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Effects of resuspension on benthic fluxes of oxygen, nutrients, dissolved inorganic carbon, iron and manganese in the Gulf of Finland, Baltic Sea

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ABSTRACT

The effect of resuspension on benthic fluxes of oxygen (O_2), ammonium (NH_4^+), nitrate (NO_3^-), phosphate (PO_4^{3-}), silicate ($Si(OH)_4$), dissolved inorganic carbon (DIC), total dissolved iron (Fe) and total dissolved manganese (Mn) was studied at three different stations in the Gulf of Finland (GoF), Baltic Sea during three cruises in June–July 2003, September 2004 and May 2005. The stations were situated on different bottom types in the western, central and eastern part, respectively, of the open GoF. The fluxes were measured *in-situ* using the autonomous Göteborg benthic lander. To simulate resuspension events, the stirring speed was increased in two of the four chambers of the lander after approximately half of the incubation time. The other two chambers were used as control chambers. Clear effects of resuspension were observed on the oxygen fluxes where an increase of the consumption was observed in 88% of the cases and on average with 59% (stdev = 53). The NH_4^+ fluxes were affected in 50% of the cases (4 out of 8 incubations) at stations with low bottom water oxygen concentrations, but in no cases where the bottom water was oxygenated (0 out of 9 incubations). The NH_4^+ fluxes decreased by $26 \pm 27\%$ in 2005 and by $114 \pm 19\%$ in 2003. There was no clear effect of resuspension on the fluxes of any of the other solutes in this study. Thus, resuspension events did not play a significant role in release/uptake of NO_3^- , PO_4^{3-} , $Si(OH)_4$, DIC, Fe and Mn in GoF sediments. However, increased oxygen consumption as a result of resuspension may lead to spreading of anoxic/suboxic bottom water conditions, and thus indirectly to increased benthic release of phosphate, ammonium and iron.

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1. Introduction

The Gulf of Finland (GoF) is the most eutrophicated sub-basin in the Baltic Sea. In spite of a decrease of the external load of nutrients to the Gulf in the late 1990s eutrophication is still the most serious environmental problem in the Gulf. The external load of nutrients decreased by 30–40%, mostly due to a decrease in agriculture and industrial production in Russia and Estonia, after the collapse of the Soviet Union (Pitkänen et al., 2001; Kiirikki et al., 2003). Internal loading, release from the sediments, has been discussed as a reason (Pitkänen et al., 2001) why the phosphorus concentration has not decreased in the water of the Gulf. High nutrient concentration leads to high biomass production and consequently to higher settling of detritus to the sea floor. The detritus settling on the sediment is a source of nutrients,

which are leaking back to the water column, if they are not buried and becoming a part of the benthic nutrient pool, or, in the case of nitrate, denitrified.

Resuspension is a common physical process that occurs when shear stress is high enough to move the sediment particles from the sediment surface into the water column. Resuspension is known to occur everywhere in the marine environment, in coastal areas as well as in the deep-sea (Gross et al., 1988; Vangriesheim and Khripounoff, 1990; Thomsen et al., 1994). It can be caused by natural events, such as strong winds, tidal currents and biological activities (Graf and Rosenberg, 1997), or by anthropogenic perturbations, such as trawling and dredging. The process leads to a transport of particles along the sea floor with currents. In fact, a major part of the organic matter found on the deep-water accumulation bottoms in the Baltic Sea originates from eroded or resuspended shallow water sediments (Jonsson et al., 1990). Jönsson et al. (2005) concluded from a model study that almost the entire Baltic Sea down to around 80 m depth is affected by wave-induced resuspension, at least once a year. In a model study of the Baltic proper, Danielsson et al. (2007) concluded that the number of resuspension events were on average 4.6/month with a

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duration of about 22 h on average. Almost one fifth of the modeled area (Baltic proper) was resuspended between one day and one week each month and in general, substantial resuspension could be found at depth down to 40–60 m.

Whether resuspension leads to increased exchange rates of solutes between the sediment and the water column has been debated during the past decades. Higher mineralization rate of resuspended material (leading to higher release of nutrients and DIC as well as stimulated uptake of oxygen) has been shown in a model study by Wainright and Hopkinson (1997) and experimentally by Ståhlberg et al. (2006). Based on laboratory studies Wainright (1987, 1990) explained increased bacterial activities at resuspension events by higher availability of nutrients and organic material. A resuspension event during onset of a storm in Mobile Bay in the NE Gulf of Mexico resulted in higher concentration of nutrients in the overlying water due to mixing of pore water and stimulated remineralisation (Fanning et al., 1982). They also showed in parallel laboratory incubations that as little as 1 mm of resuspended shelf sediment is enough to significantly increase nutrient concentrations leading to increased productivity by as much as 100–200% in the water. Morin and Morse (1999) found that about two thirds of the ammonia released from resuspended sediment originated from desorption rather than dilution of pore water. Tengberg et al. (2003) showed in an *in-situ* study in the archipelago of Göteborg (Sweden) that resuspension reduced the remineralisation rate due to dilution of the organic material. The study was made when productivity in the water was low (winter) and the organic material in the sediment was old and refractory. In the same study, Tengberg et al. (2003) concluded that resuspension could lead to a decrease of the phosphate flux. Spagnoli and Bergamini (1997) suggested that resuspended material and pore water transported to the oxic water column might stimulate formation of iron oxides, which adsorbs phosphate, with a decrease or small change of phosphate concentration in the water column as a result. In areas where the iron level is low, as in Lake Arresø in Denmark, Søndergaard et al. (1991) concluded in a laboratory study that resuspension plays a major role, by increasing the phosphate flux for the high nutrient level in the lake.

Sloth et al. (1996) argued that a marine system is just showing a short-term response to resuspension. In that laboratory study, there was a high increase in oxygen consumption, 10 times the normal, but only small changes in nutrient fluxes. Blackburn (1997) stated that natural resuspension does not significantly contribute to a long-term liberation of nitrogen from the sediment. Thus, in that model study, it was concluded that the release of nitrogen with or without resuspension is just a matter of time; it is a sudden or a gradual release but to the same extent. The author argued that at least 2.4 cm of the sediment (coastal sediment with mm scale of oxygen penetration) has to be resuspended before the transfer of nitrogen would be affected. Such important mixing is not likely to occur by natural resuspension according to Blackburn (1997).

Koschinsky et al. (2001) performed a different set of laboratory resuspension experiments on cores collected from the deep-sea (water depth around 4000 m). Adsorption to suspended particles leads to a lower change in concentration than expected. This was, however, not the case for silicic acid. One of the conclusions from this study pointed at the necessity of performing *in-situ* studies, since it is difficult to maintain *in-situ* conditions on recovered cores, especially from the deep-sea.

Higher release of nutrients from the sediment (internal load) due to resuspension events might be a reason for the high nutrient concentrations in the Gulf of Finland, in spite of the decrease of the external load. The aim of this study was to clarify the effect of resuspension on the flux of a series of solutes

between the sediment and the water column, using elaborated *in-situ* techniques at different stations and during different years.

2. Materials and methods

2.1. Study site

The Gulf of Finland (Fig. 1) is a direct extension of the Baltic Proper and is surrounded by the countries Finland, Russia and Estonia. The surface area is 29,600 km² that is about 7% of the total area of the Baltic Sea, and the average water depth is 38 m (Perttilä et al., 1995). The central GoF is deeper with an average depth of more than 60 m. The South eastern part is somewhat shallower and the easternmost part of the GoF (Neva bight) is very shallow with a mean depth of 5 m. The total volume of the GoF is 1100 km³, which is 5% of the volume of the whole Baltic Sea. The drainage area is about 20% of the total drainage area of the Baltic Sea (Alenius et al., 1998). Most of the fresh water input enters the GoF in the east where the biggest (in terms of water transport) Baltic river Neva enters the GoF from the Russian territory. The Neva has a long-term (1859–1988) mean flow rate of about 2500 m³/s. In the southeast, the river Narva enters the GoF from Estonia, with a long-term (1956–1993) mean flow rate of about 400 m³/s (Helcom, 2004). The hydrography of the GoF is typical of estuaries. It is characterised by large horizontal and vertical variations. The water exchange with the Baltic Proper is not limited by a sill, thus there are no topographically isolated water masses in the GoF (Alenius et al., 1998). Due to the large fresh water inflow in the east and the water exchange with the Baltic Proper in the west, there is a horizontal salinity gradient in the GoF from east (about 0–2) to west (5–7 in the surface and 8–9 at bottom) (Perttilä et al., 1995; Alenius et al., 1998). A permanent halocline in the west exists throughout the year at 60–80 m depth. The existence of the halocline limits vertical mixing of the water body down to the bottom (Alenius et al., 1998). The saltier water from the Baltic proper enters the GoF along the bottom.

Relative to its surface area, the GoF (together with the Gulf of Riga) is the most nutrient loaded sub-basin in the Baltic Sea. The nutrient load to GoF is to a large extent governed by the nutrient load from the River Neva, which has its origin in the Lake Ladoga (Pitkänen and Tallberg, 2007).

In this study, the three stations (Fig. 1) were occupied at multiple occasions during three cruises in June–July 2003, September 2004 and May 2005. The station PV1 (about 80 m water depth) is situated at the mouth of the Gulf on an accumulation bottom, the station Kasuuni (about 50 m) on a transport bottom, and station XV1 (about 40 m) is situated on a bottom with mainly erosion/transport character. The reason for selecting these three sites as the main project stations was that they have been extensively sampled in the past, they are evenly distributed in the Gulf, separated by approximately 180 km, and their sediment characteristics are considered to be the representative for the majority of the deeper parts of the GoF.

2.2. Benthic fluxes measured *in-situ*

The Göteborg benthic lander was used to make autonomous incubations and collect water samples to measure benthic solute fluxes of oxygen (O₂), ammonium (NH₄⁺), nitrate (NO₃⁻), phosphate (PO₄³⁻), silicate (Si(OH)₄), dissolved inorganic carbon (DIC), total dissolved iron (Fe) and total dissolved manganese (Mn) *in-situ*. Four squared chambers of 400 cm² each, mounted on the lander were used for the flux incubations. A more detailed description of the Göteborg benthic lander in general can be found in Ståhl et al.

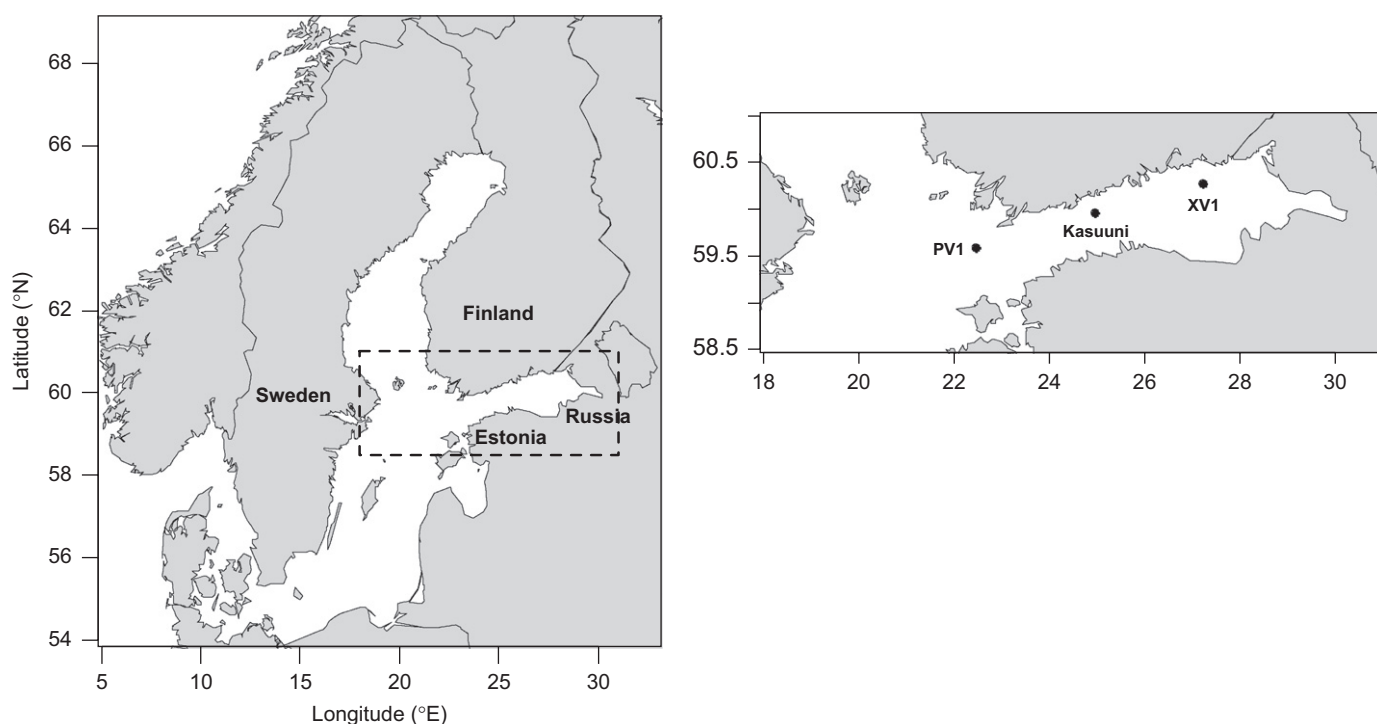


Fig. 1. Map of the Baltic Sea and the Gulf of Finland with the three stations visited during the three cruises indicated.

(2004b). The *in-situ* resuspension set-up that was improved for this project was first described in Tengberg et al. (2003), while the design and hydrodynamics of the incubation chambers are described in detail in Tengberg et al. (2004).

The incubations lasted 15–70 h (typically 23–33 h). The large range in incubation times was primary due to logistical reasons; in some cases the lander was deployed on Friday night and recovered on Monday morning. Resuspension was created in two of the four chambers, at each deployment, after about half of the incubation time by an increase of the stirring speed. In all four chambers, the amount of suspended particles in the overlying water was measured using optical backscatter turbidity sensors (model 3612A, from Aanderaa Data Instruments, www.aadi.no), mounted on the chamber lids. Such sensors have been used in numerous other projects and their performance have been evaluated and compared with other methods in e.g. Karageorgis et al. (2003).

Before each expedition, the entire incubation chambers and all the sampling syringes were carefully acid washed and rinsed in distilled water. In the beginning of the incubations, a known amount of bromide (Br^-) was injected into the chambers. The exact water heights in the chambers were calculated by determining the concentration of the bromide after dilution in the chamber water, taking into account the ambient sea water bromide concentration (e.g. Rao and Jahnke, 2004). The uncertainty of the determination of the water height from bromide data was calculated to be about 3.6% (Andersson et al., 2006). This uncertainty was not included in the estimation of the uncertainty of the effect of resuspension on fluxes, since flux measurements before and after resuspension were made in the same volume of water.

During the incubation, nine discrete samples were withdrawn at pre-set times using 60 ml polypropylene syringes. In the resuspension chambers five syringes were taken before the increased stirring speed and the remaining four syringes were taken after resuspension was created. Immediately after recovery of the lander, the water samples in the syringes were

filtered through disposable $0.45 \mu\text{m}$ pore size cellulose acetate filters. The filters were rinsed prior to use with 60 ml of ultra pure MQ-water. The linear development of the solute concentration with time together with the water height was used to calculate benthic fluxes (in $\text{mmol}/\text{m}^2/\text{d}$).

Bottom water was sampled before and after each deployment using “Niskin bottles” mounted on a CTD-rosette and on the lander frame, respectively. The bottom water was analysed for the same solutes as measured during the flux incubations, and the samples were therefore treated in the same way. The chamber fluxes were then compensated for the effects of the refill water, which was the ambient bottom water replacing the sample volume in the chambers at each sampling.

At the recovery of the lander, the incubated sediment and the overlying water in the chambers were brought to the surface. To check if there was any macrofauna in the sediment, which could have had an influence on the solute fluxes, the sediment was sieved (1 mm). Due to highly variable and frequently low oxygen conditions at the studied sites macrofauna were rarely found, and when present were at low abundance. The influence of bioturbation/bioirrigation on the solute fluxes can therefore be neglected in this study.

2.2.1. Determination of the effect of resuspension on solute concentrations and fluxes

To decide if resuspension was successfully created in different chambers, the following criteria were used: (1) the measured turbidity had to increase by at least 100% after the increase in stirring and (2) the average turbidity had to be at least 5 Normal Turbidity Units (NTU), which for the studied stations equalled an increase of resuspended sediment with approximately $6 \text{ mg}/\text{l}$ (see calibration of turbidity sensors below). If these criteria were fulfilled, the chamber was considered to be a successful resuspension chamber.

To evaluate the effects of the created resuspension on the fluxes of the different solutes, a multi-step procedure was used:

(1) a linear regression line using all the data points was drawn; (2) linear regression lines were drawn for all the data points before the stirring speed was increased and for all the data points after the increased stirring speed, respectively; and (3) fluxes with an uncertainty (explained below) greater than or equal to the flux itself were rejected and not taken into account. However, to prevent low fluxes (often with a greater uncertainty than high fluxes) to be rejected to a larger extent than high fluxes, and in this way introduce a bias, the low fluxes with an uncertainty greater than or equal to the flux were tested by a special method. First the lowest accepted flux (F_{acc}) from the whole data set was identified. Then the low flux had to be lower than the F_{acc} and the uncertainty of the low flux had to be lower than five times the flux. If this was the case, then the low flux was set to zero (Brunnegård et al., 2008a), otherwise it was rejected. (4) The slopes of the regression lines before and after the time for the increased stirring speed were tested (using t -test) and retained as an affected flux if they were significantly different ($p \leq 0.05$). The fluxes in the resuspension chambers where a significant change was found, were compared to the fluxes in the control chambers where no resuspension was induced. If fluxes in the resuspension chambers behaved differently compared to the fluxes in the control chambers, we considered effects of resuspension to have occurred.

Calculated initial fluxes are the same as the flux before resuspension for all substances, except for oxygen. As oxygen was measured with a sensor, and thus with a higher sampling frequency than the other substances, fluxes of oxygen before and after resuspension were calculated using 30–150 data points closest before and after the time when resuspension was created.

The quantification of the effect of resuspension on the fluxes was obtained by calculating the average change of the fluxes in the resuspension chambers at each deployment. Any change of the fluxes caused by other factors than resuspension in the control chambers during the same deployment was calculated in the same way and at the same time as in the resuspension chambers. The total effect of resuspension was then compensated for these non-resuspension effects.

Resuspension might also affect the concentrations in the chambers with a strong response, but with a short duration of less than the time between samples, thus giving the impression of an instant effect. To investigate this possibility, confidence intervals for the linear regressions before and after the time of resuspension were calculated. If the confidence intervals overlapped, no instant changes in concentrations had occurred.

The flux was calculated by using the slope of a linear regression line (change in concentration over time) together with the height of the overlying water in the chamber. The uncertainty of each flux was calculated by using the standard error of the slope. The standard error was then divided by the slope of the regression line and multiplied with the flux to obtain the uncertainty of the flux. If the uncertainty of the flux was larger than the flux, it was rejected.

2.3. Analytical methods

The nutrient (NO_3^- , NH_4^+ , PO_4^{3-} and $\text{Si}(\text{OH})_4$) samples were stored in polystyrene vials in a cool room (at 4–5 °C) before analysis. The determinations were made using standard photometric methods. In 2003, the analyses were performed at the Department of Marine Ecology at the University of Gothenburg using the multi channel TRAACS 800 auto-analyser (Bran and Luebbe). Total NO_3^- ($\text{NO}_3^- + \text{NO}_2^-$) was determined without specifying the contribution from NO_2^- . Samples from the cruises in 2004 and 2005 were analysed at the Finnish Institute of Marine

Research in Helsinki using a Lachat QC 8000. Both the concentrations of total NO_3^- and NO_2^- were measured. All standard solutions were diluted with artificial sea water or MilliQ in the TRAACS and Lachat, respectively. For both sets of auto-analyser determinations, a precision of about 5% (RSD) was obtained.

Determination of DIC was performed on-board of the research vessel immediately after the recovery of the lander using an automated system based on non-dispersive infrared detection of CO_2 (Goyet and Snover, 1993; O'Sullivan and Millero, 1998; Ståhl et al., 2004a).

Oxygen concentration inside the chambers and in the ambient bottom water was measured at one or two minute intervals using single point optical oxygen sensors (model 3830 from Aanderaa Data Instruments). In-between deployments and expeditions all the optodes (a total of 6) were regularly checked against Winkler titrations and found to be without drift and with an absolute accuracy within $\pm 3\%$ or $\pm 3 \mu\text{M}$ at lower oxygen concentrations (below $100 \mu\text{M}$). Also previous studies have demonstrated the high accuracy, precision and long-term stability of these optodes (Körtzinger et al., 2004; Tengberg et al., 2006).

The determinations of dissolved iron and manganese were performed on-board ship using spectrophotometrical methods. Ferrozine and formaldoxyme were used as reagents for iron and manganese, respectively. For more information about benthic Fe and Mn fluxes in the GoF and the employed analytical methods, see Pakhomova et al. (2007).

To determine if and to what extent resuspension was created inside the chambers, turbidity sensors were used to determine the concentration of suspended material in Normal Turbidity Units. In addition to sensors mounted inside the chambers, a sensor was also mounted outside the chambers measuring the background level in the ambient bottom water. The data were transformed from NTU to mg suspended material/litre by taking multiple water samples at each station, which were filtered and compared to Turbidity sensor readings according to detailed descriptions given in Tengberg et al. (2003). It was found that for the particles resuspended in the bottom water, at the three main stations, the established calibration curves varied less than 10% between years and sites. Therefore, it was decided to use an average calibration equation, shown below, for all the deployments and sites:

Bottom water-suspended particles (mg/l) = $1.2 \cdot \text{sensor value (NTU)} - 0.3$.

3. Results and discussion

The low oxygen concentration and the relatively elevated salinity in the bottom water at PV1, during the cruises in 2003 and 2005, indicated that the measurements were performed below the halocline (Table 1). In 2004, the halocline had been temporarily broken up due to an important out-flush of water along the bottom after a longer period of strong winds which built up the water level on the Finnish shores north of the station. When this station was visited in 2004, the bottom water had lower salinity and higher oxygen concentrations than in 2003 and 2005. Concentrations of other substances (PO_4^{3-} , $\text{Si}(\text{OH})_4$, DIC, dissolved Fe and dissolved Mn) also indicated different water masses in 2003 and 2005 compared to 2004 (Table 1). Also the initial fluxes of all measured substances, except for nitrate and oxygen, were higher in 2003 and in 2005, compared to fluxes in 2004 (Fig. 2). Long-term measurements of oxygen, salinity, turbidity, currents and temperature (Tengberg et al., unpublished results) showed that the area is hydrographically variable due to currents and advection, and the ambient bottom water was not only changed in-between years but also between deployments (Table 1).

Table 1
Average values of temperature, salinity, turbidity, and average concentrations of oxygen, nutrients, DIC, iron and manganese in the bottom water at the beginning of each deployment at different stations and during different years.

Station	Dep.	Year	Month	Depth (m)	Position (N, E)	Temp (°C)	Sal	Turb (mg/l)	O ₂ (μM)	NH ₄ ⁺ (μM)	NO ₃ ⁻ (μM)	PO ₄ ³⁻ (μM)	DIC (μmol/kg)	Si(OH) ₄ (μM)	Fe (μM)	Mn (μM)
PV1	1	2003	June	75	59°35', 22°28'	4.1	9.2	0.8	10.3	7.6	0.0	4.8	-	67.9	0.27	11.1
PV1	2	2003	June	73	59°35', 22°28'	4.0	9.2	3.3	1.00	2.4	1.6	3.9	-	68.4	0.19	6.8
Kasuuni	1	2003	July	-	59°57', 24°59'	2.4	7.5	1.2	162	0.3	9.1	2.9	-	42.0	0.01	1.7
Kasuuni	2	2003	July	53	59°57', 24°59'	2.5	7.6	1.0	137	0.6	9.8	2.5	-	44.5	0.40	3.0
PV1	1	2004	September	70	59°35', 22°28'	3.6	7.8	3.3	137	2.7	6.2	2.1	1737.5	37.7	0.00	2.6
PV1	2	2004	September	75	59°35', 22°28'	2.8	7.7	1.1	148	2.1	7.0	2.0	1677.6	28.2	0.01	0.1
Kasuuni	1	2004	September	49	59°57', 24°59'	2.9	7.1	1.7	210	2.3	7.3	1.9	1659.0	28.8	-	-
Kasuuni	2	2004	September	54	59°57', 24°59'	4.7	6.5	1.0	218	2.1	5.4	1.6	1590.5	19.5	0.02	1.2
PV1	1	2005	May	73	59°35', 22°28'	5.0	10.4	2.8	6.5	0.7	7.2	3.3	1919.3	53.2	0.91	9.2
PV1	2	2005	May	76	59°35', 22°28'	5.2	10.4	0.5	11.6	1.3	5.5	3.4	1939.4	52.4	0.19	7.3
Kasuuni	1	2005	May	56	59°57', 24°59'	3.4	8.1	2.5	180	0.2	7.7	1.3	1708.1	27.6	0.02	1.8
Kasuuni	2	2005	May	54	59°57', 24°59'	2.9	7.8	1.7	251	0.7	7.5	1.3	1734.2	26.4	0.01	4.2
XV1	1	2005	May	36	60°16', 27°14'	2.0	6.8	0.9	-	0.2	9.3	1.4	1634.2	23.2	-	-
XV1	2	2005	May	38	60°16', 27°14'	2.0	6.5	0.8	285	1.2	9.6	1.3	1566.4	19.1	-	-

Both stations Kasuuni and XV1 were situated above the halocline and the bottom water was oxygenated (130–285 μM) during all expeditions. The concentrations in the bottom water of all the measured substances, with the exception of nitrate and oxygen, were at these stations on average lower than at PV1 in 2003 and 2005. Initial fluxes of the measured substances were also lower at Kasuuni and XV1 with the exception of oxygen, nitrate and dissolved manganese. Fluxes of dissolved manganese were higher at the stations with oxygenated bottom water compared to PV1 with anoxic/suboxic bottom water, which was explained by the fivefold higher pore water concentration of dissolved manganese especially at Kasuuni (Pakhomova et al., 2007).

3.1. Natural vs. created resuspension

Station PV1 was characterised as an accumulation bottom and the sediment consisted of 80–90% of pelitic mud. Stations Kasuuni and XV1 were characterised as transport/erosion bottoms and the sediment had coarser grain size (Brunnegård et al., 2008b). As resuspension events occur, finer sediment particles and organic material are lifted up from the sediment surface into the water. The material is then transported with currents to deeper areas, where it is accumulated, e.g. PV1. Continuous measurements performed at the three stations about 1 m above the bottom during 10 months in 2003–2004 showed that currents were in general low (~4 cm/s). During the time of these measurements only a few small resuspension events occurred. The background turbidity values at 1 m above the bottom varied from 0.4–1.0 mg/l depending on the station and there were not more than three resuspension events at each station, of which the highest showed a turbidity of 11 mg/l (Tengberg et al., unpublished results). However, during the 2004 cruise, a current meter with a turbidity sensor, placed outside the chambers about 2 m above the bottom, recorded current speeds of up to 46 cm/s and turbidity values as high as 10 mg/l at PV1 during a lander deployment indicating a major resuspension event. Assuming that the suspended particles were limited to below 3 m above the sea floor and equally distributed in the water, they corresponded to 256 μm of the sediment surface to be resuspended into the overlying bottom water. This thickness of the resuspended sediment surface layer is similar to the maximum thickness of the sediment layer resuspended in the resuspension chambers (range 3.4–240 μm, on average 67 μm). The maximum magnitude of the simulated resuspension in the chambers was thus similar to the maximum magnitude of resuspension recorded in the ambient GoF bottom waters. We have therefore considered the induced resuspension in the chambers to be representative of natural resuspension events.

3.2. The effect of resuspension on benthic solute fluxes

Resuspension was induced in 15 of the 32 incubations performed during the three cruises. The effect on oxygen consumption was clear in 13 of them (87%, Table 2). Considering all stations and all years, the oxygen consumption increased by between 1.3 ± 0.4 mmol/m²/d ($15 \pm 3\%$) and 26.3 ± 1.4 mmol/m²/d ($175 \pm 10\%$), and on average by 59% (stdev = 53), due to resuspension (Table 3, Fig. 3). At PV1, which is a station with accumulation bottom and periods of low or no oxygen in the bottom water, the effects on the fluxes into the sediment were greatest, with increased consumption on average with 115% (stdev = 85). At Kasuuni, which is a station of transport bottom type and where oxygen is present in the bottom water most of the time, the increase of consumption was about 45% (stdev = 29). At the transport/erosion bottom station XV1, the consumption increased

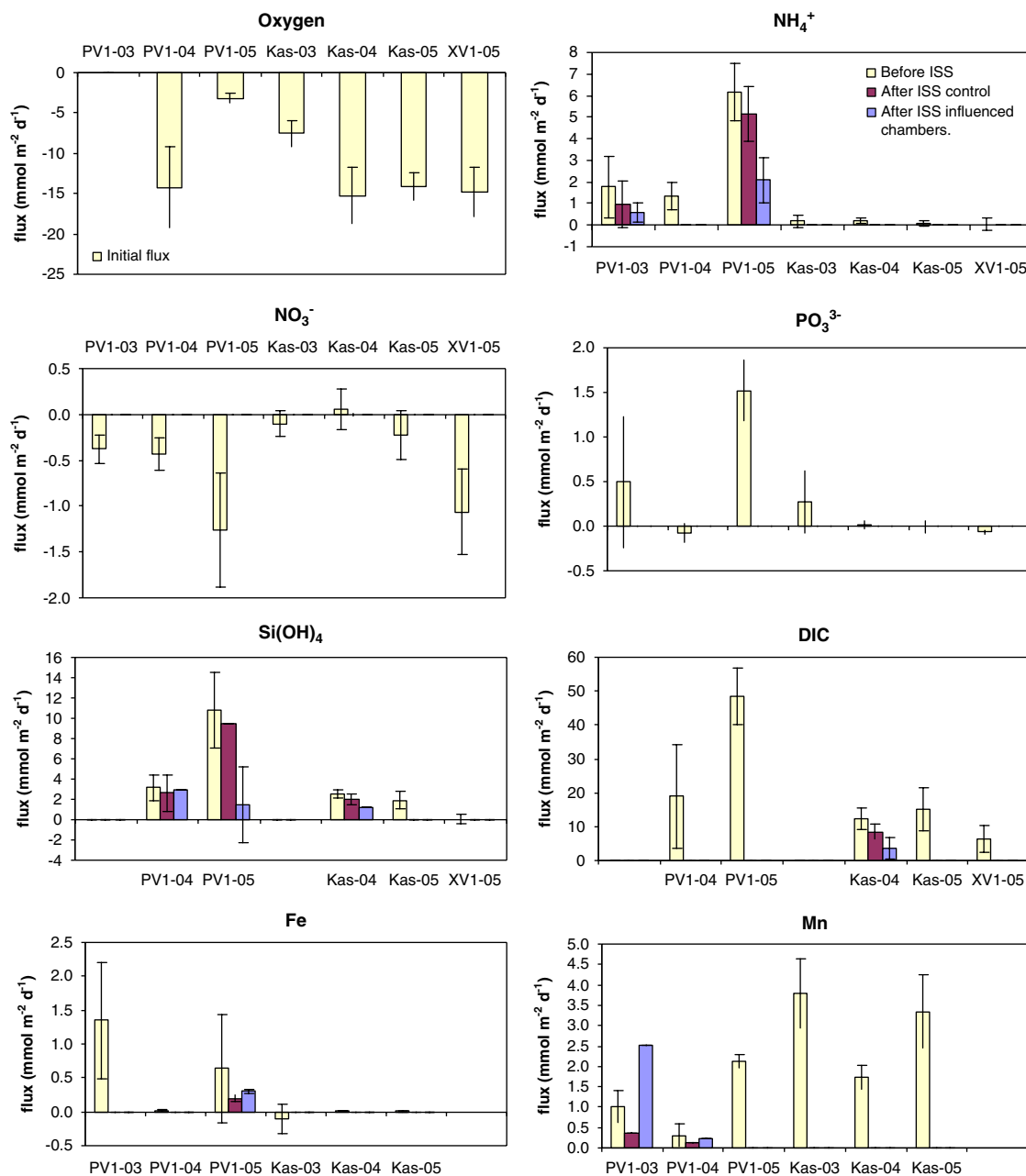


Fig. 2. The average fluxes (mmol/m²/d) of the solutes at the different stations and during the different years are shown. The first bars show the average initial flux in all chambers at each station and year (□). The second bars show the average flux after the time of increased stirring speed in the control chambers (■) and the third bars show the average flux after the time of increased stirring speed in the resuspension chambers in which an effect was observed (▨). The average fluxes after resuspension are only shown for deployments, in which effects of resuspension were observed. Displayed error bars show standard deviations. Data for Si(OH)₄ and DIC in 2003, and for dissolved iron and manganese at station XV1 in 2005, are not available. Only initial fluxes of oxygen are shown.

Table 2

The total number of successful incubations (Tot. Inc.), the number of incubations in which resuspension was created (R. chambers), the number of chambers in which (Effect of R.) and the frequency at which (Effect of R. (%)) effects of the created resuspension were observed are shown for different solutes.

Substance	O ₂	NH ₄ ⁺	NO ₃ ⁻	PO ₄ ³⁻	Si(OH) ₄	DIC	Fe	Mn
Tot. Inc.	32	34	28	29	31	30	24	29
R. Chambers	15	17	14	17	16	16	15	18
Effect of R.	13	4	0	0	5	3	3	3
Effect of R. (%)	87	24	0	0	31	19	20	17

with about 15±3% (Table 3). Examples of measured oxygen concentrations during incubations are shown in Fig. 4.

Due to low oxygen concentration (less than 12 μM) in the bottom water at PV1 in 2005 (Table 1), all oxygen was consumed in the chambers during incubations. As a result, it was not possible to study the effect of resuspension on the oxygen consumption at this station this year. The low oxygen concentrations at PV1 in 2003 and 2005 (Table 1) did, however, give the possibility to study fluxes of other solutes (e.g. metals, DIC and nutrients) at suboxic conditions which is presented in e.g.

Table 3

The fluxes (mmol/m²/d) of the solutes before and after the time of increased stirring speed (ISS) in the resuspension chambers (RC), the changes in flux (mmol/m²/d) in each chamber, the average changes in flux (mmol/m²/d) in the resuspension chambers and in the control chambers (CC), and the total effect on the fluxes (mmol/m²/d) due to resuspension.

Subs.	Year	Station	D:C	RC/CC	mmol/m ² /d flux ± unc before ISS	Flux ± unc after ISS	Change in flux ± unc	Average change ± unc	Total effect ± unc
O ₂	2003	Kas	2:3 2:4	CC RC*	-7.3 ± 0.2 -7.7 ± 0.2	-7.1 ± 0.2 -8.8 ± 0.3	0.2 ± 0.25 -1.1 ± 0.34	0.2 ± 0.25 -1.1 ± 0.34	-1.3 ± 0.4
O ₂	2004	PV1	1:2 1:4	CC RC*	-17.7 ± 0.5 -15.1 ± 0.5	-15.4 ± 0.5 -39 ± 1	2.3 ± 0.7 -24 ± 1	2.3 ± 0.7 -24 ± 1	-26 ± 1
O ₂	2004	PV1	2:2 2:3 2:4	CC RC* RC*	-13.0 ± 0.2 -11.0 ± 0.2 -11.2 ± 0.2	-13.2 ± 0.2 -18.7 ± 0.2 -15.9 ± 0.2	-0.1 ± 0.3 -7.6 ± 0.2 -4.8 ± 0.2	-0.1 ± 0.3 -6.2 ± 0.2	-6.1 ± 0.3
O ₂	2004	Kas	1:2 1:3 1:4	CC RC* RC*	-6.30 ± 0.09 -6.3 ± 0.1 -6.99 ± 0.09	-6.78 ± 0.09 -8.6 ± 0.1 -11.25 ± 0.08	-0.5 ± 0.1 -2.3 ± 0.1 -4.3 ± 0.1	-0.5 ± 0.1 -3.29 ± 0.09	-2.8 ± 0.2
O ₂	2004	Kas	2:3 2:3 2:4	CC RC* RC*	-11.5 ± 0.1 -9.0 ± 0.1 -8.2 ± 0.1	-11.54 ± 0.09 -14.8 ± 0.1 -18.3 ± 0.1	-0.1 ± 0.2 -5.8 ± 0.2 -10.1 ± 0.1	-0.1 ± 0.2 -8.0 ± 0.1	-7.9 ± 0.2
O ₂	2005	Kas	1:1 1:2 1:3 1:4	CC CC RC* RC*	-16.8 ± 0.2 -16.0 ± 0.2 -15.6 ± 0.2 -16.6 ± 0.2	-14.6 ± 0.2 -14.3 ± 0.2 -19.2 ± 0.2 -24.6 ± 0.2	2.3 ± 0.3 1.7 ± 0.3 -3.6 ± 0.3 -8.0 ± 0.3	2.0 ± 0.2 -5.8 ± 0.2	-7.8 ± 0.3
O ₂	2005	Kas	2:2 2:3 2:4	CC RC* CC*	-9.9 ± 0.1 -10.0 ± 0.1 -10.0 ± 0.1	-9.3 ± 0.1 -12.4 ± 0.1 -11.7 ± 0.1	0.6 ± 0.2 -2.4 ± 0.2 -1.6 ± 0.2	0.6 ± 0.2 -2.0 ± 0.1	-2.6 ± 0.2
O ₂	2005	XV1	1:1 1:2 1:3 1:4	CC CC RC* RC*	-12.0 ± 0.2 -11.4 ± 0.3 -10.9 ± 0.2 -12.7 ± 0.2	-13.0 ± 0.2 -13.0 ± 0.3 -14.8 ± 0.2 -14.9 ± 0.2	-1.0 ± 0.3 -1.6 ± 0.5 -3.9 ± 0.3 -2.1 ± 0.3	-1.3 ± 0.3 -3.0 ± 0.2	-1.8 ± 0.4
NH ₄ ⁺	2003	PV1 ^a	1:1 1:2 1:3 2:1 2:2 2:3	RC* RC* RC CC CC CC	3.7 ± 0.8 4 ± 1 2.1 ± 0.9 0.3 ± 0.1 0.8 ± 0.1 0.5 ± 0.2	0.27 ± 0.05 0.9 ± 0.3 -0.3 ± 0.2 0.3 ± 0.2 2.19 ± 0.05 0.3 ± 0.2	-3.4 ± 0.8 -3 ± 1 -2 ± 1 0.0 ± 0.2 1.4 ± 0.1 -0.2 ± 0.3	-2.9 ± 0.5 0.4 ± 0.1	-3.3 ± 0.6
NH ₄ ⁺	2005	PV1 ^a	1:3 1:4 2:1 2:2	RC* RC* CC CC	5.7 ± 0.5 6.3 ± 0.5 8 ± 1 6.7 ± 0.7	2.8 ± 0.6 1.3 ± 0.3 6 ± 3 4.2 ± 0.4	-2.8 ± 0.8 -5.0 ± 0.6 -2 ± 3 -2.5 ± 0.8	-3.9 ± 0.5 -2 ± 2	-2 ± 2
Si(OH) ₄	2004	PV1	2:1 2:2 2:3 2:4	CC CC RC* RC	1.7 ± 0.1 2.6 ± 0.4 2.1 ± 0.1 2.6 ± 0.4	1.4 ± 0.4 1.7 ± 0.4 3.0 ± 0.1 3.7 ± 0.7	-0.3 ± 0.4 -0.9 ± 0.5 0.8 ± 0.2 1.2 ± 0.8	-0.6 ± 0.3 1.0 ± 0.4	1.6 ± 0.5
Si(OH) ₄	2004	Kas	1:1 1:2 1:3 1:4	CC CC RC* RC	2.08 ± 0.04 1.84 ± 0.04 2.36 ± 0.04 2.47 ± 0.04	1.53 ± 0.05 1.56 ± 0.01 1.19 ± 0.09 1.8 ± 0.2	-0.55 ± 0.06 -0.28 ± 0.04 -1.2 ± 0.1 -0.7 ± 0.2	-0.42 ± 0.04 -0.9 ± 0.1	-0.5 ± 0.1
Si(OH) ₄	2005	PV1 ^a	1:3 1:4 2:2 2:3 2:4	RC* RC* CC RC* RC	9.6 ± 0.7 11 ± 1 8 ± 2 10 ± 1 8 ± 1	4.1 ± 0.9 -3 ± 1 9 ± 1 3 ± 2 10 ± 2	-5.5 ± 1 -14 ± 2 1 ± 2 -7 ± 2 2 ± 2	-9 ± 1 1 ± 2 -2 ± 1	-11 ± 3 -4 ± 3
DIC	2004	Kas	1:2 1:3	CC RC*	9 ± 1 11 ± 2	8 ± 1 0 ± 1	-1 ± 2 -11 ± 2	-1 ± 2	

Table 3 (continued)

Subs.	Year	Station	D:C	RC/CC	mmol/m ² /d flux \pm unc before ISS	Flux \pm unc after ISS	Change in flux \pm unc	Average change \pm unc	Total effect \pm unc
			1:4	RC*	9.7 \pm 0.9	4.9 \pm 0.8	-5 \pm 1	-8 \pm 1	-7 \pm 2
			2:1	CC	12 \pm 1	7.0 \pm 0.7	-5 \pm 1		
			2:2	CC	18 \pm 0.1	10.9 \pm 0.7	-7 \pm 1	-6 \pm 1	
			2:4	RC*	16 \pm 1	6.1 \pm 0.9	-9 \pm 1	-9 \pm 1	-3 \pm 2
Fe	2005	PV1	2:1	CC	0.124 \pm 0.007	0.16 \pm 0.02	0.03 \pm 0.02		
			2:2	CC	0.16 \pm 0.02	0.23 \pm 0.01	0.06 \pm 0.02	0.05 \pm 0.01	
			2:3	RC*	0.13 \pm 0.02	0.28 \pm 0.04	0.150 \pm 0.05		
			2:4	RC*	0.089 \pm 0.09	0.33 \pm 0.04	0.24 \pm 0.04	0.20 \pm 0.03	0.15 \pm 0.03
Mn	2003	PV1 ^a	1:3	RC*	1.2 \pm 0.1	0.5 \pm 0.1	-0.8 \pm 0.2	-0.8 \pm 0.2	-0.6 \pm 0.2
			2:3	CC	0.5 \pm 0.1	0.34 \pm 0.03	-0.2 \pm 0.1	-0.2 \pm 0.1	
			2:4	RC*	1.4 \pm 0.1	2.5 \pm 0.3	1.1 \pm 0.4	1 \pm 0.4	1.3 \pm 0.4
Mn	2004	PV1	2:2	CC	0.11 \pm 0.01	0.13 \pm 0.06	0.02 \pm 0.06	0.02 \pm 0.06	
			2:3	RC*	0.03 \pm 0.01	0.23 \pm 0.03	0.20 \pm 0.04		
			2:4	RC	0.19 \pm 0.02	0.18 \pm 0.02	-0.01 \pm 0.03	0.09 \pm 0.02	0.08 \pm 0.07

The uncertainties (unc) are shown after each flux; these uncertainties do not include chamber height uncertainties which do not influence the estimated effect of resuspension (see text). Only fluxes during deployments where statistically significant effects of resuspension on fluxes were observed are shown. The D:C column shows the deployment (D) and chamber (C) number. There were always four chambers in one deployment, but only chambers with a successful incubation or with a statistically significant flux are shown. If the effect on the flux is negative it means that the flux decreased. If the flux was negative from the beginning (an influx) the influx increases. The star denotes that the flux in the chamber was significantly affected by the induced resuspension, but does not mean that the overall effect (considering all stations and years) of resuspension on that solute flux was of major importance.

^a Control chambers from deployment 2 were used, when estimating the effect of resuspension, due to lack of significant fluxes in control chambers in deployment 1.

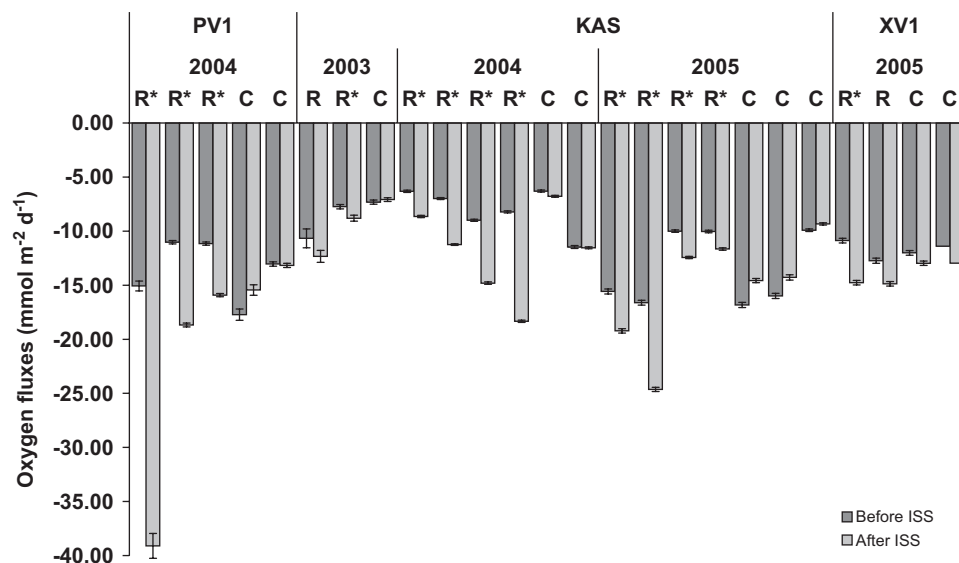


Fig. 3. The oxygen fluxes (mmol/m²/d) in each chamber of successful incubations are shown as fluxes before (before ISS) and after (after ISS) the time of increased stirring speed in the resuspension chambers. The error bars show the uncertainty of each flux. R denotes that it is a resuspension chamber and the star denotes that there was a significant change in flux due to resuspension. N denotes that the stirring speed was kept at a constant level throughout incubations. The fluxes from PV1 in 2005 are not shown due to that oxygen was depleted early during the incubation.

Pakhomova et al. (2007), Andersson et al. (2008) and Brunnegård et al. (2008b).

Along with sediment particles, pore water, including dissolved reduced substances, was also mixed into the overlying water. Thus, the stimulated oxygen consumption during the onset of resuspension events can be explained by an increased oxidation of reduced inorganic compounds (e.g. Anderson et al., 1986, and references therein). The increased stirring speed (Jørgensen and Des Marais, 1990; Tengberg et al., 2004) might also contribute to a

decrease of the diffusive boundary layer thickness and an increase in the oxygen penetration depth in the sediment and oxygen could in this way oxidise reduced compounds deeper down in the sediment than what would have been the case without resuspension, which contributes to the stimulated oxygen consumption at resuspension events. The increased oxidation of reduced inorganic substances would then be reflected in the fluxes of these substances. However, effects of resuspension were in most cases too low to be detected for solutes other than oxygen in this study.

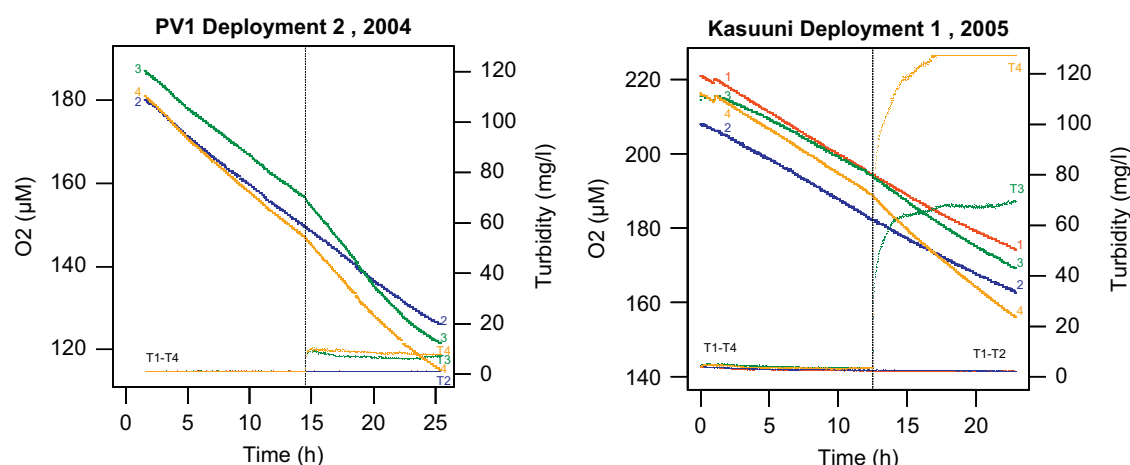


Fig. 4. Examples of the oxygen concentration versus time at PV1 in 2004 (left) and at Kasuuni in 2005 (right). The oxygen consumption increased in chamber 3 and 4 due to resuspension. This effect was not seen in the control chambers 1 and 2. The vertical dotted line denotes time for increased stirring speed, i.e. when resuspension was created. The numbers denotes the chamber numbers and the letter “T” in front of the numbers denotes the turbidity in chambers.

Significant changes in fluxes ($p < 0.05$) of ammonium due to resuspension were only observed in 4 of 17 resuspension chambers (24%, Table 2), and all of them at station PV1 during the cruises in 2003 and 2005. The effluxes decreased when resuspension was created (Fig. 2, Table 3). In the control chambers, in which the stirring speed was kept at a constant level, the fluxes generally increased (2003) or decreased less than in the resuspension chambers (2005). The resuspension affected the fluxes by $-3.3 \pm 0.6 \text{ mmol/m}^2/\text{d}$ ($-114 \pm 19\%$) and $-2 \pm 2 \text{ mmol/m}^2/\text{d}$ ($-26 \pm 27\%$) at PV1 in 2003 and 2005, respectively (Table 3). At the other stations and at PV1 in 2004, no effects on the ammonium fluxes, as a result of resuspension, were observed. Thus, all the affected fluxes were measured when the oxygen concentration in the overlying water was low (below $15 \mu\text{M}$). Examples of the evolution of different solute concentrations during chamber incubations are shown in Fig. 5.

No significant effects on the fluxes of nitrate and phosphate were observed due to resuspension. At PV1 in 2003 and 2005, the nitrate was depleted during the incubations shortly after oxygen was consumed, and no reliable fluxes of nitrate could, therefore, be calculated during these cruises.

Effects of resuspension on the fluxes of DIC were observed in 3 of the 16 resuspension chambers (19%, Table 2), and all of these three chambers were at Kasuuni in 2004 (Fig. 2). The fluxes decreased in the later part of incubations in all chambers. However, fluxes decreased to a higher extent in the resuspension chambers than in the control chambers (Table 3). The increase of oxygen consumption due to resuspension was not caused by the enhanced oxidation of organic carbon, but due to stimulated oxidation of dissolved reduced inorganic compounds in the sediment as already explained above. Thus, the DIC fluxes were not expected to increase during resuspension. The reason for decreased DIC fluxes is most likely due to decrease of the concentration difference of DIC between pore water and chamber water with time during incubations. The effect of resuspension on the DIC fluxes, in this study, was only observed at one of the stations in one year and the conclusion is that resuspension had no major impact on the DIC fluxes.

The silicate fluxes were affected by resuspension in 5 of 16 (31%, Table 2) chambers. The fluxes were affected in different ways by the resuspension events at different cruises and years (Fig. 2). At PV1 in 2004 the fluxes increased, but in 2005 and at Kasuuni in 2004, the fluxes decreased due to resuspension (Table 3). We have no obvious explanation for this behaviour of

silicate during resuspension. In principle, the silicate efflux should be less affected by the redox conditions and primarily controlled by the dissolution of biogenic silica (e.g. Rutgers van der Loeff et al., 1984, and references therein). Dissolution of biogenic silica should in theory increase during resuspension events due to the inverse relationship between dissolution rate and dissolved silicate concentration (Ragueneau et al., 2001, and references therein). However, this was not reflected in our silicate fluxes.

Effects of resuspension on the total dissolved iron fluxes and concentrations were observed in 3 out of a total of 15 resuspension chambers (20%, Table 2), and all at station PV1 (Fig. 2). At PV1 in 2005 during the second deployment, the effluxes increased with 0.15 ± 0.05 and $0.24 \pm 0.04 \text{ mmol/m}^2/\text{d}$ in the two resuspension chambers, which resulted in a total effect on the iron fluxes with $0.15 \pm 0.03 \text{ mmol/m}^2/\text{d}$ ($136 \pm 31\%$) during this deployment (Table 3). In 2003, there was an instant increase in concentration in one of the resuspension chambers. The concentration was about $1.7 \mu\text{M}$, in this chamber, just before resuspension was created and instantly increased to about $10 \mu\text{M}$ right after the onset of resuspension. At Kasuuni, a station with high oxygen concentration in the bottom water during all years, no resuspension effects on the iron concentrations or fluxes were observed.

Effects on the manganese fluxes due to resuspension were observed in 3 out of 18 (17%, Table 2) resuspension chambers. The affected fluxes were observed at PV1 in 2003 and 2004 (Fig. 2). In 2003 the fluxes both increased and decreased as a result of resuspension, but on average, the manganese fluxes increased in both years (Table 3). At Kasuuni in 2003 and 2004, all fluxes decreased during the later phase of the incubation and no effects of resuspension were observed. No effects on the Mn fluxes in any of the chambers at any of the stations were observed during the 2005 cruise.

Effects of resuspension were observed on the oxygen fluxes and on the ammonium fluxes when oxygen concentration was low (in 4 of 8 resuspension chambers). Effects of resuspension on the DIC fluxes were only found in 2004 and at one station (Kasuuni), leading to the conclusion that the overall effect of resuspension on DIC fluxes considering all deployments, stations and years was not significant. The same conclusion was reached for silicate, dissolved iron and manganese fluxes. For silicate and manganese fluxes, resuspension resulted in either increased or decreased fluxes (Table 3) without any regular pattern, which lead to the conclusion that the effect of resuspension was not significant on these solute fluxes.

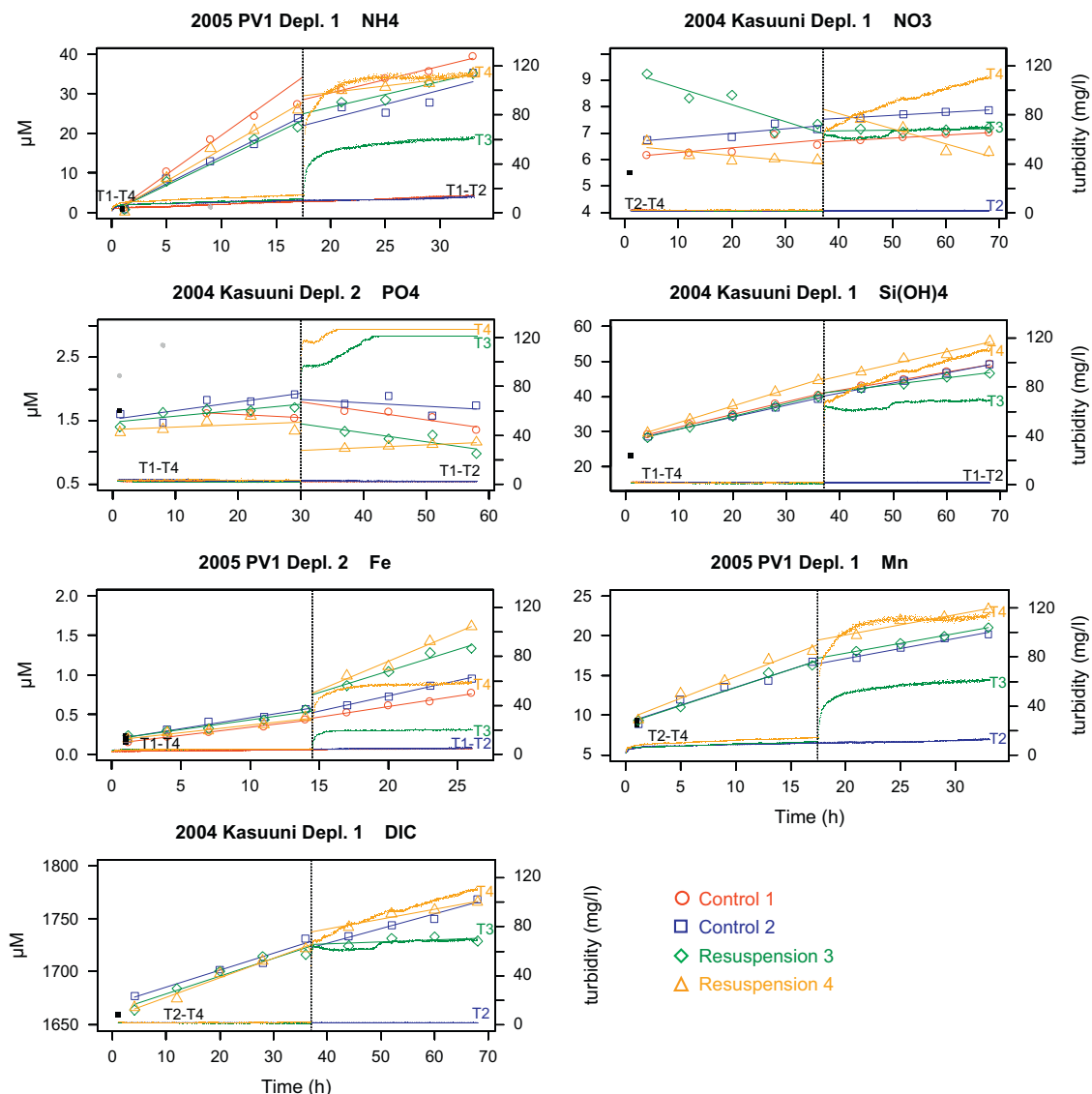


Fig. 5. Examples of evolution of solute concentrations during chamber incubations. The marks are data points and the lines show the regression for each data set. The symbols represent the different chambers. The letter "T" in front of the symbols denotes the turbidity (shown as dots) in the chamber. The vertical dotted line denotes time of increased stirring speed.

3.2.1. The effect of resuspension on solute fluxes at low bottom water oxygen concentration

Effect of resuspension on the ammonium fluxes was observed in 50% of the cases when the oxygen concentration in the bottom water was low. Resuspension was created in 8 chambers and in 4 of these there was an effect on the fluxes. The net effect of resuspension at low oxygen concentrations and thus high initial ammonium fluxes, to decrease ammonium fluxes, was likely a result of enhanced adsorption due to the resuspended load of particle surfaces. This was not observed during oxic conditions, probably because of the very low ammonium fluxes during such conditions allowing no significant effects of resuspension to be detected on the ammonium fluxes. The effect of resuspension on ammonium effluxes at low oxygen concentrations could, however, be underestimated due to the high concentration of particles in the chamber water, and thus a high adsorption effect, compared to the concentration of particles during natural resuspension events (where the water height is not limiting). However, a simple test showed no relation between the changes in turbidity and the changes of fluxes in the chambers, which indicates that any underestimation of the resuspension effect should be minor.

Fluxes and concentrations of dissolved iron were closely dependent on the oxygen concentrations, as shown in Pakhomova et al. (2007), and when dissolved oxygen was present fluxes were low or insignificant. As oxygen decreased or was depleted, new iron oxy-hydroxides were prohibited to be formed and more iron (II) was released from the sediment. When oxygen was low or absent in the ambient bottom water, and only then, resuspension appeared to influence the iron fluxes. The observed effect (increased iron concentrations and iron fluxes) was probably a result of oxygen depletion (due to resuspension) and it was, therefore, likely an indirect result of resuspension.

4. Concluding remarks: environmental significance of resuspension in the Gulf of Finland

Resuspension of sediment clearly led to a significant increase of the oxygen consumption, but had no clear effects on fluxes of ammonium, nitrate, phosphate, silicate, dissolved inorganic carbon, iron or manganese at well oxygenated conditions. However, when the oxygen concentration in the overlying water

was low (background concentrations of oxygen varied between 1 and 12 μM at station PV1 in 2003 and 2005), the ammonium fluxes were also affected and decreased during 50% of the resuspension events. Concentrations of nitrate and iron, and, therefore, the fluxes of these solutes, were also affected by low oxygen concentrations, but overall not directly affected by resuspension.

The still high phosphorus and nitrogen contents of GoF waters, in spite of decreased external load, are likely a result of internal loading, as discussed in the introduction. Our results demonstrate that resuspension events do not seem to play any significant role in the release/uptake of nutrients in GoF sediments. Resuspension does, however, play an important role in the consumption of oxygen in this area, which may enhance the spreading of hypoxic and anoxic conditions, which in turn will stimulate the release of e.g. phosphate, ammonium and iron (e.g. Balzer et al., 1983; Sundby et al., 1986; Skoog et al., 1996; Conley et al., 2002; Brunnegård et al., 2008b) as well as change reaction pathways of the nitrogen cycle (e.g. Hannig et al., 2007). Resuspension can, therefore, indirectly lead to increased fluxes of these substances from the sediment to the overlying water.

The changes in concentrations and fluxes as a result of resuspension were in this study maintained during the remaining part of the incubation time. However, for oxygen, it is clear that the stimulation of oxygen consumption declined at the end of incubations (Fig. 4). How quickly the affected solute concentrations and fluxes return, after resuspension is terminated, to levels which occurred before the resuspension events was not investigated in this study.

Resuspension is also an important process to redistribute sediment particles and organic material along the sea floor (Jonsson et al., 1990; Jönsson et al., 2005). Organic matter at transport and erosion bottoms is lifted up into the water column at resuspension events and transported, with water currents, along the sea floor. The particles can be lifted, transported and settled many times before they finally settle to a bottom of accumulation type. The particles can in this way end up at localities where the water circulation and oxygen concentration is low, and thus the benthic release pattern of nutrients and metals are different, compared to the well-oxygenated sediment from where the transport started.

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