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Influence of resuspension on sediment-water solute exchange and particle transport in marine environments

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AKADEMISK AVHANDLING

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Influence of resuspension on sediment-water solute exchange and particle transport in marine environments

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Abstract

Marine sediments contain a large pool of nutrients, which if released would contribute to increased eutrophication, in spite of decreased nutrient loads from land and atmosphere. Resuspension is a process, which might influence the release of nutrients from the sediment to the overlying water. The influence of resuspension on benthic fluxes of oxygen, dissolved inorganic carbon (DIC), nutrients, dissolved iron (dFe) and dissolved manganese (dMn) was therefore investigated in three different marine environments. The measurements were performed using a benthic lander with the advantage of operating *in situ*.

The method of measuring the effects of resuspension was developed in the archipelago of Gothenburg (Paper I). This method was then further improved and used during field studies in the Gulf of Finland (GoF; Paper II) and in a Scottish sea loch (Paper III). During the latter study also the effects of massive (simulating dredging or trawling) and repeated resuspension events on the benthic fluxes were studied. Natural resuspension significantly increased the oxygen consumption in the GoF and at a station with organic rich sediment in Scotland. There were no significant effects of natural resuspension on nutrient, DIC and dMn fluxes, but the fluxes and concentrations of dFe increased at stations with low bottom water oxygen concentrations (GoF). Massive resuspension increased the oxygen consumption enormously and instantly changed the bottom water concentrations of phosphate (which decreased), DIC, silicate and ammonium (which increased).

Results confirmed that the general magnitude of phosphate fluxes was dependent on the oxygen regime (GoF; Paper IV). However, results also showed a strong correlation between phosphate and DIC fluxes during anoxic conditions implying that phosphate fluxes are controlled by input and degradation of organic matter under anoxia. The internal load was calculated to be about 66 000 ton P yr^{-1} in the GoF. If all oxic bottoms below 40 m would turn anoxic the internal load was computed to increase with about 35 000 ton P yr^{-1}.

Results from a fully coupled high-resolution biogeochemical-physical ocean model, including an empirical wave model, showed that a large fraction of the sedimentary organic carbon has at least once been resuspended, and the largest contribution of resuspended organic matter to the total transport of particulate organic matter occurred at shallow transport and erosion bottoms (long-term average, 1979-2007) in the Baltic Sea (Paper V). The fraction of resuspended organic matter in the deepest areas of the Baltic Sea was low (< 10%) even though there was a large horizontal transport of suspended organic matter and a high sedimentary content of it. A map of different bottom types, accumulation, transport and erosion bottoms, was also created.

Keywords: Resuspension, benthic fluxes, oxygen, dissolved inorganic carbon, nutrients, dissolved iron and manganese, in situ chambers, benthic lander, organic matter transport, ecological modeling, Gothenburg Archipelago, Gulf of Finland, Baltic Sea, Loch Creran, Scotland.

Populärvetenskaplig sammanfattning

Under flera årtionden har utsläpp av näringsämnen, såsom kväve och fosfor, ökat till våra hav. Den ökade mängden näringsämnen har lett till övergödning, särskilt i kustnära områden. Tecken på övergödning kan ses genom t.ex. ökad förekomst av fintrådiga alger, större och oftare förekommande algblomningar av till exempel cyanobakterier (blågröna alger), särskilt i Östersjön, försämrat siktdjup, samt ökad utbredning av syrefria/döda bottnar. På senare tid har det dock gjorts stora ansträngningar för att minska tillförseln av näringsämnen till Östersjön, t.ex. genom utbyggnad av reningsverk.

Bottnarna innehåller stora mängder näringsämnen ifrån nedbrytning av organiskt material. Transporten från bottnarna till vattnet av dessa näringsämnen kan under vissa omständigheter öka, t.ex. om bottenvattnet blir syrefritt. Resuspension är en process som har diskuterats kunna öka flödet av kväve och fosfor ut ur bottnarna till vattnet genom att nedbrytningen av organiskt material skulle öka. Resuspension uppstår när en kraft, t.ex. vågor eller starka strömmar, får bottenpartiklar att virvla upp och blandas med ovanliggande vatten. Det kan även ske på grund av mänsklig aktivitet som till exempel trålning eller muddring. Syftet med denna avhandling är att ge svar på om resuspension bidrar till ökat flöde ut ur bottnarna av kväve, fosfor, löst oorganisk kol och lösta metaller (järn och mangan), vilket kan leda till ökad övergödning av våra hav.

Studien har utförts i tre olika områden: Göteborgs skärgård, Finska Viken och i Loch Creran (en fjord i Skottland). Vid undersökningarna har en bottenlandare använts. Det är ett avancerat instrument som släpps ner i vattnet, sjunker ner till botten och inkuberar sedimentet, d.v.s. en del av bottenytan med ovanliggande vatten stängs in i en kammare under en period. Mätningar och provtagningar görs sedan automatiskt på förutbestämda tider på det ovanliggande vattnet i kammaren. När alla mätningar är klara skickar man en signal till bottenlandaren som då kommer upp till ytan och analyser av de tagna proverna kan göras. I denna studie har resuspension av olika styrkor skapats efter en viss tid i inkubationskamrarna för att se om detta har påverkat utflödet av lösta ämnen från botten. Dels har resuspension skapats som ska efterlikna resuspension som uppstår under naturliga förhållanden vid stora vågor eller starka strömmar, och dels har kraftig resuspension skapats som ska efterlikna resuspension som uppstår vid t.ex. trålning eller muddring.

Resultaten visar att syrekonsumtionen ökar påtagligt vid både kraftig och naturlig resuspension av bottnarna. Flödet (koncentrationsförändring över tid) från bottnarna av ammonium, silikat och oorganiskt kol påverkades inte, däremot uppstod vid kraftig resuspension en omedelbar koncentrationsökning av dessa ämnen i bottenvattnet. Det beror på att dessa ämnen ansamlats i bottnarna, för att sedan blandas upp vid kraftig resuspension. Inte heller fosfatflödet från bottnarna påverkades av resuspension, men fosfathalten minskade vid kraftig resuspension. Minskningen beror på ett adsorptionsbeteende hos fosfat på järnoxider, det vill säga fosfat kan fastna på järnoxidytan. Järnoxider bildas när reducerat järn i bottnarna blandats upp och oxideras vid kontakt med syrerikt ovanliggande vatten.

I den här studien bekräftas också resultat från tidigare studier av andra forskare: Fosfatflödet från bottnarna styrs av bl.a. syrgaskoncentrationen i bottenvattnet. Då bottenvattnet innehåller syre stannar i stort sett all fosfor kvar i bottnarna. Detta beror på adsorptionsbeteendet som fosfat har på järnoxiderna. Blir däremot bottenvattnet syrefattigt reduceras järnoxiderna varvid de löses upp. Då släpps fosfat fritt och kan transporteras upp till vattnet. Under syrefria förhållanden i bottenvattnet observerades ett samband mellan flödena av fosfat och löst oorganiskt kol. Det betyder att fosfatflödet från botten kontrolleras av tillgång på och nedbrytning av organiskt material under dessa förhållanden. Med hjälp av en matematisk modell i kombination med resultat från dessa mätningar och med beaktande av de aktuella syreförhållandena beräknades fosfattillförseln till vattnet från bottnarna i Finska Viken till 66000 ton fosfor per år. Det är ca 10 gånger mer än vad som kommer ifrån landavrinningen. Om dessutom alla bottnar under 40 meters djup blir syrefria så skulle ytterligare ca 35000 ton fosfor frigöras från bottnarna per år.

Om antalet tillfällen med resuspension skulle öka på grund av t.ex. klimatförändringar skulle det således leda till ökad syrekonsumtionen vid bottnarna. Det uppstår en ond cirkel då den ökade syrekonsumtionen kan leda till ökad spridning av syrefria bottnar, vilket skulle öka läckaget av fosfor och kväve från bottnarna. Ökad fosfathalt i vattnet i Finska Viken och Östersjön gör att blomningar av cyanobakterier skulle kunna öka ännu mer. Detta trots en minskning av tillförseln ifrån land av fosfat och kväve.

Suspenderade partiklar (partiklar som flyter omkring i vattnet) av organiskt material transporteras med strömmar innan de så småningom sjunker ner till botten. Där kan de sedan resuspenderas upp till vattnet igen och transporteras ytterligare en sträcka, eller så nådde de sin slutliga destination. En matematisk modell användes i denna studie för att undersöka var organiskt material ansamlas i Östersjön och hur mycket som en gång har varit resuspenderat. Resultat visar att det huvudsakliga transportmönstret av organiskt material i Östersjön är en cirkelrörelse moturs öster om och runt Gotland. Största andelen av det transporterade organiska materialet som är resuspenderat återfinns på grundare områden längs med kusten där det ofta förekommer vågor och starka strömmar, d.v.s. där resuspension ofta sker. Resultaten visar också att en relativt stor andel av allt organiskt material i bottnarna en gång har varit resuspenderat, d.v.s. att det är upplyft från botten någon annanstans och ditflyttat med strömmarna. Resuspension kan alltså leda till att organiska sedimentpartiklar förflyttas från områden med syrerikt bottenvatten till ett område med syrebrist, vilket i sin tur kan leda till ökad återcirkulering av näringsämnen från botten till vattnet och därmed en förvärrad övergödningssituation. Resuspension kan även på detta sätt och genom stimulerad syrgaskonsumtion indirekt leda till ökad övergödning även om processen direkt på den plats den verkar inte leder till ökat utsläpp av näringsämnen från havsbotten.

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Table of publications included in the thesis

Part B

I. **Resuspension and its effects on organic carbon recycling and nutrient exchange in coastal sediments: *in situ* measurements using new experimental technology**
Tengberg, A., Almroth, E., Hall, P.
Journal of Experimental Marine Biology and Ecology 285-286 (2003) 119-142

II. **Effects of resuspension on benthic fluxes of oxygen, nutrients, dissolved inorganic carbon, iron and manganese in the Gulf of Finland, Baltic Sea**
Almroth-Rosell, E., Tengberg, A., Andersson, J.H., Pakhomova, S., Hall, P.O.J.
Continental Shelf Research 29 (2009) 807-818

III. **Effects of simulated natural and massive resuspension on benthic oxygen, nutrient and dissolved inorganic carbon fluxes in Loch Creran, Scotland**
Almroth-Rosell, E., Tengberg, A., Andersson, S., Apler, A., Hall, P.O.J.
Journal of Sea Research (submitted)

IV. **Benthic phosphorus dynamics in the Gulf of Finland, Baltic Sea**
Viktorsson, L., Almroth-Rosell, E., Tengberg, Vankevich, R., Neelov, I., Isaev, A., Kravtsov, V., Hall, P.O.J.
Aquatic Geochemistry (accepted for publication)

V. **Transport of fresh and resuspended particulate organic material in the Baltic Sea – a model study**
Almroth-Rosell, E., Eilola, K., Hordoir, R., Meier, H.E.M., Hall, P.O.J.
Journal of Marine Systems 87 (2011) 1-12

List of publications not included in the thesis

Meier, H.E.M., Eilola, K., Almroth, E., 2011. Climate-related changes in marine ecosystems simulated with a three-dimensional coupled physical-biogeochemical model of the Baltic Sea. Climate Research 48:31-55

Almroth, E. and Skogen, M. D., 2010. A North Sea and Baltic Sea model ensemble eutrophication status assessment. AMBIO 39:59-69. DOI 10.1007/s13280-009-0006-7

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Submitted manuscripts

Cathalot, C., Lansard, B., Hall, P.O.J., Tengberg, A., Almroth-Rosell, E., Apler, A., Calder, L., Bell, E., Rabouille, C. Spatial and temporal variability of benthic respiration in a Scottish sea loch impacted by fish farming: a combination of *in situ* techniques. Aquatic Geochemistry (submitted).

Manuscripts

Andersson, J. H., Almroth-Rosell, E ., Tengberg, A., Stahl, H., Middelburg, J.J., Soetaert, K., Hall, P.O.J. Respiration of organic carbon in sediments of the Gulf of Finland, Baltic Sea. Will be submitted to Biogeosciences.

Brunnegård, J., Almroth-Rosell, E., Tengberg, A., Nielsen, L-P., Roos, P., Eriksson, S., Kravtsov, V., Pankratova, N., Hall, P.O.J. Nitrogen transformations and fluxes in sediments of the Gulf of Finland, Baltic Sea. Will be submitted to Biogeochemistry

Eilola, K., Almroth-Rosell, E., Dieterich, C., Fransner, F., Höglund, A., Meier, H. E. M. Nutrient transports and interactions between coastal regions and the open sea in the Baltic Sea: A model study in present and future climate. Will be submitted to AMBIO (special issue).

List of used abbreviations

DIC	Dissolved inorganic carbon
DIP	Dissolved inorganic phosphorus
DOC	Dissolved organic carbon
DOM	Dissolved organic matter
GoF	Gulf of Finland
ISS	Increased stirring speed
Kas	Kasuuni
MB	Måvholmsbådan
NTU	Normal Turbidity Units
POM	Particulate organic matter
RCO	Rossby Centre Ocean circulation model
SCOBI	Swedish Coastal and Ocean BIogeochemical model
SMHI	Swedish Meteorological and Hydrological Institute
SRP	Soluble reactive phosphorus
UGOT	University of Gothenburg
τ	Shear stress

1 Introduction

Signs of eutrophication in the sea have been observed and discussed for decades. The enrichment of nutrients has led to larger and more frequently occurring phytoplankton blooms, e.g. cyanobacteria in the Baltic Sea, increased occurrence of fine-threaded macro algae (e.g. Wulff et al., 2001) or depletion of oxygen in bottom waters (HELCOM, 2007). The load of nutrients with rivers and via atmosphere to the sea, the so called external load, is a major contribution to the eutrophication. Large efforts are made to decrease the use of fertilizers in agriculture and to improve sewage treatment work to minimize the external load in order to achieve “clear water” (HELCOM, 2007).

However, the sediments constitute another source of nutrients for seawater. They often contain important pools of nutrients and other dissolved solutes which have accumulated through the years. These solutes can be transported to the water column, the so called internal load or integrated benthic flux, and contribute to the enrichment of nutrients in the water (Pitkänen et al., 2001). “Disturbances” of the sediment such as those created by strong currents, animal activities, dredging or trawling leading to resuspension might influence the magnitude of the integrated benthic nutrient flux and thereby the sedimentary contribution to eutrophication.

1.1 The cycle of organic matter in the sea

As phytoplankton grows (and produces organic matter) they assimilate inorganic carbon, nutrients and trace metals during photosynthesis. This process needs light as an energy source why it occurs in the top layer of the sea. This layer is called the photic zone and its maximum depth is where at least 1 % of the sunlight reaches. A bloom of phytoplankton can be defined as high concentration of a phytoplankton species in an area, caused by increased production. A bloom of algae can start if the growing conditions are appropriate, i.e. if there is enough light, nutrients and trace elements. The bloom is sometimes visible to the human eye as a discoloration of the water, e.g. caused by red tides (Duxbury and Duxbury, 1984) or accumulation of cyanobacteria in surface waters of the Baltic Sea.

Zooplankton graze phytoplankton and transfer the organic matter up the food chain in the marine food web, in which the zooplankton can be eaten by larger organisms. Dead animals (zooplankton and fish), phytoplankton, faeces and other particulate organic matter (POM) sink towards the bottom. On the way down through the water column the POM is partly remineralized and the nutrients are recycled back to the water, available for assimilation again. However, a lot of the POM reaches the seafloor, especially in shallow seas, where early diagenetic (degradation) processes (Fig. 1), such as bacterial respiration, take place.

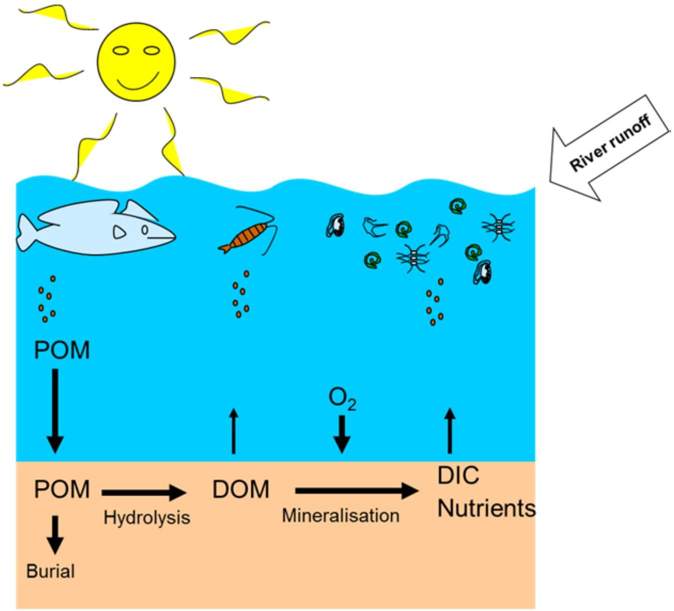

Fig. 1. A schematic description of the cycle of organic matter in the water column and in the sediment.

In the degradation process the organic matter is first hydrolyzed into dissolved organic matter (DOM), which can be transported back to the water column. In the second step the DOM is mineralized into inorganic degradation products such as dissolved inorganic carbon (DIC) and nutrients. During decomposition of organic matter bacteria need electron acceptors to gain energy. Different amount of energy is gained depending on which electron accepting substance that is used. Oxygen is the most favorable regarding energy gain and is also the one that is used (and depleted) first. Thereafter nitrate in the denitrification process or manganese is used. The gained energy using nitrate or manganese oxide as electron acceptor is of about the same magnitude. Thereafter iron oxyhydroxides are used and so on according to Table 1. A large fraction of the POM that reaches the seafloor is remineralized, but some of it is buried in the sediment and removed from the biogeochemical cycle of organic matter. It has often been found that the higher amount of POM that reaches the sea floor, the higher fraction of it is buried in the sediment (Libes, 1992, and references therein; Canfield, 1994).

1.1.1 Oxygen

Oxygen gas dissolved in surface sea water is in equilibrium with the atmosphere, and the solubility depends on temperature and salinity. Oxygen is also produced in the photic zone by phytoplankton during photosynthesis and is then distributed in the water column by advective mixing and molecular diffusion.

Oxygen is one of the most important electron acceptor in the remineralization process of organic matter (Table 1). Below the oxygenated zone of sediments, or at anoxic bottoms, other oxidants are used. The produced remineralization end products build up a pool of reduced inorganic compounds, which can be re–oxidized and oxygen is the ultimate oxidant in these oxidation reactions.

Table 1. The principal respiratory pathways and the gained free energy (ΔG^0) in kJ mol^{-1} organic carbon, with a charge of 0, and a transfer of four electrons. Modified from Canfield et al. (2005).

Process	**Chemical description**	**ΔG^0**
Oxic respiration	$\frac{1}{2}\ C_2H_3O_2^- + O_2 \rightarrow HCO_3^- + \frac{1}{2}\ H^+$	-402
Mn(IV) reduction	$\frac{1}{2}\ C_2H_3O_2^- + 2MnO_2 + 7/2\ H^+ \rightarrow 2Mn^{2+} + HCO_3^- + 2H_2O$	-385
Denitrification	$\frac{1}{2}\ C_2H_3O_2^- + 4/5\ NO_3^- + 3/10\ H^+ \rightarrow 2/5\ N_2 + HCO_3^- + 2/5\ H_2O$	-359
Fe(III) reduction	$\frac{1}{2}\ C_2H_3O_2^- + 4\ FeOOH + 15/2\ H^+ \rightarrow 4Fe^{2+} + HCO_3^- + 6H_2O$	-241
Sulfate reduction	$\frac{1}{2}\ C_2H_3O_2^- + \frac{1}{2}\ SO_4^{2-} + \frac{1}{2}\ H^+ \rightarrow \frac{1}{2}\ H_2S + HCO_3^-$	-43.8
Methanogenesis	$\frac{1}{2}\ C_2H_3O_2^- + \frac{1}{2}\ H_2O \rightarrow CH_4 + \frac{1}{2}\ HCO_3^-$	-19.98

1.1.2 Carbon

Carbon dioxide (CO_2) is a gas in seawater, which is in equilibrium with the atmosphere. In the sea most of the CO_2 reacts with water and becomes a part of the carbonate system. Most of the inorganic carbon in seawater is present as hydrogen carbonate (HCO_3^-) which is in equilibrium with carbonic acid (H_2CO_3) and carbonate ion (CO_3^{2-}). Dissolved inorganic carbon (DIC) is the sum of these components, including $CO_{2\ (aq)}$.

The primary producers (e.g. phytoplankton) assimilate DIC in the photosynthesis as they produce organic matter. Some of the primary producers as well as animals also build shells consisting of e.g. calcium carbonate ($CaCO_3$). Sinking particulate organic and inorganic matter contribute to a transport of carbon to the sea floor. As remineralization of organic matter occurs dissolved organic carbon (DOC) and DIC is released and thus available for uptake in the photosynthesis again. Some of the organic and inorganic carbon is undergoing long-term burial in the sediment and is in this way removed from the oceanic-atmospheric biogeochemical cycling.

1.1.3 Nitrogen

Nitrogen is one of the essential nutrients for primary production in the sea. It is assimilated by primary producers in the form of ammonium (NH_4^+), nitrate (NO_3^-) and dissolved organic nitrogen. Some species of the phytoplankton, e.g. cyanobacteria, can fix di-nitrogen gas (N_2). It is an energy demanding process and most of the phytoplankton species do not have this possibility to assimilate N_2.

As dead organic matter is decomposed nitrogen is released as dissolved organic nitrogen and ammonium (ammonification). If there is oxygen present the ammonium is oxidized to nitrate, with nitrite as an intermediate (nitrification). Nitrate can then be used as an electron acceptor in the degradation process of organic matter (denitrification). Nitrite is produced as an intermediate and N_2O or N_2 gas is the end product. There are also other reactions in which fixed nitrogen is removed, e.g. anammox (anoxic ammonium oxidation) where nitrite and ammonium react to form N_2 gas as end product.

A large part of the ammonium released during decomposition of organic matter can become adsorbed on particles in the sediment. The adsorption-desorption process is reversible and rapid compared to other diagenetic processes. The ammonium adsorption coefficient depends on the water content of the sediment (Rosenfeld, 1979; Mackin and Aller, 1984).

1.1.4 Phosphorus

Phosphorus is one of the essential nutrients for primary production. It is present in seawater mainly as hydrogen phosphate (HPO_4^{2-}). The term phosphate is in this thesis used synonymously to the terms dissolved inorganic phosphorus (DIP) and soluble reactive phosphorus (SRP).

Phosphate is not used as electron acceptor during oxidation of organic matter but shows an adsorption-desorption behavior to other compounds, e.g. iron oxyhydroxides (Mortimer, 1941, 1942; Froelich, 1988; Sundby et al., 1992). This sorption process is important in sediments where it can regulate the transport of phosphate back to the water column.

When dead organic matter is decomposed in the sediment, phosphate is released to the pore water. The phosphate then diffuses towards areas where the concentration is lower, as in the overlying water. In the presence of oxygen in the bottom water iron oxyhydroxides are formed in the oxygenated layer of the sediment. Phosphate adsorbs to the surface of the iron oxyhydroxides, which prevents the phosphate to be released to the water column and to be re-used in pelagic photosynthesis. If oxygen is depleted the iron oxyhydroxides are reductively dissolved and the phosphate is released from the particle surfaces and can diffuse upwards to the overlying water.

1.1.5 Silicon

Silicon is the second most abundant element in the crust of earth. Dissolved silicon is mainly transported to the sea by rivers after it has been weathered from silica containing rocks. It is mainly present in the sea water as orthosilicic acid ($Si(OH)_4$). Collectively all dissolved species of silicon can be referred to as silicate or dissolved silicate.

The phytoplankton group diatoms need silicate as they grow to form hard parts of biogenic silica. When the diatoms die a large part of the formed biogenic silica reach the sea floor as it has a rather high sinking velocity and is remineralized by dissolution and not by microbial decomposition. Silicate concentrations in pore water of the sediment is therefore often increasing with sediment depth (Libes, 2009).

1.1.6 Iron and manganese

Both iron and manganese are essential trace elements for most living organisms. They are mainly transported to the sea by rivers, but also via air and hydrothermal input at the sea floor. In sea water they are present either in oxidized forms, Fe(III), Mn(III) and Mn(IV), which have low solubility in oxic sea water and are precipitated as hydroxides, oxyhydroxides or oxides. The reduced forms, Fe(II) and Mn(II), are more soluble in low oxygen waters, but can precipitate with e.g. sulfides and carbonates. Oxidation of Fe(II) with oxygen is a microbial catalyzed process which is very fast (half-life of minutes). Oxidation of Mn(II) in solution is, however, very slow with a half-life of months. There are also abiotic pathways for oxidation and reduction of iron and manganese. Hydrogen sulfide is the most significant abiotic reductant for iron oxides and it can also reduce manganese oxides (Canfield et al., 2005).

1.2 Resuspension

The physical process when sediment particles are lifted up into the water column due to a force or mechanical disturbance is called resuspension (Fig. 2). This occur when the force acting on the sediment surface, the shear stress (τ), is larger than the threshold value, the critical shear stress (τ_{crit}), which can be different for different types of sediment. Fine particles are more easily resuspended than large and heavy particles, which results in a low τ_{crit}. If the fine sediment consists of clay or mud, which makes it cohesive, the τ_{crit} is instead high. This is often the case at e.g. accumulation bottoms where the sediments often are muddy. Strong currents and waves that reach the seafloor regulate the magnitude of the τ along the bottom. Other disturbances or processes that can result in a resuspension event are anthropogenic such as trawling or dredging or natural such as animals digging in and mixing the sediment (bioturbation).

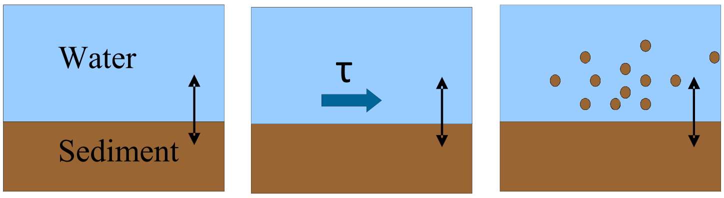

Fig. 2. A schematic figure of the resuspension process. When the τ that acts on the sediment is larger than τ_{crit} the sediment particles can be lifted up into the water column and be put into suspension

It is debated how the degradation rates of organic matter and fluxes of nutrients and other solutes across the sediment-water interface are affected by resuspension events. Some scientists (e.g. Wainright and Hopkinson, 1997; Ståhlberg et al., 2006) argue that resuspension can lead to increased remineralization rate of organic matter. They mean that an organic particle in the sediment is a target for bacterial respiration (degradation) on the available surface of the particle. As the particle is resuspended into the water its whole surface is exposed to the surrounding water, and thus to bacteria, and the degradation can increase (Wainright, 1987). Other scientists argue that the pore water mixed up into the water column due to resuspension events only causes a temporary increase of nutrient concentrations in the water column (Blackburn, 1997).

Previous investigations of the effect of resuspension are based on laboratory or model studies. The importance of *in situ* measurements has been concluded in several of the studies (e.g. Koschinsky et al., 2001).

1.3 Aim of the thesis

The aims with this thesis were to improve knowledge of the effects of resuspension on sediment-water solute exchange, and of the transport and final deposition of resuspended particulate organic matter in marine environments.

A method to measure and quantify the effects of resuspension on benthic fluxes of oxygen, DIC and nutrients was developed during a field experiment in Gothenburg Archipelago; it is described in Paper I. How sediment resuspension influences oxygen consumption and the transport of DIC and inorganic nutrients to the water column is described in Paper II-III. The benthic cycle of phosphorus in the Gulf of Finland and the important coupling to bottom water oxygen concentrations is presented in Paper IV. The transport and deposition of suspended particulate organic matter, and the ratio between resuspended particulate organic matter and total suspended particulate organic matter in the Baltic Sea, was also investigated; these model results are presented in Paper V.

2 Material and methods

Flux incubations can be performed both *ex situ*, i.e. in the laboratory, and *in situ*. For laboratory incubations it is normally desired to keep the settings as close to *in situ* conditions as possible (with respect to oxygen concentrations, temperature, light conditions, water circulation, pressure etc.), and to keep physical disturbances at a minimum. One advantage with laboratory incubations is that less advanced technology and equipment can be used which requires less specialized operators and reduced costs.

Even if laboratory incubations are done as close to *in situ* conditions as possible it is very difficult or even impossible to recreate the exact natural conditions. E.g. when studying benthic fluxes in sub-oxic or anoxic areas it is not easy to keep the laboratory incubations anoxic or when working in the deep-sea where the temperature difference between the surface and bottom water can be large, light is permanently absent and the hydrostatic pressure is very high. It is only by doing *in situ* studies that representative flux measurements can be obtained (e.g. Tengberg et al., 1995; Witbaard et al., 2000; Glud and Blackburn, 2002; Hall et al., 2007). Thus, even though *in situ* studies in the ocean are more technically challenging and much more expensive, there are several advantages: the ambient *in situ* conditions in the benthic boundary layer are better reflected in the chambers; the incubated volumes vs. sampling volume is greater, which avoids dilution problems (Tengberg et al., 1995); there are no problem keeping the sediment and bottom water anoxic or the water pressure at the correct level since the ambient bottom water conditions are not changed. Another advantage is that most *in situ* incubators (chambers) cover a larger and thus a more representative surface area than many laboratory incubators (Glud and Blackburn, 2002).

Model studies can be used to complement and extrapolate information from observations as measurements only can be performed at a limited number of stations, covering limited areas and time periods. Models may also be used to investigate functional relationships e.g. between nutrient supplies and eutrophication and water quality. The main limits of modeling ecological and physical conditions e.g. in the Baltic Sea are the computer resources and the understanding about fundamental biogeochemical processes. But of course high quality forcing of nutrient supplies from land and atmosphere, winds, cloudiness, precipitation etc. and validation data like nutrient and oxygen concentrations are needed as well. Already in the 1980s e.g. Stigebrandt and Wulff (1987) modeled ecological parameters in the Baltic proper, using a horizontally integrated one dimensional coupled physical-biogeochemical model with a high vertical resolution. The ecological and physical modeling has since then developed further and can now be rather complex depending on the research topic. At the Baltic Nest Institute the one dimensional models SANBALTS (Simple As Necessary Baltic Long-Term Large-Scale) and BALTSEM (BAltic sea Long-Term large-Scale Eutrophication Model) are used for e.g. oxygen, nutrients, long-term and climate change studies in the Baltic Sea, which is divided into 13 sub-basins connected in the models (Gustafsson, 2000; Savchuk, 2002; Gustafsson, 2003; Savchuk, 2007; Savchuk and Wulff, 2009). At some institutes three dimensional models are used for similar model studies, e.g.

RCO-SCOBI (Rossby Centre Ocean circulation model-Swedish Coastal and Ocean BIogeochemical model) at SMHI (Eilola et al., 2009; Paper V) and ERGOM (Ecological Regional Ocean Model) at the Institute for Baltic Sea Research Warnemünde (Neumann et al., 2002). Also ensemble studies where results from a number of different models are analyzed can be used (Eilola et al., 2011). As no model show perfect performance for all parameters the shortcomings of one model can be compensated by the other models and the model uncertainties can be explored from the spread of results between the models.

2.1 *In situ* studies with the University of Gothenburg lander

A common way to obtain sediment-water exchange data *in situ* is to use autonomous instruments, so called benthic landers (for a review see Tengberg et al., 1995). The general term lander refers to an autonomous, unmanned oceanographic research vehicle that descends by gravity without any cable or umbilical to the surface and operates independently on the sea-floor (for hours to years). At the end of the experimental period the lander ascends to the surface by virtue of positive buoyancy after ballast has been shed, either by use of a timing mechanism or an acoustic command.

Many landers basically consist of two parts, an inner and an outer frame. The outer frame serves mainly as a carrier platform for the buoyancy package, the ballast and the acoustic system for the ballast release (Fig. 3).

1) Syntactic foam used as buoyancy to make the lander rice to the surface after ballast weights have been shed
2) Ballast weights which consists of two pieces of expandable railway track
3) Two independent acoustic ballast release systems which are triggered from the surface
4) Inner tray (see below)
5) Antennas with flags, VHF radio transmitter, flash light and ARGOS satellite transmitter for surface spotting after deployment
6) Sediment traps and sensor package that measures ambient bottom water conditions (currents, suspended particles, salinity, temperature, pressure and oxygen)

Fig. 3. Deploying the University of Gothenburg big benthic lander in the Gulf of Finland in May 2005.

The University of Gothenburg (UGOT) lander is built of non-corrosive materials (titanium and various plastics) as a modular system in which experimental modules can be exchanged as desired. The lander carries four experimental modules and has been successfully deployed at least 150 times in water depths ranging from 20-5600 m during the last about 12 years.

The inner frame is a versatile system that carries the experimental modules. These modules can easily be exchanged (Fig. 4). The center of the inner frame holds space for three pressure cases, which are used to control different experimental modules. In the studies discussed in this thesis only chamber modules have been in operation, but it is also possible to use other instruments such as a planar optode or a microelectrode module (Glud et al., 2001; Glud et al., 2005).

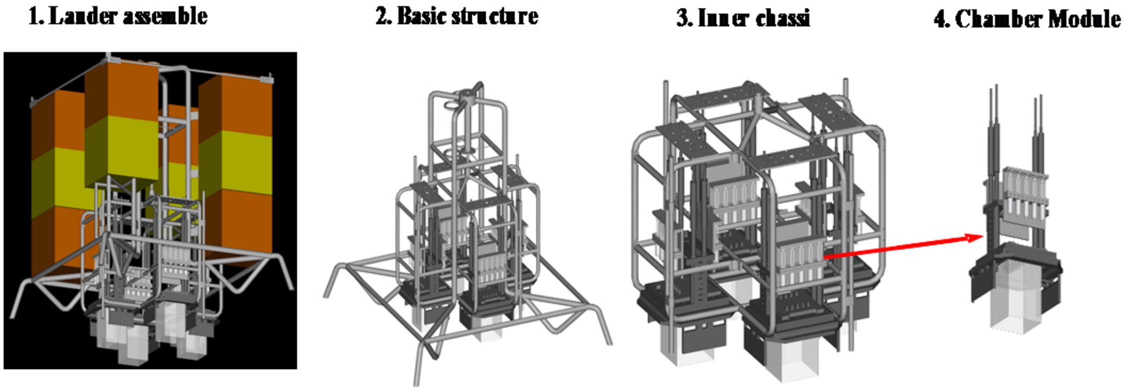

Fig. 4. Schematic drawing of the Gothenburg big lander parts with the incubation chamber used as a module. Other modules, e.g. a planar optode, can be used on the lander.

2.1.1 Chamber modules

The use of incubation chambers on landers to measure sediment-water fluxes of oxygen, DIC, nutrients, metals etc. has been common practice for over three decades even though fluxes of some solutes, such as DIC and metals, have been measured more rarely than oxygen and nutrient fluxes. The incubation principles of the UGOT lander chambers are no different from the first experiments of this kind performed by Smith et al. (1976).

Some of the features, which are special with the chamber modules of this study (Fig. 5), are that they have been carefully studied with respect to hydrodynamic properties and inter-calibrated with other chamber designs (Tengberg et al., 2004; Tengberg et al., 2005). They have also been modified to study the effects of resuspension on e.g. benthic organic carbon turnover and nutrient fluxes. The first results from such studies are presented in Paper I and since then the method and the technology has been further developed. In order to evaluate the effect of resuspension the use of control chambers in addition to the resuspension chambers appeared to be of great importance, which therefore was implemented. The UGOT big lander was then used for measurements in the Gulf of Finland during several cruises in 2002-2005 (Paper II and Paper IV), and in the Scottish Loch Creran in 2006 (Paper III).

Further improvements that were made include enhanced possibilities to create different hydrodynamic conditions and strengths of resuspension inside the chambers. The lid can now be opened and closed several times during one single *in situ* deployment, which enables studies of effects of e.g. repeated resuspension events on the same site (Paper III). Another improvement has been to include single point optical oxygen sensors (optodes) in the chambers. These sensors have demonstrated superior accuracy, precision and long-term stability compared to electrochemical sensors (Körtzinger et al., 2004; Körtzinger et al., 2005; Tengberg et al., 2006). The replacement of the previously used electrochemical oxygen electrodes with optodes has enhanced the data quality considerably as well as eliminated calibration, contamination (by e.g. H_2S) and pressure issues.

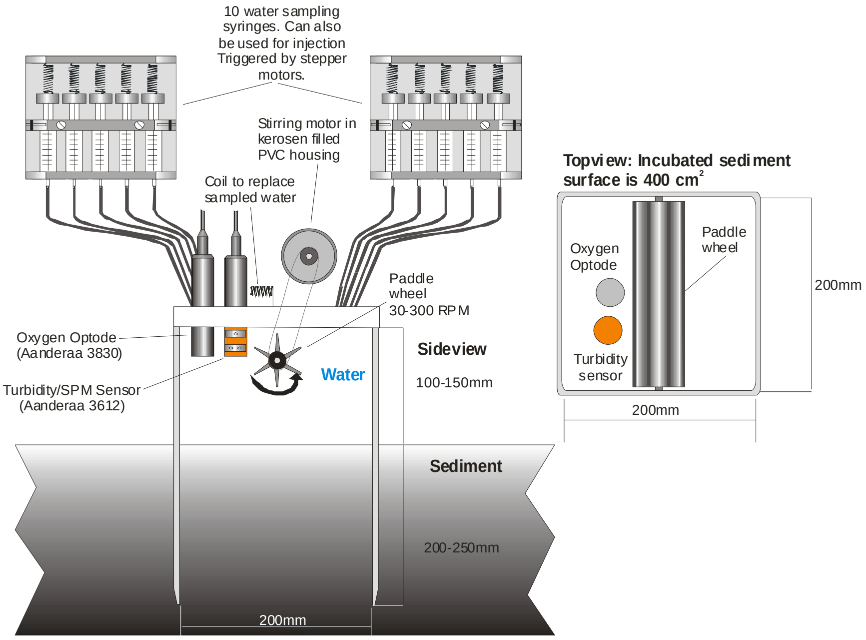

Fig. 5. Principal drawing of the chambers used on the Gothenburg lander.

2.1.2 Other sensors and experimental abilities

During operation the UGOT landers (there are today three of them) carry additional sensors and instrument that are mainly used to collect data from the ambient bottom water environment surrounding the landers. The big UGOT lander normally register data from up to 30 sensors: turbidity and oxygen sensors inside the chambers and turbidity, oxygen, salinity, depth and temperature sensors, current sensors (such as single point and profiling acoustic current meters) and a video camera outside the chambers.

For more information on the Gothenburg landers and examples of their use, see e.g. Rabouille et al. (2001), Karageorgis et al. (2003), Brunnegård et al. (2004), Ståhl et al. (2004a; 2004b; 2004c), Pakhomova et al. (2007) and Papers I-IV.

2.2 A typical deployment scenario with the big UGOT lander

After releasing the lander from the ship it descends by gravity at a rate of ~40 m min^{-1}. When the instrument has landed on the bottom it is left inactive, except that the stirring inside the incubation chambers is running at a low speed, for some time to clear any potential ”sediment cloud”, created by the bow-wave of the instrument upon landing. One to four hours later (depending on the programming) the release mechanism of the inner frame is activated and the chambers are gently inserted ~20-25 cm into the sediment. When the chambers have penetrated into the sediment, leaving ~10-15 cm of overlying water the chamber lids are closed. This starts the incubation(s). An oxygen optode monitors the oxygen concentration and a turbidity sensor gives information about the level of suspended particulate matter in the chamber(s). Data collection is normally done at 1 min intervals. For each chamber ten automatic syringes are activated during a deployment. The first or the second of the syringes is normally used to inject tracers (e.g. bromide to get the exact chamber volume and/or ^{15}N labeled nitrate to perform denitrification experiments). The remaining syringes are used to withdraw 60 ml samples from the chambers. An equal volume of ambient bottom water from outside the chamber replaces each sample taken inside through a 1.5-mm inner-diameter and 400 mm long diffusion barrier tube. The concentration of the solute measured in the bottom water taken from outside the chamber is used to compensate for the effect this so called refill water has on the solute concentration inside the chamber.

The length of the incubations varies from a minimum of 15-20 h to a maximum of 50-70 h. In the resuspension chambers (often two out of four chambers) the stirring speed was increased after about half the incubation time to increase the shear stress and create resuspension. The turbidity sensors were used to confirm if the simulation of a resuspension event was successful. At the end of the incubation the sediment is recovered, which gives the possibility to further study the incubated sediment by doing solid phase sediment investigations for e.g. grain size, carbon and nitrogen content, quantifying fauna and sampling for chlorophyll. The quality of the recovered sediment has often so far been considered insufficient to perform subsampling for pore water extraction. Such sampling is normally performed on sediment samples collected with a multiple corer.

To make the lander ascend an acoustic command is sent from the surface, which triggers the release of the ballast and the simultaneous sampling of bottom water by closure of one 5 L Niskin bottle mounted on the lander.

2.2.1 Autonomous versus non-autonomous deployment and recovery

The inner frame can be deployed and used for incubation studies without the outer frame. This can be a good alternative in shallow areas, as for example in the Gothenburg Archipelago (Paper I) and the Scottish fjord, Loch Creran, (Paper III). The inner frame is then manually lowered to the sea bottom from the ship, and the chambers penetrate the sediment immediately. The inner frame is then connected to sea surface by a rope and a buoy. This technique is working as above (section 0) with the exception of recovering the lander, which is done by catching the buoy and gently pulling the rope. One of the advantages with this system is that smaller research vessels can be used for handling the lander. On the other hand there are some disadvantages: 1) there is risk that the equipment might be run over by large boats and the rope might be cut off or get stuck in the boat; 2) the research vessel needs to be positioned with no major drift to be able to get the chambers straight down in the sediment without tilting.

2.2.2 Definition of the effect of resuspension on benthic solute fluxes

Before the effect of resuspension on solute fluxes across the sediment-water interface was analyzed the resuspension process had to be defined. The following criteria were used to determine if resuspension was successfully created in the different chambers after the increase of stirring: 1) the measured turbidity had to increase by at least 100 %; 2) the average turbidity had to be at least 5 (± 5%) Normal Turbidity Units (NTU). If these criteria were fulfilled the chamber was considered to be a successful resuspension chamber and the results were retained.

The slopes of the regression lines (change in concentrations over time) together with the water height of the overlying water in the chambers were used to calculate the fluxes of the different solutes. More detailed description of the flux calculations can be read in Paper II and III. In order to analyze the influences of resuspension on the fluxes, the initial fluxes (fluxes before resuspension was created) were compared to the fluxes after resuspension was created. An ANOVA test was used to control if there was any statistical difference between the two fluxes. In the cases where the stirring speed was increased in two steps (Paper III) both the fluxes after the 1st and 2nd increase in stirring speed (ISS) were compared to the initial flux. Except for the initial, pioneering study (Paper I), the change in flux in the resuspension chambers was then compensated for any change in flux in the control chambers, in which no resuspension was created, which might have taken place at the same time.

The study in the Gothenburg Archipelago is considered to be more of a method development study since there were no control chambers, together with the fact that there were a low number of successful incubations. The important compensations of the change in flux in the resuspension chambers for the change in flux in the control chambers could therefore not be done.

2.3 Chemical Analysis

The different methods and/or instrument used for the analysis are summarized in Table 2.

Table 2. The analytical methods and/or instrument used in the study. The references (Ref.) are shown below the table.

Measured parameter	**Instrument/Method**	**Ref.**
Oxygen	Optodes from Aanderaa Data Instruments/ Winkler titration	1, 2
Nutrients	Nutrient Autoanalyzer	
DIC	Custom developed LiCor system	3
Dissolved iron	Specrophotometric method	4
Dissolved manganese	Specrophotometric method	4
Turbidity	Turbidity sensor from Aanderaa Data Instruments	5
Currents, Salinity, Temperature	RCM 9 from Aanderaa Data Instrument	6

1. Winkler (1888) 2. Tengberg et al. (2006) 3. O'Sullivan and Millero (1998) 4. Pakhomova et al. (2007) 5. Paper I and Paper II 6. Tengberg et al. (2001)

2.4 Model setup

The modeled transport of suspended fresh and resuspended particulate organic matter, the sediment content of organic matter and its resuspeded fraction were studied in the Baltic Sea (Paper V). The used model system was the coupled ocean circulation model RCO (Meier and Kauker, 2003; Meier et al., 2003), and the biogeochemical model SCOBI (Eilola et al., 2009; Meier et al., 2011). The model domain covers the Baltic Sea including the Kattegat (Fig. 6) which is often divided into sub-basins separated with sills. In this study the transport of fresh and resuspended particulate organic matter was investigated in an area including the Baltic Proper, the Bornholm Basin and the Arkona Basin (inside the thicker black line in Fig. 6) as well as the Gulf of Finland and the Gulf of Riga.

2.4.1 RCO

The RCO model handles the physical transports of water due to horizontal and vertical advection and turbulent vertical mixing. The model is forced by atmospheric data and river runoff (see Paper V). The horizontal resolution in this model setup was 2 nm and the vertical resolution was 41 depth levels, which were 3 m thick in the surface increasing to 12 m at the bottom levels.

2.4.2 SCOBI

The SCOBI model handles oxygen (O2), inorganic nitrogen (N) as ammonium and nitrate, and inorganic phosphorus (P) as phosphate. Organic matter in the model consist of phytoplankton (three functional groups representing: A1-diatoms; A2-flagellates and other algae; A3-cyanobacteria), zooplankton (ZOO) and detritus (DET, which is dead organic matter and faeces). Hydrogen sulfide concentrations are represented by “negative oxygen” equivalents ($1 \text{ ml } H_2S \text{ l}^{-1} = -2 \text{ ml } O_2 \text{ l}^{-1}$).

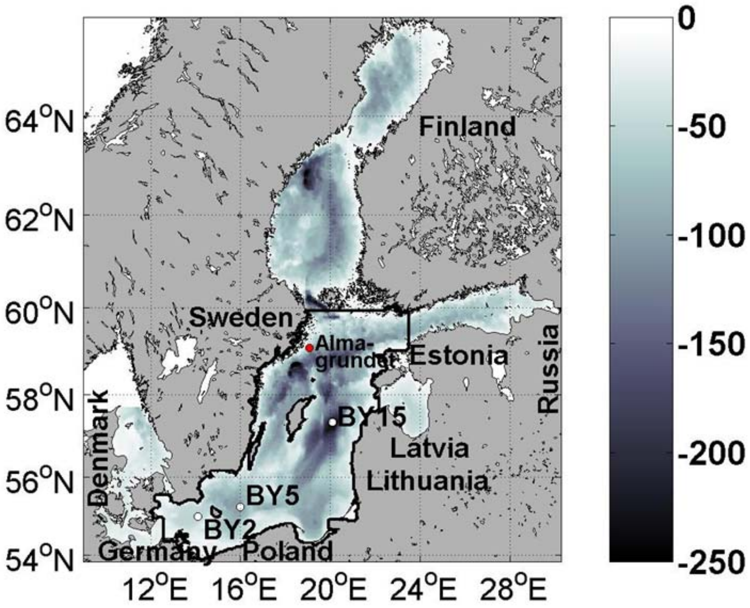

Fig. 6. The RCO-SCOBI model domain. The BY2, BY5 and BY15 are standard monitoring stations (www.SMHI.se) and Almagrundet (filled cirkel) is a light house where significant wave heights are observed.

In a simplified way (Fig. 7) the SCOBI model works like this:

Photosynthetic production of phytoplankton assimilates available nutrients in the photic zone. The phytoplankton have different sinking velocities and can sink towards the bottom while the zooplankton that graze on phytoplankton have neutral buoyancy. Phytoplankton mortality, predation of zooplankton and zooplankton faeces produces detritus that sinks towards the bottoms. The detritus is partly decomposed in the water column and the rest is deposited in the sediments. At the bottom the detritus becomes decomposed and the mineralized nutrients are divided into benthic P and N fluxes. Processes like nitrification, denitrification, and oxygen dependent adsorption of inorganic P in the sediment are parameterized in the model. Some of the benthic N and P are buried and some are released back to the water column and can potentially be re-used in photosynthetic primary production. If resuspension occur: benthic N and P in organic matter are transported back to the water column as detritus. Carbon is used as a constituent representing organic matter and the N and P content in organic matter is described by Redfield Ratio C:N:P=106:16:1. Oxygen is produced during photosynthesis and consumed during remineralization of detritus and zooplankton respiration.

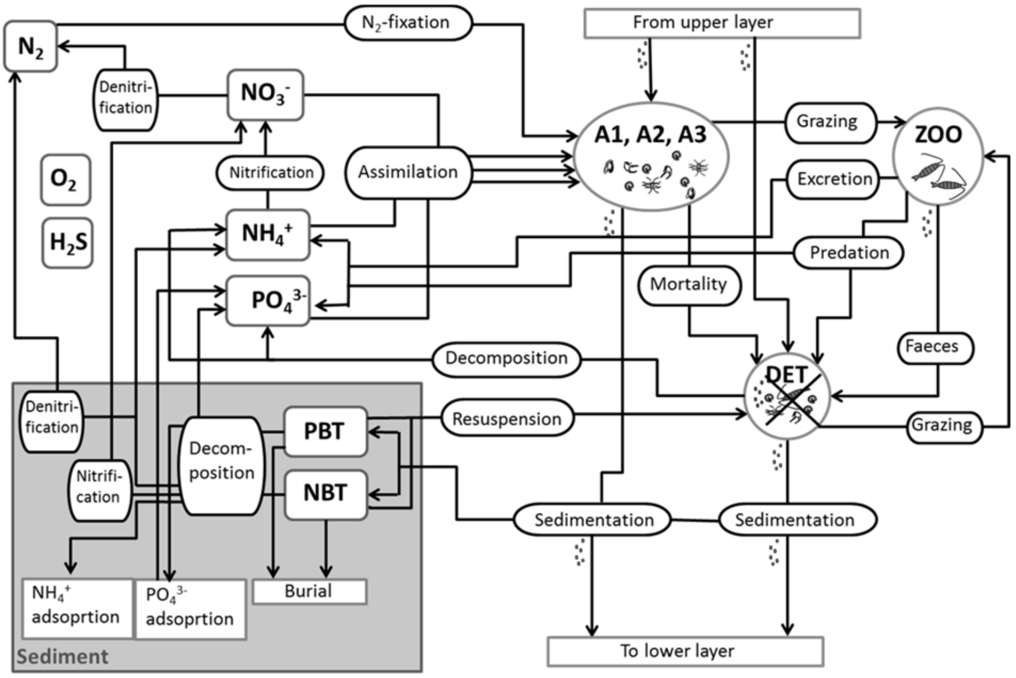

Fig. 7. A schematic figure of the SCOBI model, including three phytoplankton groups (A1, A2 and A3), zooplankton (ZOO), detritus (DET), inorganic nitrogen: the sum of nitrate and nitrite (NO_3^-); ammonium (NH_4^+), inorganic phosphorus: phosphate (PO_4^{3-}), benthic nitrogen (NBT), benthic phosphorus (PBT), oxygen (O_2). Hydrogen sulfide (H_2S) is represented as negative oxygen. Process arrows to/from the pool of oxygen are not shown in the figure.

2.4.3 The wave model and resuspension

To study the effect of resuspension in the model, waves need to be included. The simple wave model used in this model setup computes the wave heights using the fetch, the instant wind velocity and its duration (WMO, 1998). The shear stresses due to water currents and waves interact, and a net shear stress is calculated in RCO. The net shear stress is then used in SCOBI that handles the resuspension process: if the shear stress exceeds the critical shear stress set in the model, then resuspension occurs and sinking organic matter is kept in suspension.

3 Study areas

In the studies (Paper I-V) four different areas have been investigated. Resuspension studies were performed in the archipelago of Gothenburg, on the west coast of Sweden (Fig. 8); in the Gulf of Finland (GoF) in the Baltic Sea (Fig. 8); and in Loch Creran on the Scottish west coast (Fig. 9). The benthic cycle of phosphorus was studied in the GoF. Transport studies of modeled fresh and resuspended organic material were done in the Baltic Sea, particularly in the Baltic Proper, GoF, Gulf of Riga, the Bornholm Basin and the Arkona Basin (Fig. 6).

3.1 The Gothenburg archipelago

The station Måvholmsbådan (MB) was visited in January 2002 (Paper I). The station has a water depth of about 12 m and is situated in the archipelago outside the port of Gothenburg. The outflow from the Göta River enters the sea near Gothenburg and the position of the station close to the river mouth leads to a high content of terrigenic organic matter in the sediment. Video pictures taken in transects showed that the bottom was mainly flat with large areas consisting of mud with randomly scattered stones. Tracks by macro fauna were seen on the sediment surface.

3.2 The Gulf of Finland

Three stations, PV1, Kasuuni (Kas) and XV1, were visited in the GoF during three cruises in June-July 2003, September 2004 and in May 2005 (Paper II and Paper IV). The station XV1 was only visited in May 2005. For the phosphorus study (Paper IV) four additional stations, GF1, GF2, GF5 and GF6, were visited in June 2002 (Fig. 8).

The GoF is a direct extension of the Baltic Proper. The large river Neva enters the GoF in the east and the river Narva in the southeast. The more saline water in the west and the high supply of fresh water in the east leads to a large horizontal salinity gradient. Vertical mixing down to the bottom is limited by a permanent halocline (60-80 m) in the deeper parts (Alenius et al., 1998). The stations PV1, GF1 and GF2 were situated on accumulation bottoms consisting mainly of peltic mud at about 70-81 m depth. The bottom water at PV1, GF1 and GF2 is normally anoxic or hypoxic as the bottom depth of these stations is deeper than the depth of the halocline.

The other stations were situated on transport bottoms, where XV1 had more of an erosion bottom character with somewhat coarser grain size. The bottom depths at Kas, GF5 and GF6 were 49-56 m and at XV1 about 37 m. The oxygen concentration in the bottom water at the four stations was highly variable, but never went anoxic or hypoxic during our studies.

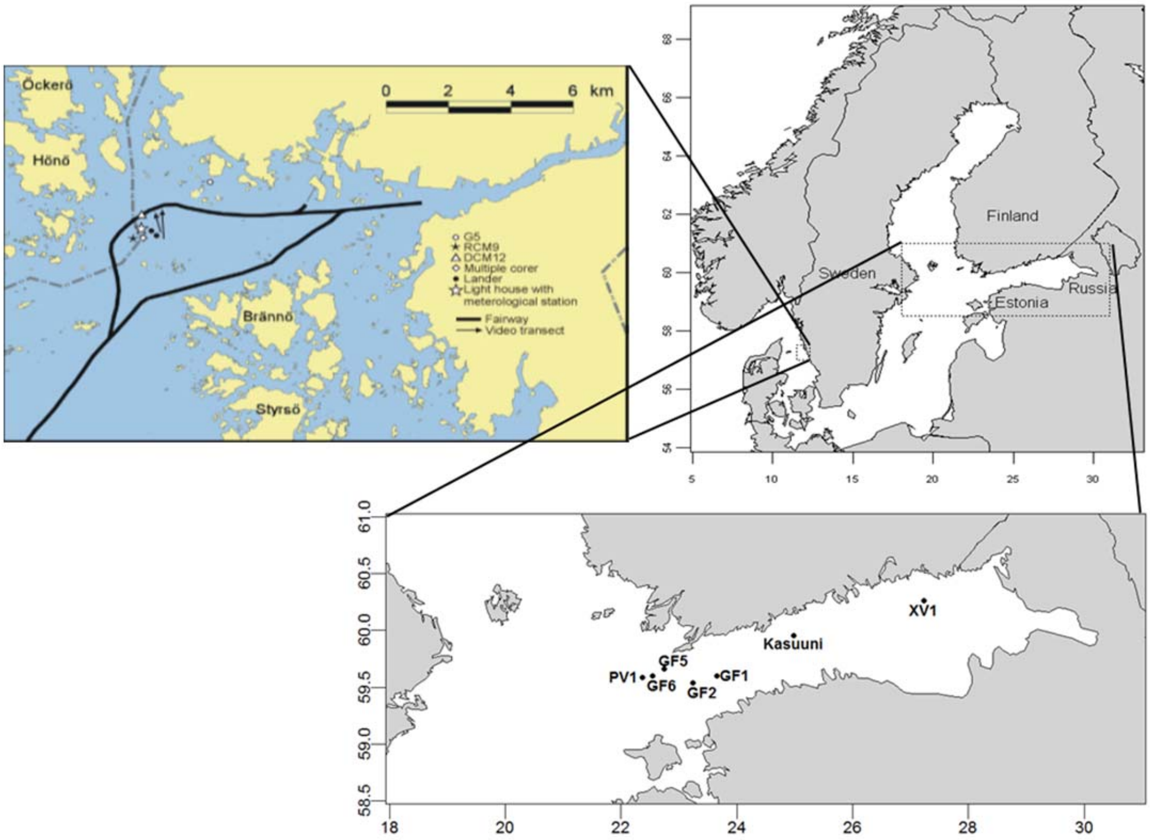

Fig. 8. The two study areas with the seven stations visited in the Gulf of Finland (lower right panel) and one station in the archipelago outside Gothenburg harbor (left). Their locations on a larger scale are shown in the figure in the upper right panel.

3.3 Loch Creran, Scotland

Two stations (S1 and S11) were visited in the Loch Creran on the west coast of Scotland (Fig. 9) in May 2006 (Paper III). Loch Creran is a loch divided into four basins by shallow sills. The stations were situated in the western part of basin 3, a relatively shallow basin (max 27 m) with soft sediment in the deepest parts. The loch is sheltered from waves, but tidal currents and wind contribute to strong mixing of the water. The bottom water is prevented from oxygen depletion due to short flushing time and the intensive mixing of the water.

Station S11 was located on an earlier position for a fish farm at approximately 25 m bottom depth. The sediment was muddy and had a high concentration of organic carbon. The S1 station was not affected by the fish farm, the sedimentary organic carbon concentration was lower, and it served as a control station.

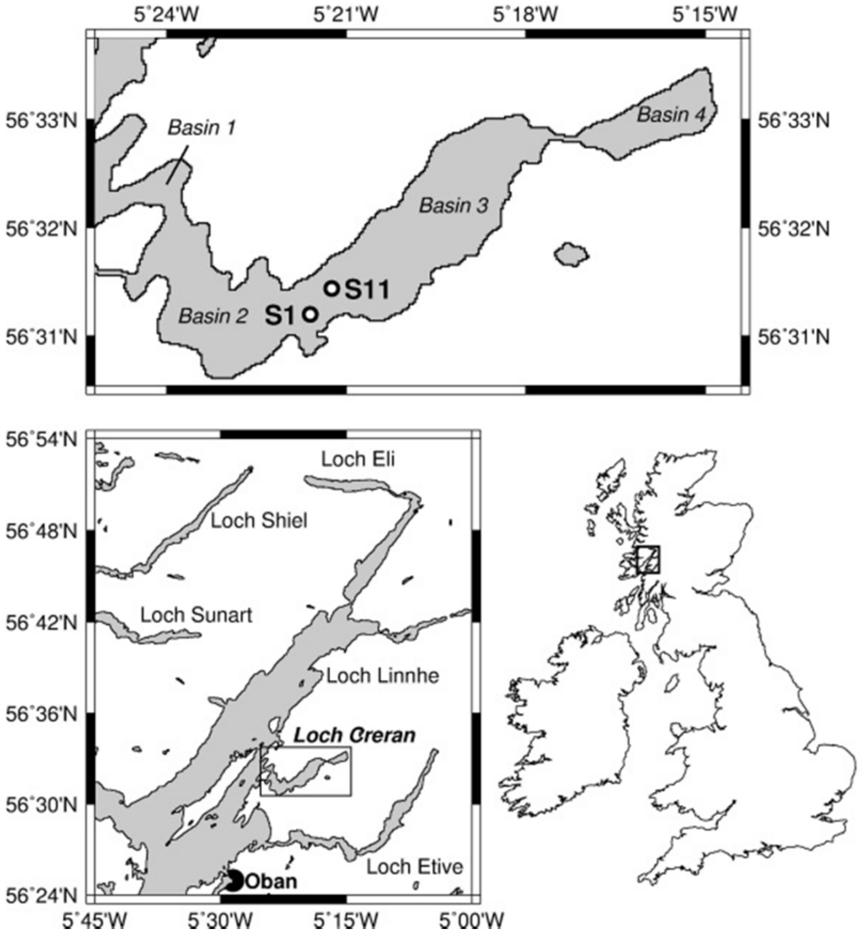

Fig. 9. A map of Loch Creran, a study site on the west coast of Scotland. Station S1 and S11 were investigated with chamber incubations using a benthic lander. Between the two stations a Recording Doppler Current Profiler (RDCP) was deployed throughout the field work in order to measure background data of oxygen, turbidity, currents, salinity and temperature.

3.4 The Baltic Sea

Nine countries have their coast lines adjacent to the Baltic Sea (Fig. 6). It is a shallow sea with a mean depth of 54 m and the maximum depth, 459 m, is found in the Landsort Deep northwest of Gotland. The Baltic Sea is connected to the North Sea by the shallow and partly narrow areas in the Danish straits (the Belts and the Öresund), which control the inflow of salt water (Lepparanta and Myrberg, 2008). A large river runoff of about 14,000 m^{-3} s^{-1} enters the Baltic Sea (excluding the Danish straits) and results in brackish water (Bergström et al., 2001) with large horizontal salt gradients and a strong halocline at about 60 m depth (Stigebrandt, 2001).

4 The effect of resuspension on benthic solute fluxes

The method to study the effect of resuspension on benthic solute fluxes *in situ* was developed and thoroughly tested in the Gothenburg archipelago (Paper I), and was then used in Gulf of Finland (Paper II) and Loch Creran (Paper III). Resuspension was created in the chambers after approximately half the incubation time in the GoF, Gothenburg Archipelago and in two deployments in the Loch Creran by increasing the stirring speed inside the chambers. In three deployments in the Loch Creran the stirring speed was increased after about one third of the incubation time, and then there was a second increase after about two thirds of the incubation, in order to further increase the strength of resuspension. In the study in the GoF and the Loch Creran two of the four incubation chambers in each deployment were used as control chambers. Thus, in these chambers the stirring speed was kept at a constant level throughout the incubation and no resuspension was created. The effect of what we call massive resuspension on benthic solute fluxes was studied in three out of five deployments in the Loch Creran.

4.1 Natural resuspension

The strengths of the simulated resuspension events in the incubation chambers were compared to the level of the resuspension events created naturally due to strong water currents. Long-term measurements of e.g. currents and turbidity at a level of one meter above bottom were performed using a Recording Current Meter (RCM9) during 10 months in 2003-2004 in the GoF (stations PV1, Kas and XV1) and at 0.6 m above bottom during one month at station MB (Gothenburg Archipelago). In the GoF these long-term measurements showed that the currents in general were low (~0.4 cm s^{-1}) and that natural turbidity varied from 0.4-1.0 mg l^{-1}. At each station natural resuspension events occurred only three times, of which the highest had a turbidity of 11 mg l^{-1}. At MB, on the other hand, it was a windy period (December, 2001-January, 2002) and a major storm passed the area (wind data was supplied from the Vessel Traffic Service Control of Gothenburg harbor). The storm did not create waves large enough to create resuspension, but sea water was build up against land and when the wind abated the water flushed back and strong currents occurred (40 cm s^{-1}), which resulted in a resuspension event with a turbidity of 12 mg l^{-1}. The same phenomenon was also observed during the field study in GoF in 2004, at station PV1. A current meter and a turbidity sensor mounted on the lander about two meters above the bottom recorded currents as high as 46 cm s^{-1} and turbidity values up to 10 mg l^{-1}. Assuming the sediment particles to be equally distributed between the sediment and the sensors, and using the porosity and the density of the top layer of sediment, the amount of resuspended particles was calculated to correspond to 18 and 256 µm of the sediment top layer at MB and PV1, respectively. In the Loch Creran no major resuspension events was observed due to large waves or strong winds. On the other hand, a difference in water level of 3 m due to tides created currents of maximum 26.6 cm s^{-1} (average 7.8 cm s^{-1}) at 3.5 m above bottom. Smaller resuspension events were thus created with a maximum of 4 Normal Turbidity Units (NTU) and an average value of about 1.4 (stdev=0.4) NTU, which corresponds to about 4.5

and 1.38 mg l^{-1} using the conversion factor from GoF. This conversion factor was calculated by measuring the amount of suspended particulate material in water samples (by filtering a known volume), which then was compared to the corresponding turbidity value from the sensors. A linear regression gave the following equation (see Paper I for a more detailed description): turbidity (mg l^{-1}) =1.2*turbidity (NTU)-0.3. A new conversion factor for the Loch Creran turbidity (NTU) values was not calculated.

At MB about 2 and 13 µm of the sediment was resuspended inside the two chambers containing a turbidity sensor. This corresponds rather well with the magnitude of the naturally created resuspension event due to the storm when about 18 µm of the sediment was resuspended. In the GoF the maximum thickness of the sediment resuspended in the incubation chambers was 240 µm (average 67 µm), while the naturally created resuspension event at PV1 in 2004 resuspended 256 µm of the sediment. In Loch Creran the turbidity in the resuspension chambers was on average 6.5 NTU and 8.9 NTU after the first and second increase in stirring speed, respectively, which corresponds to about 0.26-2.6 µm of the top sediment layer. This shows that the sediment layer that was resuspended in the Loch Creran was thinner than in GoF, but the resuspension events created by tides were also weaker creating turbidity of at most 4 NTU. From these data and calculations it was concluded that the simulated resuspension inside the chambers corresponded fairly well to the magnitude of the naturally created resuspension events at the two sites.

4.1.1 Oxygen consumption

In general a parabolic or exponential decrease of oxygen consumption with time, the so called “banana shape”, was observed during all deployments and incubations in the Loch Creran and the GoF. This type of benthic oxygen uptake kinetics has been observed and described previously (Hall et al., 1989), and after compilation of several hundred *in situ* chamber incubations it has been found to be a frequently occurring phenomenon in a large range of marine environments (M. Kononets, personal communication). The banana shape resulted in decreased oxygen consumption with time, and showed the importance of using control chambers in order to correctly evaluate the effect of resuspension on benthic oxygen consumption.

The initial consumption of oxygen was highest at station S11 and S1 in the Loch Creran (Fig. 10, left) and much lower at the stations in the GoF. The created natural resuspension clearly increased the oxygen consumption at all stations in GoF (PV1, Kas and XV1) and at S11 in the Loch Creran (Fig. 10, right). The effect on the oxygen consumption was highest at PV1 in the GoF (results from year 2004), where the consumption increased with on average 115 % (stdev 85). During the cruises in 2003 and 2005, the oxygen concentration in the bottom water at the PV1 station was very low (<12 µmol l^{-1}) and oxygen in some chambers was depleted during the incubation. At the transport/erosion bottom stations Kas and XV1 the oxygen consumption increased with on average 45 (stdev 29) and 15 %, respectively. The sediment content of organic carbon was highest at PV1, which has accumulation bottom, and lower at Kas and XV1 (5.8, 3.9 and 2.5 % of dry weight, respectively). At S11 the oxygen consumption increased with an average of 23 % during deployment 3, 4 and 5 during the first incubation. The organic carbon content at this latter station was about 7 % (Fig. 11). Resuspension did not clearly influence the oxygen consumption at S1 in Loch Creran, which had the lowest sedimentary organic carbon content, about 1.5 %.

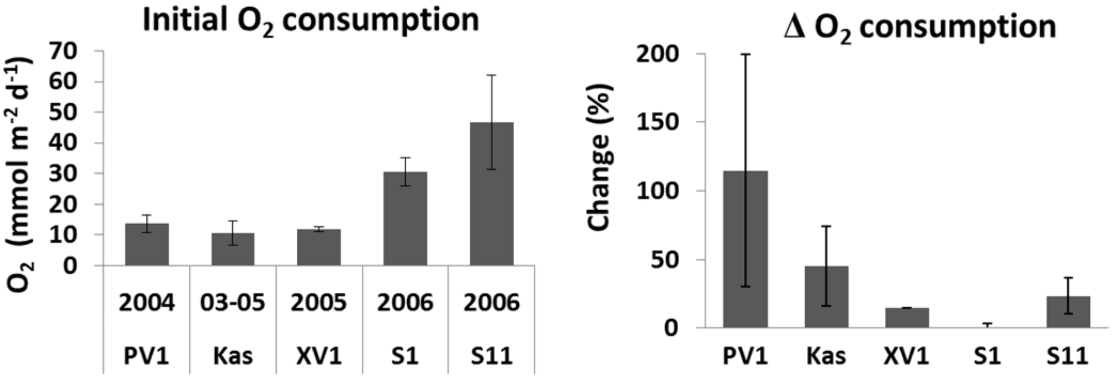

Fig. 10. The average initial oxygen consumption (mmol m^{-2} d^{-1}) and the change in consumption (%) as a result of resuspension at the different stations are shown to the left and right, respectively. At station S1 and S11 oxygen consumption and the change in oxygen consumption are shown only from the first incubation and the first increase in stirring speed.

There was no correlation between the initial oxygen consumption and the change of it due to resuspension. However, a comparison of the organic carbon content in the sediment at the different stations in GoF versus changes in oxygen consumption due to resuspension (Fig. 11, left) showed some correlation (R^2=0.76 and P-value=0.05). The higher the organic carbon content was in the sediment the higher change in oxygen consumption due to resuspension was observed. However, the stations S1 and S11 in the Loch Creran did not fit into the correlation between organic carbon content and change in oxygen consumption (Fig. 11, right).

High organic carbon content in the sediment reflects high content of organic matter, which initially preferably uses oxygen as electron acceptor in the degradation process. The more organic matter content there is in the sediment, the higher is generally the oxygen demand. Below the oxygenated surficial sediment zone other substances can be used as electron acceptors. The higher organic matter content of the sediment, the higher is the demand of these alternative electron acceptors. When these electron acceptors are consumed during organic matter oxidation, reduced dissolved inorganic compounds are produced. When resuspension occurs, particles as well as pore water from the sediment are mixed with the overlying water. These reduced inorganic compounds from the pore water then stimulate oxygen consumption as they are reoxidized when mixed with the oxygenated overlying water. This is the main mechanism by which resuspension stimulated oxygen consumption in our studies, and it also explains the correlation between organic carbon content in sediment and the magnitude of increase of oxygen consumption due to resuspension.

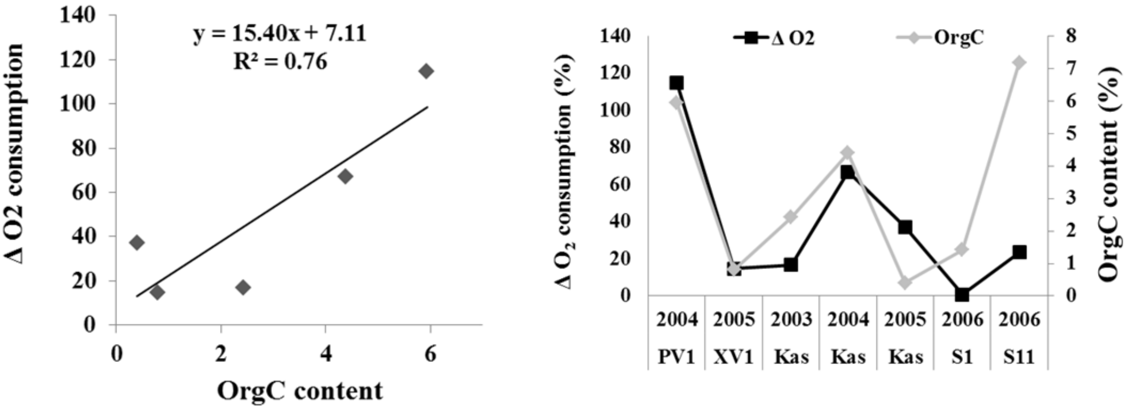

Fig. 11. There was a linear correlation between the change in oxygen consumption and the sediment content of organic carbon in the GoF (left). The change in oxygen consumption and the sediment content of organic carbon are also shown for the different stations during the different years (right), including S1 and S11 (only the change in flux due to the first increase in stirring speed and from the first incubation) in Loch Creran.

At the station S11 the organic carbon content was high, but because the bottom water never becomes anoxic reduced substances are not built up in the sediment to a large extent, as they are on e.g. PV1, which are anoxic during long periods. Station S11 had the highest initial consumption, but relatively low change in oxygen consumption due to resuspension, and rather high oxygen concentration in the bottom water (about 300 µM). A test showed some negative correlation (R^2=0.4 and P-value=0.002) between the change in oxygen consumption (%) and the initial oxygen concentration (µM) (Fig. 12). This suggests that the lower concentration of oxygen in the bottom water, the higher will the increase in oxygen consumption be during a resuspension event. At bottoms with low oxygen concentration the oxygen consumption might be transport limited by the diffusive boundary layer (DBL) at the sediment-water interface, which results in a buildup of oxygen demand, i.e. a large oxygen debt in the sediment. If the sediment also is enriched in organic matter the oxygen demand would be even larger, e.g. PV1 2004 which had low initial oxygen consumption and relatively low oxygen concentration in the bottom water (119-187 µM). During resuspension the DBL is eroded, its transport resistance is removed and oxygen can diffuse down into the sediment pore water and reduced substances are mixed with and oxidized by the overlying water, with an increase in oxygen consumption as a result. At stations with high bottom water oxygen concentration the DBL does not limit the diffusion of oxygen into the sediment, which results in a smaller buildup of reduced substances. Hence the increase in oxygen consumption becomes smaller at resuspension events.

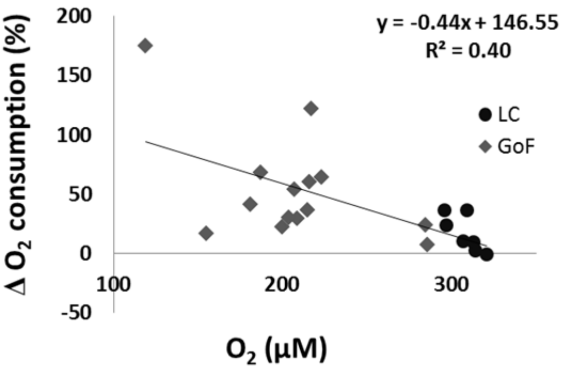

Fig. 12. The change in oxygen consumption versus the initial bottom water oxygen concentration in the different resuspension chambers at all stations in the GoF (diamonds) and Loch Creran (circles). The regression line is shown for all data points.

4.1.2 DIC and Nutrients

The studies in the Loch Creran and the Gothenburg Archipelago did not supply data adequately enough to draw conclusions about the effects of natural resuspension on the fluxes of DIC and nutrients between the sediment and overlying water. However, in the GoF fluxes were successfully measured in between 24 and 34 incubation chambers (different number of successfully measured fluxes for different solutes). Natural resuspension was created in 14-18 chambers in which successfully measured fluxes were measured. Effects of resuspension on the DIC fluxes were only observed in three resuspension chambers out of 16, and all of these at Kas in 2004 (Fig. 13). The overall conclusion from these results is that the DIC fluxes are not to a large extent affected by natural resuspension on this time scale. Many studies have been made with the conclusion that organic matter degradation rates increase during resuspension events (e.g. Wainright, 1987, 1990; Wainright and Hopkinson, 1997; Ståhlberg et al., 2006) with increased release of nutrients and DIC as a result. Those conclusions are not confirmed by this study. The incubations in the GoF study had a duration of typically 23-33 h (range 15-70 h), which might be considered to not be long enough to increase the biomass of bacteria responsible for degradation. However, since we suggest that the observed stimulation of oxygen consumption by resuspension is due to oxidation of reduced inorganic compounds, which mostly is due to bacterially mediated oxidation (Canfield et al., 2005), we still argue that resuspension does not stimulate organic matter degradation. This conclusion is further supported by the lack of increased DIC fluxes during resuspension events.

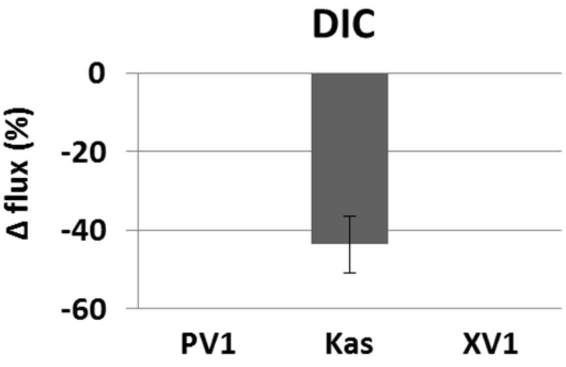

Fig. 13. A change in flux of DIC due to resuspension was only observed at Kas, and only in year 2004. The bar shows the average value of the change (%) and the error bar shows the standard deviation of the average change in flux. The negative change means that the DIC flux out of the sediment became smaller at the onset of resuspension.

Effects of resuspension on the ammonium fluxes were only observed at PV1 during the cruises in 2003 and 2005 when the ambient bottom water had low oxygen concentration. The high initial effluxes of ammonium decreased on average with 65 % (Fig. 14, left) in four of eight resuspension chambers, and this was probably due to enhanced adsorption on resuspended particles. At the stations with higher oxygen concentrations in the bottom water the initial fluxes of ammonium were very low, or even not significantly different from zero, which make any change in efflux hard to distinguish from the initial flux.

The effluxes of silicate were influenced by resuspension at PV1 and Kas. The effluxes increased at PV1 in 2004, but decreased during the incubations at Kas in 2004 and at PV1 in 2005. On average the fluxes decreased with 27 % and 21 % at PV1 and Kas, respectively (Fig. 14, right). However, the decrease of the silicate fluxes was not expected since there is a high gradient between the pore water concentrations (147-203 µM and 181-251 µM in the top sediment layer at Kas in 2004 and PV1 in 2005, respectively) and the overlying water (19-29 µM and 27-56 µM at Kas in 2004 and PV1 in 2005, respectively). Williams et al. (1985) discussed different ways for which silicate concentrations can decrease in sea water, e.g. complexation with manganese and sulfate or adsorption of silicate on clay minerals. On the other hand, Siever and Woodford (1973) suggested that dissolved silicate has to be present in concentrations higher than 1 ppm less than a crossover point of 12 ppm (125 µM) to be adsorbed to clay minerals like e.g. kaolinite. At Kasuuni the concentration of silicate was below this threshold during the whole incubation (maximum 56 µM). At PV1, the silicate concentrations reached a maximum of 109 µM which is close to the crossover point. The decrease in efflux of silicate might therefore be explained by adsorption of silicate on clay minerals (resuspended into the water of the chambers) at PV1 in 2005, but not at Kas in 2004. The experiment setup by Siever and Woodford (1973) was however only performed during oxic conditions, and at PV1 in 2005 the bottom water was anoxic (the little oxygen initially present in the chambers was totally consumed during incubations), and silicate adsorption on clay minerals may be oxygen dependent. Thus, the irregular response pattern of the fluxes of silicate leads to the conclusion that silicate fluxes were not significantly influenced by resuspension.

No effects of resuspension on the fluxes of nitrate or phosphate were observed at any of the stations. In PV1 in 2003 and 2005, when the ambient bottom water was suboxic, the nitrate was depleted during incubations and no fluxes could therefore be measured.

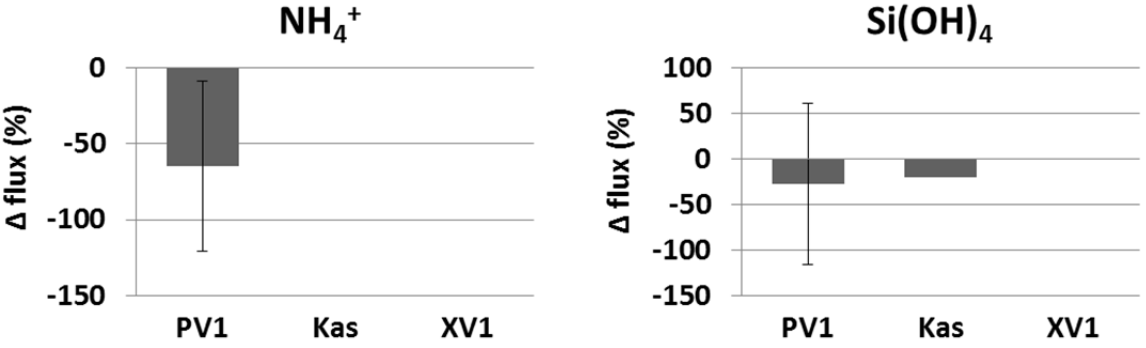

Fig. 14. The average change in flux (%) of ammonium (left) and silicate (right) due to the created natural resuspension.

4.1.3 Iron and manganese

The effects of resuspension on total dissolved iron and manganese fluxes were investigated in the GoF (Paper II). At PV1 in 2005, the fluxes of dissolved iron increased in the two resuspension chambers with on average 136 % (± 31) and in 2003 the fluxes were not influenced, but the concentration of dissolved iron was instantly increased at the onset of resuspension in one out of three chambers from about 1.7 to 10 µM. When oxygen was present in the overlying water the iron fluxes were low or insignificant. Thus, the fluxes of dissolved iron were only influenced by resuspension events when the oxygen concentration in the ambient bottom water was low or zero as at PV1 in 2003 and 2005 (Fig. 15, left). This behavior is consistent with the oxygen dependent behavior of dissolved iron discussed in other studies (e.g. Sundby et al., 1986; Widerlund and Ingri, 1996; Pakhomova et al., 2007). At oxygenated stations reduced iron in the sediment is quickly oxidized at the onset of resuspension forming particulate iron oxyhydroxides. At PV1 in 2005 and 2003, the oxygen was depleted during incubations and the reduced iron was transported to the overlying water without being oxidized.

Effects on the dissolved manganese effluxes were only observed at PV1 in 2003 and 2004. In 2003 the average fluxes increased, but were irregular, with both a decrease and an increase in the individual resuspension chambers. In 2004 there was on average an increase in the efflux of manganese (Fig. 15, right). The effects were rather low (in the range -0.6±0.2 – +1.3±0.4 mmol m^{-2}-d^{-1}), but because the initial fluxes also were rather low, the effects measured in percent were rather high. The overall conclusion from this study is that the manganese fluxes were not significantly influenced by natural resuspension.

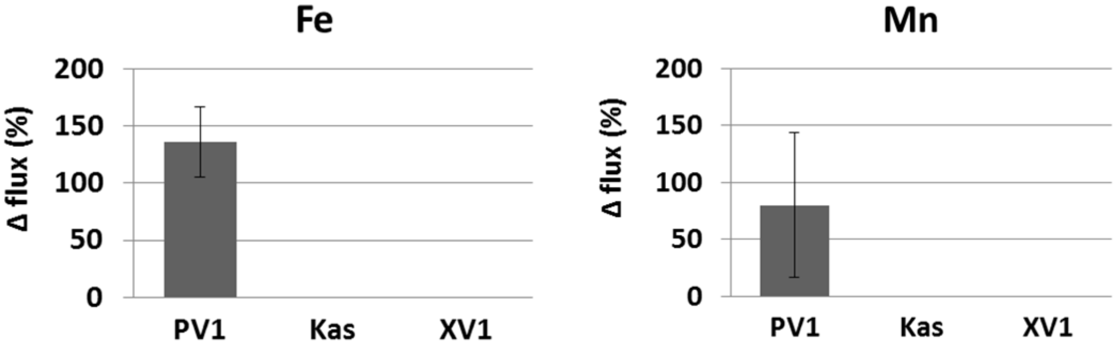

Fig. 15. The average change in flux (%) of total dissolved iron (left) and manganese (right). The error bars show the uncertainty in the change of the fluxes.

4.2 Massive resuspension

The effects of created "massive" resuspension in the chambers on solute fluxes were studied during three deployments in the Loch Creran (Paper III). Massive resuspension, which aimed to represent resuspension created by e.g. trawling or dredging, was created when the benthic lander captured the sediment within the chambers. Due to the strong feathers that pull up the chambers the incubated sediment was shaken and a massive resuspension occurred. No control chambers could be used in this study, because the sediment was captured in all four incubation chambers. The turbidity sensors inside the chambers increased from the background turbidity (about 1-2 NTU) to more than maximum value for the sensors (> 120 NTU) in most of the chambers. The sediment particles that were observed inside the sampling syringes was another evidence that massive resuspension occurred.

Massive resuspension was successfully created in seven of the eight chambers in the last incubations at station S11 during deployment four and five. In these chambers the effects of the created massive resuspension on the oxygen consumption and on fluxes as well as on concentrations of DIC and nutrients were studied. At station S1 massive resuspension was created in three chambers during the last incubation in deployment two. Only the effect of the massive resuspension on the oxygen consumption could be analyzed during this deployment since no fluxes of DIC and nutrients were measured. However, the difference in concentrations of DIC and nutrients just before and after the massive resuspension event was measured and analyzed.

4.2.1 The response of oxygen, nutrients and DIC to massive resuspension

The oxygen consumption increased dramatically in all chambers due to the created massive resuspension (Fig. 16). The largest consumption was observed immediately after onset of the massive resuspension and then decreased with time. The oxygen concentrations went low (minimum about 2 µM) inside the chambers, but the incubated water never became anoxic. The largest increase was observed at station S11, where the sediment was enriched in organic matter due to the former fish farm. The consumption increased at this station with 340-5025 mmol m^{-2} d^{-1}. At S1, which was not affected by the fish farm, the increase was lower and ranged between 250 and 980 mmol m^{-2} d^{-1}. The created massive resuspension in the chambers reached further down into the sediment compared to natural resuspension. At deeper depth in the sediment the concentrations of reduced substances was higher. Thus, the massive resuspension caused a larger amount of pore water containing higher concentrations of reduced inorganic substances to be mixed with the overlying water. This led to a huge stimulation of oxygen consumption as the reduced substances were reoxidized. At station S11 the sedimentary organic content was higher down to about 10 cm in the sediment compared to at S1. This higher organic matter content probably resulted in higher concentrations of reduced solutes in the pore water at S11. Thus, the oxygen demand at a massive resuspension event at S11 was much larger than at S1.

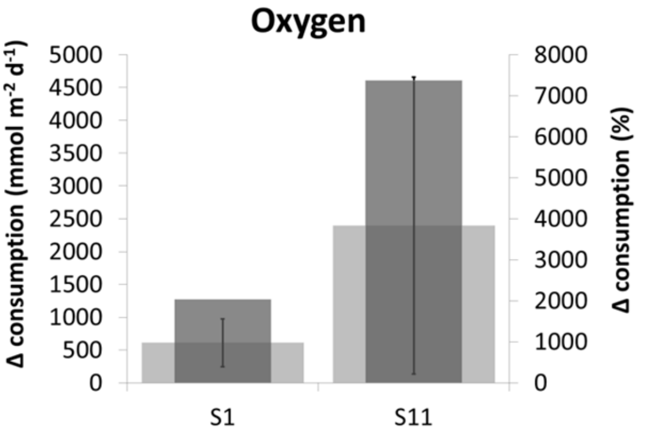

Fig. 16. The average increase in oxygen consumption, measured in mmol m^{-2} d^{-1} (light grey and broad bars) and in % (dark grey and narrow bars), due to massive resuspension at station S1 and S11 in Loch Creran. The error bars show the standard deviation of the average values measured in mmol m^{-2} d^{-1}.

In the majority of the resuspension chambers at station S11 there were no effects of massive resuspension on the effluxes of ammonium, phosphate and silicate. However, the fluxes were influenced in two, one and two chambers corresponding to 50, 14 and 33 %, respectively, of the number of massive resuspension chambers. In these cases the effluxes decreased to become very small or even influxes. The fluxes of DIC were not influenced in any of the resuspension chambers. Even though the fluxes were only affected in a few cases, there were significant changes in concentrations of all substances in all massive resuspension chambers. The concentrations of DIC, ammonium, and silicate instantly increased with on average 20, 482 and 200 %, respectively, while the concentration of phosphate instantly decreased with on average 62 % as an effect of the created massive resuspension in the chambers at station S11 (Fig. 17). The decrease of phosphate concentration was probably due to adsorption onto newly formed iron oxyhydroxides. At station S1, where no fluxes of DIC and nutrients were measured, there were statistically significant effects (t-test) on the concentrations of ammonium and silicate, which increased with 18 and 33 %, respectively, but no statistically significant effects on the concentrations of DIC and phosphate. The instant increase in concentrations of DIC at station S11, and of ammonium and silicate at both stations, probably occurred when pore water in the sediment, rich in these substances, was mixed with the overlying water. Ammonium could also be desorbed from resuspended particles, onto which ammonium was adsorbed in the sediment.

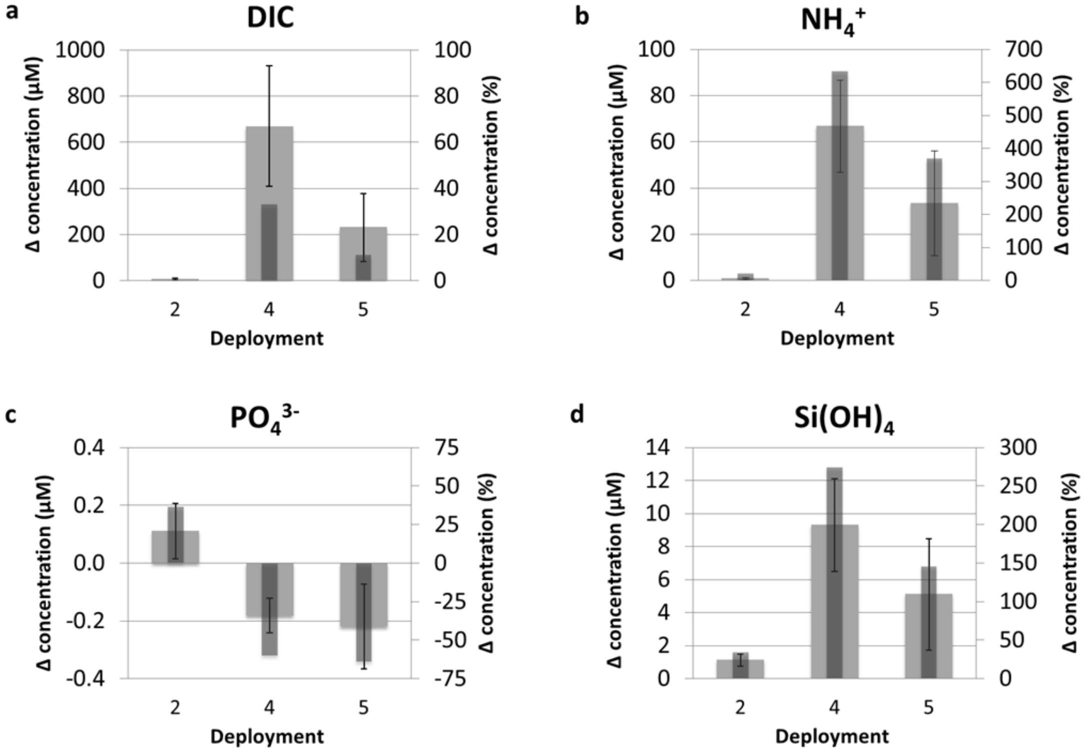

Fig. 17. The average effects of massive resuspension on the concentration in µM (light grey and broad bars)and % (dark grey and narrow bars) of DIC (a), ammonium (b), phosphate (c) and silicate (d) at station S1 (deployment 2) and S11 (deployment 4 and 5). The error bars shows the standard deviation of the average change in concentration (µM).

4.3 The effect of repeated and varied strength of resuspension on benthic oxygen consumption

In the Loch Creran the effect of resuspension on the oxygen consumption was studied also during repeated incubations during the same deployments. This was done by opening the lids of the chambers when the first incubation was completed. The incubated water was then ventilated until ambient bottom water oxygen conditions were recreated in the chambers. After that, the lids were closed again, and the next incubation started (Fig. 18). In this way effect of resuspension on benthic oxygen consumption was measured on exactly the same site several times. This study was limited to the effects on oxygen consumption, because oxygen and turbidity were the only parameters that were measured with optodes and sensors, i.e. with high temporal resolution and no limitation in the number of measurements.

Also the effect of increased strength of resuspension was studied. During each incubation the stirring speed was preprogrammed to increase in two steps. The first increase from low to medium speed occurred after about one third of the incubation time. After additionally one third of the incubation time, the second increase, from medium to high stirring speed, took place. The resuspension level or strength was in this way intensified when the stirring speed was increased the second time, which is illustrated in Fig. 18, where the turbidity increased in two steps in the resuspension chambers during the three incubations.

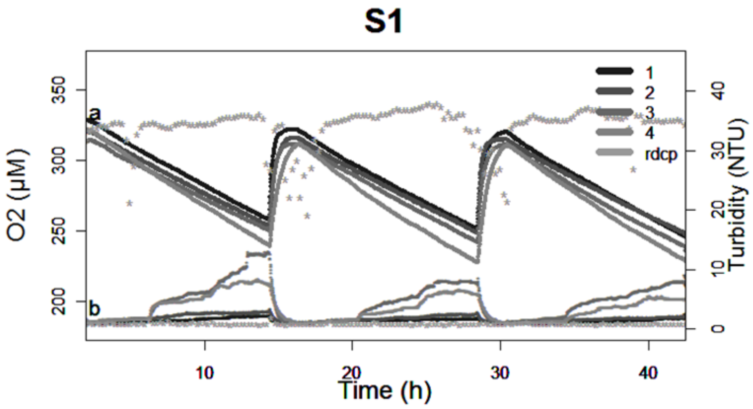

Fig. 18. Repeated chamber incubations at the same site. The concentrations of oxygen (starts with the letter a) and turbidity (starts with the letter b) are shown during repeated incubations (inc 1-3) in deployment two at station S1. The oxygen concentrations were measured both inside (lines) and outside (stars) the chambers.

The effects of resuspension in repeated incubations were studied during deployment two (at S1) and during deployment four and five (at S11), in which three and two incubations were performed, respectively. At station S11 there was a clear increase of the oxygen consumption when the stirring speed was increased the first time in both deployment four and five. The increase was larger during incubation one compared to incubation two (Fig. 19, left). Also the second ISS resulted in an increase of the oxygen consumption (Fig. 19, right), compared to the initial consumption. The difference in consumption between the two stirring speeds during the first incubation was larger compared to the difference during the second incubation. The larger increase in oxygen consumption during the first incubation, at both stirring speeds, compared to the second incubation, might be due to at least two reasons. First, there were more reduced solutes available to oxidize during the first incubation and the first increase in stirring speed, thus the oxygen demand was larger then. Second, no new organic matter, or reduced solutes, was probably transported into the chambers during ventilation between incubations. Instead some of the resuspended particles (inorganic as well as organic) were probably ventilated out from the chambers at the end of the first incubation. Observations of the turbidity showed that the level of resuspension slightly decreased between incubations, probably due to the out-ventilation of smaller particles as well as re-arrangement of the sediment particles on the sediment surface.

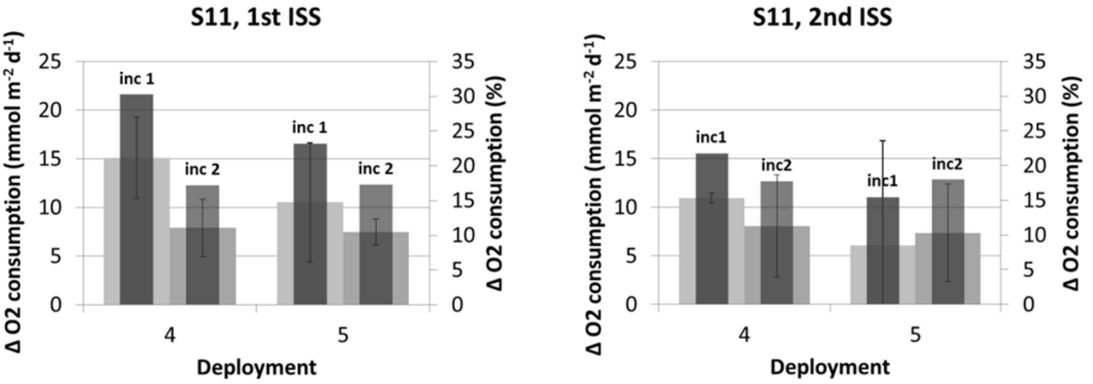

Fig. 19. The change in oxygen consumption compared to the initial oxygen consumption in mmol m^{-2} d^{-1} (light grey and broad bars) and % (dark grey and narrow bars) at station S11 during the different incubations, at the first step of increased stirring speed (ISS) (to the left) and at the second step of ISS (right). The error bars show the standard deviation of the change in oxygen consumption in mmol m^{-2} d^{-1}.

At S1 there were no clear effects of resuspension on the oxygen consumption due to the first increase of the stirring speed in any of the three incubations. The observed change in consumption was low (maximum about ±2.7 mmol m^{-2} d^{-1}) compared to the initial oxygen consumption, which was on average 31 mmol m^{-2}-d^{-1} (stdev 4.7). During the first and second incubation the changes in the different resuspension chambers were both negative and positive, with high standard deviation as a result. In the third incubation the oxygen consumption increased in both resuspension chambers, but was still very low. When the stirring speed was increased a second time the oxygen consumption on average decreased during all incubations compared to the initial flux. The decrease was lower during the first incubation and then decreased even more for incubation two and three. However, there were both negative and positive changes during incubation two with a large standard deviation as a result.

At S1, the resuspension created in the resuspension chamber did not influence the oxygen consumption significantly. Neither did the repeated resuspension event. However, at station S11, where the sedimentary organic content was higher the oxygen consumption increased due to resuspension, but an intensification of the resuspension did not further increase the oxygen consumption. Repeated resuspension caused a lower increase in oxygen consumption the second time compared to the first. These results might be due to the natural condition in the Loch Creran. Smaller resuspension events are created at a regular basis due to tides, which also cause high mixing of the water keeping the bottom water oxygenated. Thus, reduced solutes do not build up to a large extent in sediment with lower content of organic matter. In sediment with higher content of organic matter reduced solutes build up, but they get less abundant the more often resuspension events occur.

5 Benthic phosphorus cycling

Benthic phosphate fluxes were measured *in situ* using landers at seven different stations in the GoF (Fig. 8) from 2002 to 2005 (Paper IV). At stations with anoxic/suboxic bottom water conditions (GF1, GF2 and PV1 in 2003 and 2005) the phosphate fluxes were high and directed out of the sediment. At the deep station PV1 in 2004, the ambient bottom water conditions had changed and the overlying water was oxygenated. The phosphate fluxes then changed from high effluxes to become zero, or even influxes (Fig. 20, left). At the stations with well oxygenated bottom water (GF5, GF6, Kas and XV1) the fluxes were about zero, or even negative during all incubations (Fig. 20, right). This oxygen dependent behavior has been shown also in earlier studies (e.g. Mortimer, 1941; Froelich, 1988; Conley et al., 2002; Eilola et al., 2009) and is explained by the adsorption capacity on iron oxyhydroxides for phosphate. The fluxes in this study were, unlike other studies, measured *in situ*, which increased the trustworthiness of the results, especially at the anoxic bottoms. Low phosphate fluxes were measured also in the Loch Creran at stations S1 and S11 and in Gothenburg archipelago at station MB, where the bottom water was oxygenated. At S11 the phosphate fluxes was low in spite of high sedimentary organic matter content at S11.

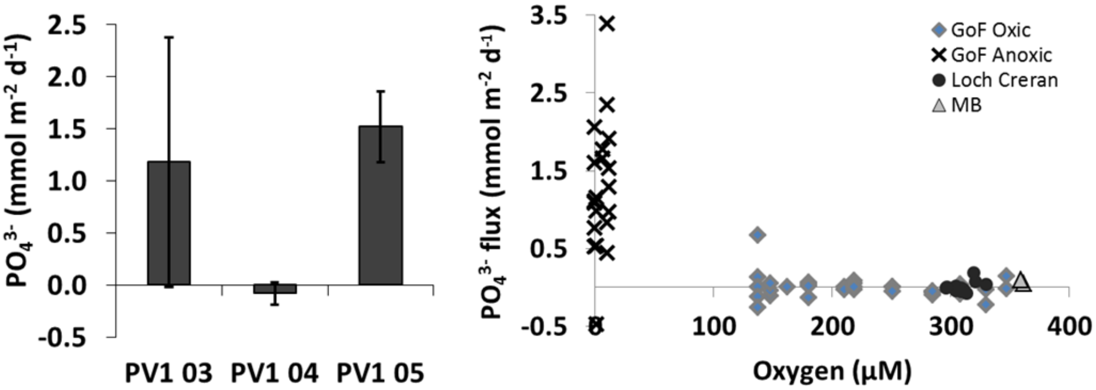

Fig. 20. The average phosphate flux at the organic-rich accumulation bottom of station PV1 in the GoF with anoxic/suboxic bottom water in 2003 and 2005, and oxygenated bottom water in 2004 (left), and the phosphate fluxes versus the bottom water oxygen concentrations at all stations (right).

On bottoms, which are permanently anoxic there are no iron oxyhydroxides present. Thus, the adsorption/release capacity of phosphate would not be of importance in controlling the phosphate flux. The fluxes of phosphate from the sediment to the overlying water would then be controlled by the release of phosphate due to degradation of organic matter. According to earlier studies, the benthic fluxes of DIC are considered to be a good measure of the oxidation and input to sediment of organic matter (Anderson et al., 1986). The initial DIC fluxes in the GoF were higher on the anoxic accumulation bottoms compared to the stations with oxygenated bottom water, which is not explained as an oxygen effect, but rather by the higher organic carbon content on the bottoms underlying anoxic water (accumulation bottoms). At station S1 in the Loch Creran the initial DIC fluxes (average

20.0 mmol m^{-2} d^{-1} (stdev=4.5)) were in the same range as in the GoF, but they were much higher on S11 (average 39.2 mmol m^{-2} d^{-1} (stdev=28.3)). These high DIC fluxes at S11 with high oxygen concentrations in the bottom water can be explained by the high organic carbon content in the sediment (from the former fish farm) in combination with very high water exchange rate in the loch.

There was a very good linear correlation (R^2=0.76) between the phosphate fluxes and DIC fluxes (Fig. 21) at anoxic bottoms in the GoF, which suggests that DIC is a good predictor for the release of phosphate on anoxic bottoms. This was used to predict the increase in internal loading of phosphate at oxic bottoms, if they would turn anoxic. The DIC fluxes at the oxic stations and the slope (=0.025) and the intercept (=0.34) from the linear regression were used to calculate the phosphate fluxes, as if the bottoms were anoxic. The theoretical increase in phosphate flux at these bottoms was then obtained when the measured phosphate fluxes at the oxic bottoms were subtracted. This gave an increased flux of phosphate of 0.69±0.26 mmol P m^{-2} d^{-1}. If all bottoms below 40 m would become anoxic, then almost 35 000 tons of phosphate per year in addition to the normal internal load would be released to GoF waters.

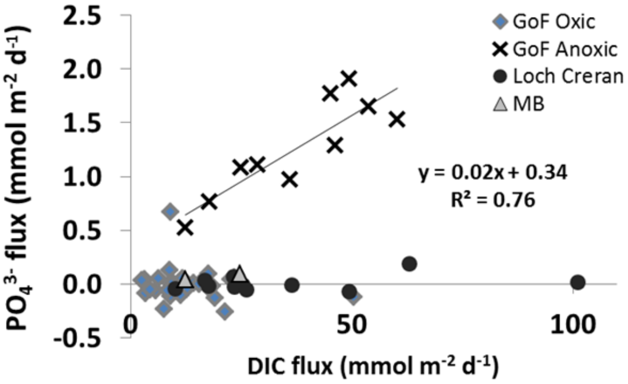

Fig. 21. The phosphate fluxes versus the DIC fluxes at stations with anoxic (crosses) and oxic (diamonds) bottom water in the GoF, the Loch Creran (circles) and at Måvholmsbådan (triangles). A linear regression trend, including equation, is shown for the data points from the anoxic stations.

The integrated internal load in the GoF for the year 2003, considering the bottom water oxygen prevailing then, was estimated to be 66 000 tons of phosphate. This number was estimated by using integrated phosphate fluxes for different bottom types together with the number of days with anoxic bottom water (<20 µM) in year 2003 at different depths. The areas for the different depth intervals and the number of anoxic days were computed from the St. Petersburg Eutrophication Model (SPBEM, developed by Ivan Neelov, P.P. Shirshow Institute of Oceanology, Russian Academy of Science (Savchuk and Wulff, 1996, 2001; Neelov et al., 2003)) and the phosphate fluxes were then extrapolated over the area of each depth interval. An assumption was made that below 60 m the area is mostly accumulation bottom, shallower than 40 m is mostly erosion/transport bottom and that the intermediate depth interval is erosion/transport bottoms to an extent of 50 % and accumulation bottom to 50 %. The average flux of 1.25 mmol P m^{-2} d^{-1} from anoxic accumulation bottoms was used for all anoxic days and for all bottom types. For oxic days in the most shallow depth interval the mean flux at transport/erosion bottoms (-0.1 mmol P m^{-2} d^{-1}) was used. In the deepest depth interval the mean flux from station PV1 2004 (-0.08 mmol P m^{-2} d^{-1}) was used for oxic conditions. In the intermediary depth interval during oxic days the average phosphate flux at transport/erosion bottoms and at PV1 in 2004 (when this station was oxygenated) was used in 50 % of the bottom area, respectively.

The assumption made above of the distribution for the different bottom types in GoF at different depth layers was compared to results from the model RCO-SCOBI, from which a bottom type map was computed (see chapter 6). Results showed that about 86 % of the bottom area at depth >60 m was accumulation bottoms while 14 % were transport bottoms. At the depth level 40-60 m the distribution was pretty much the same as for deeper bottoms: about 80 % were accumulation bottoms and 20 % were transport bottoms. At shallower bottoms about 21 % were accumulation bottoms, 61 % were transport bottoms and about 18 % were erosion bottoms. This confirms that the assumption for deeper and shallow bottoms agree well also with the RCO-SCOBI model, but on the intermediate depth level there should be a larger part of accumulation bottom in the calculation than it is. The internal load recalculated using the distribution of bottom types from RCO-SCOBI was 61 000 tons P yr^{-1}, thus about the same magnitude as the above calculated internal load.

The overall level of phosphate fluxes from sediment to overlying water was controlled by the bottom water oxygen concentrations. At bottom with oxygenated bottom water the effluxes were close to zero or even negative (influx) while there was a significant release of phosphate from anoxic bottoms. At anoxic bottoms the phosphate fluxes showed good correlation with the DIC fluxes indicating that the content of degradable organic matter in the sediment controlled phosphate fluxes under anoxic conditions. This correlation was used to predict the increased phosphate load to the GoF water if oxic bottoms below 40 m would turn anoxic. The internal load would then increase from 66 000 ton P yr^{-1} (2003) to about 101 000 ton P yr^{-1}.

6 Transport of fresh and resuspended particulate organic matter in the Baltic Sea

As particles are in suspension they follow the water currents until they sink and settle on the sea floor. This can be the final settlement for the particle or it can be resuspended again if the shear stress increases. This process might not only affect oxygen consumption and other biogeochemical processes, it also contributes to form the sediment bottom type patterns observed in the oceans. In areas with high energetic water movement (strong currents and/or large waves) the sediment often has erosion or transport bottom type character, i.e. fine material is not at all or discontinuously deposited. Accumulation bottoms are described as sediment where fine material is continuously deposited (Jonsson et al., 1990). The horizontal transport of organic carbon and its final destinations in the Baltic Sea sediments were studied using the RCO-SCOBI model (Paper V). A method was also developed to classify the sediments in the Baltic Sea as accumulation, transport or erosion bottoms using statistical properties of results from the model.

In the developed method basically the number of time steps with resuspension was summarized in each grid point during 1961-2007 and then normalized to the total number of wet grid points (water in the model) to obtain a spatial probability distribution of resuspension events in the Baltic Sea. From this distribution it is possible to divide all grid points into classes having more or less frequent events with resuspension. A digitized map (Jönsson et al., 2005) of observed bottom types (Carman and Cederwall, 2001) was used to define the ranges for different bottom types from the modeled probability distribution. In the digitized version 33 %, 50 % and 17 % of the bottoms in the Baltic Sea were classified as accumulation, transport and erosion bottoms, respectively. Hence, 33 % of the modeled grid points in RCO-SCOBI that had the lowest number of resuspension events were classified as accumulation bottoms. Accordingly, 17 % of the modeled grid points that had the highest number of resuspension events were classified as erosion bottoms while the rest was defined as transport bottoms. The results (Fig. 22) showed good agreement with observations (Carman and Cederwall, 2001; Al-Hamdani and Reker, 2007).

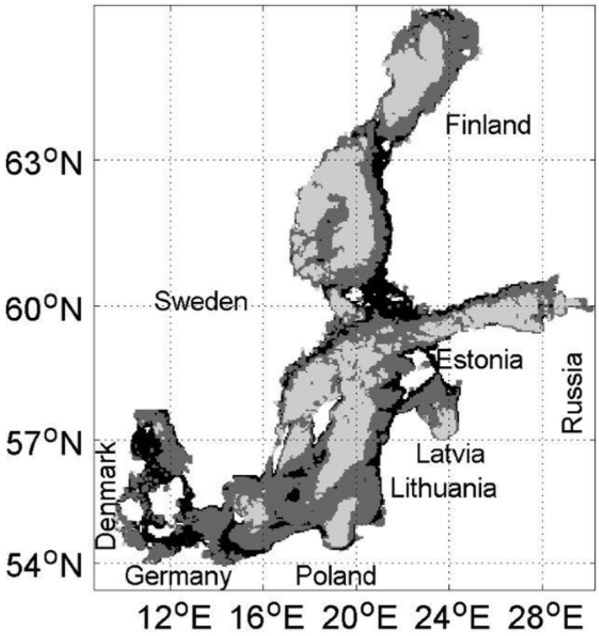

Fig. 22. The locations in the Baltic Sea of accumulation (light grey), transport (dark grey) and erosion (black) bottoms from the model.

The horizontal transport of organic carbon (i.e. detritus, phytoplankton and zooplankton) was vertically integrated from surface to bottom in each grid point of the model. The long-term average transport was then calculated for the period 1970-2007 (Fig. 23a). The fraction of the total transport of organic matter that originated from resuspended particles was calculated as well (Fig. 23b). The results showed that there was a large westerly transport of organic matter towards the Danish straits, mainly along the Swedish coast. An eastward transport entered the Arkona Basin, continued through the Stolpe channel, turned up north along the coasts of Lithuania and Latvia and then continued into an anticlockwise circulation in the Eastern Gotland Basin. Some of the largest transport continued further north, before it turned west and joined the anticlockwise circulation around Gotland.

The largest contribution from resuspended organic matter to the transport of total organic matter (Fig. 23b) generally occurred at transport and erosion bottoms (Fig. 22). In general the contribution at depth less than 50 m was between 10 % and 40 % and the highest contribution (>70 %) from resuspended organic matter to the transport was seen in the shallow areas along the Swedish and Finnish coasts. At the deepest areas the contribution was mainly less than 10 % even though high contributions were seen locally in the deeper Baltic Proper also at depth below 100 m.

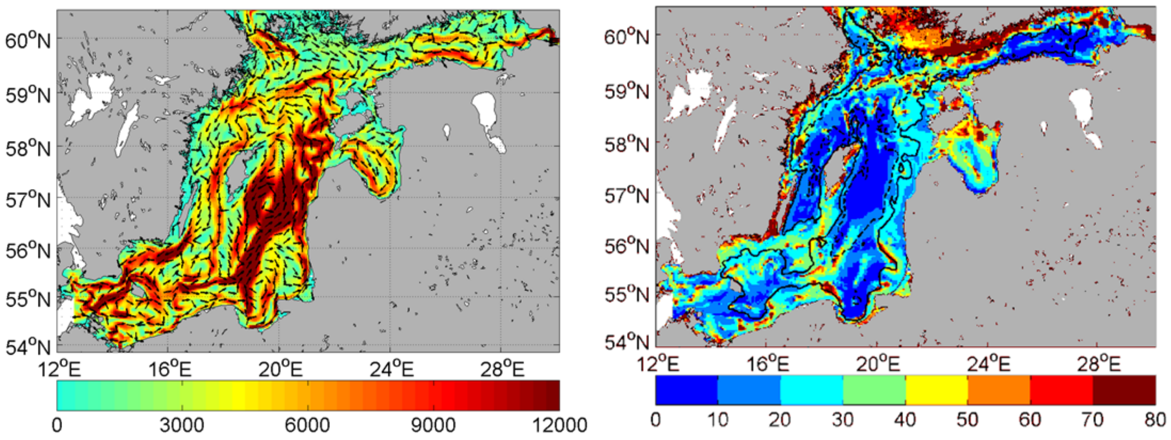

Fig. 23. The vertically integrated average (1970-2007) horizontal transport of total organic carbon (ton km^{-1} yr^{-1}, right) and the fraction (%) of it that at least once has been resuspended (left). The direction of the transport is indicated by arrows and the magnitude is shown by the background color scale. The 50 m and 100 m isolines are shown by the black solid and black dotted lines, respectively.

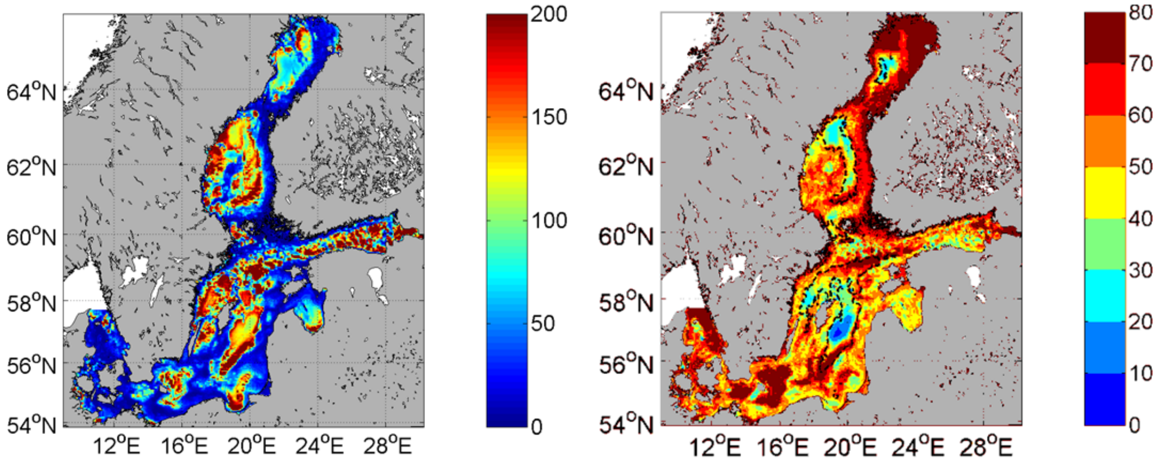

Fig. 24. The modeled average (1970-2007) distribution of benthic organic carbon concentrations (g C m^{-2}) in the Baltic Sea (left) and the fraction (%) of it that has been resuspended (right). The 100 m isoline of the model is shown by the black dotted line in the left panel.

The sediment concentration of organic matter and the resuspended fraction was calculated from the modeled long-term average (1970-2007). Largest concentrations of benthic organic matter were seen at accumulation bottoms (Fig. 22, Fig. 24a). Lowest fraction of resuspended organic matter in the sediment was seen in the deepest accumulation areas, e.g. the Gotland deep (Fig. 24b), but in general the fraction resuspended organic matter in the Baltic Sea sediments was large. Highest fractions were found on accumulation bottoms at shallower areas as e.g. the Arkona Basin, the Bornholm Basin, the Gdansk Basin and the northern Baltic Proper. Also, the inflow areas, the Stolpe Channel, and the erosion/transport bottoms along the east coast in the Bothnian Sea and Bothnian Bay had a large fraction of resuspended organic matter as well as along the 100 m isoline in the eastern Gotland Basin.

There was a seasonal variation of the resuspended fraction of organic matter in the sediment as well as of the sedimentation (deposition). The resuspended fraction was in general higher in winter than in summer and it was also decreasing with depth. The average fraction of resuspended organic matter in the shallow sediments (0-30 m) were about 60 % during summer and increased to about 75 % during winter. At the deepest bottoms (below 120 m) the variation was on average between 45 and 50 %. The fraction of resuspended organic matter of the sedimentation was of significant magnitude during winter in the surface layers (0-68 m) where it was about 70-80 %. During summer the fractions decreased to about 40-50 % in the 0-30 m layer and deeper than 68 m it decreased to about 10 %.

As for the contribution of resuspended organic matter to the total transport, the fraction of resuspended organic matter in the sediment in the GoF was larger in the northern part compared to the southern part. This pattern is consistent with the bottom type map that indicates that the sediment in northern part, along the Finnish coast, consist of erosion and transport bottoms, while the southern part mostly have accumulation bottoms.

Thus, a large fraction of the sedimentary organic carbon in the model has been resuspended. These results are in accordance with earlier studies (Jonsson et al., 1990; Christiansen et al., 1997; Struck et al., 2004) suggesting that resuspension is an important process for sediment transport from shallower to deeper areas. However, the fraction of resuspended organic matter at the deepest areas of the Baltic Sea was low even though there was a high content of organic matter and a large horizontal transport of it. This implies that the organic matter that reaches the deepest parts of the Baltic Sea originates from suspended particles, which have not been settled on the sea floor before. The matter might therefore originate from more fresh organic material that is produced in the water column or transported from external load sources, e.g. rivers. Thus, resuspension has a twofold effect on the transport of organic matter since particles also can be forced to stay in suspension, and then follow the currents to less energetic areas.

7 Environmental effects of resuspension

Natural sediment resuspension significantly increased the oxygen consumption on all sediment types in the GoF and on the organically enriched sediment in the Loch Creran. Observations also showed that areas with low bottom water oxygen concentrations will be even more sensitive for resuspension events as the increase in oxygen consumption will be larger at these bottoms than at areas with high bottom water oxygen concentrations. These results imply that if resuspension events would occur more often, e.g. due to increased frequencies of strong wind events, increased spreading of anoxic bottoms could be a result. Even though the sediment-water exchange of inorganic nutrients and DIC were not significantly influenced by resuspension, the oxygen concentration in bottom water is suggested to be important for the flux rates of e.g. phosphate and ammonium. The phosphate and ammonium release from sediments to overlying water is higher on anoxic bottoms compared to oxic. Thus, increased frequencies of resuspension events, leading to increased spreading of anoxic bottoms could lead to an increased internal load of nutrients, e.g. phosphate and ammonium. This would lead to even further increased eutrophication, thus contributing to a vicious spiral as increased eutrophication leads to increased spreading of anoxic bottoms.

According to the calculation above (chapter5), an increased internal load of about 35 000 tons of phosphorus would be the result if all bottoms below 40 m in the GoF would turn anoxic. This is additional to the internal load of about 66 000 tons of phosphorus that was calculated to occur in year 2003. While nitrogen is limiting the growth of other phytoplankton species, cyanobacteria have the ability to fix nitrogen gas and in that way supply their need of nitrogen, provided that there is enough phosphate in the water. Thus, increased frequencies and magnitudes of blooms of cyanobacteria could be a result of increased frequencies of resuspension events.

The created massive resuspension in the chambers was intended to represent resuspension created during human activities like dredging or trawling. It resulted in an enormous increase in oxygen consumption, an instant increase of DIC, ammonium and silicate and an instant decrease of phosphate concentrations in the incubated water. Thus, as massive resuspension is created it will have a large impact on the marine environment, contributing to increased eutrophication. The decrease of phosphate was probably due to adsorption of phosphate onto newly formed iron oxyhydroxides as reduced iron was exposed to oxygenated water. The oxygen concentration was quickly reduced during the massive resuspension event and would on a longer timescale probably be totally consumed leading to a release of adsorbed phosphate as the iron oxyhydroxides again would be reduced. Thus, trawling might not lead to a release of phosphate as the time scale is rather short for this kind of activities, but a long-lasting dredging project might contribute to oxygen depletion at the bottoms as well as increased internal loads of phosphate and other nutrients.

Resuspension can also have indirect effects as it leads to a transport of particulate organic matter from one area to another. The organic matter might be transported from a bottom with oxic bottom water to an area with anoxic bottom water. Then the leakage of nutrients (formed during degradation of the particulate organic matter) from the sediment to the water will be larger compared to if the organic matter would not have been resuspended from the original site. If the bottom water at the "new" deposition area is suboxic the increased oxygen consumption caused by the new input of organic matter at the new area may lead to oxygen depletion, and thus increased leakage of nutrients. Thus, resuspension can in several ways *indirectly* lead to increased eutrophication.

8 Concluding remarks

Natural resuspension increased the oxygen consumption in the Gulf of Finland with between 15 and 115 % and on organic enriched sediment in the Loch Creran with an average of 23 %. Massive resuspension caused a huge increase in oxygen consumption, between 1 013-17 000 %, on both organic enriched and not enriched sediments in the Loch Creran.

Neither natural nor massive resuspension did significantly influence the sediment-water exchange of nutrients and DIC in neither the GoF nor the Loch Creran. This study can therefore not confirm that the degradation rate of organic matter is increased as an effect of resuspension.

Phosphate release from sediments is mainly controlled by the oxygen concentration in the bottom water. At sediments with oxygenated bottom water iron oxyhydroxides are present in the oxic layer of the sediment. Phosphate can then adsorb to the surface of the iron oxyhydroxides and the release rate of phosphate to the overlying water is reduced or even negative (uptake of phosphate from the water). At sediments with anoxic bottom water, on the other hand, there is no iron oxyhydroxides present and the phosphate can be released to the overlying water. Resuspension events increase the oxygen consumption, which can lead to increased spreading of anoxic bottoms. This would in turn increase the leakage of phosphate and ammonium from the sediment to the water column.

The DIC fluxes, which are a measure of the degradation rate and thus the input of organic matter to the sediment, were used to predict the phosphate fluxes on oxic bottoms if they would turn anoxic. Calculations showed that if all bottoms below 40 m in the GoF would turn anoxic the internal load of about 66 0000 ton phosphate (calculated for year 2003) would increase with more than 50 % to about 101 000 tons of phosphate. Thus, increased eutrophication could be the result if the frequencies of resuspension events would increase. The internal load of 66 000 tons of phosphate are almost 10 times larger than the external load in the GoF, which highlights the importance of sediment processes in general and oxygen conditions in particular.

Resuspension is also an important process for the transport of particles from one area to another, which causes spatial distribution of different bottom types: accumulation, transport and erosion bottoms. The model showed that the highest fraction that has been resuspended of the total transport of particulate organic matter was found in shallow erosion and transport areas. At the deepest part of the Baltic Proper the contribution of resuspended organic carbon to the transport of total organic carbon was mainly less than 10 %, but a relatively high contribution of resuspended organic matter occurred also below 100 m depth. In general the contribution at depth less than 50 m was between 10 % and 40 %.

The sedimentary distribution of organic carbon in the model showed highest organic carbon content at accumulation bottoms, e.g. the deeper central areas of the basins. The fraction of the organic carbon in the sediment that at least once has been resuspended was in general high. A seasonal variation was seen with a higher fraction during winter than summer, and the fraction was also decreasing with depth. The average fraction of resuspended organic matter in the shallow sediments (0-30 m) were about 60 % during summer and increased to about 75 % during winter. At the deepest sediment (below 120 m) the variation was on average between 45 and 50 %. Only in the deepest part of the Gotland Basin was the fraction less than 10 %.

The high transport of particulate organic material, the high sedimentary organic content in the sediment together with the low fraction of it that is resuspended in the central Gotland Basin implies that resuspension has a twofold effect on the transport of organic matter. It is not only moving particles from one sediment area to another, organic particles can also be kept in suspension for a longer time. They can thus be transported to less energetic areas, e.g. deeper accumulation bottoms without making a stopover on the sediment floor.

9 Future outlook

There are still uncertainties of the effects of natural resuspension on the sediment water exchange of nutrients and DIC. More thoroughly field studies would be needed to clarify the strength of resuspension created by natural forces. The data could then be used to improve the method for simulation of resuspension inside the incubation chambers in order to create the correct strength of resuspension.

The modeling of transports of resuspended material can be further studied in e.g. climate change scenarios and the influence of resuspension on spreading of anoxic bottoms as well as increased frequencies and magnitudes of algal blooms in the Baltic Sea. Even though it is important to keep the model as simple as possible, it could be further improved in the description of sediment characteristics, e.g. the determination of the critical shear stress and a bit more advanced wave model could be used.

There are a lot of sediment data collected by different research teams in Sweden and in other countries. If all these data could be collected into a data base, as is done for the pelagic data, then it could be used to further improve biogeochemical models with regard to benthic fluxes and sediment content of oxygen, DIC and nutrients.

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