^{-1}$ (Fig. 5). Excluding one extreme flux event in early October 2008, fluxes were below $20 \text{ g m}^{-2} \text{ d}^{-1}$. Mean mass flux over the whole measurement period was $8.5 \text{ g m}^{-2} \text{ d}^{-1}$ (including the extreme event) and $6.7 \text{ g m}^{-2} \text{ d}^{-1}$ (excluding the extreme event). The percentage of C_{org} ranged from 2.1% to 5.8%. Highest percentages were recorded in early September 2007, the lowest percentage during the extreme event in early October 2008. Organic carbon fluxes ranged from $35 \text{ mg } C_{\text{org}} \text{ m}^{-2} \text{ d}^{-1}$ to $2643 \text{ mg } C_{\text{org}} \text{ m}^{-2} \text{ d}^{-1}$. Excluding the extreme flux event in October 2008 organic carbon fluxes were below $1000 \text{ mg } C_{\text{org}} \text{ m}^{-2} \text{ d}^{-1}$. Mean organic carbon flux over the whole measurement period was $283 \text{ mg } C_{\text{org}} \text{ m}^{-2} \text{ d}^{-1}$ (including the extreme event) and $247 \text{ mg } C_{\text{org}} \text{ m}^{-2} \text{ d}^{-1}$ (excluding the extreme event). C/N ratios ranged from 7.7 to 11.5, with highest values in September 2007. Mean C/N ratio over the whole measurement period was 9.0.

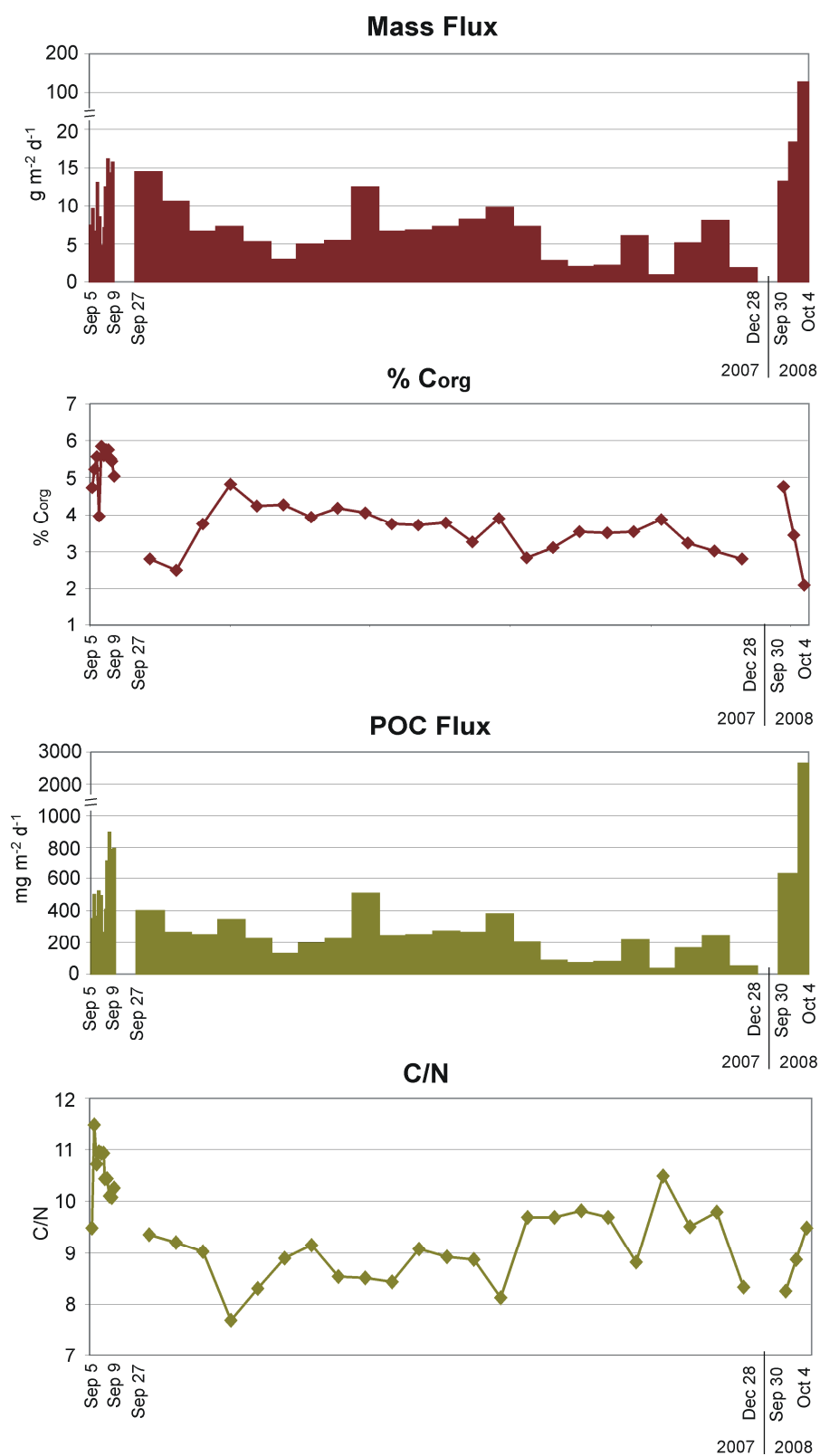


Fig. 5 Combined results on vertical fluxes from the three sediment trap deployments in 2007 and 2008. Sample cup exposure time was 8, 96 and 36 hours, respectively. (a) Mass flux, (b) Organic carbon percentage, (c) POC flux, (d) C/N ratio.

3.3 Oxygen concentration and depletion

Dissolved oxygen (DO) concentration at 20 cm above the seafloor within the reef structure next to a coral thicket varied between 5.6 ml l⁻¹ (250 µmol l⁻¹) and 6.4 ml l⁻¹ (286 µmol l⁻¹) over the course of the measurement period from 28 March to 17 June 2009 (Fig. 6). This corresponded to a saturation of 81% to 92%, as for this period the saturation level varied between 6.75 ml l⁻¹ (301 µmol l⁻¹) and 7.0 ml l⁻¹ (312 µmol l⁻¹). A small decrease in background DO concentration was observed towards late spring and early summer.

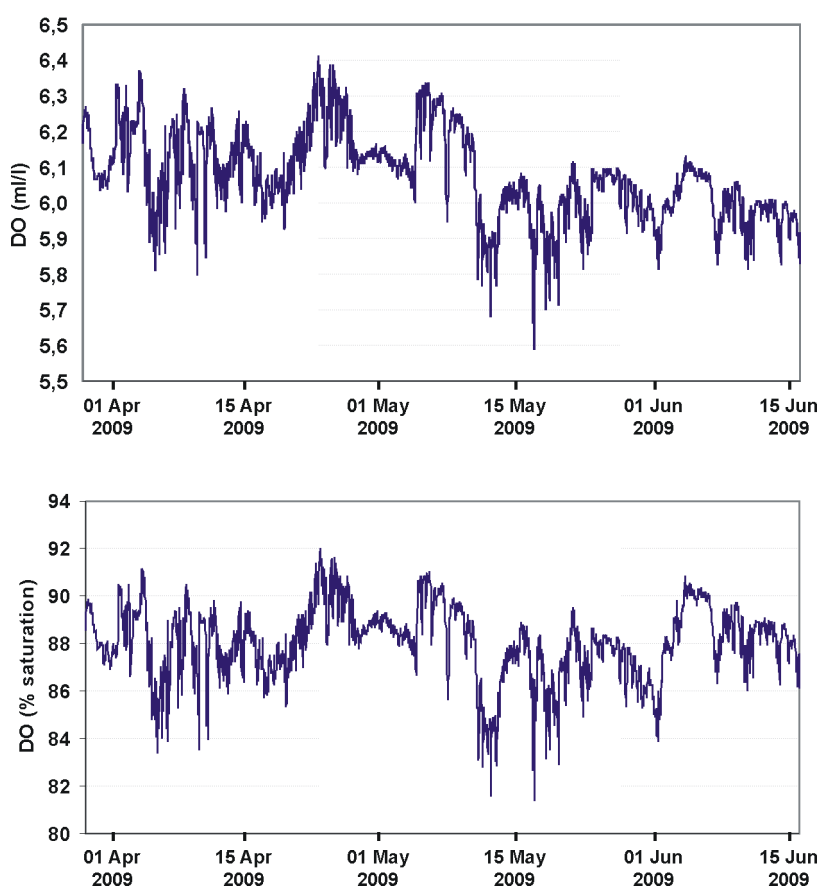


Fig. 6 Dissolved oxygen (DO) concentration and DO saturation measured at 20 cm above the seafloor within the reef structure at the centre of the reef. Note the pronounced drops in DO concentration occurring frequently.

Analyses of the time series in comparison with flow velocity revealed that DO concentration dropped rapidly during short phases of stagnant or near stagnant flow. The maximum rate of O₂ decrease within the whole measurement period was 10.02 µmol l⁻¹ (0.23 ml l⁻¹) in 30 min on 07 April. A comparable decrease of 9.34 µmol l⁻¹ (0.21 ml l⁻¹) in

30 min was observed on 17 May. Assuming a respiratory quotient (RQ) of 0.85 (Smith et al. 2001) and a constant oxygen depletion up to a height of 20 cm above seafloor (measurement height), this corresponds to a respiration rate of 981 mg C m⁻² d⁻¹ (07 April) and 915 mg C m⁻² d⁻¹ (17 May).

4 Discussion

4.1 Environmental drivers: temperature, flow and particle fluxes

The temperature range of 8.3 °C (5.6–13.9 °C) is the largest for a single CWC reef measured to date. The value of 13.9 °C is among the highest temperatures measured at any CWC reef to date, matching those from the Mediterranean Sea (Freiwald et al. 2009, Taviani et al. 2005). Furthermore, the sudden jumps of in excess of 4 °C in less than one hour, as well as the maximum temperature variation of 5.3 °C over 24 hours are the largest reported thus far. A maximum diurnal difference of 2.6 °C was previously reported for a site in 554 m depth at the Rockall Trough margin (Mienis et al. 2009). This value was even exceeded in 10 min at Tisler (2.9 °C). One main implication of such temperature fluctuations is the subsequent fluctuations in coral community respiration. *Lophelia pertusa* respiration has previously been found to be very sensitive to temperature changes (Dodds et al. 2007), which we will refer to later.

The maximum flow speeds of 86 cm s⁻¹ at 2 mab and 122 cm s⁻¹ at 7 mab are among the highest for *L. pertusa* reefs reported so far. The observed sudden increases and decreases in flow velocity of up to 34 cm s⁻¹ within 10 min and up to 46 cm s⁻¹ within 20 min demonstrate that the Tisler ecosystem is likely adapted to a highly dynamic environment. One implication of current velocity changes is the subsequent change in lateral flux of particulate matter and particulate organic carbon, with higher encounter rates between particles and suspension feeding fauna of the coral community (including the corals themselves) at high flow velocities and lower encounter rates at low flow velocities (Thomsen 2002). Another potential implication of current velocity changes is the possible occurrence of resuspension at high current velocities. However, we do not have a direct indication of resuspension at Tisler, as both the measured turbidity values and the measured sediment trap fluxes do not correlate with flow velocity.

Vertical fluxes of particulate matter and organic carbon were highly variable, as has been observed at other reefs (Duineveld et al. 2004, Mienis et al. 2009) and also reported for the Tisler Reef in a previous study (Lavaleye et al. 2009). However, the maximum values of $125 \text{ g m}^{-2} \text{ d}^{-1}$ (mass) and $2643 \text{ mg C}_{\text{org}} \text{ m}^{-2} \text{ d}^{-1}$ (POC) observed in this study in early October 2008 are the highest flux values reported so far for a *L. pertusa* reef. Whether or not resuspension contributed to these high fluxes cannot be answered, as measured sediment trap fluxes in general did not correlate with flow velocity. The mean flow velocity during the time of this high-flux event was $\sim 25 \text{ cm s}^{-1}$. This was much lower than during many other recorded periods, when the mean flow velocity was $>40 \text{ cm s}^{-1}$, but the simultaneously measured fluxes were more than one order of magnitude lower. Additionally, the maximum flow velocity (from all velocities measured during trap deployments) was not recorded during the time of the high-flux event. Interestingly also, that these high sediment trap fluxes were not accompanied by an increase in C/N ratio of the trapped material (Fig. 5d) which is to be expected when organic matter of lower quality is resuspended.

4.2 Coral community: oxygen concentration and community respiration

The well oxygenated background DO concentration (excluding the drops) of $5.9\text{-}6.4 \text{ ml l}^{-1}$ was in line with an earlier report on DO concentration in the nearby Kosterfjord at 100 m water depth, giving a long-term range variation between 4.8 ml l^{-1} (minimum in autumn) and 6.7 ml l^{-1} (maximum in spring) (Wisshak et al. 2005). Our measurements fell within the upper half of this range, which could be expected as they covered the spring and earlier summer period. The observation of rapid drops in DO concentration close to the seabed within the reef structure begs the question whether or not DO levels below the critical value of 2 ml l^{-1} or even anoxic situations possibly occur within the reef structure close to the seabed. Below DO concentrations of $\sim 3.3 \text{ ml l}^{-1}$ *L. pertusa* was shown to be unable to maintain its respiration rate (Dodds et al. 2007). Based on the maximum measured decrease of $20.04 \mu\text{mol l}^{-1} \text{ h}^{-1}$ ($0.45 \text{ ml l}^{-1} \text{ h}^{-1}$) oxygen levels of 3.3 and 2.0 ml l^{-1} would be reached at the Tisler Reef in 6 and 9 hours respectively (assuming a baseline DO level of 6 ml l^{-1}). However, as fully stagnant conditions at Tisler were never observed for such a duration during the measurement period, oxygen levels below 2 ml l^{-1} within the reef structure are very unlikely to occur. Nevertheless levels below 3.3 ml l^{-1} cannot be fully excluded yet, as such levels would be reached in ~ 3.5 hours given the lower baseline level of 4.8 ml l^{-1} reported in autumn (Wisshak et al. 2005), or even in under 2.5 hours, assuming a higher respiration rate at higher autumn temperatures of $\sim 8.5^\circ \text{C}$ (Dodds et al. 2007; see discussion

below). To obtain a general trend on the oxygen conditions within the reef environment, data were compiled on DO of reefs dominated by *L. pertusa* in the North Atlantic, Mediterranean and Gulf of Mexico (Fig. 7). The general trend follows the general latitudinal trend with increasing values from South to North, resulting from the ability of colder waters to dissolve more oxygen than warmer waters. The compilation further illustrates that DO levels below 3.3 ml l⁻¹ or 2.0 ml l⁻¹ might be reached within the reef structure of Mediterranean and Porcupine reefs quite frequently, if a respiration similar to Tisler and comparable periods of stagnant flow are assumed. However, measurements have shown that *L. pertusa* is adapted to low oxygen concentrations of <3 ml l⁻¹ in the Gulf of Mexico (Fig. 7; Davies et al. 2010).

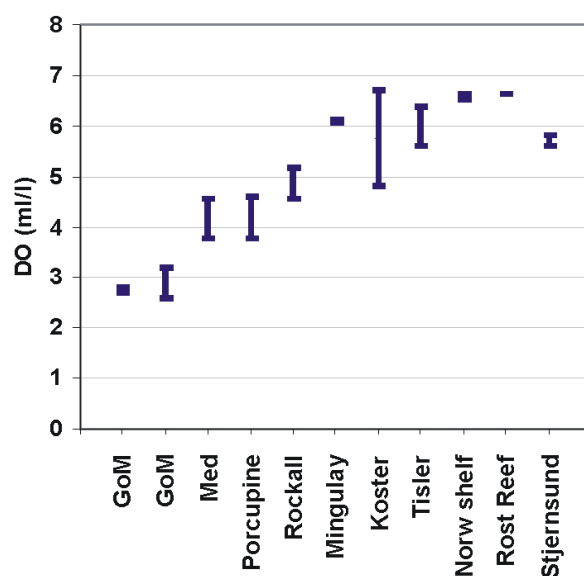


Fig. 7 Measured ranges of dissolved oxygen (DO) concentrations at CWC ecosystems dominated by *L. pertusa* in the North Atlantic, Mediterranean and Gulf of Mexico. Note that measurements were made at different times of the year. GoM: Gulf of Mexico, beginning to mid Oct 2008 (Davies et al. 2010). GoM (Schroeder 2002). Med: Mediterranean, end Sep to mid Oct 2006 (Freiwald et al. 2009). Porcupine (Dullo et al. 2008). Rockall: West Rockall Bank (Dullo et al. 2008). Mingulay: Mingulay Reef complex, mid Apr 2005 (Dodds et al. 2007). Koster: Kosterfjord at 100 m water depth, long-term measurement (many years) of the whole yearly cycle (Wisshak et al. 2005). Tisler: Tisler Reef, end Mar to mid Jun 2009 (this study). Norw shelf: Norwegian shelf (Dullo et al. 2008). Rost Reef, Jun 2007 (Wild et al. 2008). Stjærnsund, end Jul 2005 (Rüggeberg et al. 2011). Values of Dullo et al. (2008) were collected in Apr, Jun, Jul, Aug of 2004, 2005, 2007. All values (except the ones for this study) are “background” values in the BBL above the respective reef (mostly measured via CTD). Within a reef structure close to the seabed, DO concentrations may drop lower, as shown in the present study.

The pronounced drops in DO suggest the occurrence of high respiration rates at the Tisler Reef. The maximum consumption rate of DO of 20.04 $\mu\text{mol l}^{-1} \text{h}^{-1}$ translates into a community respiration rate of 981 mg C m⁻² d⁻¹, when assuming a constant oxygen

depletion up to a height of 20 cm above seafloor (measurement height) and a respiratory quotient (RQ) of 0.85 (Smith et al. 2001). Benthic community respiration rates are typically measured in benthic chambers that isolate the community from exchange with outside water masses (Glud 2008). Our oxygen consumption rate was inferred in “open water” under near stagnant conditions, but the input through lateral and/or vertical advection, dispersion of diffusion cannot be excluded. Moreover, oxygen consumption in the water body above the measuring height of 20 cm was not included, and lower oxygen concentrations towards the seafloor, which are expected when transports limits oxygen uptake by the benthic community, was also neglected. The above factors imply that the inferred respiration rate should be considered an under-estimate, but it is clear that within a 30 min interval, a community respiration at a rate of at least $981 \text{ mg C m}^{-2} \text{ d}^{-1}$ is possible at a temperature of 5.8°C .

The coral community is here defined to include the BBL-water up to a height of 20 cm above bottom. The coral community itself is defined as by van Oevelen et al. (2009), comprising (a) living corals, (b) dead coral branches with all organisms attached to them, and (c) sediments. Normally, only the benthic community respiration is measured by subtracting the BBL-water respiration as a blank value (Glud 2008). However, oxygen consumption rates in the water column of the direct vicinity to the Tisler Reef were measured to be only $0.52\text{--}0.60 \mu\text{mol l}^{-1} \text{ h}^{-1}$ (Wild et al. 2008). Though this represented more than an order of increase in the pelagic phase going from 100 m depth to close to the reef (Wild et al. 2008), it contributes <3% of the community oxygen consumption of $20.04 \mu\text{mol l}^{-1} \text{ h}^{-1}$ measured in this study, indicating that oxygen consumption in the water column is insignificant at the Tisler Reef.

The respiration estimate of $981 \text{ mg C m}^{-2} \text{ d}^{-1}$ based on the DO decrease of $20.04 \mu\text{mol l}^{-1} \text{ h}^{-1}$ was measured at 5.8°C water temperature in April. In fall and early winter, bottom water was warmer on average by $2\text{--}4^\circ\text{C}$ (Fig. 1). In a recent laboratory study, *L. pertusa* respiration was found to highly increase with increasing temperature, with very high Q_{10} values of 5.43 (for $6.5\text{--}9^\circ\text{C}$ water temperature), 8.28 (for $9\text{--}11^\circ\text{C}$ water temperature) and 7.88 (for the whole tested range of $6.5\text{--}11^\circ\text{C}$ water temperature) (Dodds et al. 2007). This would imply that our respiration estimate should be adjusted upwards for most of the annual cycle at Tisler. However, in a recent study on Rockall Bank van Oevelen et al. (2009) found coral respiration to account for only 9% of the whole community respiration. Thus, the Q_{10} value of the remaining 91% must be considered as well. Assuming a typical Q_{10} value of 2 for biochemical and physiological processes (Roberts et al. 2009) for the remaining 91%,

we calculate a coral ecosystem Q_{10} value of 2.53. Taking this value and assuming a mean yearly temperature of 7.5-8.0 °C (Fig. 1), we estimate the mean respiration of the Tisler ecosystem to be 1236-1311 mg C m⁻² d⁻¹. Following this calculation, maximum ecosystem respiration at the highest measured temperature of 13.9 °C (Fig. 2) could have been as high as 2197 mg C m⁻² d⁻¹.

The calculated community respiration rate of 981-1311 mg C m⁻² d⁻¹ is even higher than the commonly used value of 300 g C m⁻² a⁻¹ (~800 mg C m⁻² d⁻¹) for primary production of highly productive systems like shelf seas, and directly suggests that the Tisler Reef is a local hotspot for carbon cycling.

4.3 A carbon budget for the Tisler Reef

The high respiration rate in the reef community calls for a comparison with the measured vertical fluxes and data from the literature.

Carbon supply to the reef comprises three major components: (a) the vertical POC flux, (b) the lateral depositional POC flux (“biodeposition”), and (c) zooplankton uptake. The mean vertical POC flux to the BBL at Tisler Reef as measured by sediment traps was 283 mg m⁻² d⁻¹ (this study), whereas biodeposition was estimated to be 459 mg POC m⁻² d⁻¹ (Wagner et al. 2011). Zooplankton was excluded from our trap samples (“swimmer picking”) as well as from our filter samples used to determine biodeposition, such that zooplankton uptake has to be added to the budget. Zooplankton uptake amounted to 19% of total carbon ingestion at the Rockall Bank (Van Oevelen et al. 2009) and taking this as first estimate, this leads to a zooplankton uptake of 174 mg C_{org} m⁻² d⁻¹. These three components (vertical POC flux 283 mg m⁻² d⁻¹, lateral depositional POC flux 459 mg m⁻² d⁻¹, zooplankton uptake 174 mg m⁻² d⁻¹) sum to 916 mg C_{org} m⁻² d⁻¹. This total uptake is surprisingly close to the total estimated respiration of 981-1311 mg C m⁻² d⁻¹. The slight underestimation may be caused by underestimating zooplankton uptake (assumed from a much deeper reef with lower zooplankton biomass than at Tisler) and the omission of uptake of microbes and particles below <0.7 µm in size (as they were not retained on the GF/F filters used for biodeposition-determination). Additionally, vertical fluxes as derived from sediment traps might be subject to different trapping uncertainties. Over- and undertrapping are both possible, but cannot be quantified within this study. For a detailed discussion on all trapping issues see Gardner (2000) and Buesseler et al. (2007a). Furthermore, our vertical POC flux

measurements did not cover a whole year, but only the September to December period of the annual cycle, leading to some uncertainties in mean annual estimation. However, a previous study measured comparable vertical POC fluxes at the Tisler Reef, covering a 24 day period in April 2006 which included both a pre-phytoplankton-bloom period and the bloom-period itself (Lavaleye et al. 2009). They report measured values of $\sim 100 \text{ mg m}^{-2} \text{ d}^{-1}$ on the one side and $\sim 400 \text{ mg m}^{-2} \text{ d}^{-1}$ on the other side of the reef prior to the onset of the bloom and values of $\sim 250 \text{ mg m}^{-2} \text{ d}^{-1}$ and $\sim 600 \text{ mg m}^{-2} \text{ d}^{-1}$ respectively during the bloom. This summarises to a pre-bloom average of $\sim 250 \text{ mg m}^{-2} \text{ d}^{-1}$ and a bloom-period average of $\sim 425 \text{ mg m}^{-2} \text{ d}^{-1}$. Our measurement of $283 \text{ mg m}^{-2} \text{ d}^{-1}$ lies closer to the pre-bloom value. Given the fact that non-bloom conditions prevail over a far longer period of the whole year than bloom conditions, the value of $283 \text{ mg m}^{-2} \text{ d}^{-1}$ seems to be a reasonable estimate of the mean vertical POC flux to the BBL layer above Tisler Reef.

4.4 Carbon cycling by CWC reefs along continental margins

Change of carbon sources with depth

The vertical flux of POC in the ocean decreases exponentially with increasing water depth (Martin et al. 1987, Buesseler et al. 2007b). We collected data from the literature on measured vertical fluxes at CWC ecosystems (Duineveld et al. 2004, Mienis et al. 2009, Lavaleye et al. 2009, Davies et al. 2010). The general trend of exponentially decreasing vertical POC fluxes with depth is also visible in this data collection (Fig. 8). As a conclusion, we can state that CWC ecosystems receive an exponentially decreasing amount of POC with depth from direct vertical settling. On the other hand, a recent estimate of CWC ecosystem respiration for a community at $\sim 800 \text{ m}$ depth has shown an only slightly lower respiration value than estimated here for Tisler (van Oevelen et al. 2009). This high respiration value at 800 m depth together with many visible reef observations on the Northeast Atlantic margin made by ROV's, submersibles and acoustic surveys during the last two decades (e.g. Mortensen et al. 2001, De Mol et al. 2002, Kenyon et al. 2003, Freiwald et al. 2004, Fossa et al. 2005, Wheeler et al. 2007) lead to the assumption that deep reefs may in general match shallow reefs in terms of biomass and respiration. For the coral community at Rockall Bank (800 m depth) a respiration value of $688 \text{ mg C m}^{-2} \text{ d}^{-1}$ was derived (van Oevelen et al. 2009). This value accounts for 52-70% of the Tisler ecosystem respiration estimate of $981\text{-}1311 \text{ mg C m}^{-2} \text{ d}^{-1}$. On the other hand, the vertical POC flux at Rockall is only $<10\%$ of the Tisler value (van Oevelen et al. 2009). The

question thus arises: How do deep CWC ecosystems (such as that at Rockall Bank) meet their carbon demand? A combination of biodeposition and zooplankton capture must be the answer and must hence have an even greater contribution to total nutrition and respiration than at Tisler. For the Rockall Bank community, zooplankton contribution to community nutrition was calculated to be only 19%. With the vertical POC flux measured to be only 1%, the remaining 80% required to close this budget was explained by biodeposition (van Oevelen et al. 2009).

Comparison of CWC reef respiration with soft bottom communities

To evaluate the contribution of CWC reefs to benthic carbon cycling along continental margins, we compare CWC ecosystem respiration to respiration of soft bottom communities, using the empirical curve fitting of Andersson et al. (2004) for benthic soft bottom respiration. This curve was fitted to data from 490 measurements from all parts of the ocean from shallow water to the deep sea, obtained via benthic landers and via deck incubations.

Plotting the respiration values from Tisler and Rockall against the Andersson curve makes the exceptionally high respiration of CWC ecosystems visible (Fig. 8). We calculate the factors by which the Tisler and Rockall CWC ecosystem respirations are higher than “normal” Andersson values. We refer to these factors in the following as “hotspot-factors”, as they are a direct measure to evaluate the extent to which the respective system under investigation is a hotspot in terms of respiration. For Tisler, we calculate a hotspot-factor of 9.2 using the conservative estimate for mean respiration of $981 \text{ mg C m}^{-2} \text{ d}^{-1}$ (which is the value measured at 5.8°C water temperature in April). For Rockall, the calculation lead to a hotspot-factor of 15.1.

Fig. 8 reveals another important observation. Vertical POC fluxes at Tisler ($283 \text{ mg m}^{-2} \text{ d}^{-1}$ at 130 m water depth) and at the Viosca Knoll in the Gulf of Mexico ($99 \text{ mg m}^{-2} \text{ d}^{-1}$ at 476 m water depth; Davies et al. 2010) are higher than “normal” Andersson values. This could be due to higher-than-average primary production at the sea surface above the two reefs, or due to different physical processes which increase the vertical POC flux. As such processes, Taylor column development (White et al. 2005) and downwelling (Davies et al. 2009, Wagner et al. 2011) have been reported at CWC reefs. For Tisler, downwelling has been shown to occur (Wagner et al. 2011).

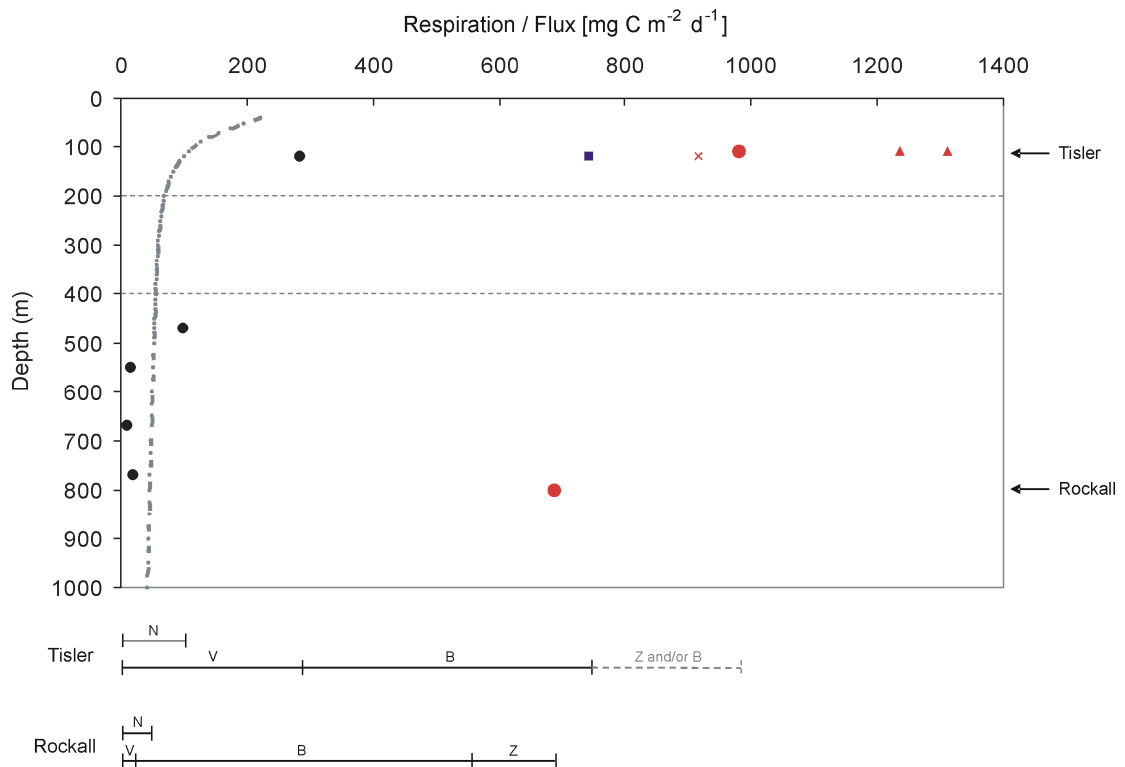


Fig. 8 Comparison of CWC community respiration rates at Tisler and Rockall (red dots) with respiration rates of soft bottom communities (dotted grey curve, as derived from Andersson et al. 2004). Red triangles are temperature-corrected respiration rates for Tisler for 7.5 °C (left triangle) and 8.0 °C (right triangle). The blue rectangle gives the sum of vertical flux and biodeposition for Tisler. The red cross gives the sum of vertical flux, biodeposition and zooplankton uptake for Tisler (assuming a zooplankton contribution to total nutrition of 19 %). Black dots show to date measured fluxes at CWC communities (from top to bottom: Tisler (this study), Gulf of Mexico Viosca Knoll (Davies et al. 2010), Rockall Bank (Mienis et al. 2009), Rockall Bank (Mienis et al. 2009), Galicia Bank (Duineveld et al. 2004)). Dashed horizontal grey lines show the depth range of the densest CWC occurrence on the Norwegian shelf and upper slope. Horizontal black bars at the bottom of the graph illustrate amounts of different carbon sources utilised at Tisler and at Rockall in comparison with “normal” soft bottom community respiration (N: “normal” respiration after Andersson et al. 2004, V: vertical POC flux, B: biodeposition, Z: zooplankton).

However, vertical POC fluxes at Rockall ($9.2 \text{ mg m}^{-2} \text{d}^{-1}$ at 675 m water depth and $\sim 16 \text{ mg m}^{-2} \text{d}^{-1}$ at 554 m water depth; Mienis et al. 2009) and at Galicia Bank ($18.9 \text{ mg m}^{-2} \text{d}^{-1}$ at 770 m water depth; Duineveld et al. 2004) were even lower than average values (Fig. 8). This suggests that CWC reefs may in some cases not rely on the mentioned additional vertical POC supply mechanisms, but may instead be fully capable of meeting nearly all of their carbon demand with a combination of zooplankton capture and biodeposition.

Contribution of CWC reefs to benthic carbon turnover along the central Norwegian shelf and upper slope – a first assessment

In a last step we try to estimate the contribution of CWC reefs to benthic carbon turnover along the central Norwegian shelf and upper slope. We are aware of the fact that this might be rather ambitious at present, but we nevertheless calculate a first estimate, which should be treated with caution.

In Norwegian waters reefs are located in the bathymetric range of 40 to 500 m depth and are most abundant in the central part of the Norwegian continental shelf (Fosså et al. 2002). The vast majority of reefs is located along the upper continental slope and at ridges of morainic origin in 200 to 400 m water depth (Fosså et al. 2002, Wheeler et al. 2007). Fosså et al. (2002) estimated the reef covered area between 61.7°N and 68.9°N latitude (referring to their regions “R2” and “R3”) to be 1305-1577 km² (total area) and 773-879 km² (excluding trawl damaged areas). Based on topographical maps, we estimate the area of the central Norwegian shelf and upper slope between 61.7°N and 68.9°N (down to 500 m water depth) to be ~220.000 km². Thus, CWC reefs are estimated to cover 0.59-0.72% (total reef area) or 0.35-0.40% (excluding trawl damaged areas) of this region.

We assume that the derived hotspot-factors of 9.2 (Tisler) and 15.1 (Rockall) are lower and upper estimates of Norwegian reef respiration, and we subsequently multiply these factors by 0.35-0.72% of the shelf area (that is covered by reefs). This leads to estimations of reef contributions to the total benthic carbon processing on the central Norwegian shelf and upper slope of 3.2-6.6% (low factor) and 5.3-10.9% (high factor).

In conclusion, the reefs on the central Norwegian shelf and upper slope may be responsible for 3.2-10.9% of the benthic carbon turnover, even though they only cover 0.35-0.72% of the seabed in this region. An important mechanism that may explain this high contribution is the high level of biodeposition occurring at CWC reefs. Though these numbers are a first estimate, they suggest conclusively that CWC reefs may play a significant role in carbon cycling, not only on the local scale, but also across continental margins as a whole.

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CHAPTER 4

The influence of drill cuttings on physical characteristics of phytodetritus

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ABSTRACT

Sinking of aggregated phytoplankton cells is a crucial mechanism for transporting carbon to the seafloor and benthic ecosystem, with such aggregates often scavenging particulate material from the water column as they sink. In the vicinity of drilling rigs used by the oil and gas industry, the concentration of particulate matter in the water column may at times be enriched as a result of the discharge of 'drill cuttings' – drilling waste material. This investigation exposed laboratory produced phytoplankton aggregates to drill cuttings of various composition (those containing no hydrocarbons from reservoir rocks and those with a <1% hydrocarbon content) and assessed the change in aggregate size, settling rate and resuspension behavior of these using resuspension chambers and settling cylinders. Results indicate that both settling velocity and seabed stress required to resuspend the aggregates are greater in aggregates exposed to drill cuttings, with these increases most significant in aggregates exposed to hydrocarbon containing drill cuttings.

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1. Introduction

The majority of the transport of material from the surface waters of the world's oceans to the depths is made by the sinking of coagulated organic and inorganic aggregates (Alldredge and Silver, 1988). These aggregates comprise of a mixture of living and dead cells of phytoplankton, zooplankton, bacteria, and protists, detritus, excretory products, such as fecal pellets and marine gels (Burd and Jackson, 2009; Kiorboe et al., 1990). They also entrain 'ballast' minerals on their surfaces, namely, opal (SiO_2), calcium carbonates (CaCO_3) and fine lithogenic minerals (sands, clays, dust) (Armstrong et al., 2001; Hamm, 2002; Klaas and Archer, 2002). Aggregates with adsorbed 'ballast' govern the POC export from euphotic zone to the ocean interior and sediments (Armstrong et al., 2001; Francois et al., 2002; Klaas and Archer, 2002). Aggregates are also microhabitats for flagellates and bacteria communities, which control remineralization of the sinking fraction of POC. Recent studies have demonstrated that bacterial production and community respiration are strongly coupled with sinking aggregates, revealing microbial activity in aggregates as an important factor in regulating POC flux in the ocean (Egge et al., 2009; Grossart and Ploug, 2000; Iversen and Ploug, 2010; Kiorboe and Hansen, 1993). Once they enter the bottom boundary layer close to the marine sediments, these aggregates are often consumed by the

benthic communities in a process known as benthic pelagic coupling (Graf and Rosenberg, 1997).

Phytodetrital aggregates formed by natural processes in the vicinity of drilling rigs operated by the offshore industry are of particular interest on the local scale as they may scavenge fine suspended lithogenic material released into the marine environment during drilling operations (Neff, 2005; Schaanning et al., 2008). This material is known generally as drill-cuttings, but these cuttings can vary in both size (from clay to coarse gravel) and material composition. Cuttings consist of a combination of (1) fragments of the various lithological types of sedimentary rock through which the drill passes, and (2) the drilling fluid used to ensure both positive drill pressure and cooling of the drill bit during drilling. The drilling fluid component can be water based, synthetic based, or oil based, and consist of a mix of various ingredients. Most of the drilling in the North Sea (focus of this study and source of the drill-cuttings used here) is performed with water based drilling fluids, with barite (BaSO_4) or ilmenite (FeTiO_3) the main components of the mix. Typically, the lithological components of water based drill cuttings consist of grey shale chips from the lithological layers drilled through; minor constituents such as hematite, limonite, goethite, and carbonate can be present, altering the color of drill-cuttings. Following release into the marine environment, coarse drill-cuttings have been observed to settle close to the discharge point, with dispersal models employed by the offshore industry indicating that the fine fraction may stay in suspension and travel over large distances before settling to the seabed (Neff, 2005; Neff et al., 1989; Rye et al., 2006).

These dispersal models predict that the fine clay-sized unflocculated fraction of the discharged drill cuttings creates a plume

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in the upper water column that drifts with prevailing currents away from the platform, diluting rapidly with the distance, and settling slowly over the large area of the sea floor. Ayers (1994) using the Offshore Operations Committee (OOC) Drilling Mud Discharge Model, predicted the dilution of 300,000 mg/l of drill cuttings at the source of discharge to 8 mg/l at ~760 m from point of release, after one hour of transport (given a discharge rate of 42,300 gal/h) (Ayers, 1994). Drill cutting discharges modeled by Voparil et al. (2009) with the same model showed dilution to 150 mg/l 100 m from the source (discharge rate 65,000 gal/l). Applying the Dose-Related Risk and Effect Assessment Model (DREAM model), Rye et al. (2006) estimated high concentrations of the suspended drill cuttings (>200 mg/l) within 50 m from the discharge point, with subsequent dilution to 50 mg/l ~100 m away from the platform (Rye et al., 2006). At the benthic boundary layer (BBL) concentrations of drill cuttings can reach 100–1000 mg/l close to the rig site (250 m), and up to 100 mg/l 5 km away from the platform site (Niu et al., 2009).

Presence of drill cuttings in the surface waters has two effects on primary production and transport of carbon from surface waters. Firstly, presence of the fine drill-cuttings fraction in suspension can lead to turbidity increase in the water column (Lynch et al., 1994), with associated light limitation that can negatively affect primary production. Secondly, fine drill-cuttings incorporated into aggregates can act as mineral 'ballast' increasing the settling rate of the aggregate, therefore reducing the residence time in the water column (Curran et al., 2002; Schaanning et al., 2008).

On the Norwegian Margin seabed there are numerous developed cold-water coral reefs. These ecosystems develop slowly, with scleractinian corals forming complex three dimensional reef structures with growth. These skeletal structures provide habitat niches for a variety of benthic organisms and reefs are considered to be local hotspots of regional biodiversity. These ecosystems are of public and legislative concern in Norwegian waters, and therefore any potential risks to their viability posed by human activity must be investigated. Previous experimental study investigating the sedimentation of fine drill cuttings onto cold water corals in laboratory experiments showed that: (1) the structure of coral branches of commonly occurring European corals such as *Lophelia pertusa* minimize the chance of surface coverage by deposited material (Larsson and Purser, 2011), a process assisted by surface cleaning by coral mucus production (Allers et al., in review). Coral polyp behavior is affected in the short term following exposure to drill cuttings, indicating a reduction in feeding with possible negative consequences on the energy budget of the organism is a possible result of exposure over a long period (Purser et al., 2010a). Given that net capture rates by *L. pertusa* are highest during low flow conditions (Purser et al., 2010b), repeated resuspension of drill cuttings followed by settling in periods of reduced flow (such a situation may be associated with tidal cycles in the region) may well reduce active feeding in the long term. (2) After 3 months of constant exposure to fine drill cuttings, respiration rates of *L. pertusa* were not affected, indicating the ability of the organism to endure long term exposure, even if active feeding is reduced (Larsson and Purser, 2011).

From the research to date, the risks posed by drill cuttings to the reef organisms are not fully understood. Given this fact, it is perhaps sensible to wherever possible minimize exposure by the reef to drill cutting material. To best achieve this, drill cutting dispersal predictions, following release to the ocean, should be as accurate as possible. This study concentrates on assessing the interactions between fine drill-cuttings and fresh phytodetrital aggregates. The main objectives of the study being to compare the effects of two classes of fine drill-cuttings on the hydrodynamic behavior of phytodetritus; one class representing pure lithogenic drill-cuttings, (hereafter referred to as regular drill-cuttings (DC)) and a further

class additionally containing hydrocarbons from the reservoir, referred to hereafter as hydrocarbon containing drill-cuttings (HCDC). According to Norwegian regulations these HCDC drill cuttings have an oil content of formation oil of less than 1% of dry matter. From 2004 to 2008, the discharge of cuttings from water based drilling fluids decreased from 86,000 t to 70,000 t/year of which up to 2500 t/year were transported to land.

Potential implications of this research are locally significant, as the alteration of physical properties of aggregates may affect transport of materials in the vicinity of drilling activities, and therefore expose regions of the seabed to material at concentrations not predicted by dispersal models which do not take into account the process of aggregation. This is an important consideration for benthic ecosystems, as the entrainment of drill-cuttings of various chemical compositions within sinking aggregates might not only impact microbial activity and remineralization processes within the aggregates, but also alter community structures and food webs within the benthic community (Sanders et al., 1987; Schaanning et al., 2008; Trannum et al., 2010). Consequently, it is essential to be able to predict the fate of fine drill-cuttings released into the water column. Given the variable quantity, hydrodynamic behavior and composition of the drill cuttings which can be released to the ocean during a drilling operation, it is important to best assess how release of this waste material can be best managed to reduce ecosystem impact.

The hypothesis investigated by this study was that

1. the discharge of drill cuttings into waters containing phytodetrital aggregates would alter the hydrodynamic characteristics of both the phytodetrital aggregates and drill cutting particles.

2. Materials and methods

To test the proposed hypothesis, three experimental investigations were conducted. The first of these investigated whether or not drill cuttings would aggregate with phytodetritus under typical oceanographic turbulence conditions. The second set of experiments focused on determining whether phytodetritus aggregates exposed to various types or concentrations of drill cuttings settle at different rates in the marine water column. The third set of experiments investigated the degree to which resuspension behavior varied between phytodetritus aggregates exposed to different drill cutting types and concentrations. Prior to carrying out the experimental investigations, phytodetrital aggregates were produced in the laboratory and drill cuttings homogenized, sieved and quantified for use in the experiments.

2.1. Production of phytodetrital aggregates

In the natural marine environment, aggregation and mass cell sedimentation often terminates a phytoplankton bloom (Crocker and Passow, 1995; Kiorboe and Hansen, 1993; Kiorboe et al., 1994). Diatoms are very abundant during blooms and play an important role in the aggregate formation process (Smetacek, 1999; Thornton, 2002). One of the crucial parameters of aggregation is the stickiness of the particles, which usually increases at the decline of diatom bloom. During this period of nutrient limitation, a special class of marine gels, called transparent exopolymer particles (TEP), is abundant in both the water and aggregates (Alldredge et al., 1993; Kiorboe et al., 1994; Passow, 2002). TEP are generated abiotically from polysaccharide precursors released mainly from diatoms as dissolved colloidal matter (DCM) (Kepkay, 1994). DCM undergoes 'annealing' when polymers from one gel diffuse and interpenetrate into neighboring gels forming microgels (Chin et al., 1998). Since the TEP are sticky, they act as biological glue, increasing attachment probability of the particles once

inter-particle contact has occurred (Passow, 2002; Prieto et al., 2002). Presence of TEP significantly reduces the time of coagulation and to a great extent determines remineralization potential of the aggregated organic matter. Moreover, this factor contributes to more rapid transfer of material to larger particles and, consequently, their faster loss from the upper Ocean (Burd and Jackson, 2009; Engel and Schartau, 1999; Prieto et al., 2002).

For this study, the pelagic centric diatom ($6\text{--}20\text{ }\mu\text{m} \times 8\text{--}15\text{ }\mu\text{m}$) *Thalassiosira weissflogii* (Bacillariophyceae) was chosen for aggregation. This microalgae is abundant in the Norwegian Sea and tends to flocculate into marine snow at the decline of the bloom (Smetacek, 1999). The cultures of *T. weissflogii* were cultivated in the laboratory at $\sim 20\text{ }^{\circ}\text{C}$ temperature under constant illumination. The cultures were weekly inoculated with fresh 32 psu saline silicon-based f/2 medium (K-medium). Laboratory-made artificial aggregates of *T. weissflogii* were generated following Shanks and Edmondson (1989) method. Cylindrical tanks with $\sim 800\text{ ml}$ of *T. weissflogii* culture in seawater (32 psu) were rotated on a motorized roller table at $\sim 0.66\text{ rpm}$ until a substantial amount of aggregates was formed (3–4 days). Minor concentrations of silicate and carbonate minerals were added into the tank in the following proportions: kaolinite ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$) – $25 \pm 0.4\text{ mg l}^{-1}$, smectite ($(\text{Al}, \text{Si})_3\text{O}_4$) – $25 \pm 0.3\text{ mg l}^{-1}$, and carbonate (CaCO_3) – $25 \pm 0.1\text{ mg l}^{-1}$. The resulting artificial aggregates represent a good biological model of natural marine snow (Shanks and Edmondson, 1989).

2.2. Drill cutting selection, homogenization and quantification

Drill cuttings used in the study were provided by Norwegian petroleum company Statoil. These drill cuttings were delivered in different sample bags each containing cuttings taken from different depths from different drill wells. The drill cuttings used in this study were cuttings from the 12.25" and 8.5" sections of well 6407/2-5S from the Nona Heidrun field, Norway (Fig. 1). The DC samples were representative for the types of reservoir and cap rocks commonly drilled through on the Norwegian Continental Shelf. The section of well 6407/2-5S that contained hydrocarbons from the reservoir was 757 m long; 30 m of which were gas filled and 41 m were oil filled sand sections.

During the selection process, 17 drill-cutting samples (originating from a depth range 2500–2800 m) were checked for hydrocarbon content. Color and texture of the drill-cutting samples were also examined. On the basis of these primary analyses, samples extracted from 2650 m to 2700 m, 2705 m and 2756 m were identified as containing small quantities of hydrocarbons from the reservoir rocks (HCDC). HCDC samples had a reddish-brownish color and distinctive hydrocarbon aroma, whereas the rest of the drill-cuttings had a typical grey appearance and did not have a strong hydrocarbon smell (DC cuttings). Analysis of a sample of the HCDC material indicated an oil content of 0.073% dry weight (measured with GC-FID and loss of ignition).

In this study we were interested in trying to determine if the different drill cutting types (DC or HCDC) would have different effects on the physical characteristics of phytodetritus after exposure. For this reason, two drill cutting samples of differing composition were selected for use in this study. Standard drill cuttings (DC) from the uncontaminated overlaying strata were selected from 2502 m drill depth, and hydrocarbon contaminated drill cuttings (HCDC) from 2705 m.

After selecting the two drill cutting types to be used in the experimental work, the raw drill cuttings of each type were sieved through a $<63\text{ }\mu\text{m}$ sieve. The wet weight/dry weight ratio of these sieved samples was determined to allow replicable addition of drill cutting concentrations of known dry weight to the experimental chambers. The decision to use $<63\text{ }\mu\text{m}$ fine fraction of drill cuttings in this study was made because this represents the

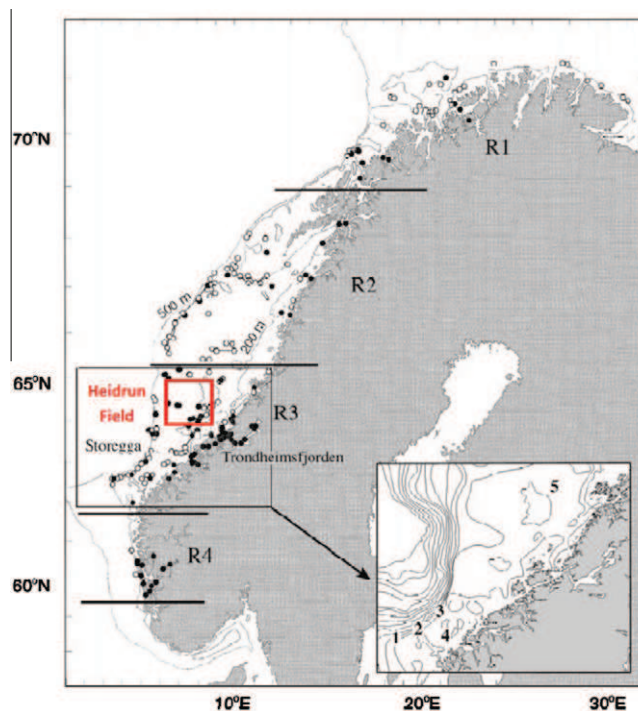


Fig. 1. Location of the Heidrun field, from which the drill cuttings used in this study originated. Figure also shows distribution of *Lophelia* corals along the Norwegian margin. The black and grey circles indicate the verified (from the literature) and non-verified records (from fishermen) of *Lophelia*. Figure is adapted from Fosså et al. (2002).

fraction of material which would stay in suspension following release of drill cuttings to the ocean. The larger drill cutting size fractions (in some cases consisting of rock chippings up to a cm in diameter) would sink swiftly to the seabed following release and therefore play no significant role in any aggregation process. The dry weight percentage of the fine fraction ($<63\text{ }\mu\text{m}$) in the regular drill cuttings (DC) used in this study was 97% and 77% for the hydrocarbon-containing (HCDC) drill cuttings. Forty five percentage and 12% by volume of the DC and HCDC drill cuttings were of $<10\text{ }\mu\text{m}$ diameter. Less than 10% by volume of either drill cutting type was of $>64\text{ }\mu\text{m}$ diameter (Fig. 3B and C).

2.3. Investigation 1: Drill cutting aggregation with phytodetritus

Throughout the experimental work, triplicate runs were conducted for each investigation. All experimental work was conducted in a thermo-constant room at a temperature of $6\text{--}8\text{ }^{\circ}\text{C}$.

Step 1: Turbidity change over time in experimental chambers containing phytodetritus. To simulate the behavior of the aggregates in the water column, semidiurnal tidal resuspension–deposition loops were created in an erosion chamber with controlled bottom stress. Four hundred milliliter of phytodetrital aggregates from the roller tank were carefully siphoned into the benthic chamber filled with 32 psu artificial seawater. These aggregates were then kept in suspension for 6 h under a bottom shear velocity [u^*] of 0.8 cm s^{-1} typical for advective flow of phytodetritus in the North Sea (Van Raaphorst et al., 1998) and North Atlantic (Thomsen et al., 2002). Turbidity variations of the sample were recorded 15, 30, 60, 120, 240 and 360 min after aggregates were added to the chamber. An Aquafluor turbidity meter (NTU) was used to record turbidity below the rotation disc of the benthic chamber. After 6 h the aggregates were allowed to settle for 8 h and subsamples taken of the settled material to determine size and settling velocities of the aggregates, as discussed in Investigation 2.

Step 2: aggregation of phytodetritus with drill cuttings. After the 8 h of sedimentation the bottom flow with a u^* of 0.8 cm/s was reestablished and the disposal of fine drill cuttings was simulated by adding pre-sieved <63 μm drill cuttings (DC) and hydrocarbon containing drill cuttings (HCDC) to provide concentrations within the chamber of 35 mg l⁻¹ and 175 mg l⁻¹ dry weight in parallel experiments. Turbidity in the sample in the chamber was then recorded 15, 30, 60, 120, 240 and 360 min after addition of the drill cuttings. Control runs were conducted with 35 mg l⁻¹ and 175 mg l⁻¹ DC and HCDCs being delivered to chambers containing no aggregates. By comparing NTU decrease over time in these control chambers with those containing algal aggregates, any effect on rates of drill cutting removal from suspension played by the aggregates would be indicated by changes in turbidity.

Step 3: After 12 h of mixing under u^* of 0.8 cm s⁻¹ the drill cuttings which had aggregated with the phytodetritus were sampled for the determination of critical shear velocity, settling velocity and particle size distribution (Investigations 2 and 3).

2.4. Investigation 2: particle size distribution and settling velocities

The variations in particle size distribution of the drill cuttings and of the phytodetrital aggregates before and after mixing with drill cuttings were measured with Laser In Situ Scattering and Transmissiometry device (LISST-100X). By using the LISST to compare the peaks in particle size distribution within the aggregates before and after addition of drill-cuttings significance of the scavenging of the drill cuttings fraction by aggregates would be indicated by the change in size spectra of the material. The particle size vs. settling velocity relationship of phytodetrital aggregates and drill cutting aggregates was investigated by using a settling cylinder (square cross-section) of 10 cm diameter (Thomsen and Gust, 2000). The particles were back-illuminated and settling rates and particle sizes determined with a digital video camera (Imageworks DFK-41F02). The camera was capable of resolving particles of >11 μm diameter. The analyses of the particle sizes and settling velocities were obtained using the ImageJ (v.1.61) software application, with aggregate diameters assumed to be the maximum straight distance observed across a particle. The resulting settling speeds were converted into a m day⁻¹ velocity for a selection of size classes, from within the 100 μm to 1500 μm particle diameter range. Average speed (with standard deviation) for each of the aggregate size classes was calculated and plotted.

2.5. Investigation 3: critical shear velocity [u_{crit}^*] variation

Critical shear velocity (u_{crit}^*) was determined by applying the erosion chamber with controlled bottom stress to the aggregates. Experimental runs were carried out with phytodetrital aggregates, and with phytodetrital aggregates which had been aggregated with DC and HCDC cuttings at the 35 mg l⁻¹ and 175 mg l⁻¹ concentrations. The u^* was increased in increments of 0.1 cm s⁻¹ every 5 min until u_{crit}^* was attained and the aggregates resuspended.

2.6. Statistics

In this study two-way ANOVA tests were conducted to determine how turbidity may change over time in experimental chambers containing various concentrations of drill cuttings (HC and HCDC in different experimental runs) and algal aggregates. The two factors used in the test were drill cutting type (none, 35 mg l⁻¹ DC, 175 mg l⁻¹ DC, 35 mg l⁻¹ HCDC and 175 mg l⁻¹ HCDC) and algal aggregate concentration (present/absent). Tests were carried out to compare % NTU reduction across treatments from readings taken 60 min and 120 min after drill

cutting delivery, with those measured 240 min and 360 min after delivery. Data was not transformed as Levene's test indicated an equal variance in NTU % values observed across treatments. Where a significant difference in NTU % reduction was observed for the drill cutting factor, a Bonferroni *post hoc* test was conducted to determine between which drill cutting level (type or concentration) these differences were significant. In this study the Kruskal–Wallis test and the Mann–Whitney *U* test were used to assess statistical validity of the settling speed comparisons between phytoplankton aggregates and those exposed to DC and HCDC cuttings at 35 mg l⁻¹ and 175 mg l⁻¹ concentrations. The Kruskal–Wallis test was applied to determine if there was difference in the size-classed settling speeds between these three groups. If a significant difference in the results was indicated, Mann–Whitney *U* tests were conducted to see which pairs were different. For statistical analysis, three size classes of aggregates of each type were selected: 100–200 μm (small), 500–600 μm (middle) and 1000–1100 (large).

3. Results

3.1. Turbidity change after drill cutting exposure

After the injection of 35 mg l⁻¹ or 175 mg l⁻¹ of drill cuttings into the experimental chambers, observed turbidity values immediately following delivery were greater than in the experimental chambers containing phytoplankton aggregates alone. An increased turbidity of a factor of 2–3 was observed for 35 mg l⁻¹ injections and roughly a 9-fold increase in chambers dosed with 175 mg l⁻¹ injections. There was no great difference in initial turbidity increase between aggregates containing DC or HCDC cutting types.

3.1.1. Impact of drill cutting type and concentration on turbidity decrease

The two-way ANOVA results showed a significant main effect of drill cuttings type on turbidity reduction in the first two hours after drill cutting delivery, $F(4, 42) = 8.43$, $p < 0.001$. Mean NTU % reductions observed for phytoplankton aggregates was $M = 0.24$ ($SD = 10.79$, $N = 22$). For DC 35 mg l⁻¹ aggregates, $M = 14.90$ ($SD = 5.86$, $N = 6$), with the higher DC 175 mg l⁻¹ concentration, $M = 16.91$ ($SD = 7.90$, $N = 6$). For the HCDC cuttings, turbidity reduction in this period for 35 mg l⁻¹ drill cutting dose was $M = 19.60$ ($SD = 12.08$, $N = 6$), the higher concentration HCDC 175 mg l⁻¹ giving % reduction of $M = 15.10$ ($SD = 11.37$, $N = 6$). The Bonferroni *post hoc* test indicated that this NTU % reduction in the first 2 h after drill cutting delivery was significantly greater in chambers containing drill cuttings in addition to the natural aggregates than those containing natural aggregates alone (DC 35 mg l⁻¹ and HCDC 175 mg l⁻¹ $p < 0.05$, DC 175 mg l⁻¹ and HCDC 175 mg l⁻¹ $p < 0.01$). The type of drill cuttings (DC or HCDC) was not a significant factor in this period.

Drill cutting type also had a significant effect on NTU % reduction rates observed after 4–6 h, $F(1, 42) = 14.67$, $p < 0.001$ and $F(4, 42) = 12.76$, $p < 0.001$. The Bonferroni *post hoc* test indicated that the significant differences were observed between the no drill cuttings runs and the DC 175 mg l⁻¹ treatment ($p < 0.005$), as well as both the HCDC 35 mg l⁻¹ and HCDC 175 mg l⁻¹ treatments ($p < 0.001$). Mean values of NTU % reduction in the experimental runs containing no algal aggregates for the various concentrations of each type of drill cutting was DC 25 mg l⁻¹, $M = 20.59$ ($SD = 7.54$, $N = 2$), DC 175 mg l⁻¹ ($M = 22.46$, $SD = 4.24$, $N = 2$), HCDC 35 mg l⁻¹, $M = 24.51$ ($SD = 10.08$, $N = 2$) and HCDC 175 mg l⁻¹, $M = 20.54$ ($SD = 3.00$, $N = 2$). No significant difference between phytodetrital aggregates and the DC 35 mg l⁻¹ treatment was observed. There

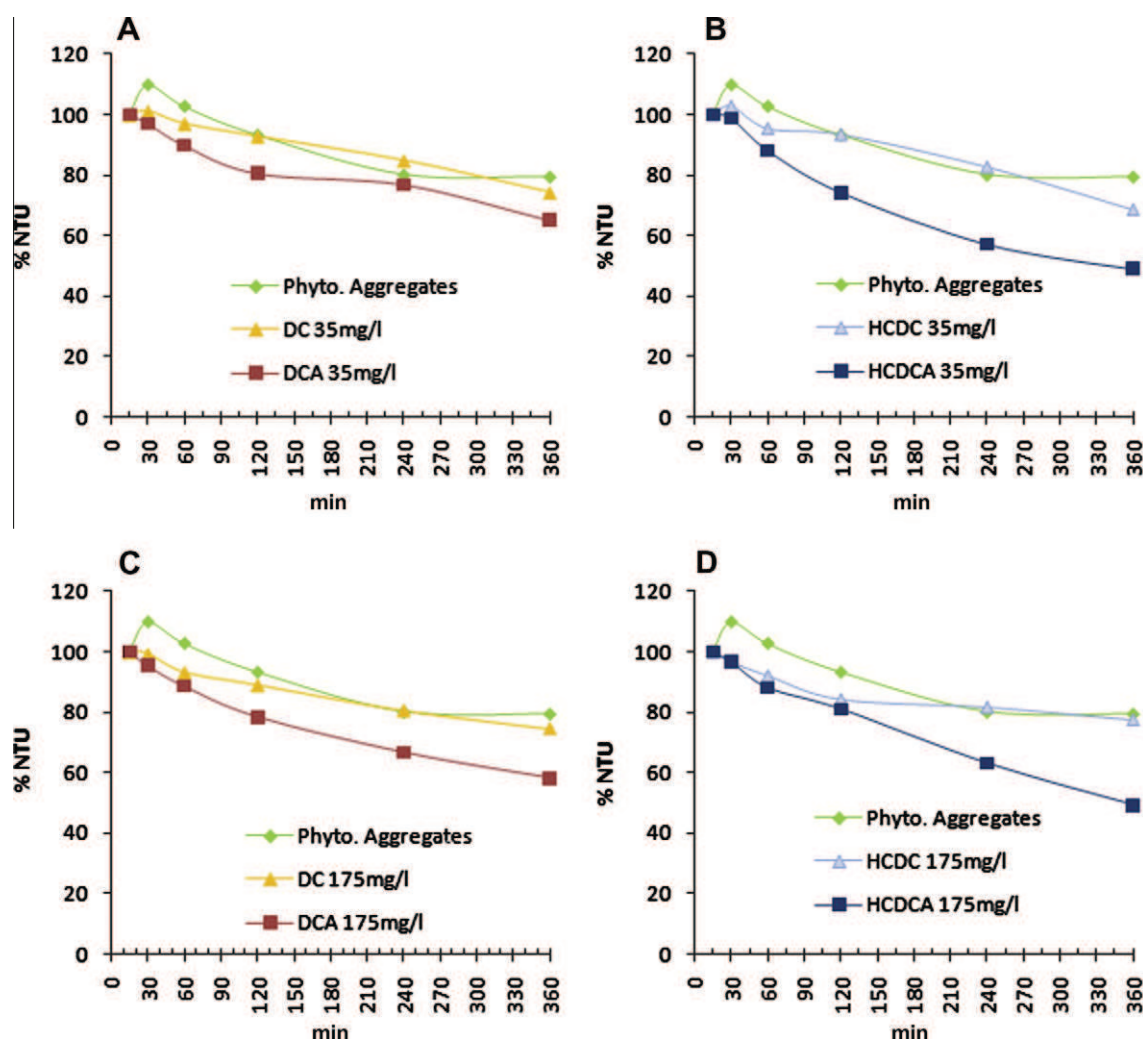


Fig. 2. Turbidity decrease over time in experimental chambers containing phytodetrital aggregates and various concentrations of either standard drill cuttings (DC's) or hydrocarbon containing drill cuttings (HCDC's): (A) 35 mg l⁻¹ DC treatment; (B) 35 mg l⁻¹ HCDC treatment; (C) 175 mg l⁻¹ DC treatment; (D) 175 mg l⁻¹ HCDC treatment.

was no significant difference in NTU % reduction between the HCDC 25 mg l⁻¹, HCDC 175 mg l⁻¹ or DC 175 mg l⁻¹ treatments. For the experimental runs with phytoplankton aggregates which had been exposed to drill cuttings, the mean NTU % reduction was greater in HCDC treatment chambers than in those injected with DC or no drill cuttings–phytoplankton aggregates, $M = 16.57$ (SD = 13.33, $N = 22$), DC 35 mg l⁻¹, $M = 29.29$ (SD = 10.61, $N = 6$), DC 175 mg l⁻¹, $M = 38.42$ (SD = 8.02, $N = 6$), HCDC 35 mg l⁻¹, $M = 47.28$ (SD = 5.20, $N = 6$), HCDC 175 mg l⁻¹, $M = 43.63$ (SD = 12.55, $N = 6$).

3.1.2. Phytoplankton aggregate presence/absence impact on turbidity decrease

There was no significant effect of algal presence/absence on NTU % uptake in the first two hours of the experiment. Additionally, there was no significant interaction effect between algal presence/absence and drill cutting type on NTU % reduction during these 2 h (Fig. 2).

For NTU % reductions observed during hours 4–6 after drill cutting delivery, presence or absence of aggregates had a significant effect on NTU% reduction, $F(1, 42) = 14.67$, $p < 0.001$. Mean NTU % reductions were for runs with algae present, $M = 35.04$ (SE = 1.903, $N = 46$) and runs with algae absent, $M = 22.04$ (SE = 3.987, $N = 8$) indicating that the presence of algal aggregates increases the NTU % reduction observed 4–6 h into the experimental runs.

3.2. Particle size distribution

The particle size distribution analysis showed that about 41% by volume of phytodetrital aggregates of *T. weissflogii* exceeded the size of 64 μm , whilst 45% and 13% by volume were in the size range 10–64 μm and <10 μm respectively (Fig. 3A).

The simulated discharge of drill cuttings into a water mass containing phytodetrital aggregates altered the particle size distribution of material within the water mass. Under discharge concentrations of 35 mg l⁻¹ the regular drill cuttings (DC) resulted in a shift of particle size from the >64 μm fraction towards the finer fractions. The injection of the same concentration of hydrocarbon containing drill cuttings (HCDC) resulted in an opposite effect: the particle size spectrum shifted towards the coarser fraction (>64 μm), Fig. 4.

3.3. Settling velocities of aggregates

For the determination of settling velocities of aggregates only particles larger than 100 μm in size were analyzed in the settling tube. Settling velocities varied between 10 m day⁻¹ and 20 m day⁻¹, never exceeded 25 m day⁻¹.

The settling velocities of the >100 μm phytodetrital aggregates ranged between 1 m day⁻¹ and 357 m day⁻¹. In general there was an increase of settling velocity with increasing size of aggregates,

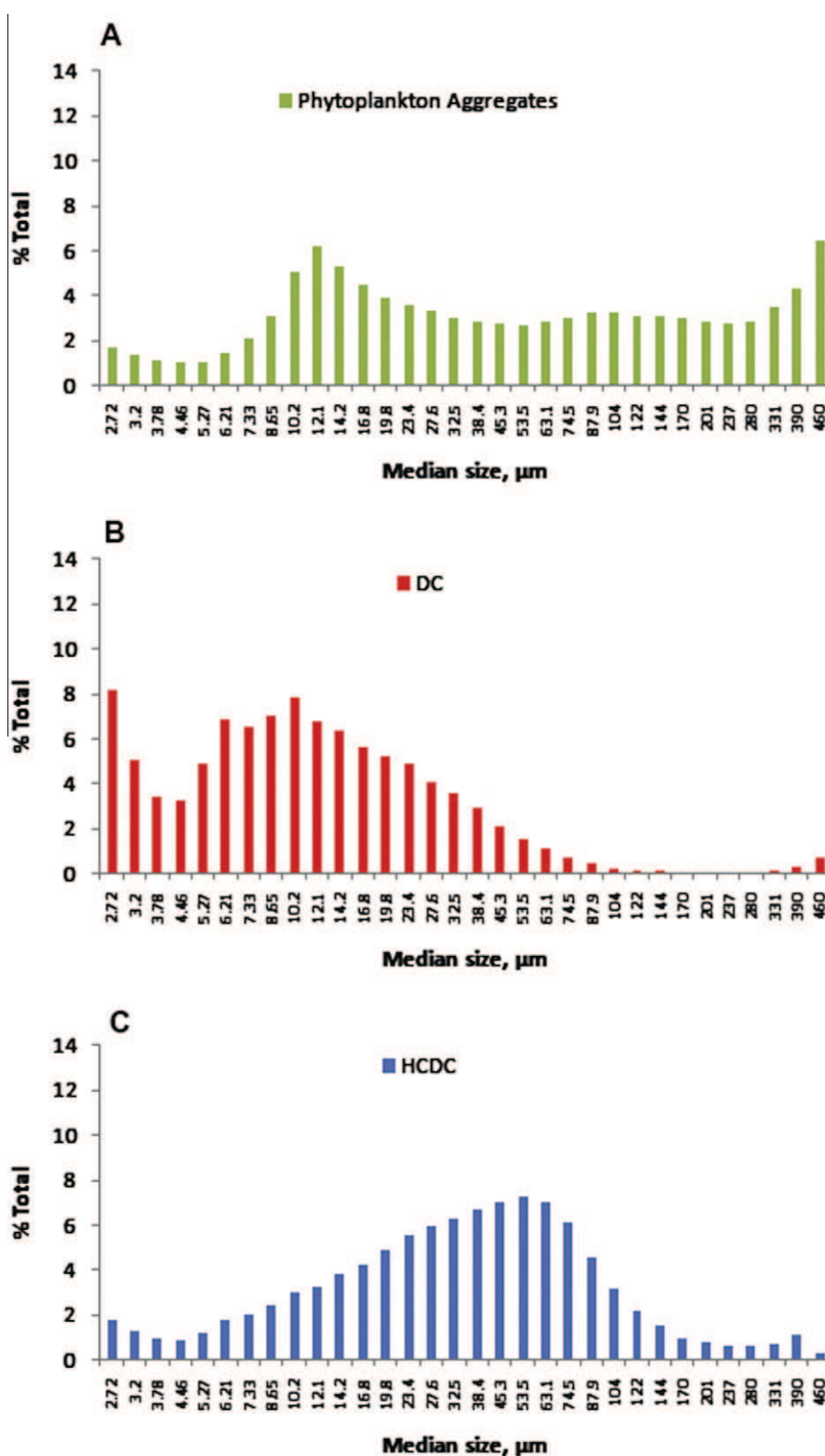


Fig. 3. Particle size distributions in phytoplankton aggregates (A), DC (B) and HCDC (C).

revealing a linear relationship. The addition of high and low doses of drill cuttings of both types considerably enhanced settling speeds of phytodetrital aggregates in all replicate experiments (Fig. 5). Under discharge concentrations of 35 mg l^{-1} HCDCs, the settling velocities of the resulting aggregates varied from

50 m day^{-1} to 500 m day^{-1} . Regular drill cuttings (DCs) also contributed to an increase in settling velocities of the aggregates. The average settling velocities rarely exceeded 70 m day^{-1} for median sizes between $100 \mu\text{m}$ and $600 \mu\text{m}$ and up to 600 m day^{-1} for the larger aggregates. Under both high and low exposure

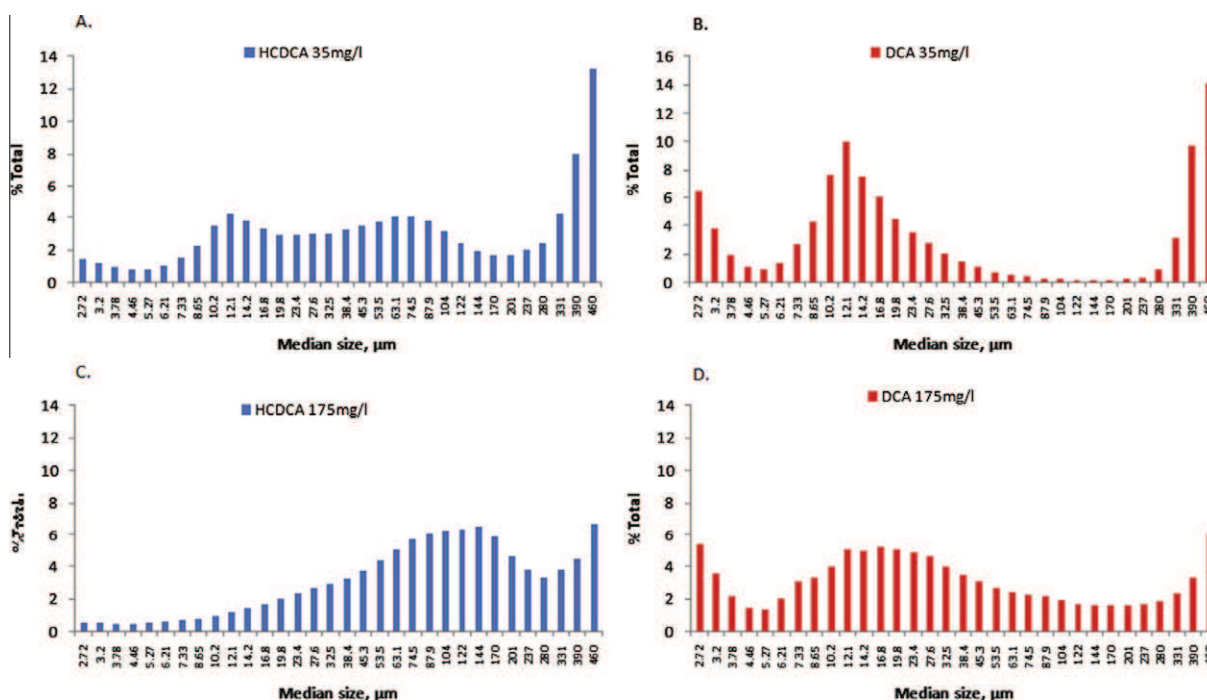


Fig. 4. Particle size distributions in phytoplankton aggregates treated with different types and concentrations of drill cuttings: (A) 35 mg l⁻¹ HCDCA treatment; (B) 35 mg l⁻¹ DC treatment; (C) 175 mg l⁻¹ HCDCA treatment; (D) 175 mg l⁻¹ DC treatment.

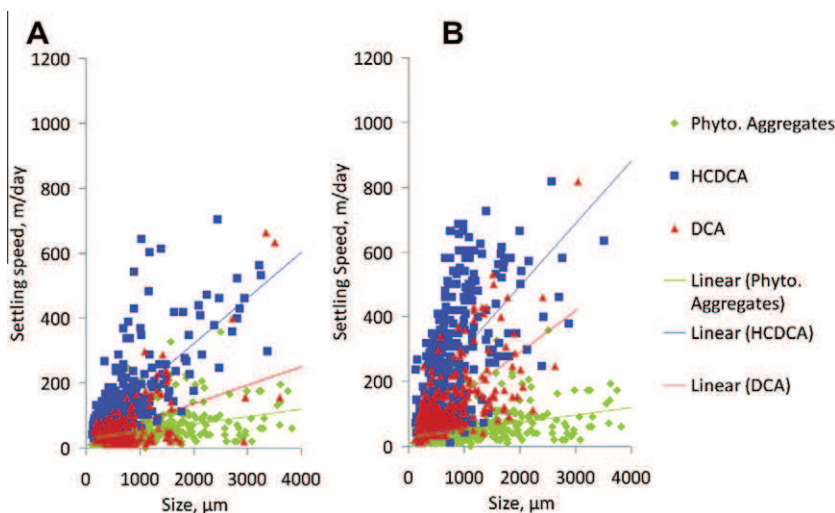


Fig. 5. Settling rates of phytoplankton aggregates, and aggregates exposed to DC and HCDCA cuttings: (A) 35 mg l⁻¹ treatment; (B) 175 mg l⁻¹ treatment.

concentrations of drill cuttings, phytodetritus exposed and aggregated with HCDCA exhibited generally higher settling velocities than aggregates exposed to DCs. The differences in settling velocities between these two aggregate types were most pronounced for the largest aggregate size class (>1000 μm).

Statistical analyses showed that there were significant differences in settling velocities between phytodetrital aggregates and aggregates exposed to the two types of drill-cuttings. For small sized aggregates (100–200 μm median diameter) exposed to 35 mg l⁻¹ DCs the difference in settling velocities were very significant, (Mann–Whitney $U = 13$, $p < 0.005$). For medium size classes of aggregates (500–600 μm), the scavenging of drill-cuttings significantly enhanced settling velocities of aggregates (Mann–Whitney $U = 23.5$, $p < 0.001$ for HCDCA drill cutting

exposures; Mann–Whitney $U = 122$, $p < 0.001$ for regular (DC) drill-cutting exposure). Exposure to HCDCA also significantly increased the settling velocities of newly formed 1000–1100 μm aggregates (Mann–Whitney $U = 11.0$, $p < 0.001$). Higher drill-cutting exposure (175 mg l⁻¹) significantly increased the settling velocities of aggregates for most tested aggregates size groups. The only exception was 100–200 μm aggregates, the settling speeds of which were not significantly altered by presence of DC drill cuttings (Mann–Whitney $U = 1$, $P = 0.34$). Differences in individual settling behaviors of phytodetrital/drill cutting aggregates of similar size were observed across treatments. Photographs of these aggregates within the settling cylinder provide good information on the variation in morphologies of the aggregates (shape structure, and porosity) by exposure. Natural

phytodetrital aggregates of *T. weissflogii* were fluffy, ephemeral, and very fragile (Fig. 6).

Phytodetrital aggregates treated with drill cuttings also showed variations in their morphology and were different in form to the natural aggregates. Fast settling aggregates appeared denser and entrained drill cuttings particles were clearly visible on photographs taken from the settling cylinder. The shapes of those aggregates varied from being totally irregular to forming chain like elongated structures. Morphological differences could be spotted between aggregates treated with low doses of HCDCs and DCs. The former were much darker in color and aggregate shapes were more rounded (Fig. 6), additionally, an increased number of small aggregates were present after the injection of DCs.

3.4. Critical shear velocity for resuspension

The alteration of the physical characteristics of the aggregates as a result of their exposure to fine fractions of drill-cuttings was further indicated by the results of the resuspension experiments. This part of the study was designed to measure the threshold for entrainment of deposited aggregates back into the water column. The results are summarized in Table 1. From observations made during the experiments in the erosion chamber, the resuspension process could be divided into aggregate bedload transport and suspended load transport.

In experimental runs phytodetrital aggregates unexposed to drill cuttings showed homogeneity in their resuspension behavior. Minimal shear flow of $u^* = 0.2 \text{ cm s}^{-1}$ was required to commence bedload transport while suspended transport began with shear velocities of $u^* = 0.3\text{--}0.4 \text{ cm s}^{-1}$.

As with settling speeds and particle size distribution, unaggregated HCDC and DC samples showed variability in their

resuspension potential. The DC sample commenced resuspension at $u^* = 0.6 \text{ cm s}^{-1}$, whereas the HCDC sample needed a minimum of $u^* = 0.7 \text{ cm s}^{-1}$ to be returned to suspension. Full resuspension for the DC sample was observed at $u^* = 0.7\text{--}0.9 \text{ cm s}^{-1}$. In contrast, the majority of the HCDC sample particles were lifted up under a $u^* = 0.8 \text{ cm s}^{-1}$.

Impact on the critical shear velocity required to resuspend aggregates by exposure to DC and HCDC cuttings was indicated after aggregate exposure to the lower concentration of 35 mg l^{-1} of either DC or HCDC cuttings. The first DC and HCDC aggregates started to weakly resuspend under a flow of $u^* = 0.3 \text{ cm s}^{-1}$. In the case of 35 mg l^{-1} HCDC treatment, peak resuspension was observed at $u^* = 0.4\text{--}1.0 \text{ cm s}^{-1}$ although some aggregates were not resuspended until $u^* = 1.0\text{--}1.2 \text{ cm s}^{-1}$. In contrast, all aggregates exposed to DC drill cuttings at this concentration were resuspended by $u^* = 0.8 \text{ cm s}^{-1}$ (replicates 1 and 2) and by $u^* = 0.9 \text{ cm s}^{-1}$ (replicate 3). Similar trends in resuspension were observed in high drill cutting exposures (175 mg l^{-1}). Here, resuspension of DC drill cutting aggregates commenced at $u^* = 0.3 \text{ cm s}^{-1}$, with peak resuspension observed at $u^* = 0.4\text{--}0.7 \text{ cm s}^{-1}$ (Table 1). Resuspension of HCDC aggregates commenced at $u^* = 0.3 \text{ cm s}^{-1}$, with the peak resuspension observed at the higher $u^* = 0.6\text{--}0.9 \text{ cm s}^{-1}$ (Table 1). There was a 'sweeping effect' observed on the aggregate bedload in the experimental chambers. This effect was most characteristic for high DC treatments, and accounted for fast removal of most of the bedload. With 175 mg l^{-1} of DCs added to the system, clearly distinguishable layers of particles could be seen resuspending. The lighter aggregates, composing the top surface of the bedload were the most easily resuspended. Mid-layer of the bedload in the chamber was dominated by heavier aggregates (also looking darker in color). The very bottom layer of the bedload mostly consisted of lithogenic material

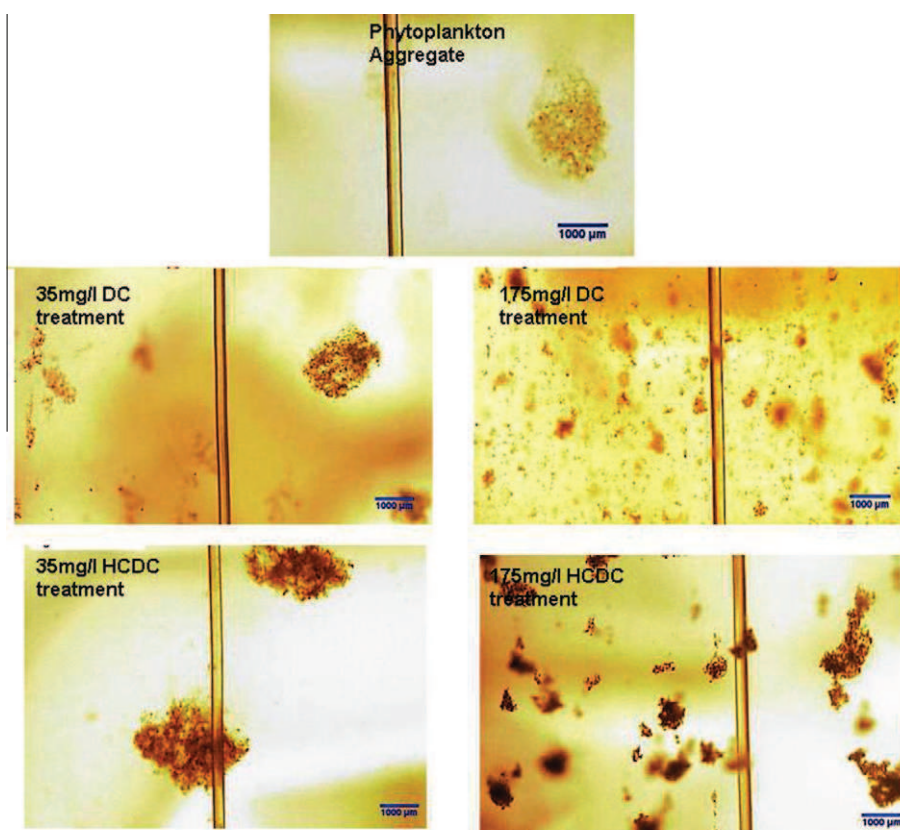


Fig. 6. Photographs of a selection of phytodetrital aggregates and aggregates exposed to drill cuttings of various concentrations and compositions.

Table 1

Resuspension behavior of aggregates exposed to the investigated types and concentrations of drill cuttings.

Resuspension type	u^* [cm/s]							
	Replicate #	DCA		HCDC		Phyto. Aggregates	DC	HCDC
		35 mg/l	175 mg/l	35 mg/l	175 mg/l			
Bedload transport	1	0.3	0.3	0.4	0.3	0.2	0.6	0.7
	2	0.3	0.3	0.3	0.3			
	3	0.3	0.3	0.3	0.3			
Suspended load transport	1	0.4–0.8	0.4–0.7	0.6–1.0	0.5–1.0	0.3–0.4	0.7–0.9	0.8
	2	0.4–0.8	0.4–0.9	0.4–1.2	0.6–0.9			
	3	0.5–0.9	0.4–0.8	0.4–1.2	0.6–1.2			

which settled shortly after DCs were introduced to the aggregates, and was the last fraction to be resuspended.

4. Discussion

4.1. Aggregation of phytoplankton material with drill cuttings

The aim of this study was to determine the effect of the discharge of drill-cuttings on aggregation and physical characteristics of phytodetritus. The results show that changes in settling velocities, resuspension behavior, particle size distribution and turbidity over time are evidence that phytodetrital aggregates can scavenge drill cuttings under turbulent flow conditions in the water column. This is a predicted interaction process when high amounts of lithogenic particles come into contact with organic rich aggregates of different hydrodynamic behavior.

Elevated fine particle concentrations in bottom waters are also a result of bottom trawling or storm induced resuspension. Palanques et al. (2001) studied the effect of bottom trawling on turbidity and showed that after the start of a trawling run, water turbidity increased first near the seabed over the initial hours following trawl deployment, and later at shallower depths in the water column over a period of 2–5 days (Palanques et al., 2001). Average turbidity in the water column increased by a factor of up to three for 4–5 days after trawling. Dounas et al. (2007) revealed that that bottom trawling may trigger off considerable productivity pulses, in addition to pulses from the natural seasonal cycle, as a result of the nutrient rich resuspended sediments (Dounas et al., 2007). In contrast however, Pusceddu et al. (2005) reported a negative effect on food lability (e.g. of phytodetrital aggregates) towards a more refractory composition after resuspended lithogenic sediments aggregated with the organic fraction (Pusceddu et al., 2005).

Our results show that the discharge of DC drill-cuttings may similarly result in lithogenically enriched phytoplankton aggregates within the water column. There is no resuspension of the seabed sediments associated with drill cutting release, so the surface phytoplankton bloom associated with trawling resuspension will not occur—the lability of surface aggregates will decrease following drill cutting release as particles of the waste material are incorporated into the phytoplankton aggregates, with no possible enrichment as observed in association with trawl resuspension. This lability decrease in aggregates may well impact negatively on the benthic ecosystem.

The discharge of hydrocarbon containing drill-cuttings (HCDCs) is expected to have a different effect. According to Norwegian regulations these drill-cuttings have an oil content of formation oil of less than 1% of dry matter. The question however remains on the percentage of oil in the fine fraction (<64 μm) which can disperse in the water column and will be subsequently scavenged by phytodetritus and then transferred to benthic communities.

It is known that clay-minerals bind to oil during as a process of clay-oil flocculation (Lee et al., 2002). The formation of these

oil–mineral aggregates (OMAs), which consist of microscopic particles of oil stabilized by fine minerals, is a well known process in marine waters. Oil associates with fine mineral particles in an aqueous medium not only as molecules adsorb onto mineral surfaces, but also as a discrete phase, to form OMAs. This process promotes the dispersion of stranded oil, and is believed to be possibly instrumental in the natural recovery of oiled shorelines. It can thus be expected that a discharge of oil containing drill cuttings will result in a preferential accumulation of the oil in association with the cutting fine fraction, which then aggregates readily with the phytodetritus in the water column.

Although the overall concentration of drill-cuttings particles (<63 μm) was maintained across experiments with both types of cuttings, their characteristics with respect to size distributions within this fine fraction was different. Regular drill-cuttings (DCs) were richer in very fine particulates (<10 μm), while hydrocarbon containing drill-cuttings (HCDCs) had predominantly larger median sizes of 10–64 μm . The percentage of the fine fraction (<63 μm) in the regular drill cuttings used in this study was 97% and 77% for the hydrocarbon-containing drill cuttings. Twelve percentage of these hydrocarbon-containing drill cuttings were in the size range <10 μm (9.2 t of 100 t). Thus for every 100 t of disposal of drill cuttings with less than 1% (1 t) of oil, this oil most probably binds in preference with the very fine drill cutting fraction (<10 μm). Hundred tons of discharged oil-containing drill cutting used in this study could thus release <1 t of oil preferably bound to 9 t, the <10 μm fraction with high clay content. These fine drill cutting fractions could therefore consist of almost 10% oil, which would then be scavenged readily by phytodetritus aggregates.

So how does this fine fraction change the hydrodynamic behavior of phytodetrital aggregates? The original hypotheses, that the aggregation process would be more pronounced when phytodetritus comes into contact with hydrocarbon containing drill cuttings (HCDCs) was confirmed by the results of the experiments with both 35 mg l^{-1} and 175 mg l^{-1} exposure. Since flow velocity, shear stress, and concentration of the drill-cuttings as well as plankton species composition were maintained across experimental runs, such physiochemical characteristics as composition, shape, particle size and settling speed of drill-cuttings were crucial in defining their potential to alter the physical characteristics of phytodetritus.

The pronounced shift towards larger particle sizes of phytodetrital aggregates after exposure to 35 mg l^{-1} hydrocarbon-containing drill cuttings was a good indication for their stickiness during the aggregation process. During the typical aggregation process many particles encounter each other but often less than 10% of these interactions result in adhesion to form larger or denser aggregates. The chance of this adhesion is controlled to a large extent by the 'stickiness' of the particles (Kiorboe et al., 1990; Kiorboe and Hansen, 1993; Thomsen and McCave, 2000). A 'sticky' hydrocarbon coating of lithogenic drill-cuttings, even as low as <1% but possibly as high as 10% of the particle mass (see discussion above) for the fine fraction of <10 μm drill cuttings will thus promote

coagulation processes in the water column and act like a chemical flocculant for organic material (Lee et al., 2002) effecting additionally the porosity, density and morphology of the resulting aggregates. The greater stickiness of hydrocarbon containing drill cuttings and the resulting higher inorganic ballast of the phytodetritus could explain the faster production of denser aggregates (as indicated by reduction in NTU) in HCDC than DC experimental runs.

4.2. Change of settling and resuspension behavior

The increased settling velocities of phytoplankton aggregates exposed to even the lower investigated concentration of DCs or HCDCs (Fig. 5) indicates that settling behavior of naturally occurring aggregates may be susceptible to rapid change following exposure to drill cutting material.

Similar factors to those that regulate settling rates of aggregates control the resuspension behavior of aggregates; size, density, porosity, shape, and stickiness of aggregates and their constituents may play a crucial role in determining u_{crit}^* for their resuspension. Phytodetrital aggregates were resuspended at lower shear velocities than aggregates treated with drill cuttings ($u_{crit}^* = 0.3\text{--}0.4\text{ cm s}^{-1}$ in contrast to $0.4\text{--}0.9\text{ cm s}^{-1}$ for drill cutting aggregates). The resuspension process took even longer for HCDC aggregates than for pure aggregates or DC aggregates, which may indicate that the characteristics of aggregates formed following exposure to drill cuttings vary in mass, density and hydrodynamic behavior related to drill cutting composition and hydrocarbon content. The outcomes of resuspension experiments would indicate that phytodetrital aggregates with drill cutting inclusions are less mobile following deposition than those not containing inclusions, indicating a possible change in food availability to the benthos over time in the vicinity of drilling rigs.

4.3. Implications

This study has shown by laboratory investigation that following exposure to concentrations of drill cuttings at operational densities observed and modeled in the vicinity of drilling rigs, the hydrodynamic behavior of the naturally occurring phytoplankton aggregates may be affected. The experimental studies carried out here have shown that at concentrations of 35 mg l^{-1} and 175 mg l^{-1} drill cuttings are incorporated rapidly into the structure of phytoplankton aggregates. In the field such incorporation could lead to a more rapid delivery to the seafloor of the drill cuttings than is predicted by currently used dispersal models based on particle size and density, which do not incorporate aggregation processes. Composition of the drill cuttings appears from this study to be a factor in the rate of incorporation of material into phytoplankton aggregates, with the settling rate of aggregates and the seabed stress required to resuspend the material after settling both affected by the drill cutting composition. These observations have wide ranging implications for carbon transport rates and food lability within the water column and at the seabed in the vicinity of drilling operations on the Norwegian margin. Ecosystem management strategies utilized by the oil and gas industry during drilling operations may be improved by taking into account the phytoplankton concentration and 'stickiness' of material in the water column at the time of drilling, and how these factors may influence aggregation rates and settling of the drill cutting material.

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CHAPTER 5

A further improvement for quantification of vertical particle fluxes in the ocean based on the IRSC trap technology – a pilot study

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1 Introduction

Vertical particle fluxes are one of the main drivers of the distribution and profiles of elements in the ocean. The downward motion of particles is estimated to account for 50-80% of the biological carbon pump (Volk and Hoffert 1985, Fasham et al. 2001). Accurate quantification of vertical carbon fluxes, especially in the mesopelagic where most of the particulate organic carbon (POC) flux attenuation occurs, now and in the future is fundamental if we are to understand the present and future marine carbon cycle.

The most important tools for the quantification of vertical fluxes are sediment traps. Potential biases and limitations of sediment traps are well known, of which the most important are hydrodynamic biases, zooplankton “swimmer” retention and sample solubilisation in the sample cups (see review papers by Gardner 2000 and Buesseler et al. 2007a). Whereas the latter two problems can be addressed quite satisfactorily, hydrodynamic biases are still not fully understood. To minimize the hydrodynamic effect,

neutrally buoyant sediment traps have been developed (Valdes and Price 2000, Buesseler et al. 2000, Lampitt et al. 2008) and have given important new insights into flux attenuation in the twilight zone (Buesseler et al. 2007b, Lampitt et al. 2008). However, a small residual slip velocity over the trap mouth of up to 0.4 cm s^{-1} (Valdes and Price 2000) and additional vertical trap motions of $0.5\text{--}1.0 \text{ cm s}^{-1}$ and occasionally more than 1.0 cm s^{-1} (Lampitt et al. 2008, their Fig. 3; Salter et al. 2007, their Fig. 2) still seem to remain. Both of these motions (relative to the ambient water), horizontal and vertical, are fast compared to the typical sinking speed of oceanic aggregates and faecal pellets ($0.01\text{--}1.0 \text{ cm s}^{-1}$). The potential effect of these motions on trapping efficiency is not fully understood to date.

Carbon cycle imbalances in the mesopelagial, as described by bacterial carbon demand (BCD) versus POC flux (Boyd et al. 1999, Steinberg et al. 2008, Balter et al. 2009, Burd et al. 2010) have been reported. One possible reason for these imbalances could be the inaccuracy of sediment traps. An imbalance factor of 3-10 was calculated while using NBST for flux determination (Steinberg et al. 2008). Explanations for imbalances are given by the authors as zooplankton migration, dark dissolved inorganic carbon fixation, and lateral advection. However, it seems unlikely that the large discrepancy of a factor 3-10 (or in other words, only 10-35% of the BCD is met by direct passive vertical fluxes) can be solely explained by these factors.

Also in the bathypelagial and along continental margins, imbalances in the carbon cycle have been detected (Biscaye et al. 1994, Wollast and Chou 2001). Detailed studies on the coupling between sinking fluxes of particulate organic matter and the activity of the benthic community (Graf 1992) revealed that vertical fluxes at continental margins were not sufficient to balance benthic community requirements. Hence, lateral advection was suggested to play a role (Thomsen 1998).

Besides sediment traps, the most commonly and increasingly used method for vertical carbon flux determination is the thorium isotope method (^{234}Th ; Buesseler et al. 2006). Application of this method have led to important spatial data sets on carbon flux and to the possibility to calibrate trap fluxes against ^{234}Th fluxes (Benitez-Nelson et al. 2006, Buesseler et al. 2006, Rutgers van der Loeff et al. 2006). Based on ^{234}Th assessments, over- and undertrapping by a factor of 1-2.5 was shown (Buesseler et al. 2007a). However, varying $\text{POC}/^{234}\text{Th}$ ratios may have an effect on the accuracy of flux determination (Benitez-Nelson et al. 2006, Buesseler et al. 2006). As there is no “absolute standard” of flux determination (Valdes and Price 2000, Buesseler et al. 2007a), evaluation of accuracy

of differently derived fluxes, like from neutrally buoyant traps or from ^{234}Th applications, may have some limitations (Buesseler et al. 2007a).

Besides the need to accurately quantify total fluxes, there is recent awareness that further progress in understanding particle export and the biological pump, and understanding the underlying mechanisms that drive these fluxes, should be made by determining sinking-velocity-specific (SVS) fluxes over the whole particle sinking spectrum found in the ocean and get a mechanistic understanding of the processes that create, change and maintain these spectra (Trull et al. 2008, Armstrong et al. 2009, Lee et al. 2009, Peterson et al. 2009, Boyd and Trull 2007).

For this purpose, Indented Rotating Sphere/Sample Carousel (IRSC) traps (Peterson et al. 1993) for separating flux into sinking velocities (SV) were developed (SV-IRSC; Peterson et al. 2005, 2009) and have already been deployed in a couple of field studies (Trull et al. 2008, Lee et al. 2009, Armstrong et al. 2009, Alonso-Gonzalez et al. 2010), showing important results on how fluxes of different compounds are related to SV. However, as SV-IRSC traps operate as normal traps, they may also be biased due to hydrodynamic issues at the collection process.

In the present paper we want to address the task of how an external non-hydrodynamically-biased standard of flux determination could be developed which at the same time also addresses the task of determining SVS fluxes of the complete sinking velocity spectrum found in the ocean. Following Kozerski (1994) and Gust and Kozerski (2000), this method should ideally determine the Sinking-Velocity-Mass-Distribution (SVMD) of the particle population outside the trap in the water column. Mass in this context means the mass of whatever compound (carbon, nitrogen etc.), a sum of different compounds, or the overall particle mass. By realisation of such a SVMD determination, this would automatically also lead to a determination of SVS *in situ* fluxes (SVS-IFs) by a multiplication of mass times the respective SV and to the total *in situ* flux (T-IF; sum of all SVS-IFs). To our knowledge, two methods for SVMD determination have been developed to date, one *in situ* settling chamber method (SCM) for lake and surface waters (Kozerski 1994, Gust and Kozerski 2000) and one shipboard or shore based method for oceanic waters (Gustafsson et al. 2000, 2006). Both methods cover the lower range of sinking velocities ($<30 \text{ m d}^{-1}$ and $<10 \text{ m d}^{-1}$, respectively). There is no method available to date for the whole SV spectrum and for an application in the ocean.

In order to go a step further in this direction, we conducted a pilot study on the determination of the SVMD on the whole sinking velocity spectrum ($<1 \text{ m d}^{-1}$ - $>980 \text{ m d}^{-1}$) of a marine water mass. This approach was made possible by a modified deployment of the IRSC trap, operating not as a conventional trap, but as a settling funnel above its rotation sphere (hereafter called the “IRSC-SVMD approach”). The water mass determined by this method was from a 200 m deep location within the Kosterfjord off western Sweden, which is characterised by oceanic water masses in its deep layers. From the so determined SVMD we calculated SVS-IFs and T-IFs. At the same location in Kosterfjord we deployed different sediment traps, including an IRSC trap, in a conventional way, leading to “classical” total trap fluxes (T-TFs) and (for the IRSC trap) SVS-TFs. By comparing both datasets on T-TFs and T-IFs we determined collection efficiencies of the trap deployments. For the IRSC case, the direct comparison of SVS-TFs with SVS-IFs enabled us to determine SVS collection efficiencies of the IRSC trap.

We present further steps to improve the IRSC-SVMD approach in order to possibly achieve a most accurate and at the same time SV specific flux determination (C, N, other elements) in the ocean. We suggest that the here introduced method complements existing methods and sampling schemes, and may allow to better quantification of sinking carbon fluxes in the ocean.

List of abbreviations

SV	Settling/Sinking velocity
SVS	Sinking-velocity-specific
IF	In situ flux
IFC	In situ flux organic carbon
TF	Trap flux
TFC	Trap flux organic carbon
IRS	Indented rotating sphere
IRSC trap	IRS carousel trap
SV-IRSC trap	IRS carousel trap operating in SV mode
SVMD	Sinking-velocity-mass-distribution
SCM	Settling chamber method (Kozerski 1994)
IRSC-SVMD approach	Determination of the SVMD via an IRSC trap
SVS-IF	Sinking-velocity-specific in situ flux
SVS-TF	Sinking-velocity-specific trap flux
SVIFD	Sinking-velocity-in situ flux-distribution
SVTFD	Sinking-velocity-trap flux-distribution
SVSD	Sinking-velocity-size-distribution
ASV	Average sinking velocity
MSV	Minimum sinking velocity

2 Methods

When this study of TF-IF intercomparison was originally conducted in September 2009 we used the SCM (Kozerski 1994, Gust and Kozerski 2000) for IF determination. The SCM, as described further below, was at that time the best method for the purpose of SVMD determination. However, it is only capable of SVMD determination within the slow settling fractions sinking $<30 \text{ m d}^{-1}$. Given that, we knew to only get a rough estimate of the T-IF and designed the whole study to mainly be a trap intercomparison one. For that purpose, four traps of different designs (including an IRSC trap) were conventionally deployed in the Kosterfjord at 200 m water depth right next to each other, sampling an identical environment and particle population on 15 September 2009. Parallel to that we conducted the SCM using water masses from the same environment as sampled by the traps at the same time. Besides TF-intercomparison we thus nevertheless got a direct comparison between the SVS-IFs within the slow settling classes $<30 \text{ m d}^{-1}$ and the IRSC-trap-derived SVS-TFs within the slow settling classes.

The idea for the main new method introduced in this paper, the IRSC-SVMD approach (as described below in detail), being able of a SVMD determination of the whole particle sinking spectrum in the ocean (<1 to $>1000 \text{ m d}^{-1}$) was born in October 2009. This idea led to a second Kosterfjord campaign at the exact same location on 19 November 2009, utilizing this new method. Because of logistical constraints a second set of parallel conventional trap deployment could unfortunately not be conducted. However, replicate water sampling and analyses from the sample location on both days (15 September and 19 November) revealed that the particle population was very similar in terms of total mass and carbon content on both days. Because of this similarity, we thus took for the purpose of this pilot study the results of the November IRSC-SVMD determination to compare with the September trap deployments.

2.1 SVMD determination and IF calculation

2.1.1 *The IRSC-SVMD approach*

In order to find an approach of SVMD determination of the whole sinking velocity spectrum found in the ocean, we identified that the IRSC trap should principally be able to conduct that. The principal idea is that the IRSC trap could, instead of separating the TF

into SV classes, separate the natural particle population (not biased and sorted by trapping processes) within the water body under investigation into SV classes.

For this purpose the IRSC trap was not used as a conventional trap, but as a “double settling funnel”. In this manner not only the funnel below the indented rotating sphere (IRS) served as a settling funnel, but also the collection funnel above the IRS served as such. This can be realised by the “collection” of a representative (not hydrodynamically sorted) part of the water mass to study, into the collection funnel, and subsequent isolation from hydrodynamic influence and water exchange with the outside. This isolation can be done by closing the collection funnel with a lid on top. While in a subsequent settling period of time the collection funnel then serves as a funnel to let the particle population settle onto the IRS, the lower funnel then serves (after IRS rotation) conventionally as the separation funnel. The difference to the conventional procedure is that not the TF, but the particle population is here separated into SV classes. Conventionally SVS-TFs, or in other words a Sinking-Velocity-TrapFlux-Distribution (SVTFD) is created, whereas in our here introduced procedure, a SVMF is created. The SVMF leads to the determination of SVS-IFs and hence to a Sinking-Velocity-In Situ Flux-Distribution (SVIFD) by multiplication of each mass with its respective SV and to the total in situ flux (T-IF; sum of all SVS-IFs). In summary, instead of SVS-TFs, the T-TF and the SVTFD, we get SVS-IFs, the T-IF and the SVIFD.

The whole procedure should ideally be conducted *in situ*. An approach to realise that will be given in the last chapter of this paper. While such an *in situ* approach is technically challenging and subject to future development, we used the following procedure for this pilot study.

Three water samples from the exact same location as the trap deployments on 15 September 2009 (2 m above the seafloor at 58°52.492 N, 11°05.580 E) were sampled with a Niskin bottle (5.2 l volume) after each other on 19 November 2009. The samples were directly transferred to the coast (ca. 20 min boat ride), where the IRSC trap was waiting ready for “operation” in the harbour in front of the Sven Loven Centre for Marine Sciences. It was “deployed” via a crane, which was able to lift and lower the trap gently up and down. The water samples were subsequently gently filled into the IRSC trap collection funnel via a pipe. Previous to starting the filling procedure, the trap was lowered until the rotating sphere was at water level. During the filling process, the trap was gently lowered by the crane at the same rate as the water level inside the collection funnel rose due to filling. This

was done to prevent harbour water to diffuse into the collection funnel, because the IRSC trap is not fully water-tight. The volume of the collection funnel allowed for filling 14.5 litre into it, so that the water level inside the funnel (and also outside by adjustment via the crane) at the end of the filling process was a few centimetres below the upper funnel end. The filling procedure took around 5 minutes, after which the funnel was closed by a lid, to prevent contact and exchange of the funnel-water with the outside environment. We chose this deployment procedure in the harbour because of two advantages over a “deployment” on land. (a) The water temperature in the harbour (6-7 °C) was the same as the temperature of the samples from 200 m water depth, allowing for conducting the experimental procedure under in situ temperature. (b) The IRSC trap is not fully water-tight. A “deployment” on land in a cool room is thus not possible, since small leakages would over the time drain the water out of the funnels and cause turbulence.

Particles were let settle for 40 minutes in order to sediment on the rotating sphere. The trap was then programmed in SV mode according to Armstrong et al. (2009) and in the same way as during the conventional deployment on 15 September 2009. As the SVMD within the slow sinking fractions of the whole spectrum was already assessed via the SCM on 15 September 2009 (as described below), the class “<50 m d⁻¹” was changed to 28.8–50 m d⁻¹, as the SCM was conducted in a way to have the fastest class >28.8 m d⁻¹. No classes <28.8 m d⁻¹ were thus measured by the IRSC-SVMD approach within this pilot study, but could normally be determined by this approach down to <1 m d⁻¹.

Directly after the separation process into the SV classes by the IRSC trap, the samples were filtered onto pre-weighed and pre-ashed 25 mm GF/F filters, and processed for weight and organic carbon and nitrogen. Filters were acidified to remove carbonate (Pike and Moran 1997) and measured for organic carbon and nitrogen with an Euro EA elemental analyser calibrated with an acetanilide standard.

SVS-IFs were then calculated for overall particle mass as well as for organic carbon (SVS-IFCs). The SV of the classes was determined by both the arithmetic mean and the geometric mean. T-IF and T-IFC were calculated as the sum of all SVS-IFs and SVS-IFCs.

Another three Niskin bottles were taken at the same location and the water filtered onto 47 mm GF/F filter in order to determine total particulate matter, organic carbon and nitrogen concentration and hence express the mass in each particle sinking class also as a percentage of the total mass, organic carbon and nitrogen.

2.1.2 The SCM for SVMD determination within the slow sinking fraction

During the time of the trap deployments on 15 September 2009, three water samples were taken in approximately equal time intervals spread over the whole trapping interval close to the trap apertures at 2 m above seafloor with a Niskin bottle (5.2 l volume), sampling the identical environment as the traps. A ground weight, automatically closing the bottle, guaranteed accurate sampling depth (accurate height above bottom). The samples were taken on the downstream side of the traps in order to not permit resuspended material from the groundweight to enter the traps. Water samples were transferred to PE-bottles, kept cool at approximately 6 °C and were rotated smoothly from time to time in order to keep the particle population as homogenous as possible. They were subsequently transferred to a laboratory cool room with 6 °C room temperature, where SVMD determinations within the slow sinking fraction of the particle spectrum were determined following the SCM of Kozerski (1994), with slight modifications. Briefly, each water sample was gently filled into two “batteries”, each consisting of four cylinders (a-d; 35 cm length and 4.65 cm inner diameter, 595 ml volume), referred to as settling chambers (Burns and Rosa, 1980; Rosa et al. 1991), which were then closed and kept undisturbed from motion. After 15, 45, 135 and 405 minutes the water of the top 30 cm was siphoned off all cylinders (a, b, c and d) respectively and the amount of settled material determined gravimetrically on pre-weighed and pre-ashed (12h at 450°C) GF/F filters (25 mm) from the concentration increase in the bottom 5 cm water mass. In order to increase weighing precision, both cylinders belonging to the same water sample were added together (“pooled”). After weighting, filters were processed for organic carbon and nitrogen as described above for the IRSC-SVMD filters. By utilizing a set of equations, SVMDs were calculated for the following five SV classes: I with $<1.1 \text{ m d}^{-1}$, II with $1.1\text{-}3.2 \text{ m d}^{-1}$, III with $3.2\text{-}9.6 \text{ m d}^{-1}$, IV with $9.6\text{-}28.8 \text{ m d}^{-1}$, and V with $>28.8 \text{ m d}^{-1}$. This was done with all three replicates.

SVS-IFs and SVS-IFCs, as well as T-IF and T-IFC were then calculated for all replicates following the same procedure as described above for the IRSC-SVMD method, with the SV of each class determined by both the arithmetic and the geometric mean.

2.2 Trap deployments and TFs

Two landers equipped with four cylindrical sediment traps of different design were deployed in the Kosterfjord, Sweden, at 200 m water depth at 58°52.492 N, 11°05.580 E (lander A) and 58°52.452 N, 11°05.610 E (lander B) on 15 September 2009 from the

research vessel *Doris* operated by the Sven Loven Centre for Marine Sciences. Lander A carried an IRSC trap (with 15.2 cm inner diameter (i.d.)) and two additional cylindrical traps, with 10 cm i.d. and 7 cm i.d.. The IRSC trap was equipped with a sphere with four extremely wide (15 mm) and deep (6mm) grooves, according to type “D” of Fig. 3 in Peterson et al. (2009). Lander B carried a 19.1 cm i.d. cylindrical trap with a rotation valve as designed by Technical University Hamburg Harburg (TUHH).

The Kosterfjord at that depth is characterised by oceanic conditions in terms of temperature and salinity. Fishing activity was stopped via the Coast Guard in the whole Kosterfjord for that day in order to prevent material to resuspend from the bottom.

The IRSC trap and the 19.1 cm trap were mounted on the landers in a way that the intake funnels were both 2 m above the seafloor. The 7 cm and 10 cm trap intake funnels were at 1.5 m above the seafloor, in order to not disturb the collection process of the IRSC trap. The landers were placed only 60 m away from each other on the seafloor in order to let them sample the exact same environment, the same particle field, in order to compare the TFs with each other. They were far away enough from each other to not interfere with each other.

The IRSC trap was programmed in SV mode with the same intervals $>50 \text{ m d}^{-1}$ as for SVMd determination in November 2009, similar to Armstrong et al. (2009).

For flow, temperature, pressure and pitch and roll measurement, an ADCP was additionally mounted on lander A. As recorded by the pitch and roll sensor, lander A was perfectly standing upright with pitch and roll combined less than 3° skewness. Lander B did not carry a device to measure pitch and roll, but was most likely also standing perfectly upright, as the lander construction was similar to lander A and the seafloor was very flat in the deployment region in the middle of the Kosterfjord.

The brine solution of the IRSC and 19.1 cm traps was 40‰. No poison was used, as remineralisation of POC in the cups could be neglected because of the short deployment time of only a few hours and rapid lab processing after recovery in the same evening and night. The samples were filtered onto pre-weighed pre-ashed glass fibre filters and weight was determined gravimetrically. They were processed for organic carbon and nitrogen as described above for the other samples.

The 7 cm and 10 cm traps were not filled with brine. After recovery, the whole water body of these traps was filtrated, but mass and carbon content of the water was subtracted, to only

determine the mass of the particles collected. TFs were conventionally calculated as per m² per day.

2.3 Filter pore size experiment

In order to study the effect of the filter mesh size on the determination of the total particle mass in a natural water sample, we sampled another three replicate water samples from the trap deployment location in approximately equal time intervals during the time of the trap deployments on 15 September 2009. For every replicate water sample, equal aliquots of 0.5 l were then filtered onto 0.2, 0.45, 0.7, 1.0 and 2.7 µm mesh size filters. In the 0.7 µm class, both 25 mm and 47 mm GF/F filters were used for comparison.

3 Results

3.1 SVMD outside the traps and IFs

The SVMD for the slower end of the sinking spectrum (<28.8 m d⁻¹), as determined by the SCM, is shown in Fig. 1. Mass is defined here by the mass which did not pass a 0.7 µm GF/F filter. Total mass on 15 September was 1775 µg l⁻¹, organic carbon mass was 169.8 µg l⁻¹. 777.5 µg l⁻¹ (43.8% of the total mass) and 84.2 µg l⁻¹ (49.6 % of the C_{org}-mass) had settling velocities slower than 1.1 m d⁻¹. Mass and C_{org}-mass decreased with increasing SV. Only 108.6 µg l⁻¹ (6.1% of the mass) and 3.2 µg l⁻¹ (1.9 % of the C_{org}-mass) sank faster than 28.8 m d⁻¹.

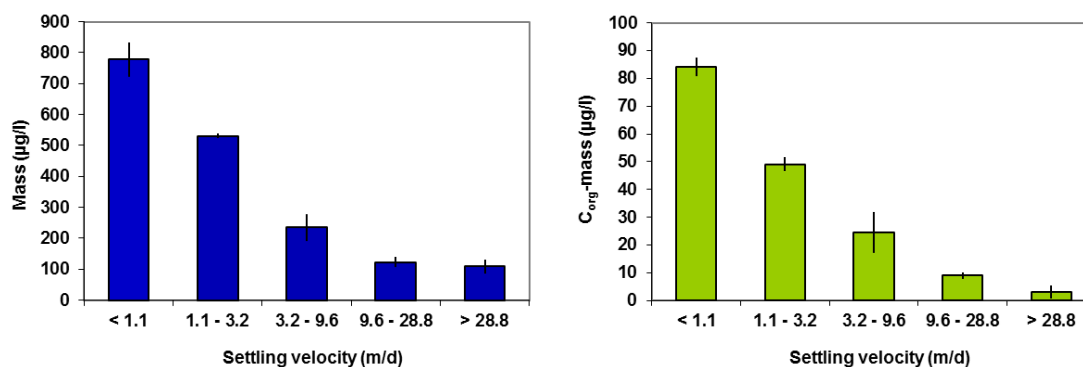


Fig. 1 SVMD derived by the SCM for the slower end of the sinking spectrum. Mass in the SV class “<1.1 m d⁻¹” refers to mass >0.7 µm. Error bars denote standard deviation from three replicates.

The SVMD for the medium and fast end of the sinking spectrum, as determined by the IRSC-SVMD approach, is shown in Fig. 2. The general trend of decreasing mass and C_{org} -mass with increasing SV continued within the medium and fast SV classes. Only $2.1 \mu\text{g l}^{-1}$ (0.12% of the mass) and $0.06 \mu\text{g l}^{-1}$ (0.04 % of the C_{org} -mass) was found to settle faster than 980 m d^{-1} .

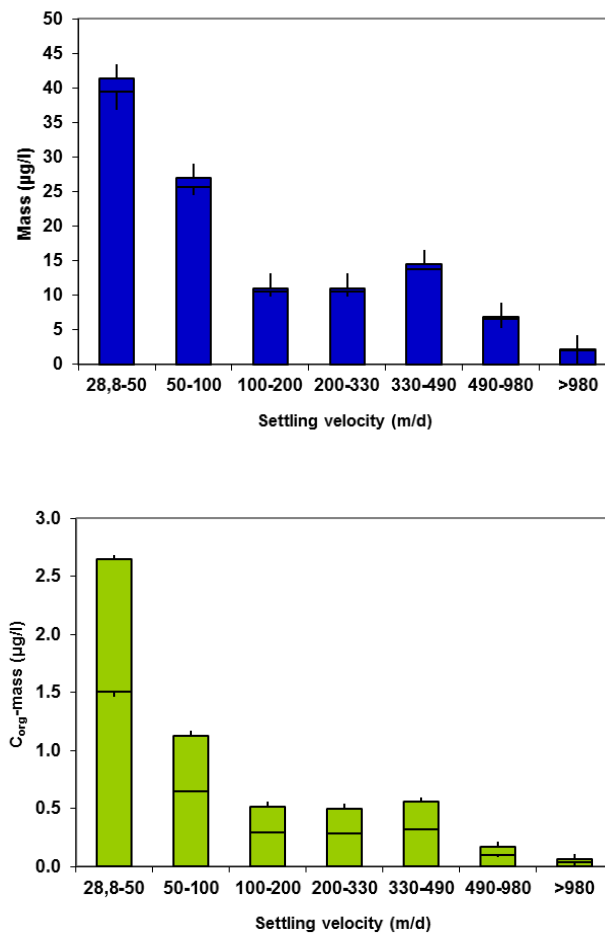


Fig. 2 SVMD derived by the IRSC-SVMD approach for SV classes $>28.8 \text{ m d}^{-1}$. Error bars denote weighing precision. Horizontal bars denote uncertainties due to differences between the SCM and the IRSC-SVMD approach and between “September water” and “November water”.

Fig. 3 combines both approaches to a SVMD on the whole SV spectrum from $<1 \text{ m d}^{-1}$ to $>1000 \text{ m d}^{-1}$.

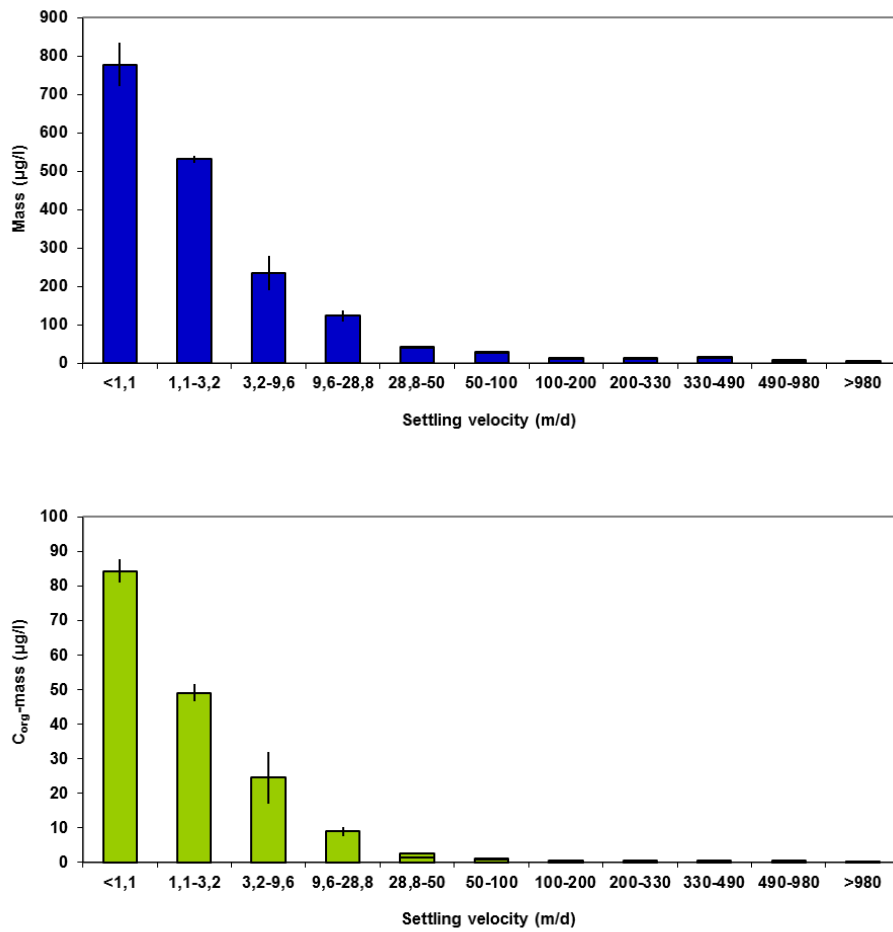


Fig. 3 Combined SVMD for the whole SV spectrum found in the ocean. Mass in the SV class “<1.1m d⁻¹” refers to mass >0.7 µm.

For better graphical illustration, Fig. 4 shows the SVMD for the whole SV spectrum on logarithmic scales, normalized to settling velocity interval (SVI; Armstrong et al. 2009).

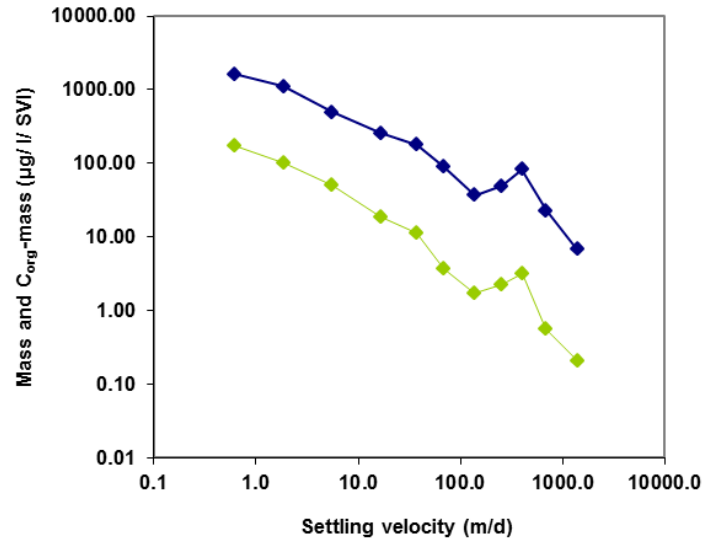


Fig. 4 Combined SVMD for the whole SV spectrum shown on logarithmic scales.

From the SVMD, SVS-IFs and the T-IF were calculated based both on the arithmetic mean and the geometric mean within each SV class. Additionally, as the IRSC-SVMD approach showed a higher overall mass and a higher mass percentage in the SV classes “>28.8 m d⁻¹” compared to the SCM, IFs for the SV classes “>28.8 m d⁻¹” were also calculated by multiplication of each mass within each SV class (as determined by the IRSC-SVMD approach) by the quotient of total SCM-mass “>28.8 m d⁻¹” divided by total IRSC-SVMD-mass “>28.8 m d⁻¹”.

The SVIFD is shown in Fig. 5 on a logarithmic scale. Values are flux densities normalized by SVI (Peterson et al. 2005; Armstrong et al. 2009).

It becomes clearly visible that despite the very low mass in the fast SV classes, these classes carried most of the IF. ~50% of the IF was in the SV classes “>330 m d⁻¹” and ~70% in the SV classes “>100 m d⁻¹”. For C_{org}, ~50% of the IF was in the SV classes >100 m d⁻¹.

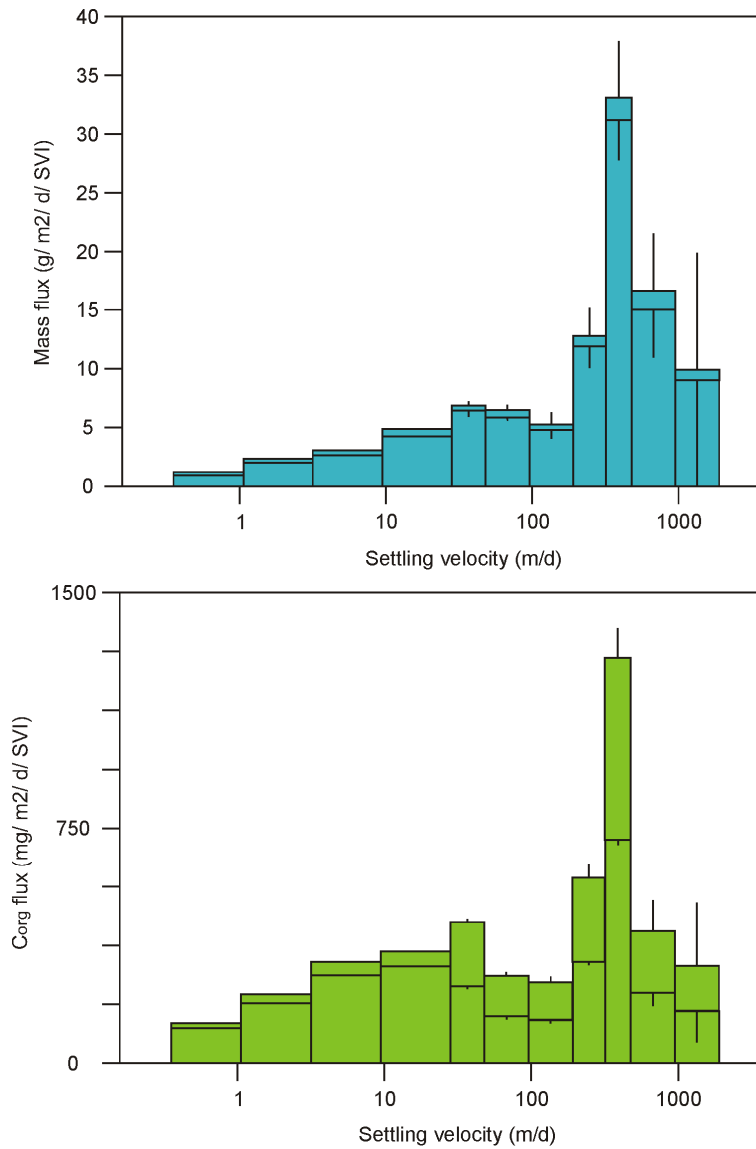


Fig. 5 SVIFDs for mass (blue) and C_{org} (green). Error bars denote weighing precision. Horizontal bars denote uncertainties due to differences between the SCM and the IRSC-SVMD approach and between “September water” and “November water”.

Besides the uncertainties in IF-calculation as described above and as marked by the horizontal bars and error bars in the graphs (arithmetic vs. geometric mean, September vs. November water, instrumental precision), the IF-calculation of both the slowest and the fastest SV class is subject to additional uncertainties, because the lower and the upper boundary respectively are not well defined in terms of SV.

Additionally, the calculated IF in the slowest SV class can vary with the filter mesh size used for mass determination. The mass of all other classes is not effected by the filter mesh

size, because particles sinking $>1.1 \text{ m d}^{-1}$ are bigger than $1.0 \text{ }\mu\text{m}$ anyway. The lower boundary of the slowest SV class within the SCM is hence defined by the filter mesh size. In order to investigate how the concentration (and percentage) in the slowest SV class and thus also the value of total particulate matter changes when the filter mesh size (used for filtration) is varied, the filter mesh size experiment was conducted (Fig. 6).

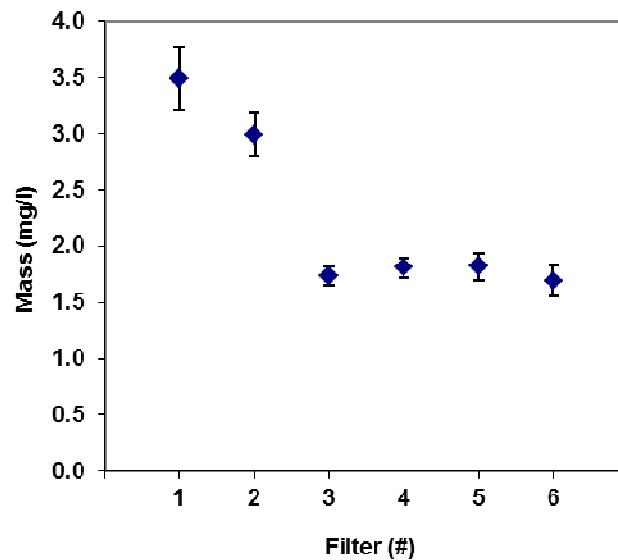


Fig. 6 Total particulate mass on the different filters used. Filter mesh size: #1: $0.2 \text{ }\mu\text{m}$, #2: $0.45 \text{ }\mu\text{m}$, #3: $0.7 \text{ }\mu\text{m}$ (25 mm diameter), #4: $0.7 \text{ }\mu\text{m}$ (47 mm diameter), #5: $1.0 \text{ }\mu\text{m}$, #6: $2.7 \text{ }\mu\text{m}$.

Values from the glass fibre filters of 0.7 , 1.0 and $2.7 \text{ }\mu\text{m}$ mesh size did not differ significantly and all showed a particle mass of $1.7\text{--}1.8 \text{ mg l}^{-1}$. In contrast to that, particle mass determined by $0.45 \text{ }\mu\text{m}$ and $0.2 \text{ }\mu\text{m}$ mesh size filters was $\sim 70\%$ more ($\sim 3.0 \text{ mg l}^{-1}$) and $\sim 100\%$ more ($\sim 3.5 \text{ mg l}^{-1}$), respectively.

By not changing the lower boundary of the slowest SV class in terms of SV, using a $0.45 \text{ }\mu\text{m}$ filter would lead to a $\sim 70\%$ higher mass in that SV class and hence to a $\sim 70\%$ higher IF in that class. For a $0.2 \text{ }\mu\text{m}$ filter this would be $\sim 100\%$ more. However, as the contribution of the slowest SV class to the T-IF was small, changing the filter to $0.45 \text{ }\mu\text{m}$ or $0.2 \text{ }\mu\text{m}$ would not have made a big difference in terms of T-IF.

In a next step we calculated the average SV (ASV) of the particle mass. It is important to notice that the ASV varies with the minimum settling velocity (MSV) included in the calculation (Armstrong et al. 2009). We followed this approach and calculated ASVs versus MSVs using the geometric mean within each SV class (Fig. 7). ASVs spanned a range of 15 m d⁻¹ (for MSV 0.4 m d⁻¹) to 470 m d⁻¹ (for MSV 200 m d⁻¹). For C_{org} the range was 7 m d⁻¹ to 430 m d⁻¹.

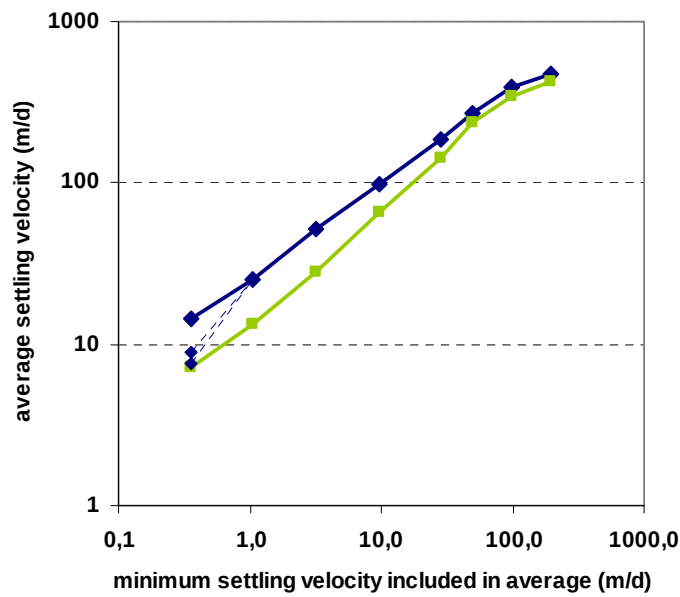


Fig. 7 Average settling velocity in relation to the minimum settling velocity included in the average calculation.

It is again important to note that (as in Armstrong et al. 2009) the ASVs of all calculated MSVs also depend on the SV value used for the fastest class (>980 m d⁻¹; here 1384.8 m d⁻¹ is used (see description above)), which is not well defined.

For the slowest SV class the MSV is not well defined and the mass of that class (as described above) depends on the filter mesh size. Therefore we additionally plotted the ASV (by using the same MSV) for a ~70% and a ~100% higher total mass. For a MSV of 0.4 m d⁻¹ this led to an ASV of 8 m d⁻¹ and 9 m d⁻¹ respectively.

3.2 TFs

T-TFs were 15.3, 17.0, 16.2 and 27.1 g m² d⁻¹ and T-TFCs were 603, 680, 616 and 1143 mg m² d⁻¹ for the 7 cm, 10 cm, 15.2 cm (IRSC trap) and 19.1 cm traps respectively (Fig. 8). With the exception of the IRSC trap, an increasing trend in T-TF and T-TFC with increasing trap diameter and aperture area was found. The percentage of C_{org} was constant at around 4% for all traps.

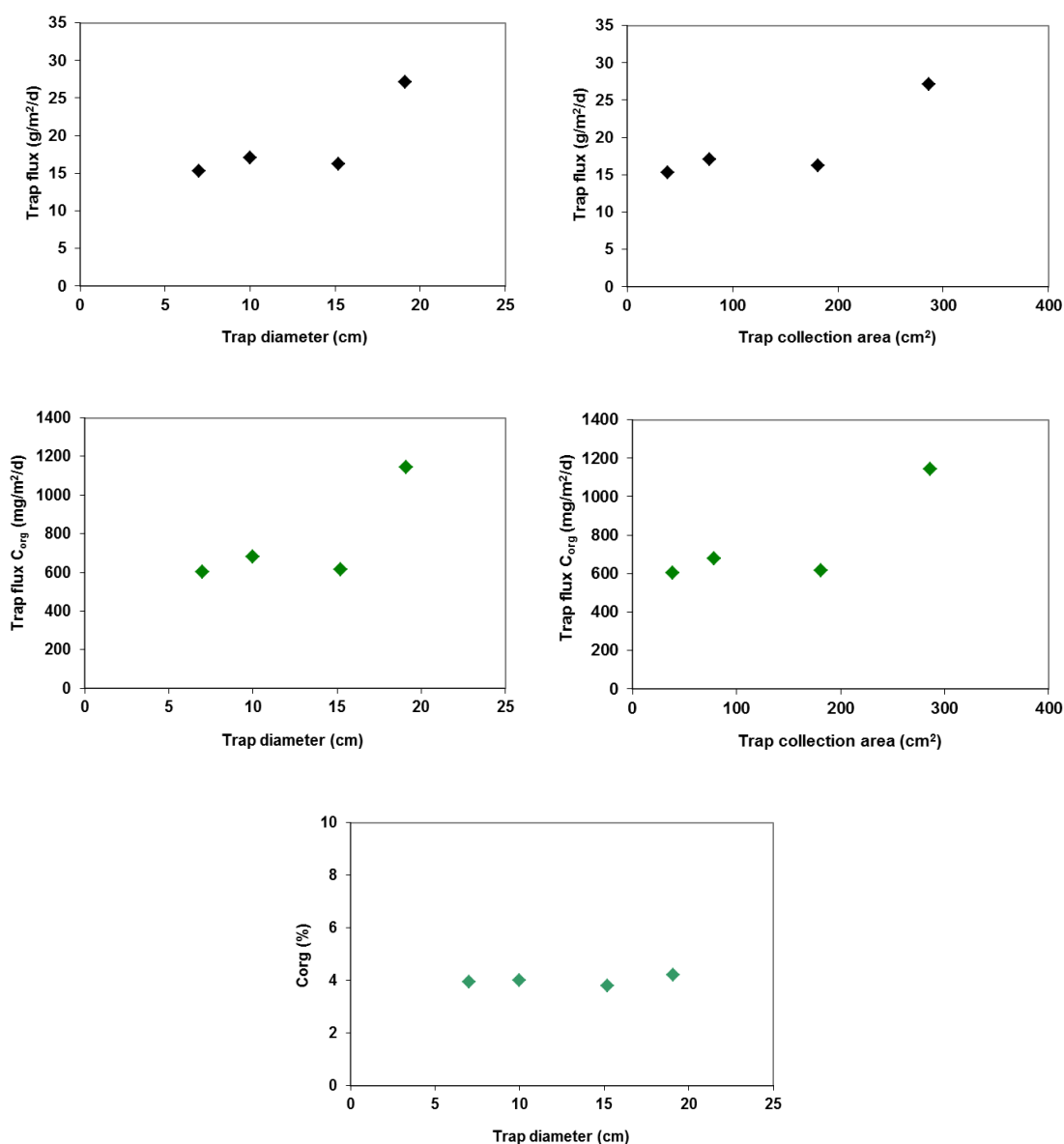


Fig. 8 Total trap fluxes (T-TFs and T-TFCs) in relation to trap diameter and collection area.

The IRSC trap derived SVS-TFs are shown in Fig. 9. Around 70% of the T-TF and nearly 70% of the T-TFC was in the very fast SV classes $>490 \text{ m d}^{-1}$.

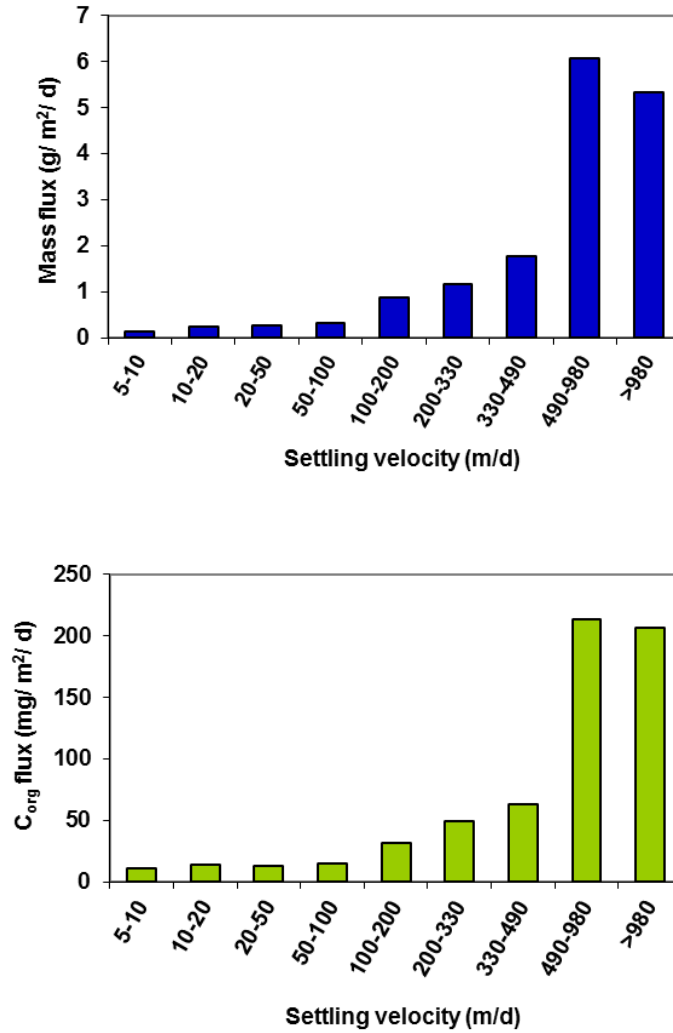


Fig. 9 IRSC trap flux from the September deployment (SVTFD)

Current velocity during the whole trap deployment time was in the range of $2\text{-}20 \text{ cm s}^{-1}$ on a one minute interval basis and in the range of $5\text{-}17 \text{ cm s}^{-1}$ on a moving average (15 min) basis (Fig. 10). Within the main comparison time, current velocity was in the ranges of $3\text{-}17 \text{ cm s}^{-1}$ (one minute interval basis) and $6\text{-}14 \text{ cm s}^{-1}$ (moving average (15 min) basis).

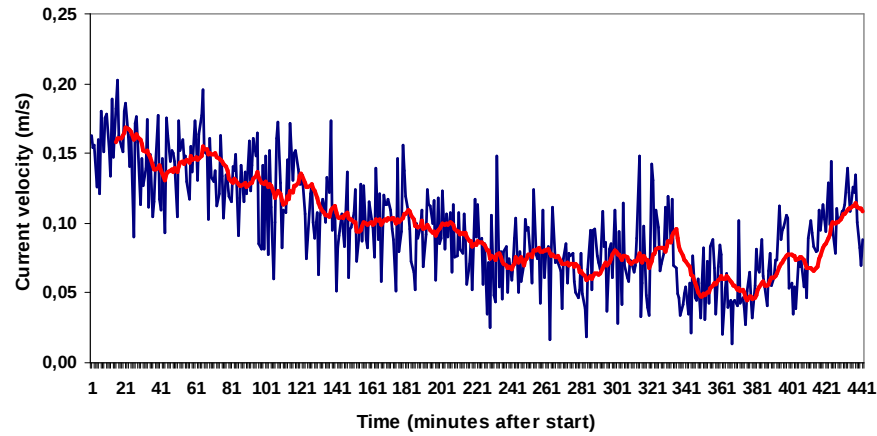


Fig. 10 Current velocity during deployment. Red line: Moving average (15 min).

3.3 TFs vs. IFs

T-TF compared to T-IF is displayed in Fig. 11, shown as deployment specific “trapping efficiency” of each trap. For the IRSC trap, T-TF is defined as $T-TF > 5 \text{ m d}^{-1}$ (as no SV classes $< 5 \text{ m d}^{-1}$ were measured) and is compared to the $T-IF > 5 \text{ m d}^{-1}$. Trapping efficiency for the IRSC trap is thus defined as trapping efficiency $> 5 \text{ m d}^{-1}$. Trapping efficiencies for the 7 cm, 10 cm and IRSC trap were < 1 , so undertrapping occurred. For the 19.1 cm trap the efficiency was ~ 1 .

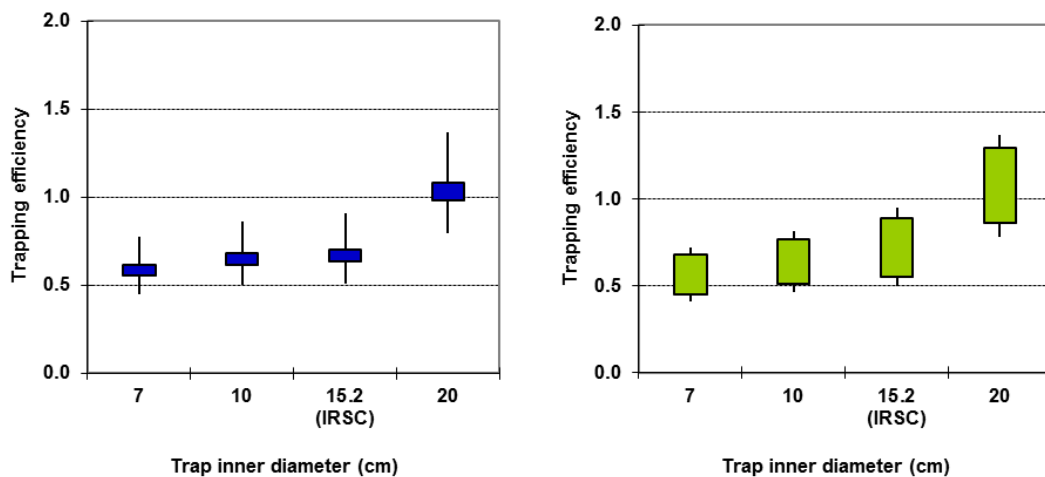


Fig. 11 Trapping efficiencies. For the IRSC trap, trapping efficiency is defined as the efficiency $> 5 \text{ m d}^{-1}$.

SVS-TFs (IRSC) are compared to SVS-IFs in Figs. 12a and 12b. For both mass and C_{org} undertrapping occurred in all SV classes $<490 \text{ m d}^{-1}$. In contrast to that, overtrapping occurred in the SV classes $>490 \text{ m d}^{-1}$.

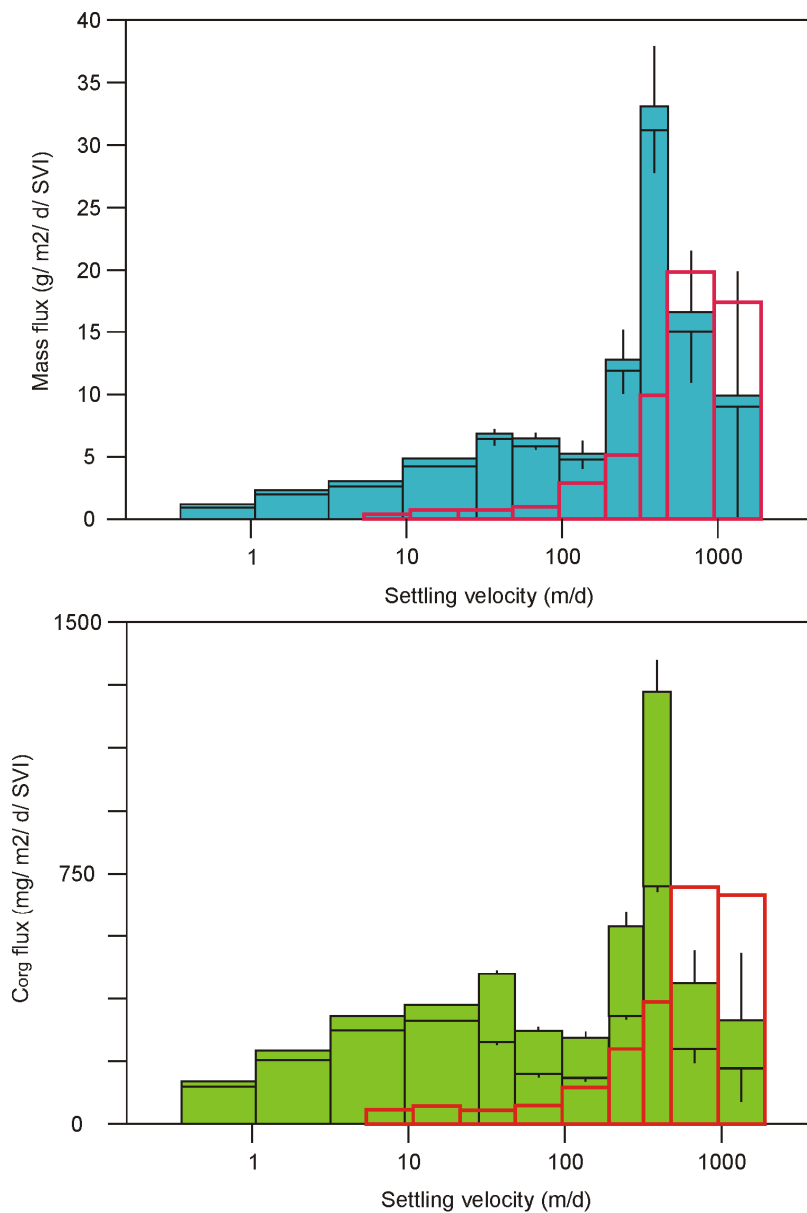


Fig. 12a Trap flux IRSC (red) vs. in situ flux for mass (blue) and C_{org} (green)

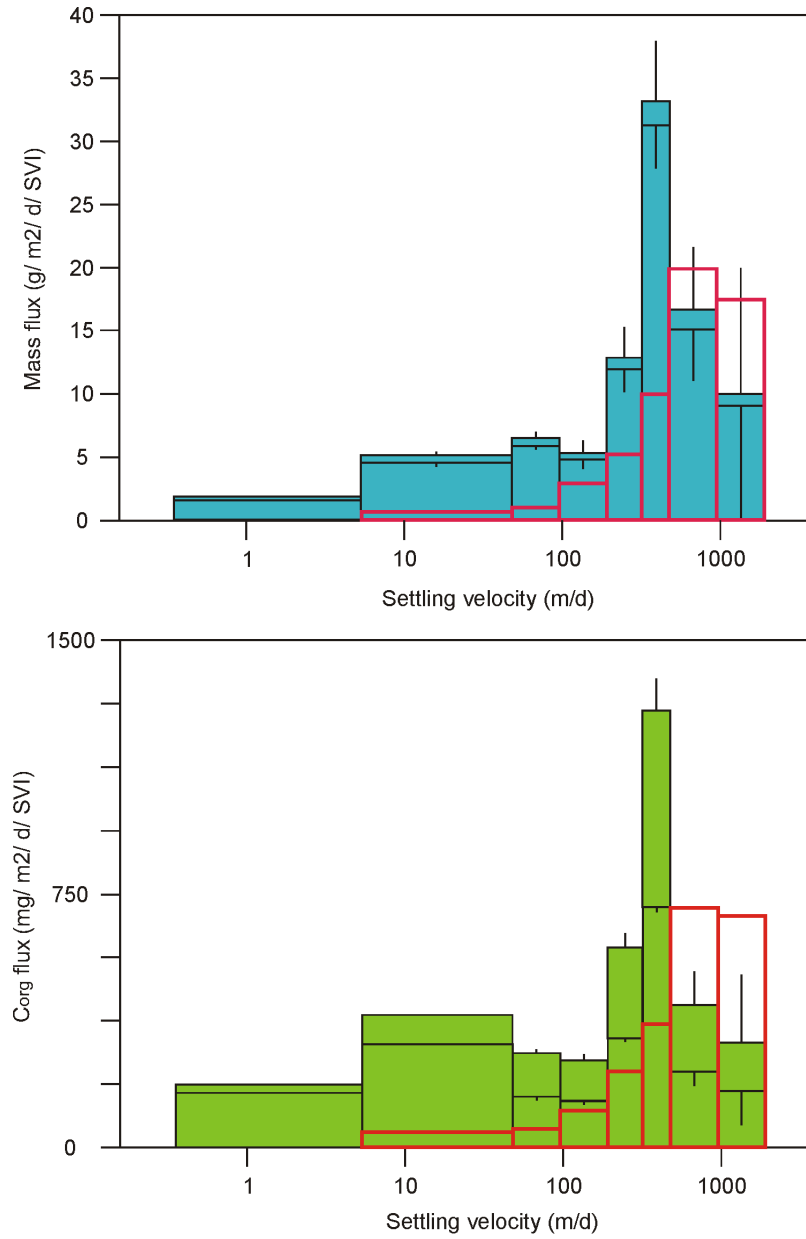


Fig. 12b Trap flux IRSC (red) vs. in situ flux for mass (blue) and C_{org} (green). IF classes $<50 \text{ m d}^{-1}$ are combined to directly compare TF and IF.

Fig. 13 shows the C_{org} -percentage versus SV for TF and IF. A clear decreasing trend in C_{org} -percentage with increasing SV is visible for both TF and IF.

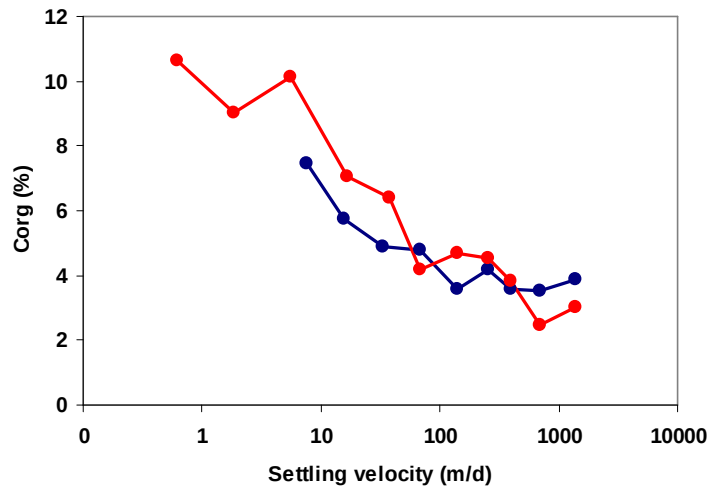


Fig. 13 C_{org} versus settling velocity for trap flux (blue) and in situ flux (red)

4 Discussion

4.1 SVMD outside the traps and IFs

4.1.1 Accuracy of SVMD determination and IF calculation

Before we discuss the results on IFs, we have to address the accuracy of SVMD determination within this pilot study. There are several potential factors which could have influenced the exact determination of IFs.

(a) Disaggregation and/or aggregation of particles during the water collection process (via Niskin bottle), the transport to the lab, and the distribution into the SCM bottles and IRSC collection funnel during IRSC-SVMD determination could have happened.

(b) Water from November and not September was used for IF determination ($>28.8 \text{ m d}^{-1}$) via the IRSC-SVMD approach. Though water mass analysis showed that particle mass and carbon content were both nearly identical in September and November, uncertainties in calculation remain, because we do not know if the SVMD $>28.8 \text{ m d}^{-1}$ was exactly the same on 15 September 2009 and 19 November 2009.

(c) The SV value for the fastest class ($>980 \text{ m d}^{-1}$) is not clearly defined. The calculated flux however is sensitive to this value.

(d) The IRSC trap itself has some uncertainties in separating particles into sinking velocity classes (Peterson et al. 2005, 2009; Trull et al. 2008). The possible factors are aggregation

and/or disaggregation on the sphere, the timing of release of particles from the sphere during rotation, a sticking of particles to the sphere, and the slightly skewed funnel.

Nevertheless given these drawbacks on exact IF determination within this study, we feel this pilot study important to report, as it demonstrates a new approach for quantifying vertical particle fluxes in marine environments. It could pave the way to a hydrodynamic-bias-free, accurate method of SVS-IF determination in the ocean, which we will present in the last chapter of this paper. We will show that uncertainties related to (a) and (b) can be avoided via an *In Situ* IRSC-SVMD approach. Furthermore, (c) can be avoided by choosing a higher boundary for the fastest SV class (e.g. 2000 m d⁻¹ or 3000 m d⁻¹) above which most likely no flux occurs. Additionally, concerns on (d) are subject to ongoing improvements of the IRSC trap (Peterson et al. 2009).

4.1.2 Spectrum of mass, flux and size

The non neglectable contribution of all investigated classes of the wide oceanic spectrum of sinking classes to the IF demonstrated again that it is very important for carbon flux studies to address the whole SV spectrum found in the ocean from <1 m d⁻¹ to >1000 m d⁻¹. This was especially shown by the non neglectable fraction of the IF which was found in the fractions <10 m d⁻¹ and >1000 m d⁻¹, as demonstrated in the case of the water mass studied in this pilot study. To our knowledge, no previous study has to date determined the SVMD of a certain water mass for its whole particle SV spectrum from <1 m d⁻¹ to >1000 m d⁻¹.

It is long known that the larger, faster settling particles are rarer and have only a very small mass-percentage of the whole particle mass suspended in the water column (McCave 1975, 1984). The exact determination of this mass-percentage, however, is difficult.

Different studies have shown that “sinking” POC contributes to only ~10% of the total POC (Stemmann et al. 2002, McCave et al. 1975, 1984, Bishop and Wood 2008). Our results support this finding, with additionally showing that the determined amount of total particulate matter, as well as the mass-percentage of every SV class, depend on the filter used.

To calculate an ASV alone is not very helpful. The present study and that of Armstrong et al. (2009) both highlight that an ASV determination has to go together with a “lower boundary determination”. The inclusion of a very low MSV and the choice of an “open” lower boundary (as for the SCM) let the ASV vary a lot, depending on what is defined as

the “mass” from which the ASV is calculated. The inclusion of even all dissolved (organic) matter (which typically has a mass around 10 times larger than the particulate mass) in the calculation would lead to a 10 times lower ASV (because the SV of the dissolved mass is zero).

There is a lower percentage of C_{org} (compared to mass) in the IF of the very fast sinking velocities, indicating that C_{org} has a lower mean sinking velocity than mass.

The shape of our SVIFD looks similar to results from other IRSC trap flux studies on their SVTFD (Trull et al. 2008, Armstrong et al. 2009, Lee et al. 2009, Peterson et al. 2009). Both this study and the other mentioned IRSC trap flux studies show that fluxes $>500 \text{ m d}^{-1}$ may have a significant contribution to total flux.

4.2 TFs

T-TF of the IRSC trap was less than T-TF of the 19.1 cm trap. Other studies have also shown that IRSC traps measure less than other cylindrical traps (Trull et al. 2008; Buesseler et al. 2009). Possible reasons for that are (a) A too low aspect ratio of 5:1, whereas the other deployed traps had aspect ratios of $> 6:1$. (b) Particles might stick to IRS surface and might not be released at rotation, with this issue also being a problem for the 19.1 cm trap though. (c) Particles might stick to the skewed settling funnel of the IRSC trap (Peterson et al. 2009).

Another possibility for the lower IRSC TF compared to the 19.1 cm TF could be that lots of IRSC TF might have been in the very slow sinking velocities $<5.4 \text{ m d}^{-1}$, as in the case of the study of Alonso-Gonzalez et al. (2010) for the NE-Atlantic. This material sinking $<5.4 \text{ m d}^{-1}$ may therefore not have reached a collection cup in the carousel, but have still been suspended in the water of the funnel during recovery, and therefore lost at recovery. The high 1 minute blank value might point in this direction. Another possibility could be a general increase in TF with trap diameter or trap Reynolds number. Whatever the reason for differing TFs is, this study again shows that TFs derived from an identical sampling environment can differ by a factor of nearly two between traps of different design.

7 cm TFs and 10 cm TFs are not discussed here in detail as the results should be treated with caution, because (a) both trap apertures were collecting at 1.5 m instead of 2 m above the seabed, (b) the time of collection was only identical for the “middle” 200 min of collection and (c) the particle mass and particulate organic carbon mass of the trap-water was subtracted.

The here presented IRSC derived SVTFD again shows that most of the TF is carried by the very high sinking velocities. The shape of the SVTFD is similar to that observed in other recent IRSC deployments, with most of the TF in the fast settling velocities of 100-1000 m d⁻¹ (Armstrong et al. 2009, Lee et al. 2010), though even more shifted towards the faster sinking velocities.

4.3 TFs vs. IFs and implications for carbon flux studies

Regarding the total fluxes (mass and carbon) both over and undertrapping occurred within this study, depending on the trap used. The range of trapping efficiencies found in this study of 0.41–1.37 is comparable to the range commonly found in the bathypelagic ocean as derived from ²³⁴Th investigations (Buesseler et al. 2007). The reason for the better similarity of the trapping efficiencies from this study with the ones from the bathypelagial might be the low percentage of C_{org} (~5%) of the investigated particle community. In the mesopelagic zone, typical values are 10-15% C_{org} (Boyd and Trull 2007), and trapping efficiencies based on ²³⁴Th are lower, commonly in the range of 0.15-1.20 (Buesseler et al. 2007).

Regarding SVS fluxes, the parallel conduction of a conventional IRSC trap deployment together with a SVMD determination via the IRSC-SVMD approach enabled us to assess SVS collection efficiencies of the IRSC trap. This confirmed, that the slower settling velocities are undertrapped and the very fast settling velocities are overtrapped, as it is in line with Gust et al. (1996) and Gust and Kozerski (2000). According to the mentioned studies, the SVTFD should normally always be shifted “more to the right” than the SVIFD. On the other hand, aggregation of particles on the upper side of the IRS during the collection process (before rotation) may also happen (Peterson et al. 2005, 2009), also leading to a shift of the SVTFD - relative to the SVIFD - to the right, even without trap collection discrimination against the slow settling velocities.

Because C_{org} sinks slower than total mass, undertrapping for C_{org} is higher than for total mass. In ocean regions where lots of C_{org} sinks slow, underestimation of the contribution of slow settling velocities by traps leads to too low TFs. In general, the slower the settling speed, the lower the trapping efficiency. This is in line with Gust et al. (1996) and Gust and Kozerski (2000) and implicates, that the “shape” of the SVMD and the SVIFD is critical for

over- and undertrapping. When very high settling velocities have a higher mass-percentage overtrapping is favoured, otherwise undertrapping is favoured. Both scenarios can originate from an identical IF intensity, which itself can originate from two different scenarios, a) a higher mass and a slower settling velocity and b) a lower mass and a higher settling velocity.

Our results could have implications for carbon cycle research. They could help explain the common known imbalance between bacterial respiration and vertical carbon flux (Baltar et al. 2009, Burd et al. 2010). Our results again show that undertrapping of slowly sinking particles by sediment traps could be one reason for the common imbalance found in many carbon cycle studies. All indicators for ecosystem processes which are coupled to the rejected, slow-settling particle fractions might be undertrapped (Gust and Kozerski 2000).

5 Conclusions and the next step: The *In Situ* (IRSC)-SVMD approach

The IRSC-SVMD approach couples a variety of advantages. As it is based on an IRSC trap, it (a) uses a swimmer free trap and (b) determines not only the bulk flux, but also SVS fluxes. Additionally to these IRSC trap advantages it (c) avoids hydrodynamic biases. The IRSC-SVMD approach enables us (when done in a repeated way) to study the dynamics of shifts in the SV spectrum and (when combined with other methods like primary production and plankton community determination) should lead to new information on the mechanistic understanding of particle export. The IRSC-SVMD approach combined with a conventional IRSC deployment (using the same SV classes) enables us to determine SVS collection efficiencies of the IRSC trap for a certain deployment.

The next step is to conduct the IRSC-SVMD approach *in situ*. This would avoid uncertainties and biases due to aggregation and disaggregation during water sampling and handling, and would at the same time give the possibility for long-term time series studies on SVMD shifts and dynamics. In the following, the conceptual and technical requirements for such an oceanic *in situ* approach are shown.

To collect a sufficient amount of particle mass per SV class in the ocean, the collected water volume must be relatively large. This could for example be realised with an array of three traps arranged vertically next to each other on a mooring, each trap being capable of

collecting 500 L. Three traps could sufficiently separate the particle community of the collected ambient waters into the whole SV spectrum from 2 m d^{-1} to 1000 m d^{-1} , for example the first trap from 100 m d^{-1} to 1000 m d^{-1} , the second trap from 10 m d^{-1} to 100 m d^{-1} and the third trap from 2 m d^{-1} to 10 m d^{-1} . A 500 L water collection could for example be realized with a collection cone of 200 cm height, 90 cm diameter at the top and 15 cm diameter at the lower end (to be placed on the IRS valve), leading to a skewness of the side walls of only 10° (thus efficiently preventing particle accumulation on the walls). Other dimensions are generally also possible.

Given a typical mesopelagic particle mass of $10\text{--}100 \text{ mg m}^{-3}$ (determined by conventional filtering through a 0.45 or $0.7 \text{ }\mu\text{m}$ mesh size filter) and considering only $0.1\text{--}1.0\%$ of the particle mass to be in the quantitatively smallest sinking classes, the collected mass in the collection cups of these classes would be $5\text{--}500 \text{ }\mu\text{g}$ per 500 L collection step. These small material masses per collection interval are not a problem, since material will accumulate over the entire sampling period. In the above example with three traps, the trap separating the highest SV classes can collect one 500 L water sample every 30 min (the time it takes for the 100 m d^{-1} particle to settle from the top of the collection cone onto the IRS; all other particles $>100 \text{ m d}^{-1}$ have settled onto the IRS during this time anyway). This leads to approximately 50 collections per day, producing a collection mass in each sample cup of $0.25\text{--}25 \text{ mg}$ per day, or $1.75\text{--}175 \text{ mg}$ per week, sufficiently enough to analyse the samples at least for mass and organic carbon during low flux periods and for all kinds of analyses including PIC, biogenic silica (bSi), dust and various biomarkers during medium and high flux periods. The amount of the collected material depends on the number of SV classes separated per trap (max 11 collection cups available in the current IRSC design) and can be varied, as the amount of material increases, but the accuracy of SV determination decreases when decreasing the number of SV classes to be separated.

The number of collections per day decreases to 5 for the second trap ($10\text{--}100 \text{ m d}^{-1}$ particle separation) and to 1 for the third trap ($2\text{--}10 \text{ m d}^{-1}$ particle separation), as the time to settle onto the IRS for the slowest particles to be determined is approximately 5 hours and 24 hours respectively. However, this does not go along with a decrease in mass collection per cup (compared to the above calculations for the trap separating the fastest sinking classes), as the mass (not the flux!) of small, slowly settling particles is in general much bigger than the mass of the rare, large, fast settling ones (McCave 1975, 1984). Thus, a collection mass per cup in the same order of magnitude as for the first trap is expected for the second and third trap, sufficiently enough for various analytical procedures.

The collected material could be analysed for all kinds of constituents. Of special interest would be the relation of POC to PIC (“rain ratio”), bSi and dust with regard to SV, to gain important insights into the controlling factors of POC export.

To increase the measurement precision within the fastest SV class, this class could be chosen as $>2000 \text{ m d}^{-1}$ (30 sec. opening time). The amount of material in that class would then probably mostly be below detection limit, but if so, that would give evidence that the $>2000 \text{ m d}^{-1}$ -flux is neglectable. Hence the SV value for the $>1000 \text{ m d}^{-1}$ -class would become definable as the geometric or arithmetic mean of a class from 1000 to 2000 m d^{-1} , as was used by assumption already in this study and previous studies (Trull et al. 2008, Armstrong et al. 2009, Lee et al. 2009, Peterson et al. 2009).

For time series measurements, a further technical improvement could be made by building a “carousel of carousels”, meaning that the collection cup carousel, which separates the material into SV classes, would be replaced in a time series mode by further empty collection cup carousels step by step.

The technical requirements for such an oceanic *in situ* approach would be (a) to build an appropriate cone for each IRSC trap, (b) to develop an *in situ* mechanism for “up and down lifting” the cone to “collect” a new water sample, possibly in a 90° angle to flush the cone with new water, and (c) to develop an *in situ* “opening and closing mechanism” for the top cover of the cone, which should open for water collection and close when the cone is down lifted onto the IRS. Both mechanisms, (b) and (c), should be programmable to operate in defined time intervals (for example 30 min, 5 hours and 24 hours for the three traps as given above).

Whatever the exact design and operation of such a new device will look like in the end, the general suggestion proposed here for epi- and mesopelagic flux studies, is to complement existing methods with this method of repeated *in situ* “water collection” and subsequent SVMD determination.

This method may serve as an additional step on the way to assess the response of the biological pump to ocean change and to better understand the mechanisms regulating the flux of POC to depths within the current and future ocean. It may further help to find explanations on what is wrong with current carbon balances (Burd et al. 2010).

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CHAPTER 6

Summary and Conclusions

The manuscripts presented in the context of this thesis have led to some important new findings regarding the ecology and biogeochemistry of CWC reef ecosystems. They have additionally also led support to a number of proposed ideas and findings from the recently published literature.

In the following I summarize the most important findings and conclusions presented in the four manuscripts which comprise this thesis.

Paper 1

1. Downwelling was shown to occur at the downstream side of the Tisler sill and was shown to play a potential role as one physical process for supply of nutrition to the Tisler Reef, as it delivers organic matter with higher lability to the downstream side of the reef. Accordingly, reefs located in similar settings (e.g. on ridges on the Norwegian continental shelf) may well also benefit from this effect, and the exact location of downwelling occurrence could help explain the spatial extent and morphology of reefs. The identification of downwelling as a potential food supply mechanism to CWC reefs is a confirmation of Davies et al. (2009) and also goes along with general physical dynamics described previously at sills (e.g. Farmer and Armi 1999, Klymak and Gregg 2004, Xing and Davies 2009).
2. The particulate fraction of *Lophelia pertusa* mucus was shown to be labile in composition, as indicated by a low C/N ratio (~6) and a high amino acid degradation index (DI) value (~0.3). Mucus was further suggested to be transported by currents towards the downstream side of the Tisler Reef, based on some evidence for mucus enrichment in the water column at the downstream reef edge. The low C/N ratio of ~6 is a confirmation of recent observations of Wild et al. (2008, 2009).
3. POM was shown to be more labile on the downstream side of the Tisler Reef. A combination of downwelling and mucus export was proposed as the probable cause of this.

4. Biodeposition of the Tisler Reef ecosystem was estimated to be $459 \text{ mg C}_{\text{org}} \text{ m}^{-2} \text{ d}^{-1}$ on average, suggesting that CWC reefs may play an important role in carbon cycling along continental margins, as was also suggested by recent other studies (Lavaleye et al. 2009, van Oevelen et al. 2009). Our study was the first assessment of biodeposition at a CWC reef.

Paper 2

5. The Tisler Reef environment was shown to be a highly dynamic one. The overall water temperature range of $8.3 \text{ }^{\circ}\text{C}$ (min $5.6 \text{ }^{\circ}\text{C}$; max $13.9 \text{ }^{\circ}\text{C}$) which the reef was exposed to, was by far the largest reported range to date for a *L. pertusa* reef. The absolute maximum temperature of $13.9 \text{ }^{\circ}\text{C}$ was among the highest reported so far for *L. pertusa* reefs. Sudden temperature jumps of up to $4 \text{ }^{\circ}\text{C}$ in less than one hour occurred and were as well much larger than previously reported values on temperature jumps. As *L. pertusa* respiration is very sensitive to temperature changes (Dodds et al. 2007), this may well lead to very large changes in respiration.

6. Variability of flow velocity was shown to be high as well. Sudden increases or decreases in flow velocity (at 2 mab) of up to 34 cm s^{-1} within 10 min and up to 46 cm s^{-1} within 20 min were observed. Maximum current velocities of $>80 \text{ cm s}^{-1}$ at 2 mab and $>120 \text{ cm s}^{-1}$ at 7 mab were among the highest reported at CWC reefs to date. Variability of flow directly leads to variability in the lateral flux of the potential food source POM.

7. Vertical particle fluxes to the reef community were shown to be highly variable, with mass fluxes in the range of $<1 \text{ g m}^{-2} \text{ d}^{-1}$ to $>100 \text{ g m}^{-2} \text{ d}^{-1}$ (mean: $8.5 \text{ g m}^{-2} \text{ d}^{-1}$) and POC fluxes in the range of $<50 \text{ mg m}^{-2} \text{ d}^{-1}$ to $>2500 \text{ mg m}^{-2} \text{ d}^{-1}$ (mean: $283 \text{ mg m}^{-2} \text{ d}^{-1}$). The maximum values are the highest reported so far for a CWC reef.

8. Dissolved oxygen concentration within the reef structure was $\sim 6 \text{ ml l}^{-1}$ and was shown to decrease rapidly during short phases of stagnant or near stagnant flow. The maximum rate of O_2 decrease was $20.04 \text{ } \mu\text{mol l}^{-1} \text{ h}^{-1}$ ($0.45 \text{ ml l}^{-1} \text{ h}^{-1}$). Based on this decrease and on the temperature data, a community respiration rate of $981\text{--}1311 \text{ mg C m}^{-2} \text{ d}^{-1}$ was calculated, again suggesting that CWC reefs may play an important role in carbon cycling along continental margins.

Papers 1 and 2 combined

9. A carbon budget for the Tisler Reef was compiled. The three components on the carbon supply side (vertical POC flux $283 \text{ mg m}^{-2} \text{ d}^{-1}$, lateral depositional POC flux $459 \text{ mg m}^{-2} \text{ d}^{-1}$, zooplankton uptake estimate $174 \text{ mg m}^{-2} \text{ d}^{-1}$) summed to $916 \text{ mg C}_{\text{org}} \text{ m}^{-2} \text{ d}^{-1}$. This total

uptake was close to the total calculated respiration of $981\text{--}1311 \text{ mg C m}^{-2} \text{ d}^{-1}$, indicating that the budget matched quite well.

10. Based on these values and on data from the literature (Andersson et al. 2004, van Oevelen et al. 2009, Fossa et al. 2002), a concept was derived to estimate the contribution of CWC reefs to benthic carbon turnover along the central Norwegian shelf and upper slope. This contribution was estimated to be 3.2-10.9%, even though CWC reefs only cover ~0.5% of the seabed in this region.

Paper 3

11. It was shown that the settling velocity as well as the resuspension shear velocity of natural aggregates increased when they were exposed to “drill cuttings”. These increases resulted from incorporation of drill cuttings into the aggregate matrix and were most significant in aggregates exposed to drill cuttings containing hydrocarbons from the reservoir rocks. Exposure to drill cuttings is often the case in the vicinity of oil and gas drilling rigs, which are commonly operated in the vicinity of CWC reefs on the Norwegian shelf. Such incorporation could lead to a more rapid and higher concentration delivery of drill cuttings to the seafloor than is predicted by currently used dispersal models (e.g. the DREAM model; Rye et al. 2006). It may therefore pose a bigger threat to ecosystems such as coral reefs than previously predicted.

Paper 4

12. To improve the quantification of vertical particle fluxes, a new measurement approach based on the existing IRSC-trap technology (Peterson et al. 1993, 2005) was proposed and was successfully tested in a shore-based pilot study. This approach can be realised *in situ* in the future and may then contribute to a better quantification of vertical carbon fluxes to CWC reefs and to the ocean interior in general. It may subsequently contribute to a better determination of “hotspot-factors” and hence to a refinement of the presented concept.

13. Based on the results of this pilot study, overtrapping was indicated for fast sinking particles, whereas undertrapping was indicated for medium and slow sinking particles. This finding is in line with previous studies (Butman 1986, Gust et al. 1996, Gust and Kozerski 2000).

The presented results allow the hypotheses presented in the first chapter to be addressed.

Answer to H1) The Tisler Reef indeed produces a measurable signal of biodeposition, which was calculated to be $459 \text{ mg C}_{\text{org}} \text{ m}^{-2} \text{ d}^{-1}$ on average.

Answer to H2) POM was not found to be more refractory on the downstream side of the Tisler Reef than on the upstream side. In contrast, it was shown to be more labile on the downstream side. The combined effect of downwelling and mucus export is proposed as a possible explanation for this.

Answer to H3) The Tisler Reef ecosystem was indeed found to be part of a highly dynamic environment. However, we cannot state with certainty that the reef flourishes in such an environment, as we do not know if the observed large variations in measured parameters are common events at the reef or if they only represented rather seldom events, which may be harmful for the coral community.

Answer to H4) Based on this study and on data from the literature, CWC reef ecosystems can indeed be considered as hotspots of carbon cycling along continental margins. However, the presented estimate for benthic carbon processing contribution should only be considered as a rough first estimate.

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CHAPTER 7

Outlook

Based on the most important findings of this thesis, I suggest that future research on CWC reefs should include further investigations regarding the two following issues.

Downwelling as a food supply mechanism to CWC communities

Based on our study and on the observation of Davies et al. (2009), we proposed that downwelling may in general play an important role for reef nutrition of CWC reefs located on sills. It would thus be straightforward to test this hypothesis in the future, for example on reefs located on ridges on the Norwegian shelf. Validation could confirm downwelling as one general food supply mechanism, along with other mechanisms such as Taylor column development (White et al. 2005, White 2007) and resuspension due to internal waves (Frederiksen et al. 1992, Mienis et al. 2007), and could help clarify which of these mechanisms is the most important for which kind of reef (reefs on the shelf, the shelf edge, sills, ridges, mounds etc.). In this context, further studies both on the physical dynamics (as can be measured via CTD profiling and ADCP measurements) and on the chemical differences between organic matter at the downstream and upstream reef edges are needed.

CWC reefs as respiration hotspots along continental margins

As this study, as well as the one of van Oevelen et al. (2009), strongly suggest that CWC reefs should be considered as hotspots of carbon turnover along continental margins, future studies should try to refine the estimates presented in this study. Therefore, more studies on biodeposition are needed. Additionally, the realisation of the here presented “*In situ* IRSC-SVMD” approach may lead to a better quantification of vertical fluxes. Furthermore, additional studies on coral community respiration are needed. Moreover, not all CWC reefs in the world are possibly discovered. The discovery of new reefs will lead to a refinement in

the estimation of the contribution of CWC reefs to benthic carbon cycling. Also, global warming could potentially increase CWC community respiration through bottom water warming, as respiration was found to be very sensitive to temperature changes (Dodds et al. 2007). Thus, the potential warming of BBL waters at CWC reefs should also be investigated.

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