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Material transport from the near shore to the basinal environment in the southern Baltic Sea
II: Synthesis of data on origin and properties of material

K. Emeis[a,*], C. Christiansen[b], K. Edelvang[c], S. Jähmlich[d], J. Kozuch[e], M. Laima[f], T. Leipe[a], A. Löffler[a], L.C. Lund-Hansen[g], A. Miltner[a], K. Pazdro[e], J. Pempkowiak[e], F. Pollehne[a], T. Shimmield[h], M. Voss[a], G. Witt[a]

[a]*Baltic Sea Research Institute, Seestrasse 15, 18111 Warnemünde, Germany*
[b]*Institute of Geography, University of Copenhagen, Øster Voldgade 10, 1350 Copenhagen K, Denmark*
[c]*Danish Hydraulic Institute, Agern Alle 5, 2970 Hørsholm, Denmark*
[d]*Department of Biology/Ecology, University of Rostock, Freiligrathstrasse 7/8, 18055 Rostock, Germany*
[e]*Institute of Oceanology, Polish Academy of Sciences, ul. Powstancow Warszawy 55, P.O. Box 68, 81-712 Sopot, Poland*
[f]*Department of Earth Sciences, Aarhus University, Ny Munkegade Building 520, 8000 Aarhus C., Denmark*
[g]*Department of Marine Ecology, Institute of Biological Sciences, Aarhus University, Finlandsgade 14, 8200 Aarhus N, Denmark*
[h]*Scottish Association for Marine Science, Dunstaffnage Marine Laboratory, P.O. Box 3, Oban, Argyll PA34 4AD, UK*

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Abstract

The Pomeranian Bight (southern Baltic Sea) is a mixing zone between waters of the Baltic Proper and the river Oder, which drains a densely populated and highly industrialised catchment of central Europe. The bight is a nondepositional area, and all material produced in its water column, from erosion of strata at the seafloor and cliffs, and delivered by rivers, is transported near the seafloor to the depositional areas of the Arkona, Bornholm and Gdansk basins. In this contribution, we assess the origin, transformation and mass fluxes of material through the bight based on an integrated field study conducted in the period 1996–1998. The transport mechanism is by wave- and current-induced resuspension and settling cycles, which effectively enrich organic-rich material and associated substances (organic pollutants, heavy metals) in deeper water; the estimated transport time is less than 6 months. The phases in which the material is transported are suspended matter in the water column, a particle- and aggregate-rich benthic boundary layer of < 1 m above the seafloor and a layer of fluffy material fed from the two other sources that covers the sandy near-shore sediments as a discrete phase; it collects up to 130 g m^{-2} of particulate material after quiescent periods lasting several days. It is easily resuspended at shear velocities around 5 cm s^{-1} and is recycled into the suspended matter and benthic boundary layer pools of material. In deeper waters (> 20 m water depth), the fluffy layer is not readily distinguished from the underlying soft, organic-rich sediment and the change in physical and chemical properties is gradual. The organic matter passing through the coastal zone in the southern Baltic is unaffected by biological or chemical modifications in composition. We find no evidence for a preferential removal of nitrogen or phosphorus, even if the speciation of phosphorus changes from biological compounds to minerals. The compositional changes which we see, i.e., in the nitrogen isotopic composition and in trace metal concentrations, are mainly caused by dilution of the river signal. In the case of

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[*] Corresponding author. Tel.: +49-381-5197-394; fax: +49-381-5197-352.
E-mail address: kay.emeis@io-warnemuende.de (K. Emeis).

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polyaromatic hydrocarbons (PAH), different solubilities and compound stabilities affect the concentrations as well and result in the enhanced accumulation of stable compounds in Arkona Basin. Seasonal changes are pronounced in the amount of freshly produced biomass, as is seen in phytoplankton pigments and their degradation products, but significant amounts of fresh biomass are swept out of the bay and supply the Arkona Basin benthic community with additional nutrition. An imbalance in carbon import and export emerges from mass balance calculations: 50,000 t of organic carbon per year may be exported, which cannot be accounted for by known sources in the river or the bight. We may exclude erosion of early Holocene peat exposures at the seafloor as a possible source, but cannot exclude either errors in our export estimate, or large-scale erosion of other organic carbon pools, for example, the stock of seaweed and its substrate in the Greifswalder Bodden.

Keywords: Sediment dynamics; Material transport; Stable isotopes; Nutrient elements; Pollution; Baltic Sea

1. Introduction

The research focus “Coast-to-Basin Transport” (subproject 3a of the *Ba*ltic Sea *Sy*stem *S*tudy, BASYS) studied the pathway of particulate material from the shallow, high-energy environment near the river Oder and in the Pomeranian Bight to the depositional area of the Arkona Basin in the southern Baltic Sea (Fig. 1). Using methods of physical oceanography, chemistry, biology and geology during the 3-

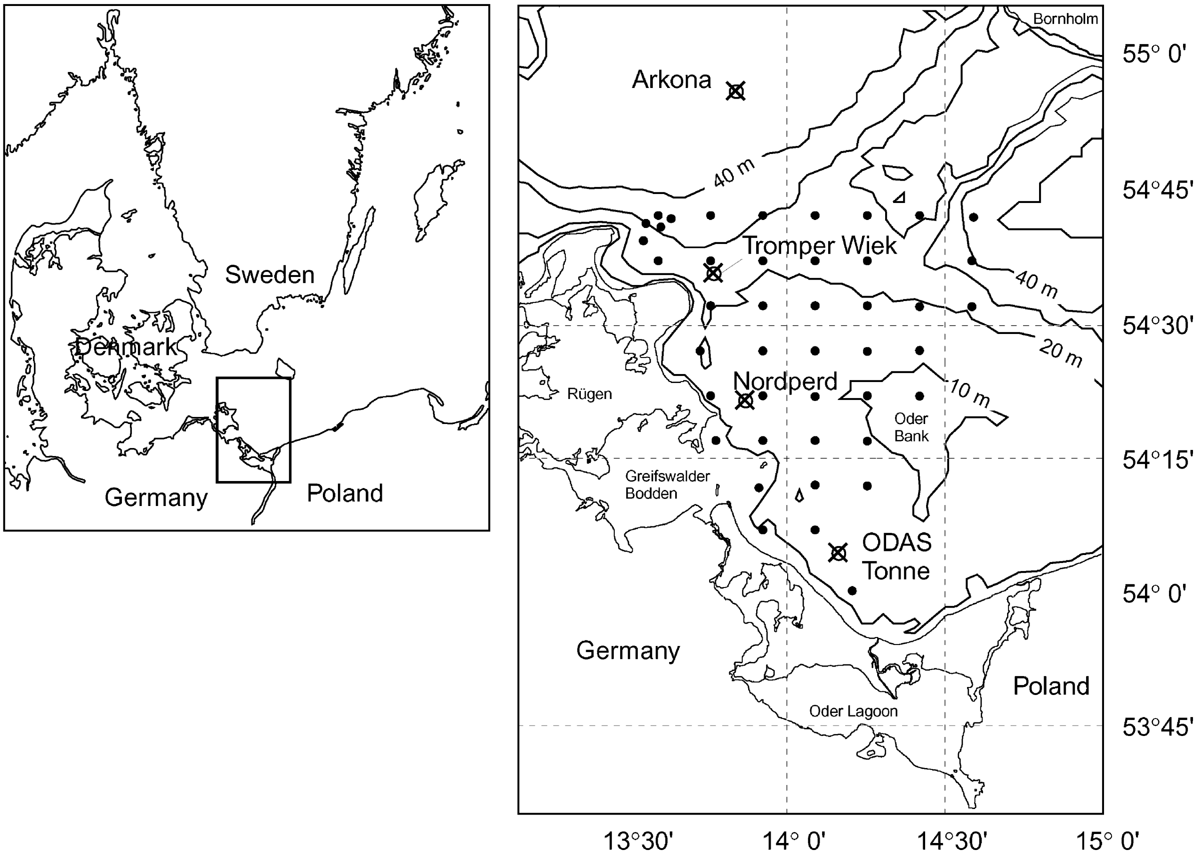

Fig. 1. Location map of stations (crossed circles) and surface sediment samples (dots).

year field programme, our group investigated the physical conditions which govern the near-bottom transport of particulate matter (Christiansen et al., 2002) and the compositional characteristics of material passing from the river mouth through shallow water (16–21 m water depth) to the offshore areas (26–46 m water depth). Our aim was to quantify the amount of material transported by near-bottom physical processes and to characterise its composition, modification and seasonal variability. This also entailed an investigation of sediment properties.

Our work was aimed at the question about the role of shallow, near-coastal areas in the Baltic Sea with regard to material fluxes. Long-term accumulation of sediment occurs on approximately 1/3 of the Baltic Sea seafloor (Jonsson et al., 1990; Pustelnikov, 1976), whereas the remainder (above wave base or above the halocline) is characterised by erosion or sediment bypassing. On the other hand, the shallow rim around the depositional areas receives all material entering the sea from land, and materials provided by biological production in surface water and by atmospheric input to the Baltic Sea. The discrepancy between input/production and deposition is clearly seen in the spatial distribution of sediment type (Emelyanov et al., 1995; Repecka and Cato, 1998). Illustrative examples are organic carbon and trace metal concentrations in sediments of the southwestern Baltic Sea (Leipe et al., 1998b). Organic carbon and trace metals are significantly enriched in fine-grained basinal sediments of the Mecklenburg Bight and the Arkona Basin, and both are highly correlated with grain size. This suggests that the coastal zone (lagoons included) may be a sieve-retaining heavy material (i.e., sand) and passing lighter material (i.e., organic matter and associated substances) on to the adjacent mud basins. The shallow and sand-covered areas of the southern Baltic Sea rim, and the discharge area of the Oder river in particular, are also among the most productive habitats for benthic organisms. We would not expect that the riverine material passes the physical and biological sieve of the shallow-water areas in the Baltic Sea unaltered, but instead we expect to recognise a gradual change in the composition of material as it is repeatedly cycled between sediment and water column on the passage through the sieve. This should be visible in compositional changes of the particulate material, in particular of organic matter, because the continued consumption and respiration should result in progressive degradation and in a change of nutrient element ratios (C/N, C/P) along the way.

In a regional scope, the motivation for our study was the debate about the transport of the Oder River material into the depositional areas below 20 m water depth. The inshore Oder lagoon, a shallow (around 10 m water depth) water body, apparently is at the upper limit of its capacity to retain riverine material because trace elements and anthropogenic substances collected by the river (Table 1) do not accumulate there (Leipe et al., 1998a). The sediment distribution within the Pomeranian Bight shows that the 20-m isobath separates erosional or nondepositional areas of the Pomeranian Bight (covered by sands or hardgrounds) from the muddy sediments accumulating below the regional halocline in the northern part of our working area (Bobertz, 1996). Previous studies have marked the Arkona Basin as a major sink for trace metals, radionuclides and anthropogenic substances discharged from the Oder and a fast responder to events in the catchment, requiring that the transfer of signals is swift and effective (Blanz et al., 1999; Leipe et al.,

Table 1
Annual discharges of the Oder River (Leipe et al., 1998a; Witt and Trost, 1999a)

Oder discharge		$17\ km^3\ year^{-1}$
River load	Concentration ($mg\ l^{-1}$)	Annual load ($t\ year^{-1}$)
Total suspended solids	25	425,000
Particulate matter ($t\ year^{-1}$)		
Particulate organic carbon (%)	15.3	65,025
P (%)	0.92	3910
Pb ($mg\ kg^{-1}$)	200	85
Zn ($mg\ kg^{-1}$)	1700	700
Cu ($mg\ kg^{-1}$)	120	50
Cd ($mg\ kg^{-1}$)	9	4
Hg ($mg\ kg^{-1}$)	2.5	1
Polyaromatic hydrocarbons ($\mu g\ kg^{-1}$)	1870	0.79
Particulate and dissolved		
Total N ($mg\ l^{-1}$)	2.94	50,000
Total P ($mg\ l^{-1}$)	0.47	8000

1995; ODER Project Members, 1994, 1995, 1996; Neumann et al., 1998; Schulz and Emeis, 2000; Struck et al., 2000; Voß and Struck, 1997).

Hydrographic observations and numerical models, on the other hand, indicate that the main transport direction of river water at the sea surface (including river-borne materials) is eastward along the coast towards the Gdansk Basin (Siegel et al., 1999). This is because winds are predominantly from the west, as is the case (at an average wind speed of 8 m s^{-1}) during approximately 2/3 of the year (Mohrholz, 1998), whereas easterly winds (at an average of 6 m s^{-1}) guiding the river plume north are less frequent. This seeming conflict requires that material of riverine origin must be returned to the W and NW below the surface waters. We hypothesised that the river particulate matter settles rapidly from the river plume, is entrained into the near-bottom counter current that has

Table 2

(a) Working areas of BASYS 3a

Station name	Position (decimal °)	Water depth (m)	Sampling depths	Oxygen average (ml l^{-1})	Salinity Average (psu)	Sediment type
ODAS Tonne	54.0808°N/ 14.1587°E	16	1 m	6.38	6.81	Fine sand (occasionally with current ripples, covered by thin fluff)
			11 m	6.28	7.34	
			0.40–0.05 over ground	5.85	7.50	
Nord Perd	54.3657°N/ 13.8620°E	20	1 m	5.85	7.50	Sand with mud, blanketed by thin fluffy layer
			16 m	6.99	7.42	
			0.40–0.05 over ground	6.86	7.67	
Tromper Wiek	54.6010°N/ 3.7607°E	26	1 m	6.63	7.45	Mud with bivalves, moderately rich (5%) in organic matter
			21 m	6.32	7.97	
			0.40–0.05 over ground	5.87	9.06	
Arkona Basin	54.9357°N/ 13.8325°E	47	1 m	6.42	7.65	Liquid mud rich in organic matter (15%)
			41 m	5.23	12.66	
			0.40–0.05 over ground	2.57	16.35	

(b) Expeditions of BASYS 3A to the Pomeranian Bight and station coverage

Expeditions/ship	Period	ODAS	Nord Perd	Tromper Wiek	Arkona	Oder Lagoon
BASYS 3A-1/PAP	1–11.10.96	×	×	×	×	
BASYS 3A-2/AvH	14–19.3.97	×	×	×	×	
BASYS 3A-3/AvH	10–15.6.97	×	×	×	×	
BASYS 3A-4/AvH	18–22.8.1997	×			×	
BASYS 3A-5/PAP	12–17.10.97	×	×	×	×	
BASYS 3A-6/PAP	1–9.12.97	×	×	×	×	
BASYS 3A-7/PAP	16–22.3.1998	×				×
BASYS 3A-8/PAP	22–27.6.1998	×	×	×	×	
BASYS 3A-9/PAP	8–13.12.1998	×	×	×	×	

PAP = r/v Prof. Albrecht Penck/IOW, AvH = r/v Alexander von Humboldt/IOW.

a dominant N–NE direction (Mohrholz, 1998) and is transported into the Arkona Basin in the form of a particle-rich bottom boundary layer.

This paper is a summary of results on the origin and variability in composition of particulate material near the sediment–water interface and the characteristics of the sediments; it is an overview of results obtained from field expeditions in 1996 to 1998, during which we visited a four-station transect in successively deeper and calmer waters and increasing salinity (Table 2). We also draw on work in the Pomeranian Bight—the mixing zone between Oder river water and the open southern Baltic Sea—in previous years. During those studies, the physical environment (Lass et al., 2001; Mohrholz, 1998; Siegel et al., 1996, 1999) and the biological environment of the Pomeranian Bight (Bodungen et al., 1995; Jost and Pollehne, 1998; Pollehne et al., 1995) have been clarified, the sediment composition has been mapped (Bobertz, 1996) and the accumulation rates of natural and anthropogenic materials in the depositional centres of the river–open sea transition have been established (Blanz et al., 1999; Leipe et al., 1995; Neumann et al., 1996, 1998; Schulz and Emeis, 2000; Witt, 1995) (see Table 3).

The detailed methodology used for sampling, analyses and details about the results are given in more specialised publications (Christiansen et al., 2002; Emeis et al., 2000; Laima et al., 1999; Leipe et al., 2000; Lund-Hansen et al., 1999, in press; Matthiesen et al., 2001; Miltner and Emeis, 2000; Pollehne et al., 1995; Struck et al., 2000; Voß et al., 1999; Witt et al., 1999). Important is the distinction between sample types. We distinguish between samples from the water column (taken by rosette sampler, down to 5 m above ground), from the benthic boundary layer (BBL, taken by a bottom water sampler [BWS] at 40, 20, 10 and 5 cm above ground) (Thomsen et al., 1994), and from the fluffy layer, which divers sampled by gently siphoning it off from the sediment surface with an on-board pump. The material was collected in 100-l jars and centrifuged from several hundred litres of water.

Table 3
Results of budget calculations for anthropogenic materials in the depositional areas adjacent to the Pomeranian Bight

	Oder Lagoon			Arkona Basin			SW Bornholm Basin		
Area (km^2) (1)	350			3876			990		
Mass accumulation rate ($kg\ m^{-2}\ year^{-1}$) (1)	0.23			1.1			0.32		
Accumulation (t FSyear^{-1}) (1)	80,500			4,263,600			316,800		
Organic carbon concentration (%) (1)	13.5			6			4.5		
Organic carbon accumulation (t year^{-1}) (1)	10,868			255,816			14,256		
Trace metal concentrations (mg kg^{-1}) (2)	62 (Cu)	820 (Zn)	120 (Pb)	50 (Cu)	160 (Zn)	90 (Pb)	30 (Cu)	90 (Zn)	60 (Pb)
Trace metal accumulation (t year^{-1}) (2)	5 (Cu)	66 (Zn)	10 (Pb)	213 (Cu)	682 (Zn)	384 (Pb)	10 (Cu)	29 (Zn)	19 (Pb)
Polycyclic aromatic hydrocarbons (kg year^{-1}) (3)	586			4733			no data		
^{210}Pb inventory (Bq m^{-2}) (1)	920–4378			7495–14,191			2484–3165		
^{137}Cs inventory (Bq m^{-2}) (1)	1926–2303			2362–3044			180.6		

Sources: ODER Project Members (1994, 1995), Neumann et al. (1998), Leipe et al. (1998a,b) and Witt and Trost (1999a).

In the following, we will give the results of calculations concerning the transport of material through the bight and examine the evidence for changes in material composition during its passage.

2. Material origin: mass estimates of gains and losses

Our objective here is to quantify the amount of material and selected elements and substances which are transported to the offshore basins annually in the near-bottom layer. We make our calculations with masses of 550,000 and 370,000 t year^{-1} of particulate matter that are annually exported into the Arkona and Bornholm Basins, respectively. The estimates derive from a numerical model simulation of water and suspended matter transport into and out of the bight for the period October 1996–October 1997 (Christiansen et al., 2002). Although based on simplified assumptions concerning particulate matter concentrations in surface and bottom water masses (medians of all stations were used) and, thus, prone to errors, the annually averaged transport rates are our current best estimate.

The *sources* of particulate material are (Table 4) as follows.

(1) The riverine discharge of particulate matter (estimated at 425,000 t year^{-1}, considering that the average annual river discharge is 17 km^3 and the average suspended matter concentration is 25 mg l^{-1}) (Lampe, 1993). Of this, approximately 65,000 t are particulate organic carbon.

(2) Biological production in surface waters (estimated to 1,000,000 t C year^{-1} in the entire Pomeranian Bight) (Anonymous, 1998). We have no means to quantify the amount of biogenic opal that accompanies diatomaceous production, but the amount of opal in the exported material was significant (5–25%) (Leipe et al., 2000). Calcite (biogenic or lithogenic) is apparently quantitatively dissolved within the bight waters.

(3) Advected particulate material in waters flowing into the bight from the Bornholm Basin. This advected material is included in the mass estimate of sediment export given in the companion paper (Christiansen et al., 2002) (see below).

(4) Material provided by the erosion of cliffs (of order 1,000,000 t year^{-1}) (Diesing et al., 1999).

(5) Eroded material from the sea floor (amount unknown).

2.1. Potential losses

2.1.1. Longshore transport of sand

Some of the coarse-grained sandy material from cliff erosion and river bedload apparently is transported to the East by longshore currents, or is accumulated in the beach zones. Diesing et al. (1999) cite evidence for eastward longshore transport of sand of order 50–200 10^3 m^3 year^{-1} in the Polish sector of the bight. Assuming that erosion of cliffs provides 1,000,000 t year^{-1} and that sand comprises around 30% of the eroded material, we would expect that 300,000 t year^{-1} of sand are annually provided by erosion, a figure approximately matching the amount of sand transported eastward along the coast. Indeed, we find no evidence for transport of coarse-grained to the North, or deposition of sand in the deeper parts of the bight: Side-scan sonar surveys performed in the Nordperd area (at water depths between 16 and 22 m) during expeditions in 1996 and 1998 (Tauber et al., 1999) indicate that sand blankets over till here are stationary and show no indication of growth within a 2-year period. The extended area of sandy sediments on the Oder Bank (Fig. 1) is apparently nondepositional, with a thin veneer of modern sand overlying fossil sands (W. Lemke, personal communication, 1998). The median grain size of sediments at Nordperd Station is that of silt, fining northward to the Arkona Basin (Bobertz, 1996), and the average weight percent of the <20-μm size fraction is $>20\%$ in the muds. All these are evidence of a preferred eastward transport of sand-sized erosion products out of the bight.

2.1.2. Respiration of organic carbon

Investigations into the coupling of riverine nutrient efflux with pelagic production suggested (Anonymous, 1998) that nutrients are quantitatively assimilated in the Bight during growth periods. The phytoplankton standing stock was estimated as 14,000 t C, and gross primary production during a vegetation period of 200 days as 1,000,000 t C. However, nutrients are cyclically regenerated and do not accumulate in either the pelagic biomass compartments—heterotrophic pelagic respiration is of the

Table 4
Mass fluxes and storage in the Pomeranian Bight

General		Ref.	Notes
Area (km^2)	5580		
Area of mud deposition (km^2)	295	Bobertz, 1996	
Biological production			
Average PP (gC m^{-2} day^{-1})	0.9	Anonymous, 1998	
Average duration of PP (day)	200	Anonymous, 1998	
Annual production (t C)	1,004,400	Anonymous, 1998	
Riverine input			
Suspended matter (t year^{-1})	425,000	Lampe, 1993	
Organic carbon (t year^{-1})	65,000	Lampe, 1993	
Dissolved and particulate P (t year^{-1})	4500–8000	Anonymous, 1998	
Dissolved and particulate N (t year^{-1})	40,000–90,000	Anonymous, 1998	
Heavy metals in TSS (t year^{-1}) (Cu/Zn/Pb)	50/700/85	Leipe et al., 1998a	
Particulate PAH (kg year^{-1})	961	Witt and Trost, 1999a	
Advective output to Arkona Basin			
TSS (t year^{-1})	550,000	Christiansen et al., 2002	
PON (t year^{-1}; at a median of 1.5 wt.%)	8250	This study	
POC (t year^{-1}; at a median of 12.8 wt.%)	70,400	This study	
Particulate P (t year^{-1}; at 0.15 ± 0.05 wt.%)	825	This study	10–18% of river input
Cu/Zn/Pb (t year^{-1})	23/116/38	This study	46%/17%/45% of river input
Fluff averages (ppm): Cu = 42 ± 19; Zn = 211 ± 108; Pb = 69 ± 28		This study	
PAH (kg year^{-1})	585		60% of river input
Fluff averages (ng/g dw): 1064 ± 340		Witt et al., 2001	
Advective output to Bornholm Basin			
TSS (t year^1)	370,000	Christiansen et al., 2002	
PON (t year^{-1}; at a median of 1.5 wt.%)	5550	This study	
POC (t year^{-1}; at a median of 12.8 wt.%)	47,360	This study	
Particulate P (t year^{-1}; at 0.15 ± 0.05 wt.%)	572	This study	7–13% of river input
Cu/Zn/Pb (t year^{-1})	16/78/26	This study	31%/11%/31% of river input
Fluff averages (ppm): Cu = 42 ± 19; Zn = 211 ± 108; Pb = 69 ± 28		This study	
PAH (kg year^{-1})	394		40% of river input
Fluff averages (ng/g dw): 1064 ± 340		Witt et al., 2001	
Sediment pools (storage (t) in 0–1 cm layer)			
Sediment density = 1.7 g cm^{-3}			average of sandy stations
Mass of sediment in 0–1 cm layer (t)	94,860,000		density × area
Medians of surface sediments		This study	
POC = 0.13 wt.%	123,300		190% of river input
P = 7.9 μg g^{-1}	749		10–17% of river input
Zn = 0.8 μg g^{-1}	71		10% of river input
Cu = 1.8 μg g^{-1}	171		340% of river input
Pb = 0.3 μg g^{-1}	29		35% of river input

same magnitude as gross primary production (Anonymous, 1998). Particulate organic carbon export out of the bight by surface waters, thus, is of minor importance. Benthic biomass in the Bight has been estimated as 76,000 t C and respires approximately 30% of gross primary production (Anonymous, 1998). Mass-balance calculations based on primary production, oxygen consumption rates and benthic respiration, thus, suggest that the pelagic biomass produced in the surface layer of the Pomeranian Bight is quantitatively respired within the bight by heterotrophic pelagic and benthic processes (Anonymous, 1998). This would imply that no organic carbon can be exported with the particulate material to the depocenters and is in conflict with our estimate of combined advective losses of order 120,000 t year^{-1} to the Arkona and Bornholm Basins, approximately twice the riverine input of 65,000 t year^{-1} (Tables 4 and 5). The estimates imply that the bight loses particulate carbon. However, the deficit may be accounted for by the large pools of organic carbon in the Bight (sediment storage and biomass standing stock), uncertainties in the estimates of biomass production and respiration and the uncertainty associated with our estimate of material export (see Table 5).

2.1.3. Sedimentation

Of the entire seafloor area in the Pomeranian Bight of 5580 km^2, only 285 km^2 are covered by silty and sandy mud; the remainder is sand or gravel and boulders overlying till (lag deposits) (Bobertz, 1996). The few depositional areas are in the immediate vicinity of the river mouths, in the depressions of the submarine fossil valley (below 20 m water depth) of Oder river hugging the coast of the island of Rügen, and in the transition to the Arkona Basin near our station Tromper Wiek. The vast majority of the seafloor is nondepositional and has no capacity to store organic matter, nutrients, or trace elements. Of 43 surface sediment samples (0–1 cm) collected in the western part of the bight in 1996 and 1997, the median value for the weight of the fraction <20 μm of total sediment is 0.3%, with higher values only in the few patches of mud. Corresponding to this predominance of sandy material are low concentrations of all trace elements and nutrient elements (Table 4).

Table 5
The organic carbon pools and fluxes in the Pomeranian Bight (compare Table 4)

Pools (t)		
Biomass standing stock: Pelagic	13,700	Anonymous, 1998
Biomass standing stock: Benthic	76,000	Anonymous, 1998
Sediment 0–1 cm	123,300	This study
Fluxes (t year^{-1})		
River input	65,000	Lampe, 1993
Advection to Bornholm Basin	47,360	This study
Advection to Arkona Basin	70,400	This study
Deficit	52,000	
Internal Cycles (t year^{-1})		
Biomass production: Pelagic	1,000,000	Anonymous, 1998
Pelagic and benthic respiration	1,420,820	Anonymous, 1998

Using medians of the element concentration values, a sediment density of 1.7 g cm^{-3} as is characteristic for the sandy stations ODAS and Nordperd (Christiansen et al., 2002), and the entire mass of sediment in the 0–1 cm layer for reference, we find that the surface sediments hold around of 15% of annual riverine phosphorus and zinc discharge, 35% of lead discharge per year, and approximately 190% of organic carbon discharge. More than three times the annual copper discharge is stored here, presumably in association with iron oxide coatings on quartz grains. But the general capacity for storing materials appears to be low; buried in the sands (by physical or biogenic processes), they are only temporarily stored and will be released when the sediment surface is again agitated by waves or currents. In summary, the sediments in the Pomeranian Bight do not constitute a significant sink of material other than (possibly) sand and those elements that are associated with iron-rich coatings around quartz grains (e.g., copper). This lack of accumulation within the bight implies that a large portion of the entire riverine input has to leave it again on time scales of less than a year.

2.1.4. Near-bottom advection of particulate material out of the area to the Arkona and Bornholm Basins

The particulate material imported to the Bight or produced there sinks to the seafloor during quiescent periods, forms a turbid, particle-rich benthic boundary layer (BBL; seen in Fig. 2 by the higher median values of TSS in the BWS samples), and accumulates at the sediment surface to form a so-called fluffy layer. This is unconsolidated material composed of aggregated biogenic and inorganic particles; it accumulates at the sediment–water interface during calm weather on sandy seafloor and is resuspended at velocities (wave or current induced) of around 5 cm s^{-1} (Christiansen et al., 2002).

The material accumulating near the seafloor, i.e., in the fluffy layer and in the BBL, is the main transport medium of biogenic material, pollutants and riverine nutrients from the shallow environment near the river mouth to the deeper and calmer sedimentary basin. The material is rich in organic matter, but is not significantly richer than suspended matter in the water column (Fig. 2). Concentration of fluff per unit sea-

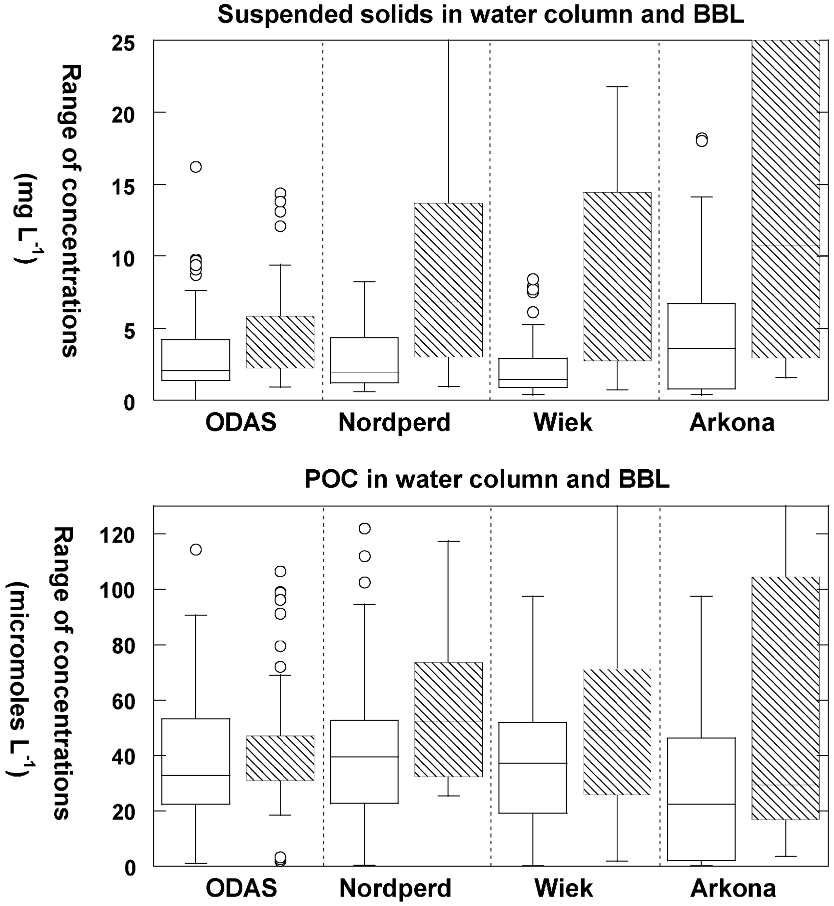

Fig. 2. Box plots of total suspended matter (TSS) and particulate organic carbon (POC) in water column (taken by rosette sampler attached to a CTD; white boxes) and bottom nepheloid layer (BBL) (taken by bottom water sampler (BWS) at 5, 10, 20 and 40 cm above ground; hatched boxes) samples. Each box encloses 50% of the data with the median value of the variable displayed as a line. The top and bottom of the box mark the limits of ± 25% of the variable population (upper quartile, UQ, and lower quartile, LQ). The lines extending from the top and bottom of each box mark the minimum and maximum values that fall within an acceptable range ($<$UQ + 1.5 × interquartile distance or $>$LQ − 1.5 × IQD). Outliers are displayed as an individual point. The mass of fluffy material at ODAS station was between 40 and 120 g m^{-2}. The BBL at all stations contained more solids than the water column (significant only at the deep stations). POC concentrations show no clear enrichment, but median values are always higher in the BBL. The medians of POC concentrations in the fluff were ODAS: 7.6 ± 2.3%, Nordperd: 7.4 ± 0.8%, Wiek: 5.6 ± 2.3% and Arkona: 5.8 ± 1.2%.

floor was extremely difficult to assess, and its components were calculated on a basis of dry weight. Because there is no net directed current at the seafloor in the Pomeranian Bight, seaward transport of suspended matter is mainly by repeated cycles of deposition at the sediment–water interface and resuspension, resulting in preferential enrichment of fine-grained material in deeper depositional areas (Christiansen et al., 2002). Enrichment in deeper water is topography-driven and is aided by the presence of a halocline because the bottom shear induced by waves is lower in deeper areas and is also attenuated by density interfaces in the water. There is some indication for directed transport and preferential movement along depressions on the seafloor: Oriented sedimentary features on the seafloor at station 2 (Nordperd Rinne) include abundant clusters of bivalves (*Mytilus edulis*) that are aligned along the trough axis and suggest that the elongated depression running NW–SE acts as a conduit for near-bottom transport of "edible" material (Tauber et al., 1999).

For the estimate of net material export northward through an E–W plane at the latitude of Tromper Wiek station (approximately equivalent to the 20-m isobath), a figure of 550,000 t year^{-1} has been calculated, for the eastward transport into the Polish sector and on to the Bornholm Basin, a figure of 370,000 t year^{-1}; these estimates are based on a numerical modelling run bracketing the time from October 1996 to October 1997 (Christiansen et al., 2002). Using averages of fluffy layer samples (see below) and suspended matter from the BBL taken at the stations in the bight, we calculated the export of natural and anthropogenic substances via suspended matter from the bight (Table 4). The modelled export, together with estimates for material stored in the sediments, indeed account for most of the material discharged by the Oder. This is the case for PAH (Witt et al., 1999), most of the trace metals (Table 4) but not for phosphorus, which apparently is mineralised to a significant extent in the sediments (Laima et al., 2001) and is possibly recycled within the bight or leaves in dissolved phase. In the case of organic carbon, we are faced with a deficit of input versus output (Table 5). The deficit is approximately 50,000 t C annually. Barring errors in our export estimate, the deficit would require that either organic carbon is provided by erosion of older strata on the seafloor (for which we have no evidence; see below), or that an additional organic carbon source has not been recognised.

3. Composition of material transported at the sediment–water interface

If sediment (only at the distal stations), fluffy layer, material in the benthic boundary layer and suspended matter are indeed a continuum, this implies that they are essentially the same material that cycles between these compartments. Further implications are: that the fluffy layer material in stations closer to the river should have a larger proportion of river-derived substances, which should be progressively diluted with distance from the river mouth, that the residence time of fluffy layer material should be longer at deeper stations (because it gets resuspended less frequently), and that the fluffy layer material should contain fingerprints of all sources that contribute to material in the bight.

None of the major constituents of fluffy layer material showed conclusive changes in composition that would distinguish nearshore from offshore material. It is composed of organic matter and varying amounts of opal, quartz, clays and accessory minerals such as feldspar, apatite, sulphides and minor amounts of calcite only at station ODAS (Table 6). In the clays, mixed-layer minerals of illite are the most dominant component.

Neither the lithological composition, nor bulk concentrations of elements C, N or P in the different compartments of advected material were suitable to discriminate between the material from different stations (Fig. 4, cross-hatched boxes). However, the con-

Table 6

Medians (bold numbers) and standard deviations of major minerals (all minerals = 100%) in fluffy layer samples

	ODAS Tonne	Nordperd Rinne	Tromper Wiek	Arkona Basin
Opal	**10.3**	**14.7**	**9.2**	**5.9**
	8.0	2.3	2.2	1.0
Quartz	**20.3**	**25.8**	**21.3**	**22.6**
	4.0	6.2	6.8	3.1
Sum clays	**50.9**	**47.0**	**58.6**	**61.2**
	6.8	7.8	7.1	5.9

The remainder are accessory minerals (Leipe et al., 1999; 2000).

centration of organic carbon by weight of solid material consistently decreases towards the sediment, which is due to a progressive increase in the concentration of mineral matter (Fig. 3). The large interquartile distances and error bars result from seasonal changes that are very pronounced in the water column (rosette samples) and the BBL (BWS samples). The figures in the Arkona Basin converge to a very narrow concentration range for the material at the seafloor, and are undistinguishable from that of the sediment. The variability in elemental composition of the organic matter was low in samples from the bight and did not indicate a loss of nitrogen or phosphorus in neither BBL nor fluff. Average molar C/N ratios in samples from the water column, the BBL, and the fluffy layer in the three shallow stations are virtually indistinguishable (Fig. 4). Compared to C/P ratios in the fluffy layer, sediment C/P ratios are low and point to an enrichment of the surface sediments with phosphorus (Laima et al., 2001).

Based on these results, we can state that over the period of 2 years—in spite of large seasonal differences in the amount of material transported in the water column as suspended matter, in the BBL and in the form of fluff—the compositional modifications of bulk organic during passage through the bight and on the way to Arkona Basin are small. The molar ratios of C, N and P do not change significantly on the way to the depositional basin, and the material deposited in the Arkona Basin and the Tromper Wiek resembles the near-shore material in terms of their molar C/N and C/P composition. This is an indication that the bulk of the material passes the coastal zone without a significant change in nutrient element ratios, even though the speciation of phosphorus changes from a primarily biological (in organic matter) to an inorganic fraction associated with redox-sensitive iron- and manganese oxides (Laima et al., 2001). The sandy sediment in the shallow stations has completely different ratios and differs greatly from the overlying fluffy layer material, but the properties of surface sediment and fluffy layer appear to converge in the deeper basins. This is consistent with our observation that the fluffy-layer/sediment transition is gradual in the mud deposition areas.

3.1. Indicators of river load

Three more specific properties of the near-seafloor material show clearly that the fluffy layer and BBL are enriched with riverine material in the inshore stations and are progressively diluted by autochthonous mate-

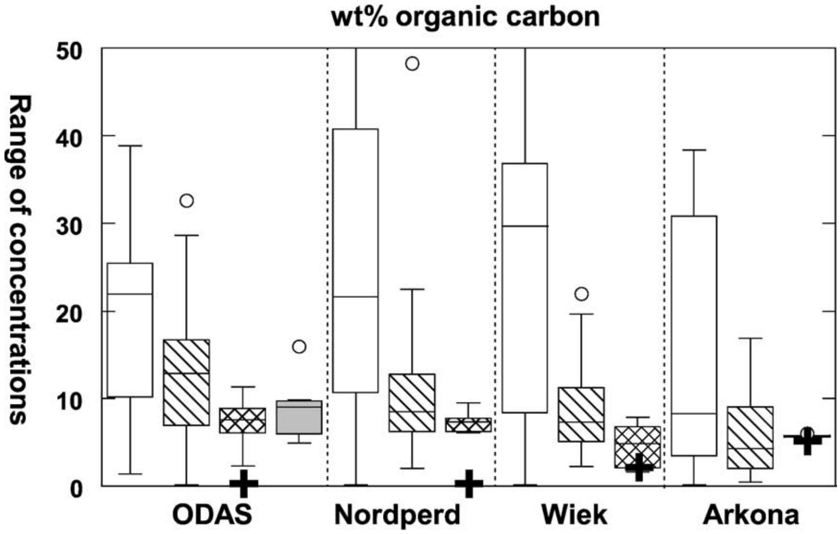

Fig. 3. Ranges and medians of organic carbon concentrations in TSS (white box), BBL (hatched) and fluffy layer (cross-hatched) at the four stations. The sediment values (0–1 cm) are indicated by (+). The range of values for sediment trap material at station ODAS is marked by a grey box.

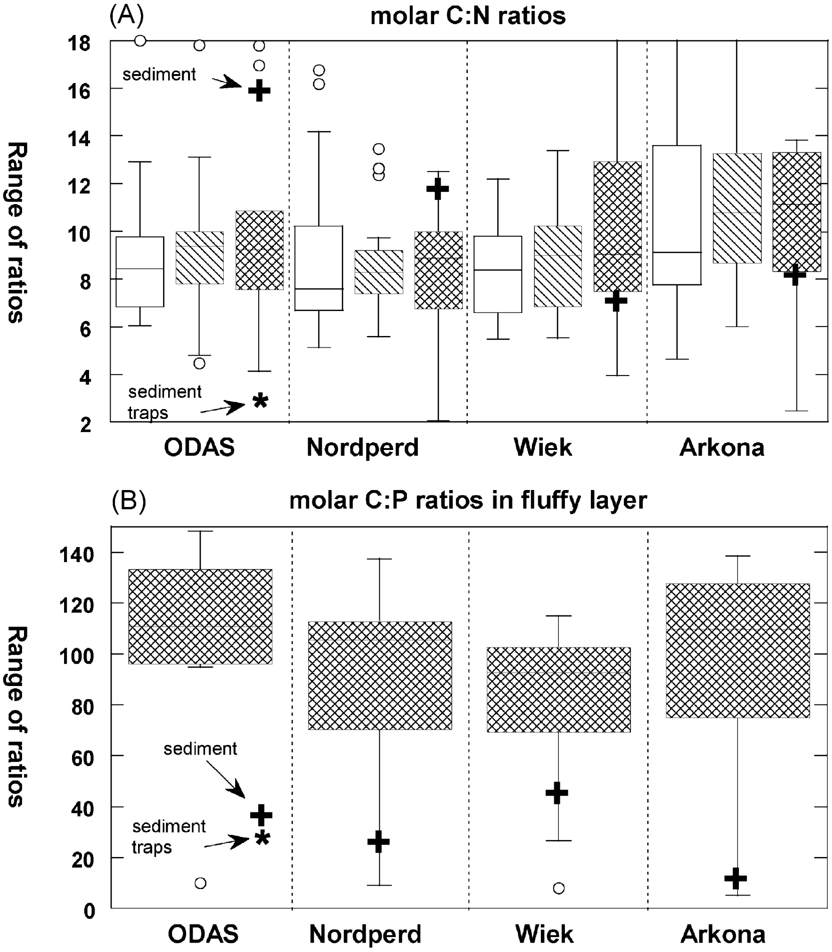

Fig. 4. (A) Ranges and medians of molar ratios of C to N in TSS (white box), BBL (hatched) and fluffy layer (cross-hatched boxes) at the four stations. (B) Ranges and medians of molar ratios of C to P in fluffy layer samples. The ratios for sediments (0–1 cm) are indicated by (+). Sediment trap material at ODAS station is indicated by (*).

rial during passage through the bight. The isotopic signature of nitrogen shows the most distinct gradient: All three compartments (water column, BWS and fluffy layer) have heaviest values at ODAS station and lightest values in the Arkona station. This reflects the heavy isotopic fingerprint of nitrogen in sediments of Oder lagoon, which is caused by fractionation of a very large nitrogen supply in the catchment of the river (Voß and Struck, 1997) (Fig. 5). The gradient is best seen in the fluffy layer material and the sediments, but generally, surface sediments, suspended matter and trapped material in the bight are very similar in isotopic composition at each station. The exception is material sampled from the BBL (0–40 cm above seafloor) in the bight, which is consistently isotopically lighter by as much as 1‰ in the median values; as yet, the reasons for this are not clear. At Arkona station, the material from the BBL is isotopically heavier than sediment and fluff and may bear an imprint of material coming from the bight. End-member mixing calculations based n fluffy layer isotopic composition, using a value f δ^{15}N = 12.8‰ (measured in sediments of the n-shore Oder lagoon) for the terrestrial and δ^{15}N = 4.7‰ for the marine end-member in the Arkona Basin (median of water column values), suggest that

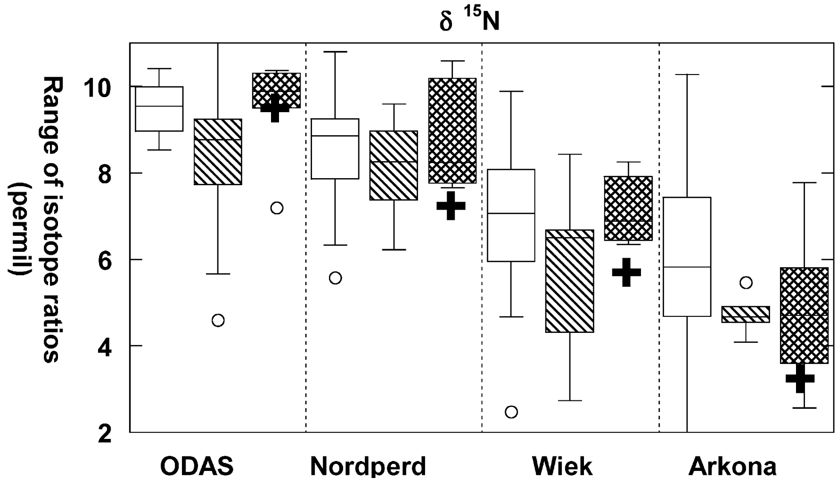

Fig. 5. Box plots of nitrogen isotopic composition in suspended matter (white boxes), the BBL (hatched boxes), fluffy layer material (cross-hatched boxes) and sediment trap material (at ODAS station only; grey box). Pluses (+) mark the values for the surface sediments.

60% of the particulate nitrogen in fluffy layer, sediment and suspended matter of ODAS station originate from the lagoonal end-member in nitrogen (Voß et al., 1999) (Table 7). At station Nordperd, this decreased to 40%, 30% at Tromper Wiek and the Arkona Basin BBL still has approximately 10% of the river signal. In fluff and sediment, the signal vanishes.

In contrast to the mineralogical composition, which was homogeneous and showed little spatial or temporal differences, the trace element content of the fluffy layer material also reflects the influence of the Oder river discharge and the progressive dilution away from the river mouth.

This is shown in Fig. 6 for the element zinc, which has been normalised to the aluminium concentration to account for dilution with quartz, opal or clay minerals. At the ODAS Tonne station nearest to the Oder river estuary trace Zn/Al ratios are highest and decrease towards Arkona because of dilution by admixed marine material and possibly by release of adsorbed trace metals from particulate material, e.g., Mn-oxihydroxides (which occur only at ODAS Tonne and Nordperd Rinne in high amounts) or organic matter. The ratio increases slightly at the Arkona Station, possibly because other sources contribute to the basin's trace element load.

A third fingerprint of land-derived material is the concentration of polyaromatic hydrocarbons (PAH) in the fluffy layer material, which have very high concentrations in the Oder Lagoon because here they are focussed from the entire catchment of the river Oder

Table 7
Medians of δ^{15}N (permil) of solids and calculated percentage of riverine nitrogen

	Station	Percentage of PON originating from the lagoon
δ^{15}N of suspended matter		
9.5	ODAS Tonne	60
8.9	Nordperd	51
7.0	Tromper Wiek	29
4.7	Arkona	0
δ^{15}N of nepheloid layer		
8.8	ODAS Tonne	50
8.3	Nordperd	44
6.5	Tromper Wiek	22
5.8	Arkona	14
δ^{15}N of fluffy layer		
9.9	ODAS Tonne	64
8.2	Nordperd	44
6.9	Tromper Wiek	27
4.7	Arkona	0
δ^{15}N of sediment		
9.8	ODAS Tonne	63
8.1	Nordperd	42
6.9	Tromper Wiek	27
5.0	Arkona	4

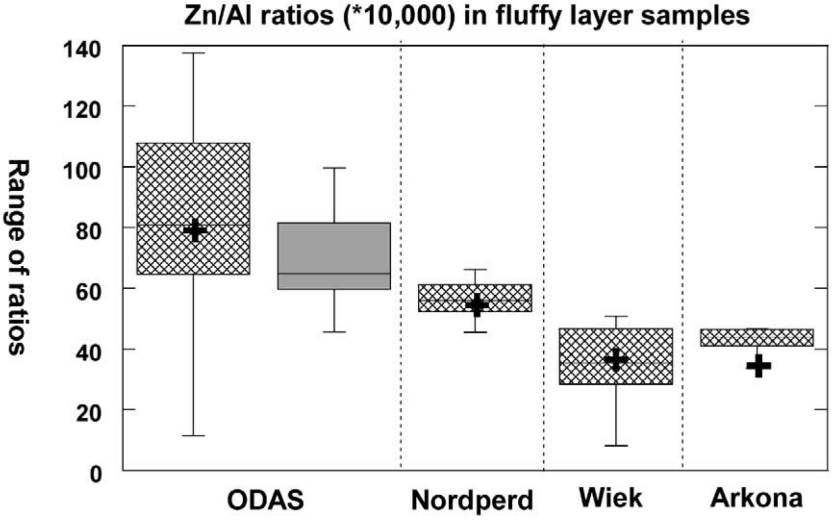

Fig. 6. Box plots of zinc concentrations (normalised to aluminium concentrations) in fluffy layer material (cross-hatched boxes) and sediment trap material (at ODAS station only; grey box). Values for surface sediment (0–1 cm) are marked by (+).

(Fig. 7) (Witt and Trost, 1999b). The distribution patterns of individual monomers are similar at all sites with clear dominance of the four-ring aromatics. The concentration of the PAHs with low molecular weight was highest in the Oder Lagoon, which is continually influenced by the Oder River discharge. An enrichment of the five- and six-cyclic aromatics was observed in fluffy layer samples from the Arkona Basin. The concentration gradient of the lower molecular weight PAHs is attributed to the degradation of the lower molecular weight PAHs during transport from the urban regions of the catchment to the sedimentation basins; higher molecular weight PAHs are more persistent and are not degraded and are relatively enriched in Arkona Basin fluff (Witt et al., 1999; Schulz and Emeis, 2000).

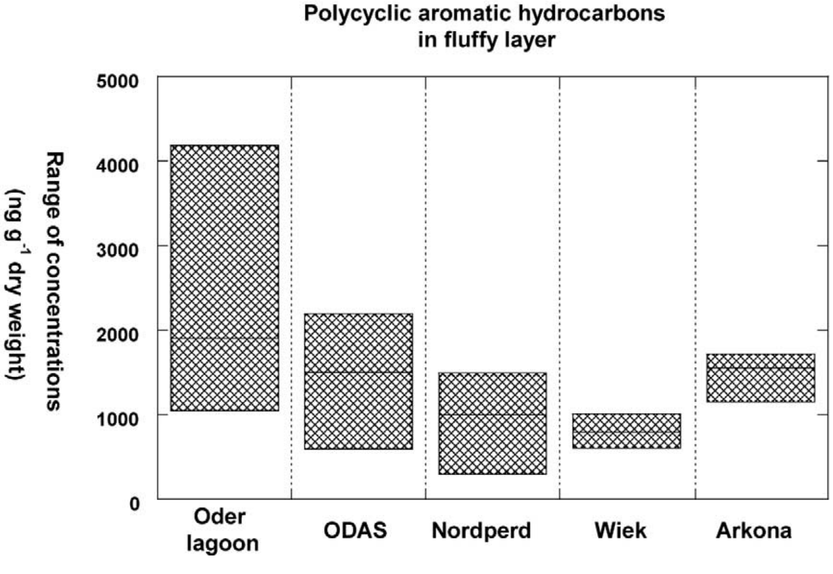

Fig. 7. Box plots of concentration ranges of polyaromatic hydrocarbons in fluffy layer material.

4. Seasonal variations in organic carbon

Several parameters suggest that differences exist in the composition of the material collecting near the sea floor depending on the season during which the material has been sampled. The seasonality is introduced by variable river input and biological productivity in the water column. As may be expected, seasonal variations are strongest in the amounts of photosynthetic pigments and their degradation products, but are also seen in specific marker pigments for diatoms (bloom in spring) and bluegreen algae (blooms in summer) (Voß et al., 1999). Temporal variability in pigment concentrations are pronounced because they reflect immediate input to the seafloor from blooms in the surface waters (Fig. 8).

We can use the pigment data to estimate the contribution of fresh organic matter or newly produced biomass to material in the water column and in the BBL by using a relationship between chlorophyll *a* content and biomass established (Anonymous, 1998) for the Pomeranian Bight: 1 μg l^{-1} Chl $a = 50$ μg POC l^{-1}. As shown in Fig. 9, this calculation suggests that the material in the BBL is comparatively older and more degraded than that of the water column. The BBL in spring contains between 10% and 20% of POC of fresh biomass, decreasing to around 10% in summer and fall. The range of calculated fresh POC in winter water column and BBL samples is surprisingly high and is in the same range as values of summer samples.

The main contribution to POC in the fluffy layer and BBL other than phytoplankton biomass is lignin-rich organic matter derived from land and from seaweed. The sum of phenols in sediments of the Oder lagoon was 7.6 mg g^{-1}C, the average value in the sediments as well as in the fluffy layer was 3.2 mg g^{-1}C. The lignin concentration of organic matter in the fluffy material is, thus, the same as in the underlying sediments, and in both cases is approximately 40% of that of material in the lagoon with no offshore gradient (Miltner and Emeis, 2000). The composition of lignin is generally similar at all stations, but the highest contribution from nonwoody tissue was found in the fluff at Nordperd station, and the highest contribution of angiosperm tissue in both fluff and sediment at the Arkona Basin station. At the two deep stations Tromper Wiek and Arkona, the lignin character of fluffy layer samples is very similar to the underlying sediment, whereas at the two shallow stations, Nordperd and ODAS, the fluffy material has a high contribution of nonwoody material. The Nordperd station apparently receives material from the Greifswalder Bodden, where seaweed (*Zostera*

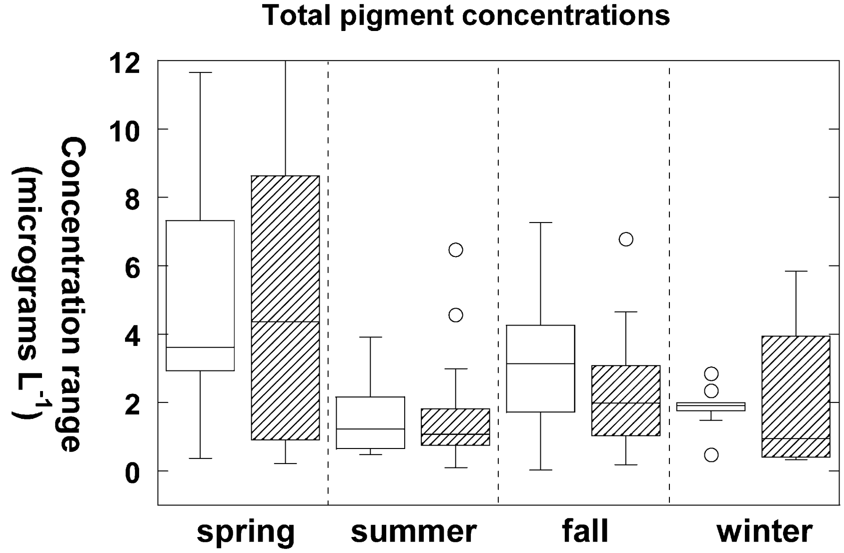

Fig. 8. Ranges for the sum of pigments in CTD (white boxes) and BWS (cross-hatched boxes) samples.

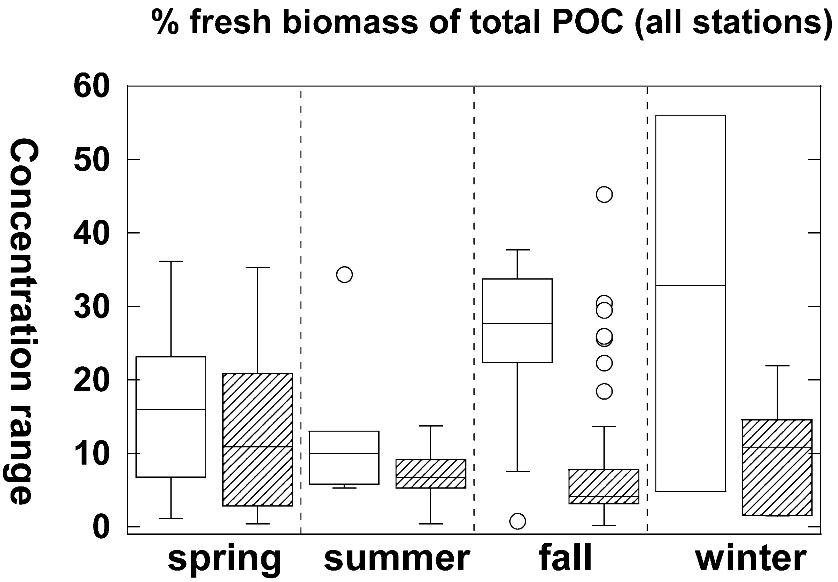

Fig. 9. Estimated percentage of fresh algal biomass in CTD (white boxes) and BWS (cross-hatched boxes) samples.

marina) is abundant and causes a different composition. The temporal variability of the lignin concentration and composition within the fluff was low. Humic substances in fluffy layer material (dominantly humic acids and subordinate fulvic acids) have a mean concentration of around 3% and do not vary along the depth gradient or seasonally.

The lignin composition in fluff is also suitable to test if exhumed organic matter from seabed erosion is a candidate to close the budget of organic carbon, which we estimate to have a deficit of at least 50,000 t year^{-1}. The postglacial rise in sea level resulted in deposition of considerable peat deposits in the Pomeranian Bight (Kolp, 1983), which may be eroded at the sea floor and washed out of the bight. However, the lignin composition of a peat sample from Nordperd station and of fluffy layer samples differ greatly, making it improbable that submarine erosion contributes significant amounts of organic carbon for export (Miltner and Emeis, 2000).

5. Conclusions

From the data gathered in our project, we may state that transport in the shallow-water coastal environment (water depths shallower than 20 m) is quasicontinuous at seasonal scales, where many events of wind speeds exceeding 10 m/s create conditions when material is resuspended from the seafloor. Any particulate substance entering the coastal environment near the mouth of the river Oder will be deposited in the mud accumulation areas of Tromper Wiek (26 m) and Arkona Basin (>40 m) within less than approximately 1 year. The bight is not a storage area for riverine materials.

The organic matter passing through the coastal zone in the southern Baltic is unaffected by biological or chemical modifications in composition. We find no evidence for a preferential removal of nitrogen or phosphorus, even if the speciation of phosphorus changes from biological compounds to minerals. The compositional changes which we see, i.e., in the nitrogen isotopic composition and in trace metal concentrations, are mainly caused by dilution of the river signal. In the case of PAH, different solubilities and compound stabilities affect the concentrations as well and result in the enhanced accumulation of stable compounds in Arkona Basin. Seasonal changes are pronounced in the amount of freshly produced biomass, as is seen in phytoplankton pigments and their degradation products, but significant amounts of fresh biomass are swept out of the bay and supply the Arkona Basin benthic community with additional nutrition. We may exclude erosion of early Holocene peat exposures at the seafloor as a possible source of particulate organic carbon.

The Arkona and Bornholm basins (and all mud accumulation basins of the Baltic Sea), thus, integrate the sedimentation history in its submarine catchment. Based on our results, the lag time between an event near the coast, such as a contamination event in the river lagoon, and a response in the sediment basin may be assumed to be less than a year. This is of general importance to studies concerned with reconstructions of past conditions in the Baltic Sea from sedimentary records in the mud basins. Generalizing for the entire Baltic Sea, a considerable amount of material deposited in the accumulation basins is from lateral transport. The chemical properties of that material are not altered during transit, and the passage is short in time. Events registered in the sediments of the basins should have no significant lag after an event in the Baltic Sea catchment.

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