ELSEVIER

Journal of Marine Systems 35 (2002) 133–150

JOURNAL OF MARINE SYSTEMS

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Material transport from the nearshore to the basinal environment in the southern Baltic Sea I. Processes and mass estimates

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Received 19 May 2000; accepted 20 March 2002

Abstract

Processes involved in erosion, transport and deposition of cohesive materials are studied in a transect from shallow (16 m) to deep (47 m) water of the SW Baltic Sea. The wave- and current-induced energy input to the seabed in shallow water is high with strong variability and suspended matter concentrations may double within a few hours. Primary settling fluxes (from sedimentation traps) are less than 10 g m^{-2} day^{-1}, whereas resuspension fluxes (evaluated from sedimentation flux gradients) are 15–20 times higher and the residence time for suspended matter in the water column is 1–2 days. Settling velocities of aggregates are on average six times higher than for individual particles resulting in an enhanced downward transport of organic matter. Wave-induced resuspension (four to six times per month) takes place with higher shear stresses on the bottom than current-induced resuspension (three to five times per month). The short residence time in the water column and the frequent resuspension events provide a fast operating benthic–pelagic coupling. Due to the high-energy input, the shallow water areas are nondepositional on time scales longer than 1–2 weeks. The sediment is sand partly covered by a thin fluff layer during low-energy periods. The presence of the fluff layer keeps the resuspension threshold very low (<0.023 N m^{-2}) throughout the year. Evaluated from 3-D sediment transport modeling, transport from shallow to deep water is episodic. The net main directions are towards the Arkona Basin (5.5×10^5 t per year) and the Bornholm Basin (3.7×10^5 t per year). Energy input to the bottom in deep water is low and takes place much less frequently. Wave-induced resuspension occurs on average once per month.

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PII: S0924-7963(02)00126-4

Residence time of particles (based on radioactive isotopes) in the water column is half a year and the sediment accumulation rate is 2.2 mm year^{-1} in the Arkona Basin.

Keywords: Sediment dynamics; Aggregates; Sedimentation; Resuspension; Material transport; Models; Baltic Sea; Pomeranian Bight

1. Introduction

It is well known that unconsolidated, fine-grained sediments and their organic matter content do not stay for long on the seafloor in high-energy shallow water environments. Frequent wave (Weir and McManus, 1987; Sandford, 1994)- and/or current (Sandford et al., 1991)-induced resuspension entrain such material and ultimately transport it to its final deposition in sheltered or deep water areas (Floderus and Håkanson, 1989; Laursen et al., 1992; Christiansen et al., 1997). Knowledge on erosion, transport, deposition and consolidation of cohesive material is essential as pollutant dynamics are closely linked to the distribution of particulate matter (Wiltshire et al., 1994).

An additional effect of high shear stresses on the bottom is that resuspension changes sediment to water fluxes of nutrients and redox sensitive species (Laima et al., 1998) as well as oxygen penetration depths into the sediment (Christiansen et al., 1997). Resuspension may, thus, enrich the water column by nutrients from the sediment. The input is both related to desorption from resuspended particles and to mixing of pore water nutrients into the water column (Simon, 1989). Another ecological consequence of resuspension is the potential enhancement of phytoplankton growth since cells are periodically carried back into the euphotic layer (Garcia-Soto et al., 1990). The resuspension process is, thus, one of the mechanisms that provide a coupling between the benthic and the pelagic ecosystems. Resuspension may also reduce the algal growth through light attenuation by the increase of turbidity (Hellström, 1991).

Due to resuspension, major parts of the areas with water depths less than 40–50 m in the western (Christiansen and Emelyanov, 1995) and less than 70–80 m in the central Baltic Sea (Jonsson et al., 1990) are generally considered nondepositional and it is estimated that 80% of the organic matter and nutrients deposited in the deep water basins of the central and northern Baltic Sea originate from erosion of shallow water sediments (Jonsson et al., 1990).

As a consequence of resuspension and transport, sediments making up the seafloor are often observed to become finer in a shallow water to deep water depth profile (e.g., Christiansen et al., 1997). It should, therefore, be expected that threshold velocities for resuspension should decrease in a shallow to deep water depth profile. Such threshold velocities may, however, be affected by the potential presence of a fluff layer (Stolzenbach et al., 1992) on the bottom. This unconsolidated layer is composed of aggregated biogenic and nonbiogenic particles; it accumulates at the sediment–water interface during calm weather. The fluff material is rich in organic matter, trace elements, organic contaminants and has a large surface area settled by bacteria (Emeis et al., 2002). A fluffy layer is easily resuspended because of the low effective density of the flocks. The flock effective density (difference between flock bulk density and water density) depends on flock size but typically lies in the range of 10–100 kg m^{-3} (Fennessy et al., 1994). An effective density of zero would mean that a flock is neutrally buoyant, whereas a value of 1600 is close to the effective density of a quartz grain. Biological activity is also important in this context. On one hand, bioturbation may enhance the potential for resuspension by reducing the strength of the cohesive forces in the sediment (Rhoads and Young, 1970). On the other hand, the presence of biofilm or an algae mat, which protects the bottom, may strongly increase the threshold velocity needed for resuspension (Kornman and De Deckere, 1998; Austen et al., 1999).

As part of the BASYS (*Ba*ltic Sea *Sy*stem *S*tudy) initiative the present paper aims at quantifying processes and masses of transported material in a coast-to-basin profile of the southern Baltic Sea. Knowledge of such processes and their timescale may help to understand the role of hydrographical variability in benthic–pelagic coupling and in suspended matter concentrations and their transport and thereby help to optimize environmental monitoring frequencies.

2. Study area

The present BASYS study area is situated in the southwestern Baltic Sea concentrating on the Pomeranian Bight and the Arkona Basin (Fig. 1). Four working stations have been selected along a coast-to-basin gradient. Positions and station characteristics are given in Table 1. The ODAS station is a shallow turbulent environment where sand ripples are overlain by a thin fluff layer. Because of its proximity to the Oder River mouth, the ODAS station is directly influenced by Oder River discharges and shows great variability in sedimentary conditions at the sea floor (Laima et al., 1999). The Oder River has a drainage area of 130,000 km^2, its freshwater input to the Pomeranian Bight is 15–17 km^3 year^{-1} and the supply of terrestrial suspended matter is estimated at 425,000 t year^{-1} (Pohl et al., 1998; Emeis et al., 2002). The Rinne station lies in a morphological depression where material derived from shallow water is channelled during periods of intense near-bottom transport, and mud is deposited during quiescent periods. Evaluated from side scan images the seafloor is erosional with boulder beds as well as sand and muddy sand in the deepest parts. The Wiek station lies at the shoulder of the southern Arkona Basin in an area affected by sediment movement during strong wind periods. The seafloor consists of sandy mud and appears featureless on side scan sonar images. Pycnocline depth is around 20 m giving varying near-bottom oxygen conditions at the station. The Arkona Basin is the deepest part of the cross-section where mud accumulates at a rate of up to 2 mm year^{-1} (Leipe et al., 1998) and where the majority of land derived material is supposed to be deposited after a series of intermediate storage and modification processes. Combined the four stations cover the Oder Rinne, i.e., the pathway of material emanating from the Oder River to its (possible) grave in the Arkona Basin (Oder Project Members, 1995). The Oder project studied the pathway and com-

Table 1
Positions, depths and summary characteristics of the top 0–1 cm of the sediments of the four stations

Station name	Position	Depth (m)	Median grain size (μ)	Organic matter (%)	Density (g cm^{-3})
ODAS	54.0808°N, 14.1587°E	16	186	0.3	2.301
Rinne	54.3657°N, 13.8620°E	20	200	0.9	2.365
Wiek	54.6010°N, 13.7607°E	26	68	5.4	1.435
Arkona Basin	54.9357°N, 13.8325°E	47	6	15.1	1.231

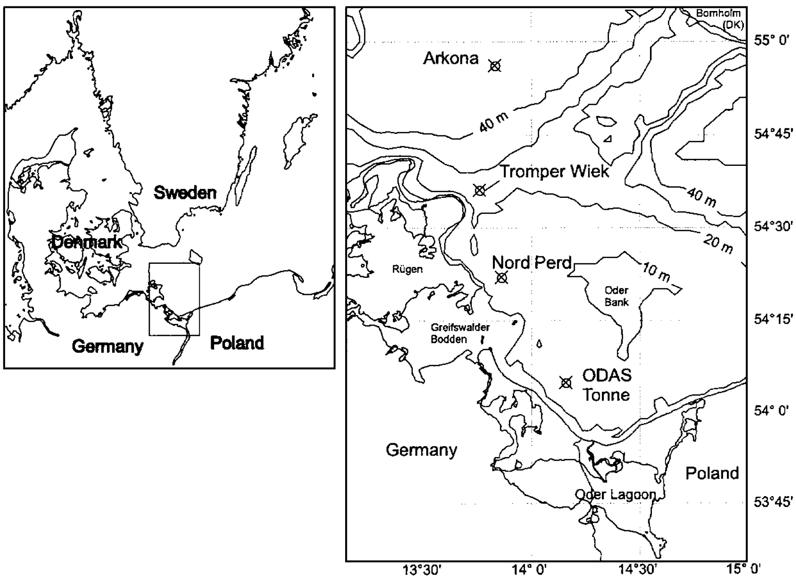

Fig. 1. Location of the study area and position of main sampling stations.

position of material emanating from the Oder river (Oder Project Members, 1995) and the BASYS 3A project studied origin of the material and its changing properties during transport from shallow to deep water (Emeis et al., 2002).

3. Methods

3.1. Near-bottom dynamics and sedimentation rates

A tripod system consisting of a 2-m high stainless steel frame equipped with five sediment traps, pressure recorder, transmissometer and current meter (Fig. 2) was deployed at the ODAS station. The sediment traps consisted of stainless steel tubes closed at the lower end. The tubes were 25 cm long with an inner diameter of 5 cm giving an aspect ratio of 5. This is considered the optimal aspect ratio for measuring sedimentation fluxes in horizontal flows with moderate current speeds (Hargrave and Burns, 1979). Trap openings were placed 0.35, 0.70, 1.05, 1.40 and 1.75 m above the seabed. Pressure recordings (1 m above the seabed) consisted of time series of two measurements per second over 4 min measured every second hour. Pressure recordings were converted into water height using a calibration of the pressure transducer. The DST (PC 9202) transmissometer measured light attenuation of a 630-nm wavelength beam over a distance of 0.5 m at 56-s intervals. The transmissometer was placed 0.5 m above the bed. The Aanderaa (RCM 8) current meter measured current speed, conductivity and temperature every 10 min at 1.0 m above the seabed. Material collected in the sediment traps was filtered using preweighed GF/F Whatman filters and dried for 24 h at 60 °C before weighing.

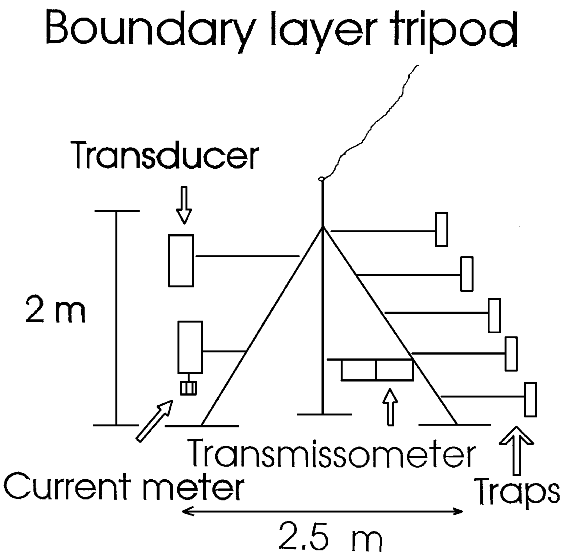

Fig. 2. Tripod equipped with sediment traps, current meter with salinity and temperature sensors, transmissometer and pressure transducer.

3.2. Sediment and water sampling

Diver observations documented the presence of a fluffy layer even on top of the sandy sediment (often in between the crests of the ripples) on the shallow water ODAS Station. This fluffy layer was lost during sampling with the use of a conventional box corer. Therefore, sediment cores were sampled either by divers who gently pressed a cylindrical corer into the sediment and sealed it before recovery or by means of a new video-controlled, hydraulically damped box corer (Lund-Hansen et al., 2001).

Water samples from the benthic boundary layer were sampled with the BIOPROBE (Thomsen et al., 1994). The samples were taken at 5, 10, 20 and 40 cm above the sediment after a waiting period of 10 min to prevent errors due to resuspension when the BIOPROBE is placed on the bottom. Additional samples were taken with Niskin bottles at 5 m above the sediment.

3.3. Resuspension threshold velocity

Threshold velocity for resuspension was measured directly on the cores by the use of the LABEREX chamber (Lund-Hansen et al., 1999a). Near-bottom current velocity in this chamber is gradually, but very slowly stepwise increased until an increase in near-bottom suspended matter is recorded. This increase in suspended matter is reflected in measurements of light attenuation. Current-induced shear stresses in the chamber were calculated from the velocity profile. A detailed description of the chamber and its use can be found in Lund-Hansen et al. (1999a). Maximum wave-induced orbital velocity (U_{max}) on the bottom was calculated from surface wave characteristics assuming Airy wave theory (e.g., Beach Erosion Board, 1975):

$$U_{max} = \pi H/T \sinh(2\pi h/L) \tag{1}$$

where H is wave height, T is wave period, L is wavelength and h is water depth. Wave shear stress, τ_w, was calculated from

$$\tau_w = 0.5\ \rho_w f_w U_{max}^2 \tag{2}$$

where ρ_w is water density, f_w is a wave friction factor (Jonsson, 1966) and U_{max} is the maximum near-bottom orbital velocity.

3.4. Sediment and suspended matter characteristics

Water content (105 °C, 24 h), organic matter content (550 °C, 6 h) and porosity were determined in duplicates of original sediment cores. Sediment samples used for determination of total phosphorus were burned at 550 °C for 12 h and extracted with 1 M HCl for 20 min at 80 °C (Svendsen et al., 1993). These acid samples were filtered and P was measured in the supernatants using the molybdate method (Murphy and Riley, 1962). Total organic nitrogen was measured by titration using a Tecator Kjeltec Analyser. Organic carbon was determined gravimetrically from CO_2 evolution (Nörnberg and Dalsgaard, 1996).

Transparent exopolymer particles (TEP) were analyzed from water samples preserved in buffered formalin according to Passow and Alldredge (1995). Water (20 cm^3) was filtered onto a 0.4-μm Nucleopore filter and stained with Alcian blue. The dye formed a complex with TEP, which was then redissolved and measured spectrophotometrically. Concentrations of TEP are expressed as gum xanthan equivalents (μg dm^{-3}). Particulate organic carbon (POC) was concentrated onto precombusted glassfiber filters. Before CHN analysis (Carlo-Erba-NA-1500 Analyser), carbonate was removed by a 3-h HCl vapour treatment.

3.5. Benthic release analyses

Release of particulate forms of P and Fe during resuspension was measured on three to five sediments cores collected at each station. Sediment overlying water was sampled with a syringe and filtered through 0.45-μm pore size cellulose acetate filters. The filters + suspended matter were transferred to plastic vials containing 10 ml of 0.2 M $HONH_3Cl$ (hydroxyammine hydrochloride) at pH = 2 and were stored at 4 °C. $HONH_3Cl$ is a reducing solution capable of dissolving newly formed Fe oxides and, thus, releasing phosphate that is bound to the surface of Fe oxides.

Vials containing $HONH_3Cl$ and material collected on filters were heated in a water bath at 50 °C during 3 h, which was found suitable for the dissolution of Fe and P from the particulate matter (Matthiesen, 1998). By using the total volume of $HONH_3Cl$ solution (10 ml), the volume of filtered water (10 or 20 ml) and the water height in the LABEREX chamber, the concentrations of suspended Fe and P were recalculated to the "amount resuspended per unit area." Dissolved phosphate was measured spectrophotometrically using the phosphomolybdate method (Murphy and Riley, 1962). Dissolved Fe in porewater was measured spectrophotometrically with the 2,4,6-tripyridyl-*s*-triazine method (Collins et al., 1959). Primary standard for Fe was $(NH_4)_2Fe(SO_4)_2 \cdot 6H_2O$, the detection limit was 2 μM and the relative standard deviation on replicates was below 1% ($n = 3$). The dissolved Fe is interpreted as Fe(II), because the solubility of Fe(III) is low ($< 10^{-8}$ M) at natural conditions ($6 < pH < 8$). Iron which had been oxidized to Fe(III) during storage, was reduced to Fe(II) with $HONH_3Cl$. Lower concentrations of dissolved Fe were measured with AAS using magnesium nitrate as matrix modifier and a furnace program optimized from Sturgeon et al. (1979). The detection limit was 40 nM (2 ppb). As primary standard, a commercial Fe standard from Merck was used. All materials had been cleaned for 12 h in a 0.02-M H_2SO_4 bath and all chemicals were of analytical grade.

The exchange of solutes between sediment and overlying water can be expressed as:

$$F_i = \mathrm{d}n_{i,w}/A\mathrm{d}t \tag{3}$$

where F_i is the flux of solute i per area unit per time unit, A is the sediment surface area and $\mathrm{d}n_{i,w}/A\mathrm{d}t$ is the change in number of moles in the water overlying the sediment per time unit. The number of moles can be expressed by V (water volume) and C_i (concentration of i in the water)

$$F_i = \mathrm{d}(VC_i)/A\mathrm{d}t = 1/A \cdot \partial C_i/\partial t + C_i\ \partial V/\partial t \tag{4}$$

In batch systems where only a limited sample amount is collected during incubation, the flux is most conveniently calculated from $(\mathrm{d}n_{i,\mathrm{w}}/\mathrm{d}t)/A$, where $n_{i,\mathrm{w}}$ is the total amount of i in the chamber and in the sampled water. $n_{i,\mathrm{w}}/\mathrm{d}t$ is estimated from the curve slope in a $(n_{i,\mathrm{w}},t)$ plot. Fluxes were corrected for adsorption onto core walls and volume changes in the overlying water. A positive flux means that the flux direction is from sediment to overlying water and a negative flux means that the flux direction is from overlying water towards the sediment surface.

3.6. Size distributions and settling velocity

Grain-size distributions of the sediments were measured using laser diffraction size analysis (Agrawal et al., 1991), whereas in situ size distributions of the flocks were measured with image analysis (Kennedy and Mazzullo, 1991; Thomsen et al., 1996) on video recordings. The method is described in detail in Thomsen et al. (1996) and Jähmlich et al. (1998). The particle camera system focused on the water layer at 40-cm heights above the sediment. The system consisted of a pressure housing containing a Hi8 Sony TR 3 camcorder, two batteries and an additional magnification lens, which allows resolution of aggregates down to 50-μm diameters. The water column photographed had a volume of 1.9 cm^3. For back illumination, the camera was directed vertically towards a 10-W halogen lamp. Between the window of the camera and the lamp was a distance of 46 cm. The back illumination system, in which the particles appear dark on a light background, allowed the use of short exposure times (Fennessy et al., 1994). Before each field deployment of the particle camera system, a snapshot of a metric grid was taken to calibrate the video pictures in the laboratory. The image analysis system was calibrated with polymer microspheres of known diameter (163 μm, CV 6%) and fishing line of 80, 200, 400 and 600 μm (CV 3%) (Thomsen et al., 1996). Videotapes of the stations were copied onto a Blaupunkt S-VHS video recorder with a jog-shuttle system. Forty-nine steps with the jog-shuttle correspond to 1 s of videotape. Particle images were then digitized and analyzed with the "Image 1.4" image analysis program. From random samples, images of 250–300 (sharp-edged) aggregates were analyzed for each station. Mean settling velocity of the flocks (w_{sf}) in the benthic boundary layer were calculated by using Gibbs (1985) equation for coastal regions:

$$w_{\mathrm{sf}} = 1.73D^{0.78} \tag{5}$$

where D is flock diameter. Mean settling velocity of nonflocculated material (w_{sp}) in the benthic boundary layer were determined from

$$w_{\mathrm{sp}} = p\beta\kappa u^* \tag{6}$$

where β is a numeric constant ($\approx$ 1), κ is the von Karman constant of 0.41 and u^* is the bottom shear velocity. The Rouse number p was calculated by

$$C_z = C_a\ (a/z)^p \tag{7}$$

where C_z is the concentration 5 cm above the bottom (height z) and C_a is the concentration in the reference height of 500 cm above the bottom (height a).

Water samples for direct determination of settling velocity of suspended matter high in the water column were collected on each station 1 m below the surface and at middepth with a Braystroke settling tube and settling velocity were measured in the tube following the method described in Pejrup (1988).

3.7. Transport pathways and horizontal sediment fluxes

The transport and fate of suspended matter in the Pomeranian Bay and adjacent areas were modeled using the 3-D modeling system MIKE 3. The basic MIKE3 HD module computes the hydrodynamics using the Reynolds-averaged Navier–Stokes equations in three dimensions for solving the full nonlinear equations of continuity and conservation of momentum (for a complete description, see DHI, 1998). A newly developed mud transport module (MT) (Edelvang et al., 2002) was dynamically coupled to the HD module, and simulations were carried out for a year covering the period 1 October 1996 to 1 October 1997.

The model bathymetry was derived from sea charts and consists of a rectangular grid with a constant grid spacing of 3704 m. Vertical resolution is 2 m and the temporal resolution in the model is 300 s. Averaged data are stored for 2 h in the model. The model covers an area stretching from the mouth of the Oder River at Swinoujscie to the south to the southern tip of the Swedish peninsula to the north. The western border is closed at the tip of the Rügen peninsula and to the east the model is cut off at Dziwnow. The model covers an area of approximately 18,000 km^2, of which 3/4 is open sea. The boundary conditions are extracted from a regional, 3-D model covering parts of the Baltic Sea and the Danish waters (Fehmarn Belt, 1998).

Changes in hydrodynamic conditions of the model area are driven both by density as well as barotrophic currents. The wind data used for the model simulations were HIRLAM windfields supplied from the Danish Meteorological Institute. Water level measurements at various stations within the model area together with measurements of current velocities at the ODAS station during the periods 1–8 October 1996 and 11 June–19 August 1997 0.5 m above the seabed were used for calibration of the hydrodynamics. Suspended matter concentrations measured 0.5 m above the bottom together with measurements of fluff densities at the various stations, grain size distribution and in situ flock settling velocities were used to calibrate the sediment transport description (Fig. 3).

The MT module has various parameters that can be applied to describe cohesive sediment properties, the bed properties and the dynamic interaction between sediment and water. The erosion formula, as suggested by Parchure and Mehta (1985) takes the form:

$$S_E = Ee^{(\alpha\sqrt{\tau_b - \tau_{ce}})} \tag{8}$$

where S_E = Erosion rate of the bottom sediment, τ_b = the bottom shear stress, τ_{ce} = the critical bottom shear stress for erosion and E and α are empirical constants. The parameter values used in the model are taken from the in situ measurements to the extent that they were available. The initial sediment bed is assumed to have a constant excess density of 150 kg/m^3 (see Table 1). The critical shear stress for erosion of the fluffy layer is generally set at 0.02 N/m^2 in accordance with field measurements for the area (see Table 4). Consolidation of the bed is not included in the model, because the residence time of the fluffy material is relatively short. The critical shear stress for deposition (value below which the suspended sediment will settle) was estimated to be 0.1 N/m^2. A background concentration of 1 mg/l was applied to the whole area. This is based on measurements during the present expeditions and earlier investigations (e.g., Pohl et al., 1998) and in accordance with the background concentration also found in Øresund (Edelvang, 1999). The discharge from the Oder River was estimated to have a mean TPM of 25 mg l^{-1} (Emeis et al., 2002) except for the Oder flood situation in July 1997, where concentrations reached higher values (Siegel et al., 1999b). The settling velocity of the suspended sediment was described by the use of a simple power function originally established by Burt (1986):

$$w_s = K\mathrm{SSC}^m \tag{9}$$

where w_s = settling velocity of sediment, SSC = Suspended sediment concentration and K and m are constants that has to be determined empirically. Here, w_s was given a mean of 13×10^{-6} m/s. This is much lower than the near-bottom values given in Table 2, but consistent with field measurements (ranging 5–

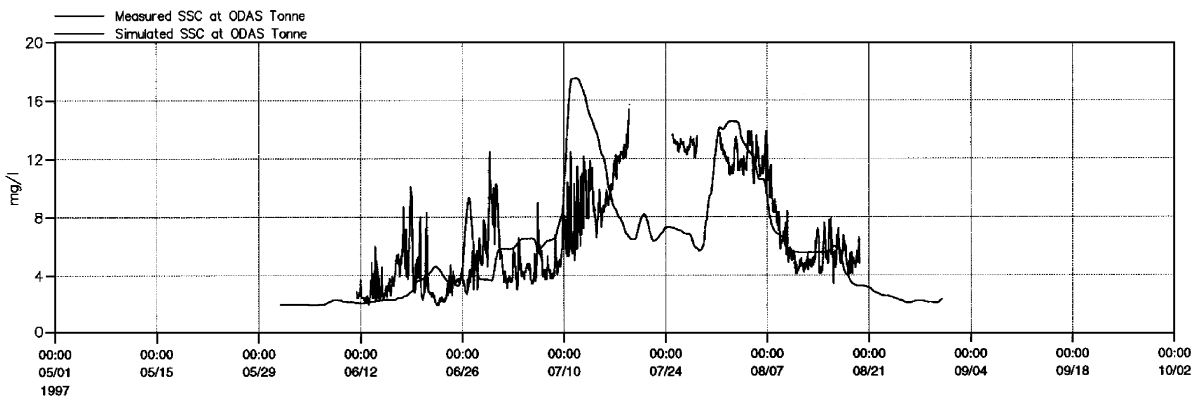

Fig. 3. Comparison of model results with measurements 0.5 m above the bottom from June to September 1997 at the ODAS station.

Table 2
Total suspended matter and calculated settling velocities and residence times for the analysed aggregates (>50 μm) and the suspended fraction (particles < 50 μm) as well as flow velocity

Cruise	Total suspended matter (mg l^{-1})	Flow velocity (cm s^{-1})	Settling velocity (cm s^{-1})		Percent aggregates/TPM	Residence time (h)		Aggregate	
			Aggregates	Suspended particles		Aggregates	Suspended particles	Mean size (μm)	Abundance (l^{-1})
October 1996	8.09 ± 4.03	7.12	0.116	0.035	15	3.61	30.88	301.61	369
March 1997	4.46 ± 1.91	8.758	0.149	0.054	91	2.85	36.43	522.62	211
June 1997	2.16 ± 0.67	4.238	0.106	0.023	60	4.34	31.97	324.35	305
August 1997	6.68 ± 5.86	4.125	0.107	0.044	41	3.92	24.67	306.57	650
October 1997	11.92 ± 7.12	5.78	0.087	0.042	6.4	4.8	16	211.27	472
December 1997	7.88 ± 7.06	5.008	0.069	0.039	8.6	6.21	31.68	210.77	539
June 1998	2.94 ± 1.55	3.855	0.087	0.03	13	5.12	13.97	246.71	308
December 1998	12.02 ± 7.06	13.65	0.117	0.025	7.6	3.6	11.13	370.94	328

Also given are the mean aggregate sizes, the percentage of material aggregated in flocks and the abundance of particles over all visited stations for the different cruises. All values are from 40 cm above the seafloor.

77×10^{-6} m/s) in the water column. It was found to be necessary to use these lower settling velocities from the free water column and not the values from the near-bottom 40 cm since the vertical resolution of the model is 2 m. Flocculation was included in the model calculations by letting flocculation depend on suspended matter concentrations and using a settling index (m) of 1.37.

4. Results

4.1. Suspended matter concentrations

Water column averaged suspended matter concentrations in the depth profile generally ranged between 2 and 12 mg l^{-1} during expeditions (Table 2). The mean flow velocity ranged between 4 and 14 cm s^{-1} (Table 2) and correlated significantly with the amount of material suspended in the water column ($r^2 = 0.5$, $n = 8$, Spearman Rank test, $p < 0.01$) (see further details in Section 4.4). Independently, there was a gradient in suspended material from 5 m to 5 cm above the seabed. At all stations, the amount of suspended material increased toward the seabed as a result of near-bottom transported fluffy material. The highest percentage transported near-bottom was at the stations Arkona and Rinne, whereas the smallest increase toward the bottom was observed at the ODAS station (Fig. 4). However, long-time series of near-bottom concentrations in shallow water showed higher values and strong variations on time scales less than 1 day. During a 24-h experiment at the ODAS station with sampling every 4 h strong variations in the near-bottom transported material were detected as a result of the windstress that forced the near-bottom currents. The bottom flow as well as the amount of suspended material followed the changes in wind speed with a time lag of 3–4 h (Fig. 5). Similar variations were observed in shorter time series from deeper waters. These variations were due partly to resuspension and partly to advection of material. Advection played a large role during the 1997 Oder flood event (Laima et al., 1999).

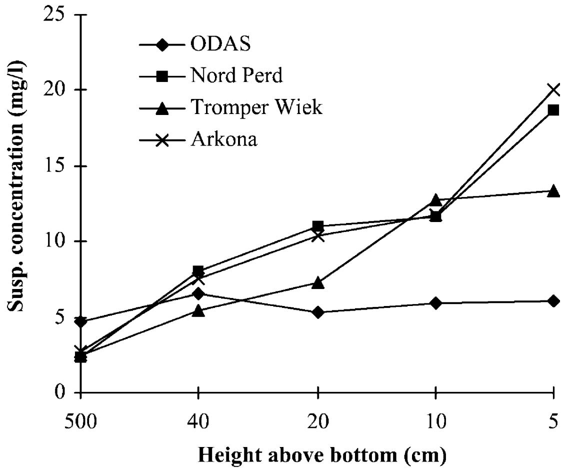

Fig. 4. Gradients of suspended matter in the benthic boundary layer (BBL) of the Pomeranian Bight.

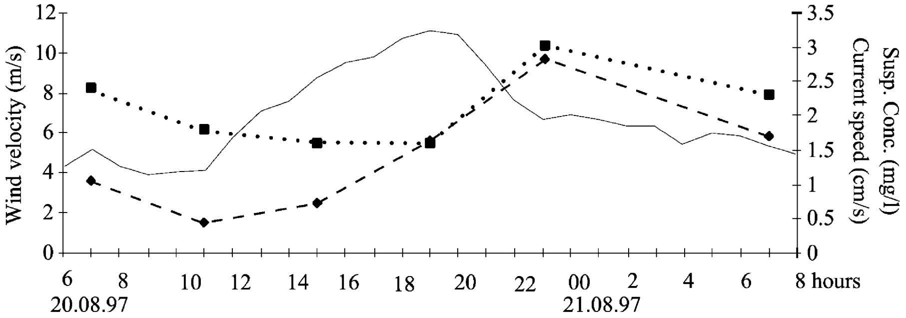

Fig. 5. Wind velocity, current speed (1 m above the bottom) and amount of suspended material during the time experiment in August 1997. Current speed (broken line with rhombs), wind velocity (full line) and TPM (dotted line with squares).

The modeled suspended matter concentrations compare well to the values measured at the various test stations on dedicated cruises. In Fig. 6, the simulated yearly variation in suspended sediment concentrations for the whole modeling area is compared to the point measurements during cruises. The variation is given for the level approximately 1 m above the seabed. All in situ values represent periods with calm weather conditions representing low suspended sediment concentrations. The suspended sediment concentration varies between 1 and 16 mg l^{-1} with the highest values found at the ODAS station.

4.2. Suspended matter aggregation

Aggregate size (in this case flocks larger than 50 μm in diameter) was observed to depend on the following. (1) Turbulence level. Calculated turbulent eddies was always larger than mean aggregate size in the benthic boundary layer (BBL). This turbulence level depends on the bottom flow velocity and the bottom shear stress. (2) Stickiness of the material. The amount of transparent exopolymer particles (measured according to Passow and Alldredge, 1995) that mainly influences the collision efficiency between particles

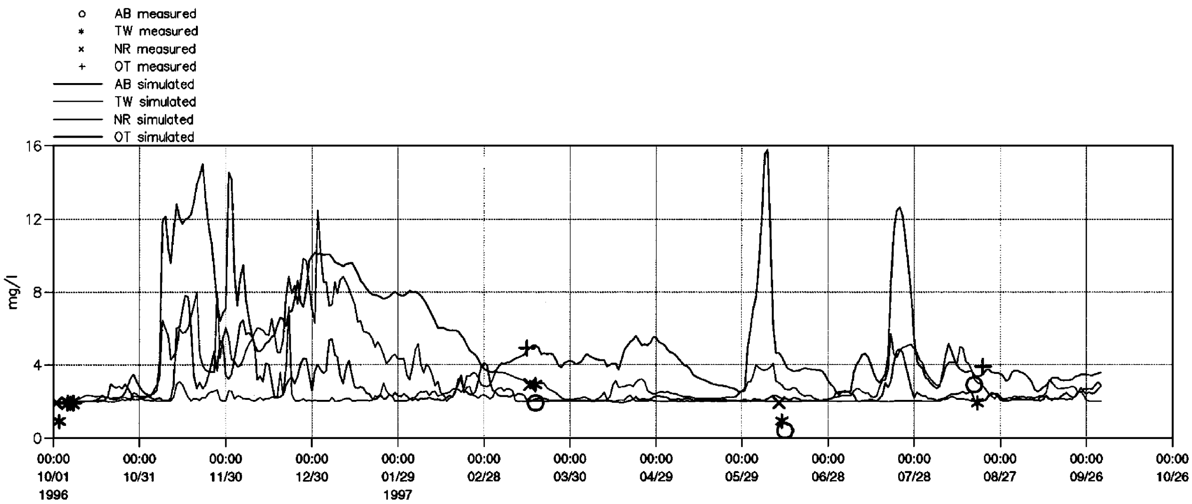

Fig. 6. Comparison between model-simulated and measured suspended sediment concentration 1 m above the sea bed at the four measuring stations.

showed a strong correlation (Spearman Rank test, $n=27$, $p<0.01$) with the aggregate size (Fig. 7). (3) To a lesser degree, on chlorophyll and organic carbon content. Their in situ mean size from image analysis of video recordings typically ranges 200–500 μ. However, in the form of "stringers" they may be several centimeters long. The abundance of aggregates was found to be between 200 and 650 l^{-1} and did not correlate with the aggregate size. By calculating the settling velocity of the aggregates in the water column, it is possible to estimate the residence time of aggregates before they reach the BBL and might be incorporated in near-bottom transport cycles. The residence time of these large flocks in 15 m water depth was calculated to be between 3 and 6 h. By using a mean width and length of the flocks and calculating a spheroid, the density of a single aggregate can be calculated by rearranging Stokes law. This density together with the abundance of aggregates per liter allows estimations of the total mass of aggregates in a water volume. The percentage of aggregated material (in flocks larger than 50 μm) on total suspended material varied between 6% and 90% (Table 2).

Aggregates have a high content of organic matter and nutrients. When using the minimum and maximum values of POC in 5 m above the sea floor analyzed during all cruises (minimum 0.03 mg l^{-1}, December 1997, Arkona station; maximum 0.72 mg l^{-1}, October 1996, Rinne station) and using the derived residence time for aggregated and nonaggregated material, it is possible to calculate an increase in flux of organic carbon by aggregation of particulate material. The flux of POC by aggregated material was 0.17–4.02 g m^{-2} day^{-1}, the flux for POC by non-aggregated material was 0.03–0.70 g m^{-2} day^{-1}, this means that aggregation increases the downward transport of POC up to six times. These data correlate quite well with the values mentioned above by the sediment traps when assuming that around 8% of the total settling matter is particulate organic carbon (in the TPM of the BBL, the percentage of POC varied between 3% and 45%).

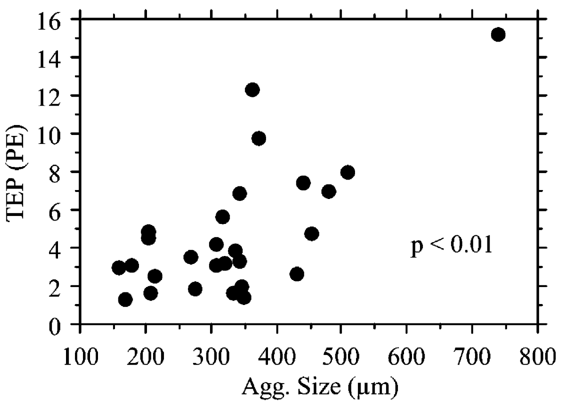

Fig. 7. Correlation between the amount of transparent exopolymer particles (TEP) in photometric equivalents and the mean aggregate size. Linear regression $r=0.67$, Spearman Rank nonparametric test $n=27$, $p<0.01$.

4.3. Sedimentation

Primary sedimentation along the cross-section both takes place in the form of aggregates which in the benthic boundary layer have settling velocities ranging between 0.06 and 0.149 cm s^{-1} and as non-flocculated suspended matter with lower settling velocities ranging between 0.023 and 0.054 cm s^{-1} (Table 2). Based on suspended matter concentrations in the water column, the settling velocities suggest that the residence time for suspended matter in shallow water is only about 1–2 days. These estimates are corroborated by residence time estimates of suspended matter in the water column based on radioactive isotopes (Shimmield et al., 1999).

Sedimentation fluxes measured with sediment traps on the tripod during short period calm weather situations are less than 10 g m^{-2} day^{-1} (Fig. 8). According to Pejrup et al. (1996), the linear increase in fluxes towards the bottom indicates that they represent primary settling fluxes. Using data from Table 2, the average total particulate matter content per square meter in a 16-m high water column would range between 32 and 192 g. This means that with no supply during calm weather situations, the water column would be emptied of suspended matter during 3–19 days.

Sedimentation fluxes measured during 2–3 months observation periods show average rates of 80–115 g m^{-2} day^{-1}. This indicates that the resuspension rate up to 1.75 m above the bottom in shallow water is about 8–10 times higher than the primary sedimentation fluxes. Rates of resuspension up to 0.35 m above the bottom are much higher. At this level, average

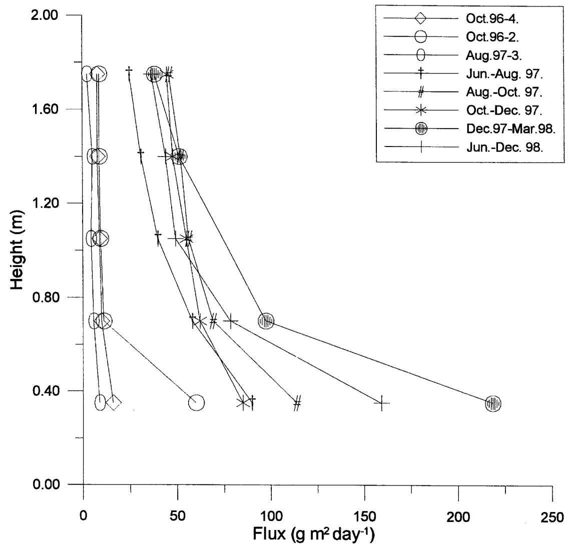

Fig. 8. Sedimentation fluxes 0.35–1.75 m above the bottom on the ODAS station. Oct.96-4 in the legend means 4 days in October 1996.

sedimentation rates up to 225 g m^{-2} day^{-1} were recorded during 2–3 months observation periods. It is important to note that the June–August 1997 observation period includes effects of the Oder River flood event in July 1997 (Laima et al., 1999). Although this major event caused high concentrations of near-bottom suspended matter (Laima et al., 1999), the average daily sedimentation rate was not higher than in other 2–3 months observation periods. This indicates that advected material only makes up a minor part of material involved in vertical fluxes in shallow water.

4.4. Resuspension

Resuspension in shallow water is due both to waves and currents and appears very frequent. Wave-induced orbital velocities resulted in shear stresses above the threshold for resuspension 17 times during a 4-month summer period of 1997 (Fig. 9) and 16 times during a 4-month winter period of 1996–1997 (not shown). Current-induced resuspension occurs with almost the same frequency (Fig. 10). However, a comparison of Figs. 9 and 10 reveals that most current-induced resuspension episodes coincide with wave-induced resuspension episodes and that, generally, current-induced shear stresses are smaller than wave-induced stresses. This means that wind is a very important factor in near-bottom dynamics. Because of the high near-bottom energy level, the shallow water parts of the profile are nondepositional on time scales longer than 1–2 weeks but act as temporal stores for the sediment transport. As a consequence of resuspension, the sediment in shallow water shows no seasonal variation in the nutrient concentration. Nutrient concentrations in the settling particulate matter trapped in the near-bottom sediment traps are much higher than concentrations in the sediment, which stays on the bottom (Table 3) meaning that high-energy shallow water sediments may not reflect the eutrophication level in the water column.

In deeper water especially, wave-induced resuspension appears much less frequently. During a 3-month observation period, the number of resuspension events is six at a depth of 26 m and two at a depth of 47 m (Fig. 9). Compared to the inner stations, the outer Arkona station has a long fetch from the W, so the relatively rare wave-induced resuspension on this station often do not coincide with episodes on the inner stations. Because of the low-energy input, the bottom in deeper water becomes depositional. Residence time for the particulate matter in the water column in deep water (47 m) based on radioactive isotopes is up to 6 months and ^{137}Cs and ^{210}Pb dating methods on cores suggest long term sedimentation rates of 2.2 mm $year^{-1}$. The dating indicates that the sediment accumulation rate has gone up in recent years (Shimmield et al., 1999).

It may be noted from Table 3 that nutrient concentrations in the upper 0–1-cm part of sediment increase along the coast-to-basin profile and that P concentrations in the settling particulate matter measured at the shallow water station area are similar to those measured in the deep water Arkona sediment. In accordance with Emeis et al. (2002), this indicates that the Arkona Basin sediments have nearly the same characteristics as the fluffy layer material in shallower water. The fluff layer is present everywhere in the profile and it is very easily resuspended. Therefore, in spite of the large variation in water depths, grain-size distributions and resuspension frequency there is no clear temporal variation in critical shear stress for resuspension at the four positions (Table 4). A very weak spatial trend with decreasing critical shear stress

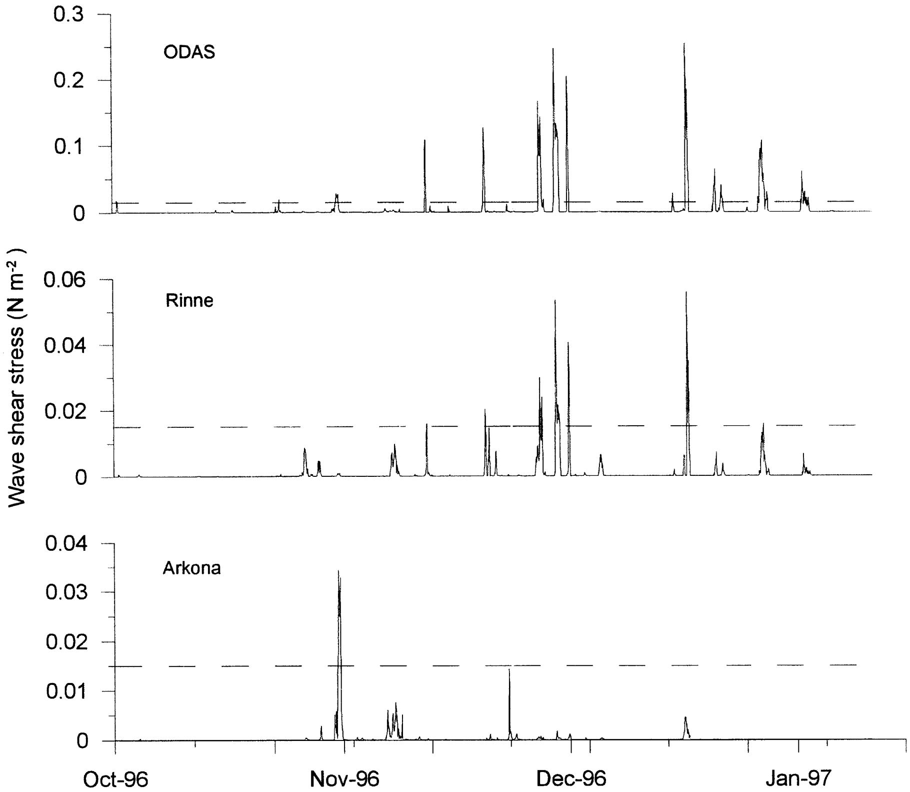

Fig. 9. Wave-induced shear stress on the bottom of three stations from October 1996 to January 1997. Also shown (hatched line) is the threshold shear stress for resuspension. Note different scales on *y*-axis.

may be observed from the ODAS station towards the deep Arkona basin.

4.5. Resuspension effects on benthic releases

Episodes with high near-bottom current speeds and resuspension were experimentally shown to have strong influence on sediment to water fluxes of dissolved and particulate phosphorus and iron and thereby to have importance for the general shallow water to deep water transport of material. For all stations, there were clear effects of shear stress on the release of particulate forms of P and Fe to sediment overlying water. Between March and June 1997, P and Fe release to water increased along the coast-to-basin profile, about 30 nmol P cm^{-2} and 120 nmol Fe cm^{-2} were measured at ODAS and 600 nmol P cm^{-2} and 2700 nmol Fe cm^{-2} were measured in the Arkona basin. Except at ODAS, linear correlations were found between particulate P and Fe in the resuspended matter. The correlations may be predicted from pore water dynamics (Table 5). This suggests locally formed phosphate binding iron oxides as an important source of P and Fe in the resuspended matter. The fluffy layer on the sea floor has most of its compositional characteristics from the suspended matter in the water column (Emeis et al., 2002). However, laboratory experiments during the present study have shown that P rich particles in the fluff layer may be formed by in situ diffusion of P from the pore water to the fluff layer (Matthiesen et al., 2001).

ODAS differs from the other stations in that concentrations of particulate Fe and P are low and their correlation is absent. This lack of correlation is nevertheless expected at ODAS because physical forcing effects are relatively high, sediment porosity is higher compared to other stations (Table 1) and so is the diffusive flux of dissolved P (Laima et al., 2001). On

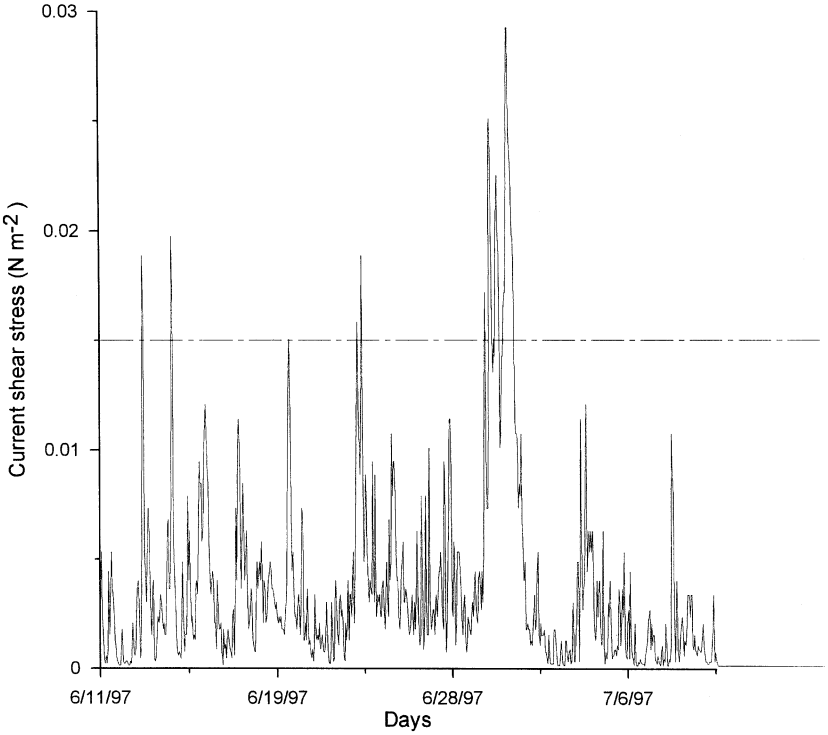

Fig. 10. Current-induced shear stress on the bottom of the ODAS station from June to September 1997. Also shown is the threshold shear stress for resuspension.

the other hand, seasonal measurements of sediment–water fluxes at critical shear stress for fluff layers showed a flux increase of particulate P in the Arkona Basin from March to June 1997 (~ 0.4 mmol cm $^{-2}$) and a negative flux from June 1997 to June 1998 (~ 0.8 mmol cm $^{-2}$). This negative flux could be explained by ongoing cohesive processes at the sediment surface, which increased the threshold velocity for resuspension above the measuring range. Another explanation could be associated with the heterogeneity of sediments or even transport by bottom currents. However, additional research is needed to further support these hypotheses.

Resuspension experiments showed that resuspension processes may also be a source for transport of significant quantities of Fe and P. Using a shear stress of 0.015 N m $^{-2}$ that should be realistic for the Arkona Basin, we measured resuspension quantities in the order of 4.5 mmol P m $^{-2}$ for March 1997 and 8 mmol P m $^{-2}$ for June 1997. Reported primary sedimentation rates for P are 38 mmol P m $^{-2}$ year $^{-1}$ (ICES, 1992) and the maximum yearly diffusion rate

Table 3
Mean nutrient concentrations (June–December 1997) in the upper 0–1 cm sediment on the four stations compared to mean concentrations in near-bottom (0.35–1.75 m.a.b) trapped settling material on the ODAS Station

Station	C (μmol g $^{-1}$)	N (μmol g $^{-1}$)	P (μmol g $^{-1}$)
ODAS Traps	1883	683	61
ODAS	301	19	8
Rinne	387	33	14
Wiek	935	132	20
Arkona Basin	1125	138	91

Table 4
Critical shear stress (N m $^{-2}$) at the four positions

	ODAS	Rinne	Wiek	Arkona
March 1997	0.021	0.013	0.016	–
August 1997	0.021	–	0.015	–
December 1997	–	0.013	0.018	–
March 1998	0.021	0.026	0.018	0.015
June 1998	0.024	0.018	0.015	–

(–) means no data.

Table 5
P/Fe ratios in the suspended matter (from resuspension experiments) compared to the expected P/Fe ratios resulting from measured upward pore water diffusion in the sediment

Station name	Expected upward porewater diffusion ($nmol\ cm^{-2}\ day^{-1}$)			P/Fe ratio in the suspended matter (mol/mol)	
	P	Fe	P/Fe ratio	March 1997	June 1997
Rinne	(1.1)	(2.9)	(0.38)	0.16	0.11
Wiek	1.5	12	0.13	0.19	0.13
Arkona Basin	2.4	11	0.22	0.23	0.23

Numbers in brackets are uncertain as the pore water profile did not indicate occurrence of diffusion controlled transport.

of P from sediment is about 10 mmol P m^{-2} $year^{-1}$. This suggests that resuspension is an important factor related to the P budget.

4.6. Transport of suspended matter

The fine-grained suspended matter in the Pomeranian Bay appears to be discharged from the Oder River, supplied from primary production, from local erosion and imported from the Baltic in general. The results of the model simulations indicate that transport is episodic and governed by the overall hydrodynamics. General transport direction patterns for the Oder River discharge including time-scales varying between one week and several months are both towards the Arkona Basin to the north and towards the Bornholm Basin to the east depending on the prevailing wind for the period. The transport directions were checked by following one particle a day in the model from its discharge from the Oder River into the Pomeranian Bight. The particles are neutral, which means that they just follow the water mass they are discharged with. Sediment particles will to certain extend follow another path as they take place in the transport–settling–deposition–resuspension cycle. On the other hand, as described elsewhere in this paper, the settling velocity of individual particles in the water column is low, which makes the material easily transported. During the simulated period from 1 October 1996 to 1 October 1997, about 1/3 of the particles discharged from the Oder were directed towards the north directly to the Arkona Basin. The remaining part of the particles was directed to the east towards the Bornholm Basin. This is consistent with findings by Siegel et al. (1996), who proved a strong correlation between wind direction and the dynamics of the Oder river plume in general.

The flux of water in the model from the Pomeranian Bay into the Arkona Basin across a boundary defined at grid point 20 (close to the 20 m isobath which Siegel et al., 1999a, defined as the northern boundary of the bight) has a net northward direction into the Arkona Basin of about 3800 $m^3\ s^{-1}$. The net flux of water further on out of the model area towards the Belts and the Øresund is about 15,500 $m^3\ s^{-1}$. This compares well to Siegel et al. (1999a), who reached a mean value of some 15,000 $m^3\ s^{-1}$ of net flow out of the east Baltic.

The calculated net flux of sediment (Table 6) discharged from the Oder River is partly directed downstream along the net flux of water towards the Arkona Basin with a yearly transport of 550,000 t and partly directed upstream against the net water transport with a yearly transport of 370,000 t towards the Bornholm Basin. This implies higher suspended sediment concentrations when the water leaves the bight than when it enters the bight. These higher concentrations of suspended matter in the Pomeranian Bight compared to the background concentration in the Baltic in general come from Oder River discharges and local erosion.

During the simulation period, the total sediment discharge from the Oder is some 425,000 t. This indicates that an amount of sediment about twice as high as the total volume of sediment discharged from the Oder River is transported to the two deep basins.

Table 6
Modeled water and sediment fluxes from the Pomeranian Bight to adjacent deep water basins

Simulated fluxes per year	Directed eastward	Directed westward	Net transport (− into bay, + to Bornholm)	Directed northward	Directed southward	Net transport (− into bay, + to Arkona)
Water (m^3)	3.7×10^{11}	4.7×10^{11}	-1.0×10^{11}	5.4×10^{11}	4.2×10^{11}	$+1.2 \times 10^{11}$
Sediment (t)	1.0×10^{6}	6.3×10^{5}	$+3.7 \times 10^{5}$	9.3×10^{5}	3.8×10^{5}	$+5.5 \times 10^{5}$

5. Discussion

The time series of suspended matter concentrations in shallow water showed strong variability with time with 100% increase within 4 h and the model showed strong wind influenced variations in transport directions. Such results corroborate the findings by Mohrholz (1998) that the Pomeranian Bight is a wind driven system where bottom currents react with a time lag of approximately 3–4 h. The hydrodynamics of the Pomeranian Bight is complicated including two-layer flows in periods influenced by density variations and the present model simulations show water mass characteristics of the open boundaries to have a strong bearing on the model results. This is not in line with Siegel et al. (1999b), who claimed the currents in the Pomeranian Bay to be more or less isolated from the large-scale circulation of the Baltic Sea.

During all expeditions a layer of fluffy, organic rich material consisting of settled aggregates covered the sediment surface on all stations. This material is resuspended at current speeds on the bottom as low as 4–5 cm s^{-1}. The measured critical shear stresses on all four stations are low and because of the small temporal and spatial variations it is concluded that the low critical shear stresses are due to the presence of fluff layers. This layer has a much smaller critical shear stress than the sediment below it. Maa et al. (1998) observed similar low critical shear stress values in fluff layers. Because the fluff layer is easily resuspended, it means that most of the time, this material is in motion in shallow water, and the actual transport depends on the height up to which the material is resuspended. Similar effects of near-bottom transported fluff layer material have also been described for the continental margin (Thomsen and Gust, 2000). Lund-Hansen et al. (1999b) correspondingly showed that transport from shallow to deep water in a coastal lagoon depended on resuspension height.

The concentrations of resuspended material normally increase towards the seabed. This was the case at three of the four stations. No increase was observed at the ODAS station. This may be a result of the smallest water depth and the most direct impact of the wind on the mixing of the water column.

The hydrodynamic situation, flow, shear and turbulence in the BBL are the major impacts that influence both the quantity and the quality of particles as well as the aggregation of particulate material (Thomsen and Graf, 1995; Thomsen and Ritzrau, 1996; Jähmlich et al., 1998). The stickiness of the suspended material influences the aggregation efficiency and, therefore, the mean aggregate size but also the maximum aggregate size. In the present study the TEP (which is a measure of stickiness) (Jähmlich et al., 1998) was the most important factor for aggregate size whereas other factors like content of chlorophyll but also the amount of POC were negligible. Although there was no clear seasonality found in the amount of pigments in the BBL, seasonality was found in the amount of material in the form of flocks larger than 50 μm. In March, June and August 1997, up to 91% of the total suspended material was aggregated, whereas this amount declined below 10% in October and December 1997 and December 1998. The change in the amount of aggregated material might reflect the change in the stickiness of the suspended material although it is not clearly seen in the TEP data.

There were strong differences in nutrient concentrations and C/N ratios between trapped material and material on the seafloor below the traps. In accordance with observations of much faster decomposition rates of organic N in the water column than in the sediment (Nixon and Pilson, 1983), the differences point at a preferential loss of N compared to C during resuspension and transport in shallow water areas. In their trap studies from the Kattegat, Valeur et al. (1995) estimated that mineralization of C and oxidation of N to nitrate following resuspension may cause an oxygen consumption that corresponds to approximately twice the oxygen content in an oxygen-saturated water column of 15 m heights. Such findings may suggest that part of the oxygen deficit observed in the study area following 1997 Oder River flood (Matthäus et al., 1998) can be explained by post flood resuspension episodes of the discharged material. Resuspension processes, thus, may have important effects on the biota.

The sediment to water fluxes of redox sensitive species depended on hydrodynamics. Nutrient concentrations in shallow water areas, thus, do not depend solely on terrestrial supply but hydrographically factors such as advection and resuspension may explain episodic concentration variations in the water column. As the hydrographical variability in shallow water is very high, hydrographically induced concentration variations may blur long term trends in concentrations and knowledge on hydrographical variations is, therefore, essential when planning sampling frequency in nutrient monitoring programs. Further, the use of data from self-recording hydrographical stations may help to separate between natural and anthropogenic-induced changes.

There are deviations in Fig. 3 between modeled and measured suspended matter concentrations especially during the summer. Parts of these deviations may be due to differences in scale between in situ single spot measurements at a specific height above the bottom and the simulated results representing a grid of 14 km^2 with average results for a 2-m high water column. However, the fact that these deviations are largest during summer and that simulated concentrations are higher than in situ concentrations indicate that bioflocculation (Kiørboe et al., 1990) (not described in the model, where flocculation depends only on suspended matter concentrations) plays an important role for suspended matter behavior. Such effects clearly need to be described in a future version of the MT module. However, the overall behavior of the model appears to be reasonable. Edelvang et al. (2002) used NOAA AVHRR satellite images to validate the general trends in the simulated distribution of suspended matter at the surface and showed that suspended matter concentrations in the Oder river plume were well reproduced both in westerly and easterly wind situations.

Even though suspended matter concentrations in the area are generally low, the large volume of water means that a significant amount of material is transported to and settles in the deeper parts of the area. This is comparable to findings from the Øresund between Denmark and Sweden, where concentrations are also generally low, but where sediment is observed to settle in the deeper areas (Pejrup and Larsen, 1994). The modeled sediment trajectories for individual particles seem to document that the Oder River is not the direct main source of the sediment deposited in the Arkona basin as only about 1/3 of the particle trajectories directly end in here. The sediment flux calculations, on the other hand, point to the conclusion that approximately the same amount of sediment as discharged by the Oder River is transported across the northern boundary but not necessarily settling in the Arkona Basin. This means that the net flux of sediment across the northern boundary includes a substantial amount of sediment supplied from erosion in the study area and from the east Baltic area in general. There are reasons to believe that this latter part may include a proportion of reimported suspended matter once lost from the Pomeranian Bight over the eastern boundary of the model area (such material is no longer followed in the model and, therefore, not registered when eventually returned). Oder project members (1995) and Leipe et al. (1998) showed that the Bornholm Basin had much lower concentrations of anthropogenic material than the Arkona Basin sediments and Emeis et al. (2002) gave a number of evidences showing that the export of material towards the east to Gdansk Basin and Bornholm Basin mainly takes place in form of sandy material.

Acknowledgements

The Captains and the crews of RV A. v. Humboldt and RV Prof. Albrecht Penck provided perfect conditions during field campaigns. Wind data were kindly supplied by the Danish Meteorological Institute according to DMI J no. 99-254-64. The support from BASYS EU-Mast III Project Contract no. MAS3-CT96-0058 (DG12-DTEE) is gratefully acknowledged. Very helpful comments from the referees strongly clarified parts of the text.

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