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Transport of fresh and resuspended particulate organic material in the Baltic Sea — a model study

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ABSTRACT

A fully coupled high-resolution 3-dimensional biogeochemical–physical ocean model including an empirical wave model was used to investigate the long-term average (1970–2007) distributions and transports of resuspended matter and other types of suspended organic matter in the Baltic Sea. Modelled bottom types were compared to observations and the results showed that the model successfully managed to capture the horizontal, as well as the vertical, distribution of the different bottom types: accumulation, transport and erosion bottoms. The model also captured well the nutrient element contents in the sediments. On average the largest contribution of resuspended organic carbon to the transport of total organic carbon is found at erosion and transport bottoms. Although the relative transport of resuspended organic carbon at deeper accumulation bottoms in general is low (<10% of total), the central parts of the sub-basins act on average as sinks that import organic matter while the more shallow areas and the coastal regions acts as sources of organic carbon in the water column. This indicates that the particulate organic matter produced in erosion and transport areas might be kept in suspension long enough to be transported and settle in less energetic areas, i.e. on accumulation bottoms.

1. Introduction

Organic matter produced in the photic zone of the ocean or transported to the sea from land and atmosphere may sink through the water column to the sea floor and contributes in this way to the benthic pool of nutrients. Decomposition and oxidation of this organic matter in sediments play an important role e.g. for the regulation of deep water oxygen concentrations and the internal loading of dissolved nutrients in the Baltic Sea (e.g. Conley et al., 2009). Eutrophication, which is a large environmental problem in the Baltic Sea, is reflected during recent decades in the larger and more frequent phytoplankton blooms of e.g. cyanobacteria and increased bottom areas with hypoxia ($O_2 < 2$ ml L^{-1}) (e.g. Conley et al., 2009; Diaz and Rosenberg, 2008; Wulff et al., 2001a). The increased nutrient concentrations in the top layer of the water column lead to high biomass production and consequently to higher sedimentation of organic matter.

When the critical shear stress (τ_c) on the sea floor is exceeded sediment particles are lifted up into the overlying water and resuspension is induced. Resuspension is a common physical process that occurs everywhere in the marine environment, in coastal areas as well as in the deep sea (Gross et al., 1988; Thomsen et al., 1994; Vangriesheim and Khripounoff, 1990). The shear stress can be a result of bottom currents induced from wind waves or from barotropic (differences in sea levels) and baroclinic (differences in density) forcing mechanisms. In contrast to many other coastal areas of the world, the tides in the Baltic Sea are negligible and are not contributing to resuspension events. Resuspension can also be induced by biological activity (Graf and Rosenberg, 1997) or by anthropogenic perturbations such as trawling and dredging. Bottom friction created by wind waves is an important element of sediment transport (e.g. Bobertz et al., 2005; Christiansen et al., 2002; Jönsson et al., 2005; Lund-Hansen et al., 1999; Schwab et al., 2006) and it is therefore essential to have a consistent wind wave model included to describe the sediment transport between the sea-floor and the water column.

Transport of resuspended organic material between different bottom types seems to be an important process in the ecological system and it has been suggested that particles settling at accumulation bottoms in the deeper parts of the Baltic Sea often originates from shallower areas (e.g. Glasby and Szefer, 1998; Jonsson et al., 1990). In the Baltic Sea the sediment at depth as great as 80 m may be affected by wave-induced resuspension at least once a year (Jönsson et al., 2005). As sediment particles are in suspension in the water column, they can move above and along the bottoms with ambient

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water currents and in this way strongly influence the spatial distribution of the benthic nutrient pool. Christiansen et al. (1997) investigated the transport of nitrogen and phosphorus due to resuspension in the Kattegat and found that wave induced resuspension was more important than current induced resuspension for the nutrient dynamics in near shore areas. They concluded that resuspension effects on the nutrients should be taken into consideration when nutrient budgets in shallow-water areas are studied. Transports of resuspended organic material from shallow to deeper areas were found to be of importance also in a field study in the southern Baltic Sea (Arkona Basin) (Christiansen et al., 2002).

Repeated resuspension–deposition events may move and expose organic material containing nitrogen and phosphorus to different bottom water conditions, like different oxygen concentrations. This may change rates and patterns of sediment–water exchange of the nutrients mobilised during degradation of the organic material (Almroth et al., 2009; Conley et al., 2009). The impacts of resuspension on degradation rate of organic material in the sediment and on fluxes of different solutes between sediment and overlying water have been studied by a number of research teams (e.g. Almroth, 2008; Almroth et al., 2009; Blackburn, 1997; Spagnoli and Bergamini, 1997; Ståhlberg et al., 2006; Tengberg et al., 2003; Wainright, 1987, 1990; Wainright and Hopkinson, 1997). Some results indicated that the degradation rate of organic material was affected by resuspension while others found no effects. Also the conclusions regarding the impact of resuspension on benthic fluxes of solutes varied between the different studies. Most of these studies were performed in the laboratory or with models and in other parts of the world; only Almroth et al. (2009) performed their studies both in-situ and in the Baltic Sea. Their results from measurements using an autonomous benthic lander showed no significant effects of resuspension on benthic nutrient fluxes or on the degradation rate of organic material. Further, Christiansen et al. (1997) found that the oxygen penetration depth into the sediment decreased after resuspension indicating that oxygen consumption increased. This was verified also in the in-situ study by Almroth et al. (2009), who showed that oxygen consumption was significantly enhanced due to resuspension, which most likely was related to stimulated oxidation of dissolved reduced inorganic compounds in the sediment.

An important factor determining the spatial distributions of organic matter and nutrient elements in sediments is pattern and mode of transport of the particulate material. There is however still an incomplete understanding of the long-term transports and the final deposition areas of resuspended matter as well as suspended organic matter in the Baltic Sea. The biogeochemical importance of resuspended organic matter relative to other sources of organic matter in the deep Baltic Sea also needs to be quantified. In the present investigation we therefore used a fully coupled high-resolution 3-dimensional biogeochemical–physical ocean model to investigate the distributions and transports of resuspended matter and other types of suspended organic matter. The present 2 nautical mile (nm) model with new atmospheric forcing is based on the 6 nm model presented by Eilola et al. (2009). We also used a simplified wave model and a calibrated uniform τ_c for the entire Baltic Sea to calculate the wave and current induced shear stress and thus the resuspension of organic material.

The aim of the present study was to investigate: 1) the importance of resuspension for the transport and redistribution of particulate organic matter; 2) the distribution of resuspended organic material in the water column and sediments; and 3) a method to classify the modelled bottom types.

2. Materials and methods

2.1. Study area

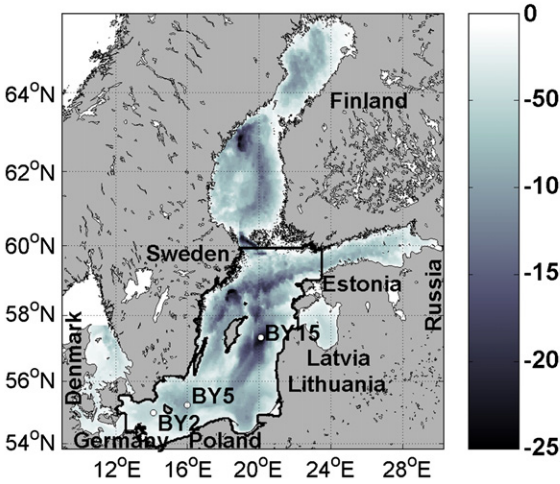

Fig. 1. The model area and bathymetry (depths in meter) are shown by the grey colour scale. The Baltic Proper is here defined by the thick black solid line. The locations of the monitoring stations, BY 02, BY 05 and BY 15 are shown as white circles.

Nine countries have their coast lines adjacent to the Baltic Sea located in northern Europe (Fig. 1). This shallow sea (mean depth 52 m; Al-Hamdani and Reker, 2007) is connected to the North Sea by shallow (maximum depth about 8 and 18 m) and partly narrow areas in the Danish straits that control the inflow of salt water. The Baltic Sea is often divided into large sub-basins separated with sills. The Baltic Proper is the largest sub-basin where the deepest areas are found east and northwest of Gotland with maximum depths of 249 m and 459 m, respectively. The mean annual river runoff to the Baltic Sea, excluding the Danish straits and Kattegat, is about 14,000 $m^3 s^{-1}$ for the period 1950–1990 (Bergström et al., 2001). The large river runoff to the semi-enclosed Baltic Sea results in brackish water with large horizontal salt gradients and a strong halocline at about 60 m depth separating the in winter well mixed surface layer from the saltier bottom layer (Stigebrandt, 2001). More information about the characteristics of the Baltic Sea can be found e.g. in Wulff et al. (2001b).

2.2. Model description

The model system is based on the Swedish Coastal and Ocean Biogeochemical model (SCOBI) (Eilola et al., 2009; Meier et al., in press) and the Rossby Centre Ocean circulation model (RCO) (Meier and Kauker, 2003; Meier et al., 2003). The model domain of the RCO-SCOBI model covers the Baltic Sea including the Kattegat (Fig. 1) with a 2 nm horizontal resolution and a maximum depth of 250 m in the present setup. The vertical resolution of the model is 41 levels with an increasing layer thickness from 3 m in the surface layers to 12 m in the deep Baltic Sea.

RCO is a Bryan–Cox–Semtner primitive equation circulation model with a free surface (Killworth et al., 1991) and open boundary conditions in the northern Kattegat (Meier et al., 2003). It is coupled to a Hibler-type sea ice model (Hibler, 1979) with elastic–viscous–plastic rheology (Hunke and Dukowicz, 1997). Subgrid-scale mixing is parameterised using a turbulence closure scheme of the k-ε type (Meier, 2001) and the deep water mixing is assumed to be inversely proportional to the Brunt–Väisälä frequency with a proportionality factor following dissipation measurements in the eastern Gotland Basin (Lass et al., 2003). To improve the simulation of gravity-driven dense bottom flows a bottom boundary layer model is embedded to allow the direct communication between bottom boxes of the step-like topography (Beckmann and Döscher, 1997). A flux-corrected transport scheme following Gerdes et al. (1991) is used to guarantee positive definite solutions. No explicit horizontal diffusion is applied.

The SCOBI (Fig. 2) model (Eilola et al., 2009) handles dynamics of nitrogen (N), oxygen and phosphorus (P) including the inorganic

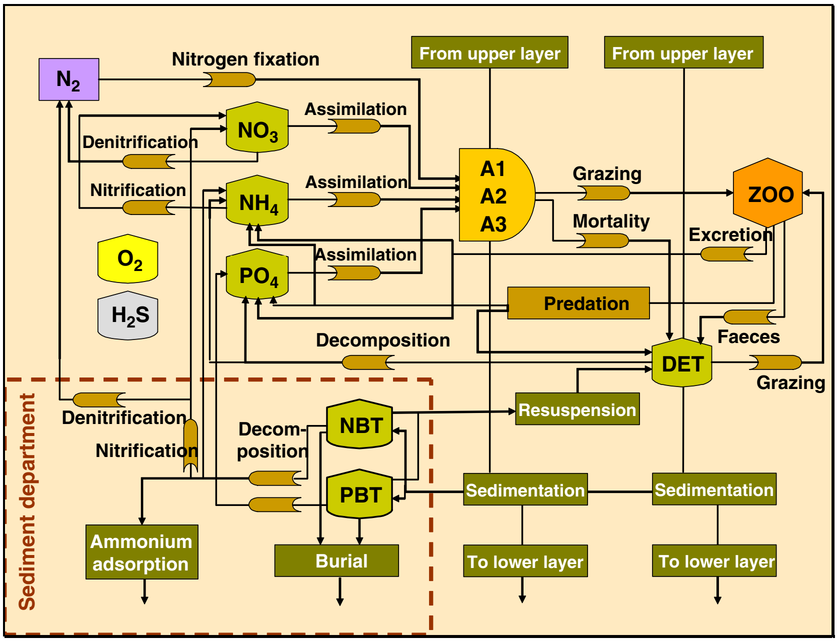

Fig. 2. Schematic of the SCOBI model. Sediment variables and processes are shown in the lower left box. Note that the process descriptions for oxygen and hydrogen sulphide are much simplified for clarity.

nutrients nitrate, ammonia and phosphate, and particulate organic matter consisting of phytoplankton (autotrophs), dead organic matter (detritus) and zooplankton. Primary production assimilates the inorganic nutrients by three functional groups of phytoplankton (diatoms, flagellates and others, and cyanobacteria). Organic material may sink and accumulate in the model sediment as benthic nitrogen and phosphorus. Carbon (C) is used below as the constituent representing organic matter. The nitrogen and phosphorus content of autotrophs, zooplankton and detritus are described by the Redfield molar ratio C:N:P = 106:16:1 and the sediment content of carbon is similarly computed from a C:N ratio of 106:16. In addition, two tracers are implemented in the model to keep track of the organic material that at least once has been resuspended from the sediments. The tracers are used for studying the magnitude and direction of the transports as well as the deposition areas of the resuspended organic material.

2.2.1. Model forcing and setup

A dynamical down-scaling of the ERA40 atmospheric forcing with a high-resolution coupled atmosphere–ice–ocean–land surface model (the Rossby Centre Atmosphere Ocean model, RCAO; Döscher et al., 2002) is used (Höglund et al., 2009). The resolution of the atmospheric forcing grid is 25 × 25 km. In order to initialize the horizontal nutrient distributions in the sediments initial conditions were produced from a spin-up using atmospheric and hydrological forcing from 1961 to 2007. The results from the end of the spin-up were used as initial conditions for the simulations and the first 9 years of the period were left out of the analysis of the results which then covers only the period 1970–2007. The simulations are performed with climatological nutrient supplies (Eilola et al., 2009).

2.2.2. The wave model and resuspension in the model

Two different approaches implementing a wave model into an ocean model like the one used for this study are possible. A fully functional wind wave model like SWAN (Holthuijsen et al., 1989) might be used. However, this would require a significant increase of the computational resources. In the present study an empirical approach with formulations of the fetch, duration and the instant wind velocity is chosen (WMO, 1998). For each wet grid point the fetch is calculated as the mean distance to the coast within 8 sectors of wind directions. It provides significant wave height and peak frequency as a function of time and space assuming a mean duration of 7 h. The wave model is therefore not fully coupled with the ocean model because only the extra shear stress generated by the waves is considered without taking the possible feedback from the waves to the currents into account. Further, the simplified approach does not take the depth into account in order to compute the significant wave height. This is a shortcoming in shallow areas. The bottom friction that results from the wave and current interaction is computed with the formulae by Soulsby et al. (1993) using the set of coefficients from Fredsøe (1984).

The resuspension process itself is handled by the SCOBI model. The upward or downward fluxes, S, of nutrients in the sediments are computed using a similar parameterisation as the one by Wang and Pinardi (2002);

$$S = \begin{cases} S_o\left(\frac{\tau}{\tau_c}-1\right) \; if \; \tau > \tau_c \\ W_s\left(1-\frac{\tau}{\tau_c}\right) \; if \; \tau < \tau_c \end{cases} \qquad (1)$$

S_o and W_s are the maximum upward flux of sediments and the sinking velocity, respectively. τ_c is the model dependent critical shear stress. Using such a formulation means that resuspension occurs when the bottom stress exceeds τ_c.

For the calibration of the critical shear stress the vertical variation of horizontally averaged sediment nitrogen and phosphorus concentrations were compared to estimations from corresponding observations in the upper 1 cm of the sediment in the different sub-basins (Carman and Cederwall, 2001). The calibration was also constrained by oxygen and nutrient concentrations that were compared to observations (SHARK: data from the Swedish Oceanographic Data Centre, http://www.smhi.se) from standard monitoring stations (Fig. 1). The value of the critical shear stress that resulted in best biogeochemical model properties was $\tau_c = 0.15\ \mathrm{N\ m^{-2}}$, which is assumed to be uniform for the entire model domain.

During a modelled resuspension event particulate organic material is transferred from the sediment to the bottom water pool of detritus. Mass conservation in the model therefore requires that the resuspended organic material also follows the assumed Redfield molar ratio. Inorganic particulate matter is not included in the modelled resuspension and in accordance with the experimental results by Almroth et al. (2009), neither the flux rates of inorganic nutrients nor the degradation rates of organic matter are assumed to be affected by resuspension.

2.3. Definition of bottom types

The sea bottoms can be classified as accumulation (A), transport (T) or erosion (E) bottoms. A-bottoms are defined as bottoms where the sediment consists of fine material (<medium silt) that is continuously deposited. T- and E-bottoms are bottoms where fine material is deposited either discontinuously or not at all (e.g. Jonsson et al., 1990). The results by Jönsson et al. (2005) showed a statistically significant relation between the bottom stress and the three different bottom types which suggests that the distribution of bottom types is mostly linked to physical processes. The aim of this section is to use a method based on physical statistical properties that can be used for bottom type classifications in the RCO model.

For a wide range of given τ_c values the number of time steps with resuspension ($N_{i,j}$) was summarized at each grid point (i,j) during 1961–2007. For each given τ_c we computed the number of grid points having $N_{i,j}$ in consecutive ranges between N and $N+\Delta N$ where N increases from 0 to infinity. A normalization of these numbers to the total number of wet grid points gives a density function $f(N)$ that describes the probability to find a place with a given number N of time steps with resuspension somewhere in the Baltic Sea. From a comparison with the results from a theoretical log-normal probability function $T(N)$ (Eq. (2)) it can be shown that $f(N)$ in the Baltic Sea behaves log-normally distributed for its mean value $\mu(f(N))$ and standard deviation $\sigma(f(N))$:

$$T(N;\mu,\sigma) = \frac{1}{N\sigma\sqrt{\pi}} e^{-\frac{(\ln(N)-\mu)^2}{2\sigma^2}} \tag{2}$$

Hence, as $f(N)$ follows a log-normal distribution for our bottom type classification we may use the natural logarithm of $f(N)$ that has a normal distribution $g(N)$ from which we define the boundaries between the different bottom types:

$$g(N) = \ln[f(N) + 1] \tag{3}$$

The number 1 is added to avoid infinite numbers when $f(N)$ approaches zero.

The ranges between the different modelled bottom types were defined from a digitized version (Jönsson et al., 2005) of the bottom type map in Carman and Cederwall (2001) that was kindly supplied by Åsa Danielsson (Linköping University). The bottom type map from Carman and Cederwall (2001) is based on measurements in the Baltic Sea of sediment water content and similar sediment maps from different research groups (see Carman and Cederwall (2001) and references therein). The Kattegat, the Danish Straits and parts of the Arkona Basin are not covered by the dataset. For the present study the resolution of the digitized map was increased and transformed to match the RCO grid. Accumulation, transport and erosion bottoms in the adjusted digitized map covers about 33%, 50% and 17% of the wet grid points, respectively. Hence, the ranges of the modelled bottom types are defined as:

1. Accumulation bottom is defined by:	$g(N) < 33$rd percentile
2. Transport bottom is defined by:	33rd percentile $\geq g(N) \geq$ 83rd percentile
3. Erosion bottom is defined by:	$g(N) > 83$rd percentile

2.4. Transports, sources and sinks of organic matter

The long-term average transport patterns of organic matter were computed for each velocity grid point from six hourly snapshots including all data from 1970 to 2007. The transports are the vertically integrated horizontal fluxes from the sea floor to the sea surface.

For each snapshot and each horizontal grid cell the total net import of organic carbon was computed. The net import from horizontal fluxes was vertically integrated from the sea floor to the sea surface. Finally, from all snapshots during 1970–2007 the long-term average spatial patterns were computed. Positive average values indicate import (sink) and negative values indicate export (source).

3. Results and discussion

3.1. The wave model and resuspension

3.1.1. Modelled waves

The results for the year 1997 of the simplified wave model used in RCO were compared to the results of the state-of-the-art spectral wave model SWAN (Holthuijsen et al., 1989) and to observations of the significant wave height at the Almagrundet light house in the north-western Baltic Proper.

Even though the wave model is simplistic the representation of waves from the empirical model is found to be realistic. The spatial variability of the mean significant wave height corresponds to the results from SWAN although some areas like the south-western part of the Baltic Sea and the eastern coast show some differences (Fig. 3). Also the representation of the extremes (e.g. the 90th percentile) as simulated with the simplified wave model is consistent with SWAN although differences can be noticed in the same areas as for the mean value (not shown). Although the main features of the fields are well represented, overall the significant wave heights are slightly underestimated. For instance the mean significant wave heights in the Bothnian Bay and Gulf of Finland are underestimated although the modelled fetch is relatively large for westerly and south-westerly winds. This suggests that wave propagation, which is not included in the simplified approach, might play a significant role in some areas.

The comparison with significant wave height measurements made at the light house Almagrundet during 1997 showed that the time variability is well represented by the simplified wave model (Fig. 4). However, some extreme peaks are underestimated in the simplified approach. In 1997 the median value and the 1st and 3rd quartiles of the observed significant wave height at Almagrundet were 0.87 m, 0.46 m and 2.11 m, respectively. For the simplified wave model we found corresponding values of 0.83 m, 0.44 m and 1.4 m indicating that extreme events are systematically underestimated. Largest differences between simulated and observed significant wave heights were found during March and April of the selected year 1997 (Fig. 3). During late spring, summer and autumn, the significant wave heights were better reproduced because of the less intense wind events during that period.

3.1.2. Modelled resuspension

Sediment particles become finer from shallow to deep areas and the critical shear stress threshold values seem to decrease slightly from shallow to deep localities in the Arkona Basin in the southern Baltic Sea (Christiansen et al., 1997, 2002). In the present setup a uniform critical shear stress was used for the whole Baltic Sea. This is a simplification of the reality and could of course be discussed since e.g. the critical shear stress of the finer sediment might also be affected by its more cohesive character (e.g. Miller et al., 1977). The threshold value for organic matter should also depend on the fluffy layer that exists on almost all sediment surfaces and which is easily resuspended (Stolzenbach et al., 1992). Christiansen et al. (2002) showed that the fluffy layer was present everywhere in a section from shallow to deep

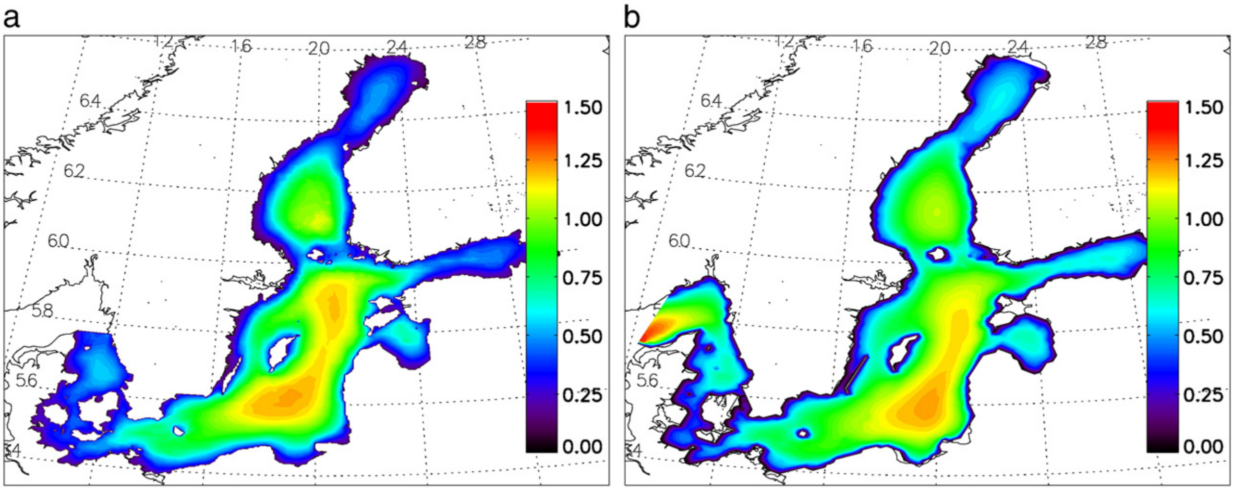

Fig. 3. Mean significant wave height in the Baltic Sea (in meters) for 1997 in RCO to the left (a) and SWAN to the right (b).

water sediments in the Arkona Basin and therefore their critical shear stresses were considered to be of the same value. Other studies using different sediment grain size fractions having different critical shear stresses have been performed. E.g. Blom et al. (1992) tested two different model setups, one with three different grain sizes and a second with only one grain size. Both models reproduced well the concentrations of total suspended solids during a two week period, but during the first week with higher sedimentation the model with three fractions showed better comparison with estimations from sediment traps while the other model underestimated the sedimentation flux. Other model studies (Lou et al., 2000; Schwab et al., 2000) have shown that models with only one grain size can manage to reproduce the general patterns of high turbidity events in Lake Michigan. According to a review by Jönsson et al. (2005) critical values of U_* found in the literature are in the range of 0.4–4.0 cm s^{-1} with most observations found in the range 1.0–2.8 cm s^{-1} that corresponds to critical shear stress values $\tau_c = \rho_w U_*^2$ (where ρ_w is the water density) in the ranges 0.016–1.6 N m^{-2} and 0.1–0.8 N m^{-2}, respectively. Hence, the value of $\tau_c = 0.15$ N m^{-2} used in the present model is within the range of most observed critical shear stresses.

The calculated bottom type map is in good agreement with the digitized map from Carman and Cederwall (2001) (Fig. 5). However, some differences can be noticed as well. In the Bothnian Sea and Bothnian Bay for instance, the western side of the basin is modelled as an accumulation bottom although the digitalized map suggests erosion and transport bottoms. According to the more detailed bottom type map from the BALANCE Interim Report (Al-Hamdani and Reker, 2007) the same area is covered by mud (as presented in Fig. 8b) which thus should be classified as accumulation bottom (Jonsson et al., 1990). Also some areas of accumulation bottoms in the digitized map should be classified as transport or erosion bottoms instead. In the Baltic Proper and the Gulf of Finland the patterns of the sediment categories in the model are more scattered which corresponds better with the bottom type map from the BALANCE report than with the digitized map from Carman and Cederwall (2001). However, the extent of accumulation areas in the south-western Baltic Proper seems to be underestimated by our bottom type model. Further, the model is able to reproduce bottom types in the Gulf of Riga which is basically an accumulation bottom because it is partially protected from westerly winds. In some other cases, like the Åland archipelago, the extension of the erosion bottom is too high in the model. An explanation might be the fetch computation that can only take into account islands represented on the model grid resolution. Because of this shortcoming many islands are not taken into account and the coastal area they are supposed to shelter does not exist.

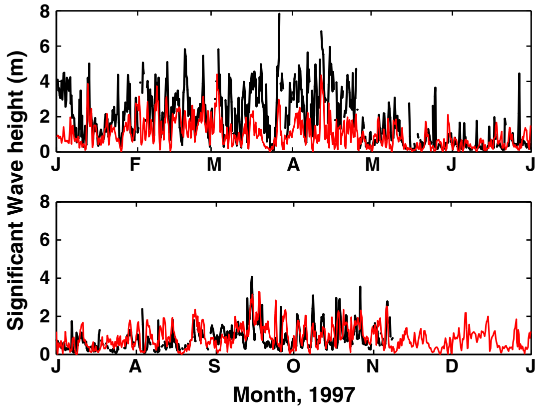

Fig. 4. Significant wave height (in meters) at Almagrundet light house (59°09′N, 19°08′E) during 1997 measured on-site (black line) and simulated with the wave model implemented in RCO (red line). Upper and lower panels show months January–June and July–December, respectively.

A comparison of how the coverage of the bottom types in the Baltic Sea defined by Fig. 5a is distributed vertically at different depths in the model and in the digitized map shows a good agreement (Fig. 6). Accumulation bottoms have their largest contribution in about 100 m depth while erosion bottoms are found at depths shallower than 50 m. Transport bottoms range from the surface to about 150 m depth with largest contributions in the upper 100 m.

The modelled accumulation bottoms on average have less than about 2 days with resuspension each year while erosion bottoms have more than about 36 days with resuspension each year. The average number of resuspension days in shallow bottoms 0–50 m and deeper bottoms below 50 m is about 33 and 3 days per year, respectively. The model results seem to be in fair agreement with the results by Danielsson et al. (2007) who found that substantial resuspension events may occur at depths down to 40–60 m with durations ranging from 1 day to 2 weeks. Further, our model results agree also relatively well with the results by Christiansen et al. (1997) who found from their model study that in the most shallow parts of their study area resuspension occurred 55–127 days (15–35%) of the year and in the deepest parts (20–25 m) sediment resuspension occurred less than 11 days (<3%) of the year.

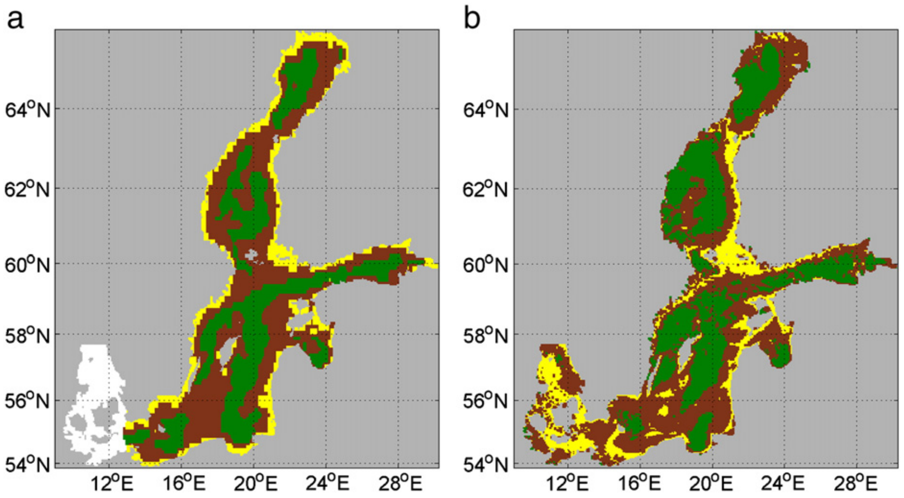

Fig. 5. Digitized map of bottom types adjusted to RCO 2 nm model grid to the left (a) and the modelled bottom type map to the right (b) obtained with the present model. Green colour denotes accumulation, brown transport and yellow erosion bottoms, respectively.

3.2. The origin, transport and destination of organic material

3.2.1. Transport patterns of total organic matter

The long-term average transport pattern of total organic matter, i.e. phytoplankton, zooplankton and detritus in the model, indicates a transport towards the Belt Sea and the Sound mainly along the Swedish and German coasts of the Arkona Basin with largest transports found in the northern parts (Fig. 7a). An eastward transport that enters the central Arkona Basin from the Danish straits and a clockwise circulation around the Bornholm Island add to the average inflow pattern that continues through the Bornholm Basin into the deeper Baltic Proper and to the Bay of Gdansk in the south-eastern Baltic Proper. A counter-clockwise circulation around the Gotland Island characterizes the general circulation in the Baltic Proper with the largest transports confined more towards the eastern and northern Baltic Proper and along the western coast of Gotland. A coil of the circulation penetrates into the central Bornholm Basin from the north-western Baltic Proper and continues back into the Eastern Gotland Basin. An internal counter-clockwise circulation is also found in the Eastern Gotland Basin. Largest exports of organic carbon to the Bothnian Sea takes place mainly west of the Åland Island. A clockwise transport takes place in the northernmost parts of the Baltic Proper and continues into the Gulf of Finland. This circulation meets the outflow from the Gulf of Finland which takes place mostly along the southern coasts of the inner parts of the Gulf of Finland. In general the transports are larger in deeper areas than in shallow areas due to the vertical integration with depth through the water column. But the transports of organic carbon in the deepest places of the sub-basins are relatively low due to the tendency of circular transport patterns that arise around the slopes of the pits in these areas.

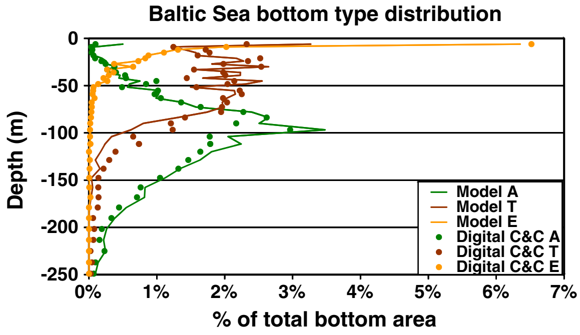

Fig. 6. Vertical distribution of the area covered by different bottom types. The area is normalized to the total bottom area and the results are presented as percent. Model results are shown by green (accumulation), brown (transport) and yellow (erosion) lines. Results from the digitized map are shown by dots in corresponding colours.

The relative contribution of resuspension to the long-term transport patterns of organic carbon is shown in Fig. 7b. The shallow areas along the Finnish and Swedish coasts generally show very high (>70%) contributions of resuspended organic matter. High contributions are also seen locally in the deeper Baltic Proper even below 100 m depth while in general the contribution is in the range from below 10% in the deepest parts to about 30–40% at depths shallower than about 50 m. The results indicate that on average the largest contributions of resuspended organic material are found at coastal erosion and transport bottoms (Fig. 5) in the northernmost Baltic Proper, in the southern inflow regions and on the eastern side of the Baltic Proper and in the shallow areas south of Öland and Gotland. Generally the transports of resuspended organic carbon are lower on the deeper accumulation bottoms in the south-eastern Baltic Proper and in the central parts of the eastern and western Baltic Proper and also the inner central parts of the Gulf of Finland.

The green colours in Fig. 8a indicates the areas in the model that on average import organic matter. On longer time scales these areas therefore become net sinks that remove organic matter from the water. The imported organic matter either becomes decomposed and mineralized in the water or becomes deposited in the sediments. A fraction of the deposited matter is permanently buried while the rest is mineralized and may contribute to the efflux of inorganic compounds from the sediments to the overlying water. The sink areas correlate well with the accumulation bottoms and the muddy parts of the detailed sediment map from the BALANCE Interim Report shown in Fig. 8b. Divergence (yellow in Fig. 8a) indicates that organic matter is on average exported from the area. Most of these areas act as net sources of matter originating from primary production. The central parts of the sub-basins are generally sinks while more shallow areas and the coastal regions are sources for organic carbon. The source areas also correlate well with the areas of erosion and transport bottoms in the model (Fig. 5). This indicates that organic matter produced in these regions is in suspension long enough until it is transported to a less energetic sea area. One may also note the good correlations of green and yellow bottom areas with the 50 m and 100 m depth contours in Fig. 8a, which is in accordance with the vertical distribution shown in Fig. 6.

3.2.2. Distribution of resuspended organic matter

The model results (Fig. 9a) indicate in general that a large fraction of the organic matter found in the sediments of the Baltic Sea is

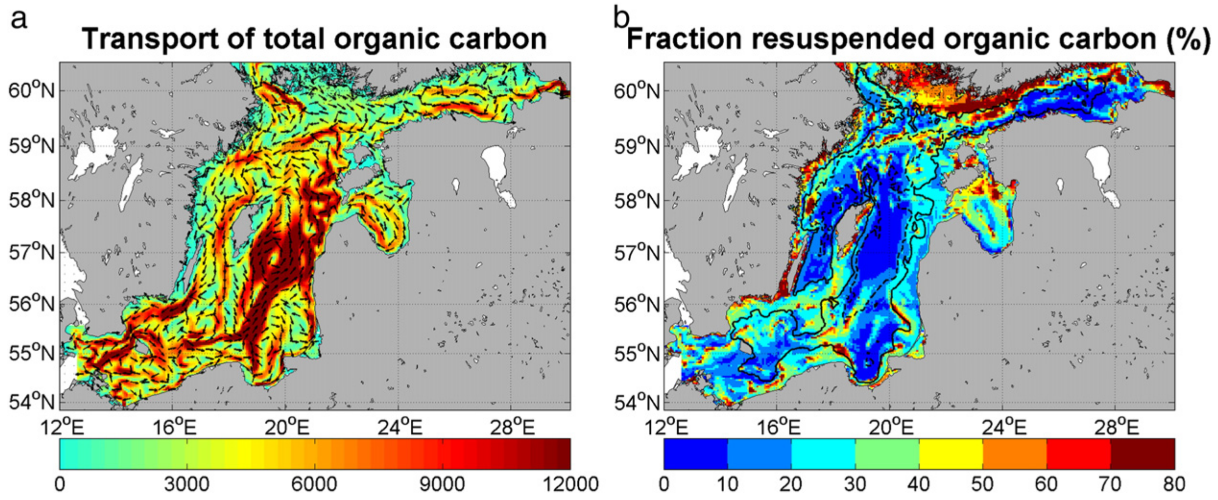

Fig. 7. Vertically integrated average (1970–2007) horizontal transport of total organic carbon (ton C km^{-1} year^{-1}) to the left (a) and the fraction of resuspended organic carbon (%) to the right (b). The direction of the transport is indicated by the arrows and the magnitude is shown by the background colour scale. In the right panel (b) the 50 m and 100 m isolines are shown by the black solid and dotted lines, respectively.

resuspended organic matter. This is explained by the shallow average depth that allows for wave-induced resuspension to occur in large areas of the Baltic Sea. The distribution pattern of organic matter accumulated in the sediments indicates that on average the fraction of resuspended organic carbon relative to the total benthic organic carbon is relatively low in the deepest areas of the Baltic Sea. Major areas in the deeper Baltic Proper with very high relative contributions of resuspended matter are found in the inflow region, i.e. the Arkona and Bornholm Basins, Stolpe Channel and the northern Gdansk Basin, and along the 100 m isoline in the eastern Gotland Basin. In the northern Baltic Proper the relative contribution of resuspended matter is even large below 100 m depth. One may note that the areas with highest organic carbon concentrations (Fig. 9b) correspond well with the sink areas of Fig. 8a and the muddy areas of the BALANCE Interim Report (Fig. 8b). The concentrations of organic matter are much higher at accumulation bottoms compared to shallow areas and compared to transport and erosion bottoms.

The long-term average fraction of resuspended organic matter in the shallow (0–30 m) sediments of the Baltic Proper, Gulf of Finland and the Gulf of Riga varies from a fairly constant value below 60% in summer time (May–August) to about 75% in late winter (February)

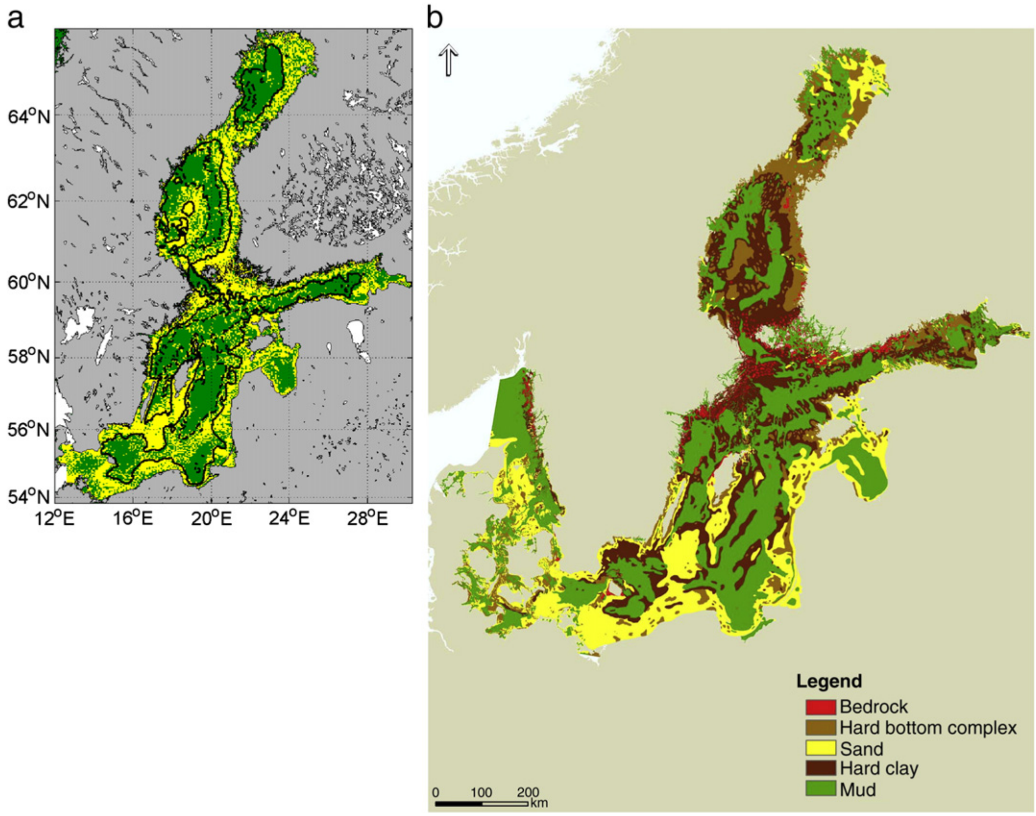

Fig. 8. Vertically integrated average (1970–2007) accumulation of organic carbon to the left (a). Average import (sink) of organic carbon occurs in green areas, while organic carbon is on average exported (source) from yellow areas. The 50 m and 100 m isolines are shown by the black solid and dotted lines, respectively. The detailed sediment map from the BALANCE Interim Report from Al-Hamdani and Reker (2007) is shown to the right (b). The different sediment classes are shown by the legend. The figure was kindly supplied with permission from Dr. Al-Hamdani.

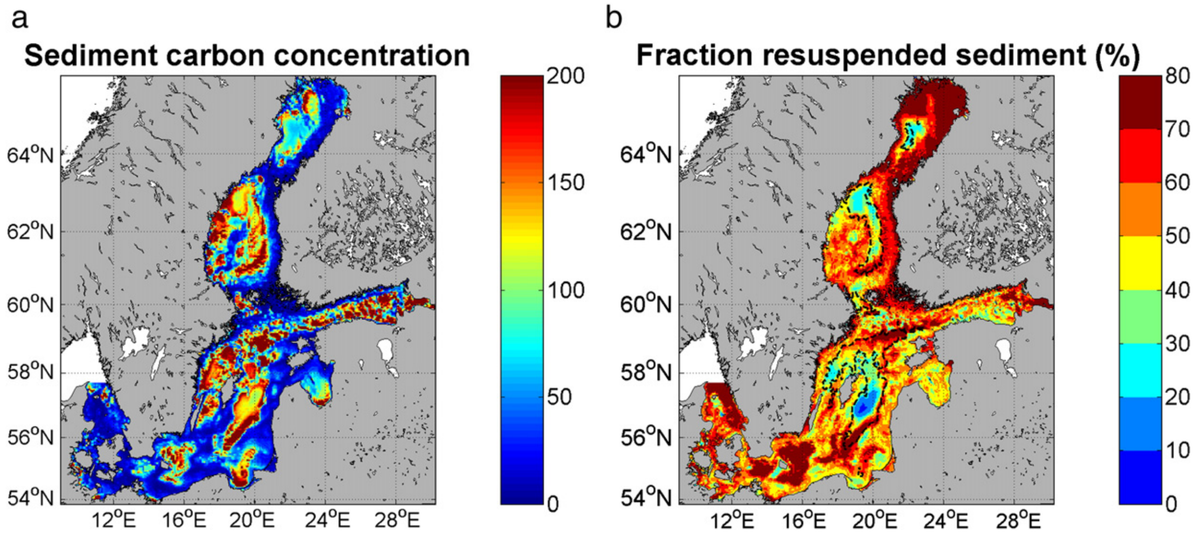

Fig. 9. The modelled average (1970–2007) benthic organic carbon concentrations (g C m^{-2}) in the Baltic Sea is shown to the left (a) and the fraction of resuspended carbon (%) is shown to the right (b). The 100 m isoline of the model is shown by the black dotted line in the left panel.

with an observed minimum of 43% and a maximum of 91% during the modelled period (Fig. 10a). The seasonal variability is largest in the upper 70 m but decreases with depth and in the deepest layer (below 120 m) the average variation is between 45% and 50%. In the deeper layers the maximum fraction resuspended carbon is observed later than in the upper 30 m; in the depth range 30–68 m it is observed in February–March and in the deepest layers in April–May. There is also an inter-annual variability (not shown) which seems to be governed by major inflows and periods with high winds that increases the resuspended fraction also in the surface waters.

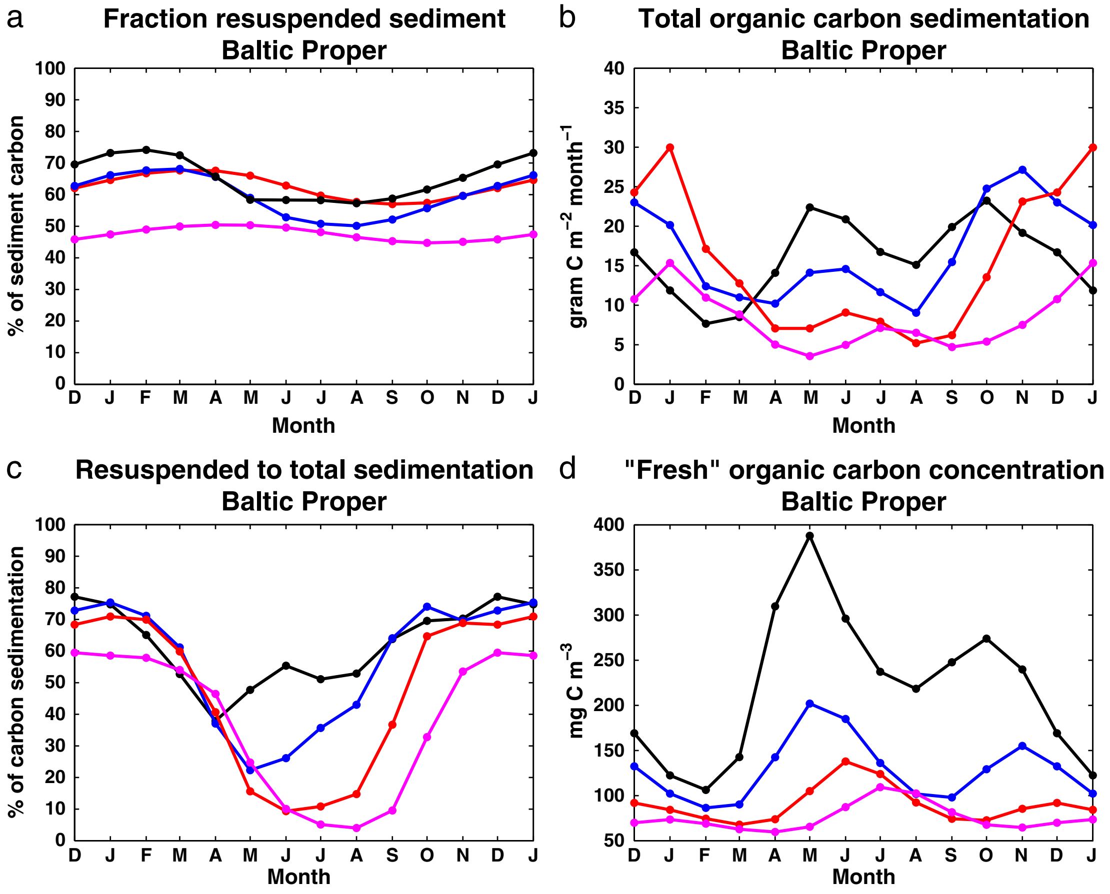

Fig. 10. The monthly means (1970–2007) of the fraction of resuspended organic carbon to total organic carbon in the sediments are shown in the upper left panel (*a*). The averages for different depth levels, including the sediments of the Baltic Proper, the Gulf of Finland and the Gulf of Riga, are shown by the black (0–30 m), blue (30–68 m), red (68–120 m) and magenta (120 m- depth) dotted lines, respectively. The corresponding means of the total sedimentation of organic carbon (g C m^{-2} month^{-1}), the fraction of resuspended matter in the sedimentation, and the concentration of fresh organic carbon in the water (mg C m^{-3}) are shown in the upper right (b), lower left (c) and the lower right (d) panels, respectively.

The modelled average total sedimentation (deposition) of organic carbon (1970–2007) is about 190 g C $m^{-2}year^{-1}$ (0.5 g C m^{-2} day^{-1}) in the upper 68 m, about 160 g C m^{-2} $year^{-1}$ (0.4 g C $m^{-2}day^{-1}$) below 68 m and about 90 g C $m^{-2}year^{-1}$ (0.2 g C m^{-2} day^{-1}) in the layer below 120 m (Fig. 10b). These values are comparable with numbers from Savchuk and Wulff (2001) on modelled spring and autumn bloom sedimentation rates at 25–50 m depth of about 0.5–0.6 g C m^{-2} day^{-1} and 0.25–0.5 g C m^{-2} day^{-1}, respectively. The net sedimentation is however lower since about 90%, 70% and 30% of the sedimented carbon is resuspended again in the upper 68 m, in the range 68–120 and below 120 m depth, respectively. Resuspended organic carbon is a significant fraction throughout the year of the sedimentation in the upper 30 m, but decreases to about 40–50% during spring and summer (Fig. 10c). In the deeper layers below 68 m the fraction of resuspended organic carbon is significant from about October to March, but decreases below 10% in summer. The highest amounts of resuspended organic carbon are found in wintertime when the main part of the resuspension events occurs because of generally higher wind speed in winter. This was also concluded in the model study by Jönsson et al. (2005). The lower importance of resuspended organic carbon in summer corresponds also to an increased amount of fresh organic matter in the water (Fig. 10d). The vertical distribution of fresh organic matter in the water column is a result of the seasonal primary production in spring and fall. The peaks of concentrations in the upper 70 m are found in May and October. In the deepest water layer the peak of sinking fresh organic matter from the blooms are found about 2 months later. The concentrations decrease with depth due to degradation of the organic matter on the way down through the water column as well as due to sedimentation at shallower water depths. On average more than 80% of the fresh organic carbon in the Baltic Proper is found in the productive surface layers (0–45 m) while the 80% fraction of resuspended organic carbon is found in the bottommost 25–30 m of the water column.

The results indicate that organic matter in sediments at all depth ranges except in the deepest bottoms (cf. Fig. 9a) contains relatively large fractions of resuspended organic matter. This is in accordance with e.g. Jonsson et al. (1990), Christiansen et al. (1997) and Struck et al. (2004), who all concluded in their studies that resuspension is important for the sediment transport from shallower to deeper areas. The importance of sediment transports in shallow waters (10–30 m depth) has been discussed by e.g. Christiansen et al. (1997) and by Wallin and Håkanson (1992) who investigated shallow (depth of 11–47 m) coastal areas in the Baltic Sea and showed that about 50–60% of the material caught in sediment traps was resuspended particles.

Emeis et al. (2000) found that the accumulation rates of organic material were higher than the accumulation rates of mineral matter in the Gdansk and Gotland basins. According to their suggestion this indicates other sources of organic material than fluvial input or erosion from shallower areas. Their findings are in agreement with the present results that also show relatively low contributions from resuspension in the deepest parts of these basins (Fig. 9a). From stable nitrogen isotopic analysis in the Baltic Sea sediments Voss et al. (2005) found that inputs of nutrients and organic material from land are mostly trapped in the coastal rim of the Baltic Proper thus mostly contributing to the coastal eutrophication. These findings correspond to our results where the transport pattern of resuspended organic matter seems to occur mostly along the shallow areas and at the coasts. Resuspended particles are often settled close to the area from where they were resuspended, but might finally reach deeper areas (Brydsten and Jansson, 1989). Important to note is that the impact from resuspension is however twofold since events of resuspension also prevents settling of organic matter that has not been in contact with the sediments. Transports of “fresher” organic matter that is kept in suspension e.g. from the productive shallower areas or adjacent sea areas is therefore an important source for sediments e.g. in the deeper Baltic Proper and the southern Gdansk Basin where the concentrations of organic matter are high although the relative contribution of resuspended organic matter is low (Fig. 9a and b). A detailed quantification of this process is however out of scope of the present study and is left for future investigations.

It was found from model experiments that oxygen concentration in the deeper parts of the Arkona and Bornholm basins becomes too high without resuspension in the model (not shown). In the present experiment a large fraction of resuspended matter is found in the inflow regions of the modelled Arkona and Bornholm basins. Actually about 80% of the organic matter in the sediments in the deep Bornholm Basin and more than 70% in the deep Arkona Basin is resuspended organic matter. Decomposition of the resuspended organic matter transported to the inflow region therefore has a great impact on the rate of oxygen consumption of the inflowing denser water. This largely determines the conditions for the oxygen renewal in the deepest parts of the Baltic Proper. This is in agreement with the model calibration by Gustafsson and Omstedt (2009), which indicated that the oxygen removal rate in the Arkona Basin was twice the rate in the Bornholm Basin, which in turn was twice the rate in the eastern Gotland Basin.

3.2.3. Sediment nutrient content

In Fig. 11 the modelled average (1970–2007) nutrient content in the sediment at different depth intervals and bottom types is compared to estimates of the nutrient content based on observations summarized by Carman and Cederwall (2001). They presented nutrient concentrations (mmol N g^{-1} sediment) and the corresponding density of the sediment (kg m^{-2}) for the top 1 cm of the sediment surface. The observed concentrations were converted to mmol N m^{-2} and integrated similar to the model results over the modelled bottom types in the Baltic Proper, the Gulf of Finland and the Gulf of Riga.

Modelled nutrient contents on accumulation bottoms are within the observed range given by the nutrient content of the top 1 to 5 cm of the sediment (Fig. 11). The comparable active sediment layer that should be used for the integration might vary e.g. between different bottom types and different sediment characteristics and is not clear at present. Also the availability of the sediment nutrients for the biogeochemical cycles is uncertain. For instance, on Baltic Proper accumulation bottoms the estimated pools vary between 810 and 3600 ktons (10^3 tons) N and 149–564 kton (10^3 tons) P according to Carman and Cederwall (2001) depending on the depth of integration (0–1 cm or 0–5 cm).

The model generally seems to underestimate nutrient content at the transport bottoms and especially at the erosion bottoms. For these bottoms there was no information given by Carman and Cederwall (2001) on thicker or thinner layers of the sediment than 1 cm. The results however indicate that the impact from resuspension might be too large in the model when compared to the uppermost 1 cm of the sediment. The reason for this is not clear at present. It might e.g. be that the structure of the sediment, that becomes coarser on erosion bottoms, prevents resuspension from reaching into the depth of the sediment, which then may leave more nutrients undisturbed below the surface of the sediment. The present simplified uniform model description of critical stress and the sediment uplift velocity of resuspended matter may not capture this kind of structural differences. This discussion is however somewhat uncertain since similar to the accumulation bottoms we do not know to what depth in the sediment the integration should be performed.

The fraction of nutrients that are found at erosion bottoms in the Baltic Proper are less than 4–8% for N and 13-–0% for P of the total amount according to the estimates from Carman and Cederwall (2001). The lower range corresponds to an integration 0–5 cm at accumulation bottoms and the high number is obtained when including only the upper 1 cm. Hence, the overall impact of a possibly underestimated nutrient content on erosion bottoms could be important in some

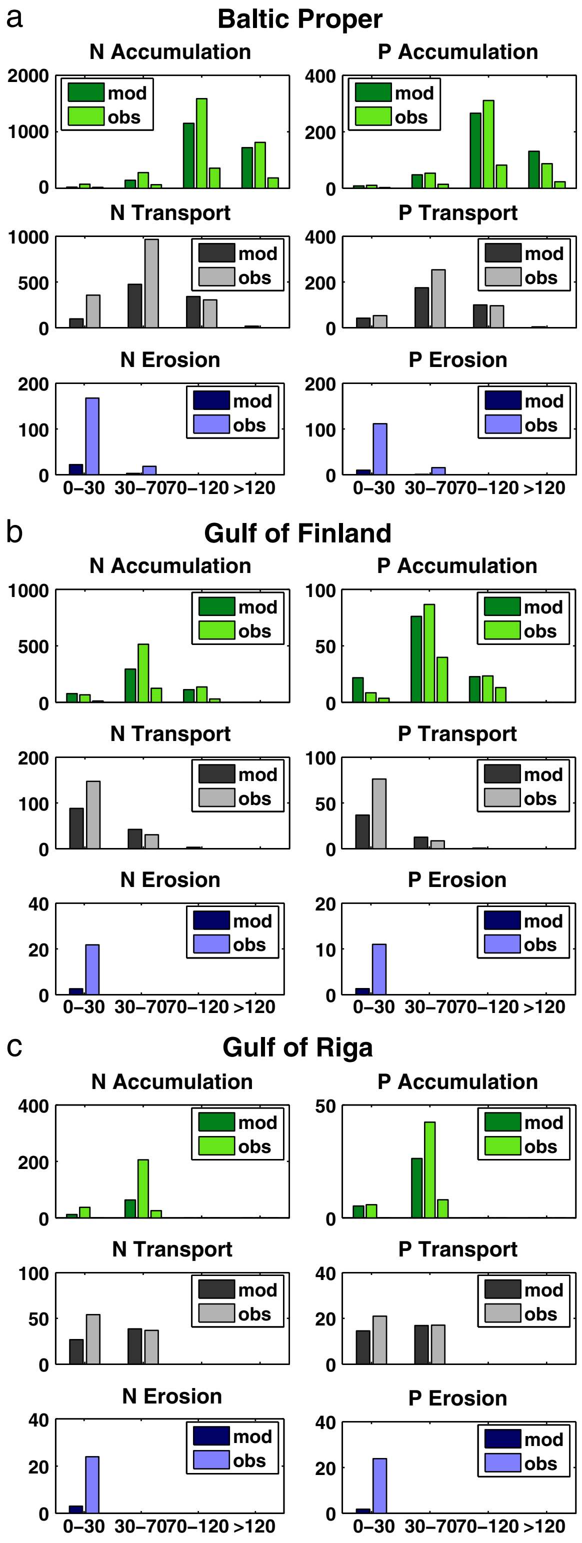

Fig. 11. The nutrient content (kton) at the different bottom types and different depth intervals in the Baltic Proper to the left (a), the Gulf of Finland in the middle (b), and the Gulf of Riga to the right (c). Model results (model) are compared to estimations (obs) based on observations from Carman and Cederwall (2001). At accumulation bottoms the lower and higher observed values correspond to the top 1 cm and 5 cm of the sediment, respectively.

shallow coastal waters, especially for phosphorus, but is not crucial for the overall model performance.

The comparison with observations gives a first rough validation of model sediment characteristics, but there are uncertainties regarding e.g. how large fractions of the observed sediment nutrients actually are incorporated in the biogeochemical cycling and also about how representative the observations are for the entire sub-basins discussed here. In addition, sediment carbon is not explicitly modelled here but estimated from a constant C:N ratio of 106:16 which is lower than seen from the estimates of sediment nutrient concentrations presented by Carman and Cederwall (2001). For example the average observed C:N ratio of accumulation bottoms is about 150:16 in both the Baltic Proper and Gulf of Finland and about 160:16 in the Gulf of Riga. This is most likely due to preferential mineralization of organic N compared to C in the water and also during early diagenetic stages in the sediments (Carman and Cederwall, 2001). Preferential mineralization is not accounted for in the present model setup. The role of low oxygen concentrations and anoxia in the deep water on the mineralization rates of organic N and P is uncertain. It has been suggested that mineralization rates may decrease with decreasing oxygen concentrations (Gustafson and Stigebrandt, 2007; Hall et al., unpublished results), which therefore could cause higher concentrations of organic N and P in the sediments. These effects are not accounted for in the present model setup. There is a need for more research regarding the importance of these issues.

4. Conclusions

In the present study we updated a high-resolution 3-dimensional biogeochemical–physical model with a simplified empirical wave model to calculate the wave and current induced shear stress and thus the resuspension of organic material. The representation of waves from the empirical model proved to be realistic as compared to a state-of-the-art spectral wave model. The modelled bottom types were compared to a digitized bottom type map based on observations and also to a highly detailed sediment map from the BALANCE Interim Report (Al-Hamdani and Reker, 2007). The results showed that the model successfully managed to capture the horizontal as well as the vertical distribution of the different bottom types, i.e. accumulation, transport and erosion bottoms. The average frequency of days per year with resuspension at different depths is also well captured in the model and compares well to studies by Danielsson et al. (2007) and Christiansen et al. (1997).

In general the transports of total organic carbon are larger in deeper areas than in shallow areas due to the vertical integration with depth through the water column. On average the largest contribution of resuspended organic carbon to the transport of total organic carbon are found at erosion and transport bottoms. Although the transport of resuspended organic carbon in general is low (<10% of total) at deeper accumulation bottoms, the central parts of the sub-basins act on average as sinks that import organic matter while the more shallow areas and the coastal regions act as sources of organic carbon in the water column. These findings are related to the two-fold impact of resuspension events; to resuspend particles from sediments and to hinder deposition of fresh material in the water column.

A large fraction of the organic matter in the sediments of the modelled Baltic Sea is resuspended organic matter, i.e. it has at least once before been lifted up from the sediments. This is due to the shallow average depth that allows for wave-induced resuspension to occur on large areas of the Baltic Sea. The transports of resuspended organic matter occur mostly along the shallow areas and at the coasts. This indicates that the organic matter produced in erosion and transport areas might be kept in suspension long enough to be transported and settle in less energetic areas, i.e. on accumulation bottoms. There is also a seasonal variation, where the highest amounts of resuspended organic carbon in the sediment are found in wintertime when the wind speed generally is higher.

The model also captured well the nutrient element contents in the sediments, but seemed to underestimate the nutrient content at the erosion bottoms. Future model investigations might therefore also include more information about the structure of the sediment e.g. by including a thinner top layer of the sediment in the model (e.g. Blom et al., 1992). Another reason for too less nutrient content at erosion bottoms might be the neglect of damped wave height in shallow waters leading to an over-estimation of the frequency and strength of resuspension events. This could be improved in future wave models as well. There is at present a lack of sediment nutrient data to be able to do a more extensive validation of the model performance in this paper. Compiling of data available from different field campaigns is ongoing and will be used in future model development and validation exercises.

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