Continental Shelf Research 29 (2009) 807–818

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

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

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ARTICLE INFO

Article history:
Received 4 February 2008
Received in revised form
16 December 2008
Accepted 20 December 2008
Available online 1 January 2009

Keywords:
Resuspension
In-situ incubation
Oxygen
Nutrients
Dissolved inorganic carbon
Dissolved metals
Baltic Sea
Gulf of Finland

ABSTRACT

The effect of resuspension on benthic fluxes of oxygen (O_2), ammonium (NH_4^+), nitrate (NO_3^-), phosphate (PO_4^{3-}), silicate ($Si(OH)_4$), dissolved inorganic carbon (DIC), total dissolved iron (Fe) and total dissolved manganese (Mn) was studied at three different stations in the Gulf of Finland (GoF), Baltic Sea during three cruises in June–July 2003, September 2004 and May 2005. The stations were situated on different bottom types in the western, central and eastern part, respectively, of the open GoF. The fluxes were measured *in-situ* using the autonomous Göteborg benthic lander. To simulate resuspension events, the stirring speed was increased in two of the four chambers of the lander after approximately half of the incubation time. The other two chambers were used as control chambers. Clear effects of resuspension were observed on the oxygen fluxes where an increase of the consumption was observed in 88% of the cases and on average with 59% (stdev = 53). The NH_4^+ fluxes were affected in 50% of the cases (4 out of 8 incubations) at stations with low bottom water oxygen concentrations, but in no cases where the bottom water was oxygenated (0 out of 9 incubations). The NH_4^+ fluxes decreased by $26\pm27\%$ in 2005 and by $114\pm19\%$ in 2003. There was no clear effect of resuspension on the fluxes of any of the other solutes in this study. Thus, resuspension events did not play a significant role in release/uptake of NO_3^-, PO_4^{3-}, $Si(OH)_4$, DIC, Fe and Mn in GoF sediments. However, increased oxygen consumption as a result of resuspension may lead to spreading of anoxic/suboxic bottom water conditions, and thus indirectly to increased benthic release of phosphate, ammonium and iron.

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1. Introduction

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

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

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doi:10.1016/j.csr.2008.12.011

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

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

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

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

Higher release of nutrients from the sediment (internal load) due to resuspension events might be a reason for the high nutrient concentrations in the Gulf of Finland, in spite of the decrease of the external load. The aim of this study was to clarify the effect of resuspension on the flux of a series of solutes between the sediment and the water column, using elaborated *in-situ* techniques at different stations and during different years.

2. Materials and methods

2.1. Study site

The Gulf of Finland (Fig. 1) is a direct extension of the Baltic Proper and is surrounded by the countries Finland, Russia and Estonia. The surface area is 29,600 km^2 that is about 7% of the total area of the Baltic Sea, and the average water depth is 38 m (Perttilä et al., 1995). The central GoF is deeper with an average depth of more than 60 m. The South eastern part is somewhat shallower and the easternmost part of the GoF (Neva bight) is very shallow with a mean depth of 5 m. The total volume of the GoF is 1100 km^3, which is 5% of the volume of the whole Baltic Sea. The drainage area is about 20% of the total drainage area of the Baltic Sea (Alenius et al., 1998). Most of the fresh water input enters the GoF in the east where the biggest (in terms of water transport) Baltic river Neva enters the GoF from the Russian territory. The Neva has a long-term (1859–1988) mean flow rate of about 2500 m^3/s. In the southeast, the river Narva enters the GoF from Estonia, with a long-term (1956–1993) mean flow rate of about 400 m^3/s (Helcom, 2004). The hydrography of the GoF is typical of estuaries. It is characterised by large horizontal and vertical variations. The water exchange with the Baltic Proper is not limited by a sill, thus there are no topographically isolated water masses in the GoF (Alenius et al., 1998). Due to the large fresh water inflow in the east and the water exchange with the Baltic Proper in the west, there is a horizontal salinity gradient in the GoF from east (about 0–2) to west (5–7 in the surface and 8–9 at bottom) (Perttilä et al., 1995; Alenius et al., 1998). A permanent halocline in the west exists throughout the year at 60–80 m depth. The existence of the halocline limits vertical mixing of the water body down to the bottom (Alenius et al., 1998). The saltier water from the Baltic proper enters the GoF along the bottom.

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

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

2.2. Benthic fluxes measured in-situ

The Göteborg benthic lander was used to make autonomous incubations and collect water samples to measure benthic solute fluxes of oxygen (O_2), ammonium (NH_4^+), nitrate (NO_3^-), phosphate (PO_4^{3-}), silicate ($Si(OH)_4$), dissolved inorganic carbon (DIC), total dissolved iron (Fe) and total dissolved manganese (Mn) *in-situ*. Four squared chambers of 400 cm^2 each, mounted on the lander were used for the flux incubations. A more detailed description of the Göteborg benthic lander in general can be found in Ståhl et al.

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