Spatial variability of recent sedimentation rates in the Eastern Gotland Basin (Baltic Sea)

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Abstract

In order to study recent sedimentation rates in the Eastern Gotland Basin, 52 short sediment cores collected from the deepest part (< 150 m) of the Basin in 2003 were investigated. The upper parts of all the cores were distinctly laminated and dark in colour, followed by a homogeneous, greyish lower part. The thickness of the laminated sequences varied from 17 to 300 mm. ^{210}Pb dating analyses of selected cores revealed that the change from non-laminated to laminated sediments happened about 100 years ago, indicating a shift from predominantly oxic bottom water conditions to anoxic conditions. Used as a time marker, this shift in the sediment texture enabled sediment accumulation rates to be estimated for all sediment cores. The observed mean linear sedimentation rate for the whole basin was 0.93 ± 0.67 mm yr^{-1}. The respective bulk sediment accumulation rates ranged from 10.5 to 527 g m^{-2} yr^{-1} with an average of 129 ± 112 g m^{-2} yr^{-1}, indicating a high spatial variability of sedimentation rates within the basin. This agrees very well with the long-term sedimentation pattern since the Litorina transgression. The observed pattern clearly reflects the hydrographic conditions at the seafloor as studied by modelled near-bottom current velocities.

1. Introduction

The main motivation of this study was to provide reliable estimates of sediment accumulation rates, as this is a prerequisite for studying the

The complete text of the paper is available at http://www.iopan.gda.pl/oceanologia/

accumulation of e.g. nutrients, heavy metals and organic pollutants. This is of special interest because it has been shown recently that sediments play a decisive role in nutrient cycling in the Baltic Proper (Conley et al. 2002, Hille 2005, Hille et al. 2005), particularly with respect to phosphorus. The present study was performed in the Eastern Gotland Basin (including the Gotland Deep), a large depression that is generally considered to be the final major natural sink for fine-grained sediments and associated organic matter within the Baltic Proper (Jonsson et al. 1990). The sediment map compiled by Repecka et al. (1998) indicates that pelitic mud, i.e. fine-grained sediments dominated by silt particles (≤ 63 μm) with a significant contribution of clay (≤ 2 μm), is the prevailing sediment type.

The accumulation of sediments on the seafloor is not evenly distributed and depends basically on the bottom topography and hydrographical conditions. Frequent wave- (Sanford 1994) and/or current-induced (Sanford et al. 1991) resuspension ultimately carries fine-grained particles to their final deposition places in sheltered bays or deep water basins (Eckhell et al. 2000, Christiansen et al. 2002). Thus, a general observation is that sediments become finer along transects from high-dynamic shallow-water to low-dynamic deep-water environments. As a result of frequent resuspension, large areas, especially in the western Baltic where the water depth is less than 20 to 40 m (Christiansen & Emelyanov 1995), are dominated by sandy sediments. As reflected in the sediment map by Repecka et al. (1998), the deeper basins of the western and central Baltic Sea are characterised by increasing contents of fine-grained particles (silt and clay).

Sedimentation rates are usually defined either as the linear sedimentation rate (LSR [mm yr^{-1}]) or the sediment mass accumulation rate (MAR [g m^{-2} yr^{-1}]). Because of compaction processes, the 'visible' LSR decreases downcore even if MAR remains constant. Thus, comparisons of LSR are recommended for sediment layers representing the same time interval, but MAR is needed for calculating mass balances or element accumulation rates.

2. Material and methods

2.1. Study area and sampling

The present study is based on investigations of 52 short sediment cores from the deepest part (<150 m) of the Eastern Gotland Basin. Sediment sampling took place during a research cruise with the r/v 'Prof. A. Penck' from June 4th–19th, 2003 (Fig. 1). Sediment cores were collected with a multiple corer device (MUC) as described by Barnett et al. (1984), but improved with a core catcher. The MUC was equipped with 8 acrylic tubes,

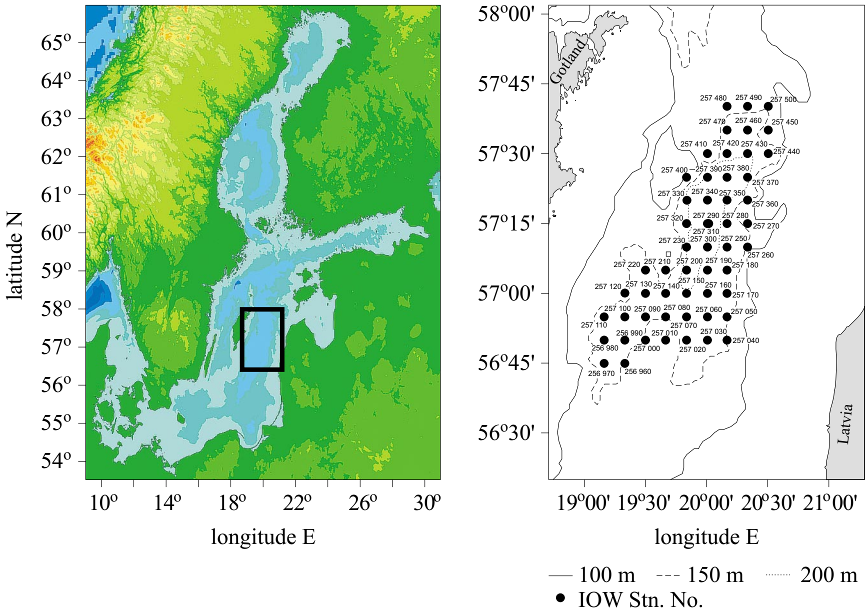

Fig. 1. Map of the Baltic Sea with the location of the study area (left); detailed map showing sediment sampling stations in the Eastern Gotland Basin with IOW station numbers and bathymetry according to Seifert et al. (2001) (right)

each with a length of 60 cm and an inner diameter of 10 cm. Based on the sediment classification of Emelyanov et al. (1994) all the studied sediments could be classified as pelitic mud, i.e. fine-grained sediments dominated by silt particles (≤ 63 μm) with a significant contribution of clay (≤ 2 μm). The sediment cores were documented by digital photographs.

Directly after extraction the sediment cores were cut into 1 cm or 2 cm slices, thereafter by extrusion with a plunger device. The samples were stored in PE Petri dishes and kept frozen until retrieval to onshore laboratories. Upon return to the shore, the sediments were desalted, lyophilised and homogenised for later geochemical investigations.

2.2. Sediment physical properties

The sediment water content was obtained from the loss of weight during drying to constant mass in a freeze dryer and calculated as follows:

$$\text{water content [\% WM]} = \text{net wet weight [g]} - \text{net dry weight [g]} \times \times 100/\text{net wet weight [g]} \qquad \text{(eq. 1)}$$

For calculating the dry bulk density the following equation was applied:

$$\text{dry bulk density [g cm}^{-3}] = \text{dry weight [g]/wet volume [cm}^3] \qquad \text{(eq. 2)}$$

2.3. Geochemical properties

Investigations of geochemical properties were carried out on selected sediment cores. Total carbon (TC) was determined on a Jena Analytic CS analyser (multi EA 2000) with a precision of $\pm 5\%$. A synthetic standard from Eltra was applied for calibration purposes. Carbonate carbon (TIC) was determined with the same element analyser as TC: samples were treated with 1 M phosphoric acid and the carbon dioxide produced was measured with an infrared detector. Organic carbon (TOC) was then calculated from the difference between TC and TIC. Total nitrogen (TN) was measured on a CE instrument CHN element analyser (EA 1110) with a precision of $\pm 0.5\%$.

Samples used for determining aluminium (Al) and trace metals were completely dissolved using a cocktail of HF/HCl and $HClO_4/HNO_3$ acids in pressure bombs at 180°C for 3 h as described by Neumann et al. (1997). The digestion method was validated using commercial reference material (MESS-2). The digested elements were measured with ICP-AES equipment (Liberty 200, Varian). Titrisol standards (1000 mg dm^{-3}) from Merck were used for calibration purposes.

Since 1993 the laboratories at the Institute for Baltic Sea Research Warnemünde have successfully participated in the international QUASIMEME quality assurance programme (Cofino & Wells 1994). In addition, in-house standards (non-certified) have frequently been used as continuous controls in each sample batch.

2.4. ^{210}Pb dating

Recent sedimentation rates were obtained from the dating of dried sediment slices using low-level gamma-ray spectrometry, as described in detail by Kunzendorf et al. (1998). The samples were analysed for ^{210}Pb, ^{137}Cs and ^{226}Ra at the Radiation Research Department, Risø National Laboratory, Roskilde and at the Gamma Dating Centre, Institute of Geography, University of Copenhagen, using a Canberra low-background reverse-electrode coaxial Ge(Li) detector (10% rel. efficiency) with energy resolution values of 640 eV (at 5.9 keV) and 1.7 keV (at 132 keV). ^{210}Pb was measured via its gamma peak at 46.5 keV, ^{137}C via its peak at 661 keV and ^{226}Ra via the granddaughter ^{214}Pb at 352 keV. By subtracting ^{210}Pb supported, i.e. the ^{210}Pb activity derived from the decay of ^{226}Ra, from the total ^{210}Pb activity, the unsupported activity of ^{210}Pb was obtained, which was then used to estimate average linear sedimentation rates for the cores using the constant initial concentration model (CIC) as described in detail by e.g. Appleby (2001). The historical sediment accumulation rate was then calculated using dry bulk densities of the sediment slices and the above-mentioned CIC-model results.

2.5. Modelling current velocities

Near-bottom velocities were derived from a 3-D model. The data were applied to study their possible impact on the observed spatial distribution of sedimentation rates. The model comprises the whole Baltic Sea and parts of the Skagerrak from 8°14′E to 30°32′E and from 53°50′N to 65°56′N. The transition area and the Baltic Proper up to 21°56′E and 59°02′N is covered by a regular spherical grid with a spacing of 6′ longitude and 3′ latitude, i.e. approximately 3 nautical miles or 5.5 km. In the outer parts the model grid is stretched up to 9 nautical miles. Vertically, the water body is divided into 77 levels. The upper 18 layers are 1.5 m thick to resolve the shallow Belt Sea. Below, the layers become coarser up to 5 m, down to a maximum water depth of 268 m. The model is based on the MOM-31 code (Pacanowski & Griffies 2000) with a consistent treatment of tracers and sea surface height (Griffies et al. 2001). The model is driven by forcing through wind, heat fluxes calculated from solar irradiation, air pressure, air temperature, clouds and air humidity. The fresh water discharge from rivers is an important boundary condition for the thermohaline circulation. A thermodynamic ice model, after Winton (2000), accounts for the modification of surface fluxes by sea ice. The meteorological fields were taken from the BALTEX dataset (BHCD, no year). Monthly mean river discharge data were gleaned from Mikulski (1982) and Bergström & Carlsson (1993).

2.6. Mapping

Maps were generated by the Surfer software package (Version 8.01; Golden 2002) based on measured point data. The program estimates values between the points automatically by using a kriging interpolation routine (Deutsch & Journel 1992, Senarath et al. 2001). The search ranges were derived from spherical variograms. The authors are aware that using decimal degrees will cause some inaccuracies because of the anisotropic nature of that projection system. However, this error is acceptable because the maps were created only for visualisation purposes and not for budget calculations.

3. Results

3.1. Sediment physical and geochemical proxies

The photographs (Fig. 2) give an impression of the sediment texture. All cores showed the same characteristic pattern. An organic-rich mud of blackish colour overlay a homogeneous greyish mud. At all stations the uppermost part of the sediments were distinctly laminated, as is the case for the cores presented here.

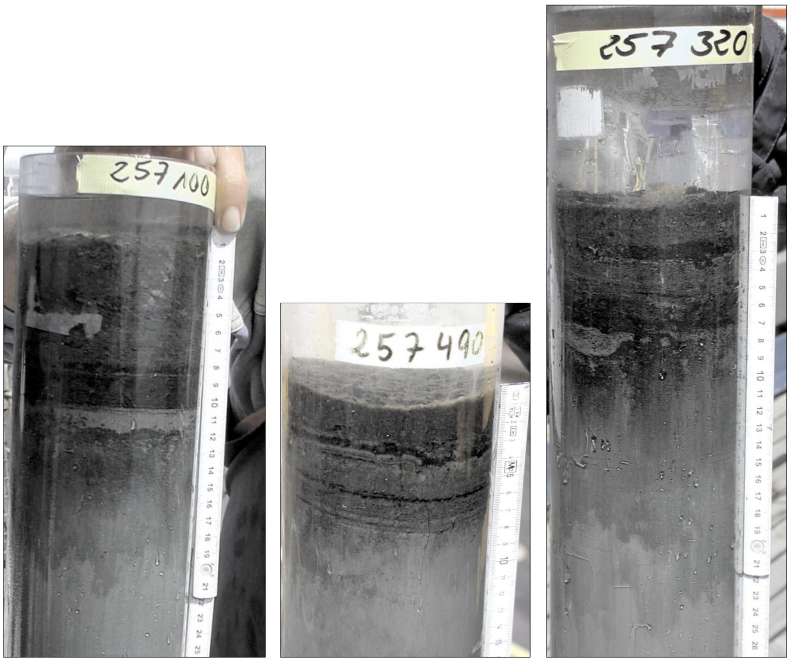

Fig. 2. Photographs of cores 257 100, 257 490 and 257 320 with scale (in centimetres)

However, the thicknesses of the laminated horizons were highly variable (range 17–300 mm). This sudden change in the sediment texture is most probably related to changing environmental conditions during the time of deposition and will be further discussed.

The laminated sediment columns are characterised by higher contents of TOC and nutrient elements as compared to the homogeneous layers (Table 1). The heavy metal profiles are given in Fig. 3 using core 257 320 as an example. The TOC profile indicates increasing values towards the sediment surface. TOC reaches more or less constant values (background) at a sediment depth of 10 cm below the surface. It should be noted that at

Table 1. Mean element composition of laminated sediment layers (n = 54) compared with non-laminated layers (n = 92) as studied in 9 sediment cores, and the results of the Mann-Whitney-U Test (U and p-values)

Characteristic	Unit	Laminated	Non-laminated	U-Test	
TOC	% DM	10.0 ± 2.8	4.0 ± 0.70	−9.87	< 0.000
TP[1]	% DM	0.119 ± 0.022	0.086 ± 0.006	−9.23	< 0.000
TN	% DM	1.19 ± 0.40	0.44 ± 0.10	−9.66	< 0.000

[1] $n = 91$.

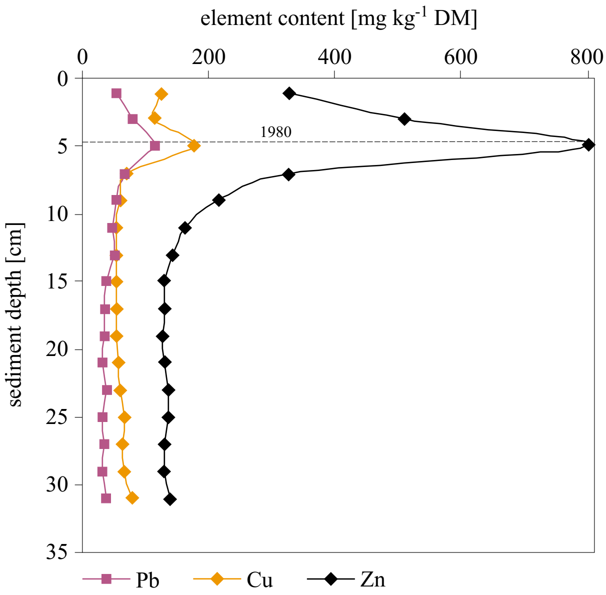

Fig. 3. Downcore profiles of Lead (Pb), Zinc (Zn) and Copper (Cu) profiles in sediment core 257 320. The dashed greyish line indicates 1980

that depth the sedimentary texture changes from a homogeneous greyish mud to an organic-rich laminated mud of blackish colour (see also Fig. 2).

In order to study the correlation between TOC (as a proxy for organic matter) and Al (as a proxy for mineral matter), orthogonal linear regression analyses were performed (Table 2). In all cases negative correlations were found. For 6 of 9 sediment cores the linear relation is significant (coefficient of determination $r^2 > 0.5$). However, the slopes of the individual cores are variable and range from −0.319 to −0.577.

Table 2. Output of the orthogonal regression analyses $y(= \text{Al})$ over $x(= \text{TOC})$. Significant regressions are marked in bold

Core	Slope	r^2
256 970	−0.389	0.473
257 070	**−0.378**	**0.893**
257 150	**−0.467**	**0.588**
257 170	**−0.474**	**0.903**
257 230	**−0.319**	**0.733**
257 290	−0.107	0.239
257 320	**−0.577**	**0.805**
257 350	−0.113	0.272
257 440	**−0.333**	**0.610**
all	**−0.351**	**0.524**

The vertical profiles of Pb, Cu and Zn in core 257 320 are displayed in Fig. 3. In all the cores the heavy metal concentrations in the upper laminated part were very much higher than in the lower non-laminated part. However, diminishing concentrations towards the sediment surface were observed.

3.2. ^{210}Pb dating

To study the temporal development of sedimentation, two sediment cores (257 350 and 257 320) were selected and used for the investigation of ^{210}Pb activity. The investigations were carried out at the Gamma Dating Centre at the University of Copenhagen and at the National Environmental Institute (RISØ), Roskilde, Denmark. For validation purposes ^{137}Cs activity was also measured (data not shown). The vertical distributions of ^{210}Pb are displayed in Fig. 4.

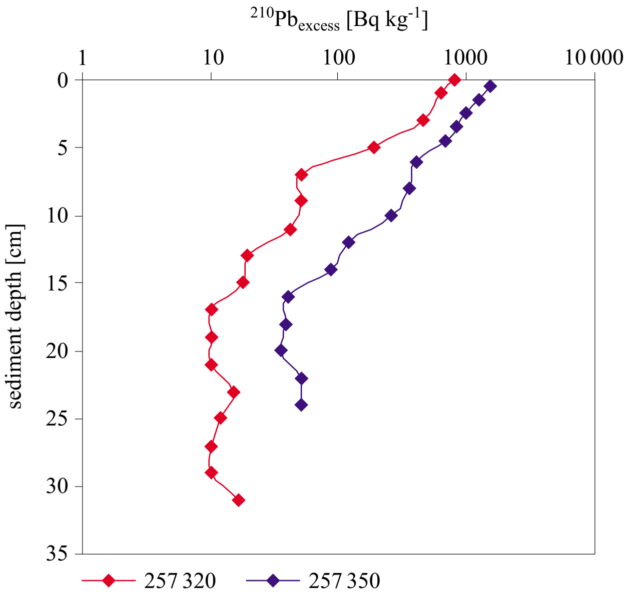

Fig. 4. Downcore profiles of $^{210}Pb_{excess}$

The activity of ^{210}Pb decreases continuously from the sediment surface towards deeper horizons at both stations. The steepest decline is visible in the upper part of the profiles. At station 257 320 the steepest gradient terminates at a depth of approximately 10 cm, whereas at station 257 350 this occurs at a depth of approximately 16 cm; further down the activities correspond to only 2 to 5% of the surface activity, which is equivalent to 3 half-lives (∼100 yr). From these depths the activities decline only slightly; some activity may have been caused by the contamination of deeper sediments by mixing (smearing) with sediments from the upper part while sampling.

In Fig. 5 ^{210}Pb activity is plotted against cumulative sediment accumulation. This plot gives some insight into the nature of sediment accumulation in time. More specifically, it provides information on whether there have been any major changes in the accumulation rates within the considered period of time. Note that sediment accumulation is expressed on a logarithmic scale and that only data from the steepest part of the profiles presented in Fig. 4 have been included (10 cm for station 257 320 and 16 cm for station 257 350). These layers account for approximately the last 100 years. Both profiles exhibit a nearly perfect exponential fit with high coefficients of determination (257 320: $r^2 = 88\%$, 257 350: $r^2 = 89\%$; both regressions are significant with $p < 0.001$). This indicates that the sediment accumulation rates at both stations have been more or less constant for at least the last 100 years, which suggests that the CIC-model (Constant Initial Concentration, as described e.g. by Appleby (2001)) is applicable at both sites.

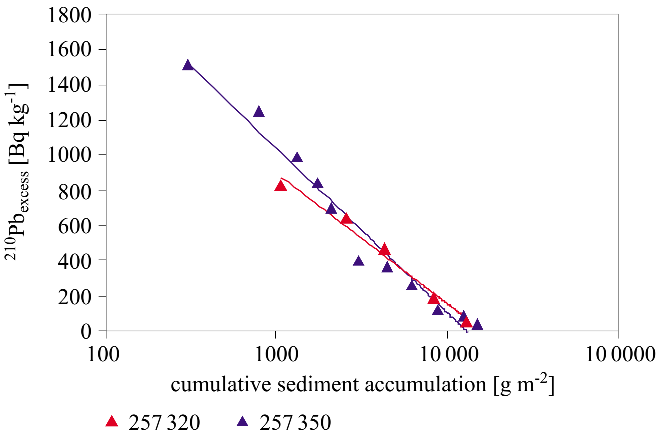

Fig. 5. $^{210}Pb_{excess}$ vs. cumulative sediment accumulation in sediment cores 257 320 and 257 350 and linear regression fits

The summary of the age modelling and estimates of sediment accumulation rate are set out in Table 3. The CIC model assumes a constant rate of sediment mass accumulation in the investigated time interval. Based on this assumption the total amount of accumulated sediment is portioned for the entire core profile based on dry bulk densities. It is evident (see Table 3) that the sediment accumulation rate increases gradually with rising densities. The linear sedimentation rates decrease with depth as a result

Table 3. Estimates of sediment accumulation (MAR) and linear sedimentation rates (LSR) based on CIC-modelling

Core	Depth [cm]	DBD [g cm^{-3}]	MAR [g m^{-2}] per depth interval	MAR [g m^{-2}] cumulative	LSR mm [yr^{-1}]	Age [yr]	Year A.D.
257 320	0–2	0.054	1079	1079	2.4	8	1995
	2–4	0.077	1530	2609	1.7	12	1983
	4–6	0.087	1730	4339	1.5	13	1970
	6–8	0.199	3979	8319	0.7	30	1940
	8–10	0.242	4844	13163	0.5	37	1903
257 350	0–1	0.030	302	302	5.0	2	2001
	1–2	0.048	481	782	3.1	3	1998
	2–3	0.055	546	1328	2.8	4	1994
	3–4	0.041	413	1741	3.7	3	1991
	4–5	0.037	374	2115	4.0	3	1989
	5–7	0.047	941	3056	3.2	6	1983
	7–9	0.072	1432	4488	2.1	10	1973
	9–11	0.087	1741	6229	1.7	12	1962
	11–13	0.130	2591	8820	1.2	17	1945
	13–15	0.182	3636	12456	0.8	24	1921
	15–16	0.263	2634	15090	1.1	17	1903

of sediment compaction. The long-term average linear sedimentation rate (100 years) is calculated by dividing the obtained depths (converted to mm) by 100 years, which yields 1.0 mm yr^{-1} for station 257 320, and 1.6 mm yr^{-1} for station 257 350, respectively. The significant differences from the maximum values (2.4 and 5.0 mm yr^{-1} respectively) are due to increasing sediment compaction with depth. It can be further read from Table 3 that the average bulk sediment accumulation rates are 132 g m^{-2} yr^{-1} at station 257 320 and 151 g m^{-2} yr^{-1} at station 257 350, respectively. It should be noted that in both cases the sediment layer that was dated to an age of 100 years corresponds to the upper laminated horizon of the sediments. The hypothesis was validated by sediment cores 20 000, 20 001, 20 004, 20 007, 20 030, 201 301, 201 302 and 201 303 from the GOBEX study (Christiansen & Kunzendorf 1998, Emeis & Struck 1998). This provided an opportunity to use the thickness of the laminated sequences as time markers and was applied to all the other sediment cores where ^{210}Pb activities were not measured. Subsequently, on the basis of the calculated cumulative sediment accumulation in the laminated sediment layers (based on DBD) and the assumed age (100 yr), the average sediment accumulation rates were calculated for all the investigated sediment cores.

3.3. Linear and bulk sediment accumulation rates

The obtained LSR have to be regarded as average values for the past 100 years for each individual core. The respective values range from 0.17 to 3.0 mm yr^{-1}. The estimated MAR range is from 10.5 to 527 g mm yr^{-1}.

The spatial distributions of LSR and MAR are displayed in Fig. 6. Both the long-term linear sedimentation rate and the sediment accumulation rates show similar spatial patterns. They reach their highest values in the NE part of the study area and have a second, but much smaller, local peak in the SW part. The remaining parts are characterised by much lower rates. The variability in both cases is high. The differences between the lowest and highest numbers for each parameter are of one order of magnitude.

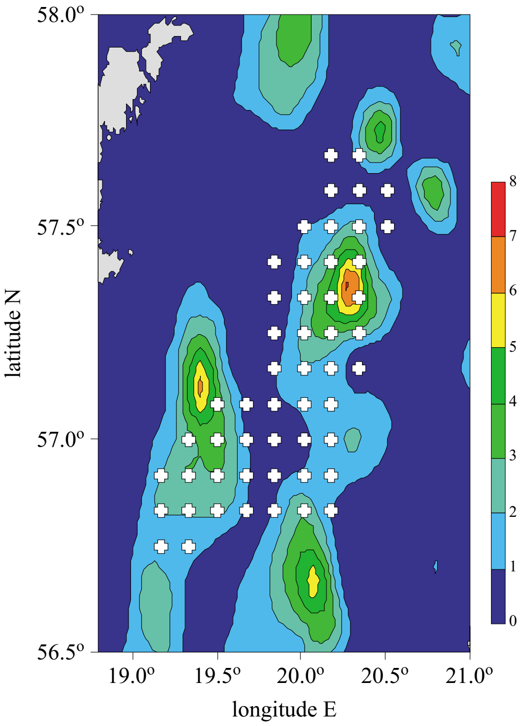

Fig. 6. Thickness of post-Litorina mud layer [m] after Bonacker (1998)

3.4. Near-bottom currents

The numerically modelled bottom velocities are representative of a 23-year simulation period (1970 to 1993). Fig. 7 displays the mean circulation by vectors over a base colour map that corresponds to the maximum velocities above the sea bottom. The main bathymetry is indicated by dashed isolines for 100, 150, and 200 m depth. Basically, the circulation is characterised by an anticlockwise current pattern. The highest velocities,

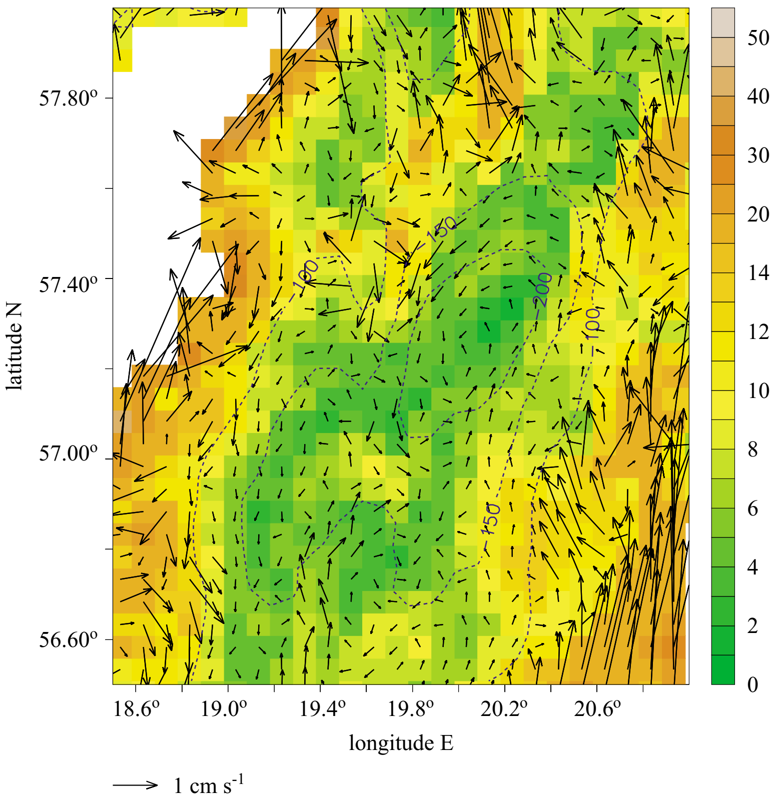

Fig. 7. Maximum near-bottom current velocities [cm s^{-1}] as derived from a 3-D model for the simulation period 1970–1993. The main bathymetry is indicated by dashed isolines for 100, 150 and 200 m depth

reaching current speeds of > 40 cm s^{-1}, have been simulated at the shallow margins beyond 100 m. Towards the centre of the basin the maximum velocities decrease strongly < 10 cm s^{-1}) and the average current is weak (< 1 cm s^{-1}). It should be noted that these data are based on three-dimensional model fields averaged over 5 days. In general, the modelled data are in fairly good accordance with the observations of Hagen & Feistel (2004).

4. Discussion

4.1. Sediment records as a mirror of palaeo-environmental conditions

By studying sediment cores a large amount of information can be obtained about the conditions in the sea and its drainage basin. Sediments contain particles that derive from different sources. Particles reach the seafloor by vertical transport or by near-bottom lateral transport. Minerals come mainly from terrestrial sources, and organic matter and nutrients originate from primary production in the water column (Leipe & Gingele 2003). Some of the particles undergo diagenetic alteration during transport in the water column, and after the formation of sediments diagenetic processes continue. In well-ventilated sea areas, for instance, benthic fauna is abundant at the sea bottom (Laine 2003) and causes a mixing of sediments (Graf 2000, Werner 2002). Through bioturbation, recently deposited material is mixed with older sediments so that temporal differences with respect to the composition of the material will be masked. Bioturbated sediments are thus difficult to use for environmental monitoring.

Inspection of the laminated sediments at the top of the cores indicates undisturbed conditions during sedimentation. That means they developed unaffected by sediment mixing caused by resuspension or by bioturbation. It can thus be concluded that the oxygen supply in the deep water was insufficient to allow the long-term establishment of benthic fauna. Oxygen concentrations less than 2 ml dm^{-3} are life-threatening to marine macrofauna and meiofauna (Diaz & Rosenberg 1995, Swanson et al. 1979). According to Tyson & Pearson (1991), these conditions are defined as hypoxic to anoxic. Jonsson et al. (1990) studied the expansion of hypoxic/anoxic bottoms during the 20th century by counting laminas. The biggest increase occurred between the 1960s and 1970s with an annual rise of 2000 km^2. These authors discuss this phenomenon as the result of anthropogenic eutrophication. The expansion of naturally laminated sediments (i.e. formation not related to man-made impacts) in the Baltic Proper was estimated at approximately 20 000 km^2 by Jonsson et al. (1990). This area covers the deepest parts of the Baltic Proper, where oxygen depletion is expected most frequently (Unverzagt 2001). These findings agree with the few oxygen data available for the deeper areas of the Baltic Proper for the 19th century (Melvasalo et al. 1981).

The laminated sediments provide excellent conditions for tracing anthropogenic discharges into the Baltic Sea with a high temporal resolution (Suess & Erlenkeuser 1975, Perttilä & Brügmann 1992). The significant higher contents of TOC and nutrient elements in the laminated sediment columns as compared to homogenous layers (Table 1) may reflect a higher productivity or a better conservation of sedimentary organic matter during periods of bottom water anoxia or most likely a combination of both. In this study the vertical distribution of trace metals was investigated in the sediment cores. The profiles presented here in Fig. 3 display a similar vertical pattern. Starting from natural background concentrations, the contents of Zn, Cu and Pb increase markedly and reach their maxima in the

1980s. Declining concentrations after the 1980s indicate reduced inputs as a result of effective measures in the polluting industries (Rühling & Tyler 2001); the reduction in Pb is a consequence of the introduction of unleaded fuel. Some authors found evidence that the distribution of certain metals in sediments is affected by the trapping of metals on organic matter or as sulphides in anoxic conditions (Brügmann 1988, Brügmann & Lange 1990, Perttilä & Brügmann 1992). However, this does not accord with declining concentrations in recent times because, as observed in the present study, anoxic conditions are still present and organic matter accumulation remains at a high level. The distinct profiles of trace metals are a further indication of undisturbed sedimentation in the study area and they further confirm the estimated age of the upper laminated sediment layer (see below).

The investigated sediment cores mirror those before c. 1900 A.D. Non-laminated sediments were formed in the Eastern Gotland Basin. These homogeneous sediments indicate bioturbated conditions and thus suggest an oxygenated environment at the seafloor. However, the shift from oxygenated to hypoxic/anoxic conditions in the study area cannot be related to eutrophication effects as discussed by Jonsson et al. (1990) because it occurred 100 years ago and thus before major anthropogenic eutrophication became manifest in the open Baltic Sea. The change in the sedimentary facies happened in parallel with observed climate changes. More specifically, a colder climate period was replaced by a warmer one (von Storch et al. 2004). That warrants the investigation of other potential reasons. One possible explanation could be changes in hydrography forced by climate change. Bearing in mind that strong inflows of highly saline, oxygen-rich North Sea water and the subsequent ventilation of the deep Baltic basins are mainly forced by specific weather conditions (Schinke & Matthäus 1998), this causal relationship is most likely.

4.2. Temporal variation in sedimentation during the past 100 years

The present ^{210}Pb profiles (Fig. 5) suggest constant accumulation rates of bulk sediments for the past 100 years and the applicability of the CIC-model (Constant Initial Concentration) according to Appleby (2001). This observation is in contrast to previous studies in the Gotland Basin, from which was inferred increasing sediment accumulation during the past century based on studies in the GOBEX project (Christiansen & Kunzendorf 1998, Emeis & Struck 1998, Emeis et al. 2000, Christiansen et al. 2002). These authors attributed the increase in accumulation to the erosion of shallow water areas and subsequent basinward transport, consequently resulting in a higher burial of organic matter. Consequently, the CRS model was applied for estimating sediment accumulation rates. This model assumes that sedimentation rates vary throughout the core.

However, data from GOBEX cores No. 20 000, 20 001, 20 004, 20 007, 20 030, 201 301, 201 302 and 201 303 have been re-calculated, and in all cases the application of the CIC model appears to be more suitable than the CRS model (T. J. Anderssen, pers. communication), which thus confirms our finding that the sediment accumulation rates have not changed markedly during the past 100 years.

The increasing accumulation of mineral matter can be excluded from this study with reference to the aluminium profiles. Generally, aluminium can be used as a proxy for mineral matter because it is predominantly associated with clay minerals. The aluminium content in all the investigated sediment cores declines towards the sediment surface (data shown in Hille 2005). The data presented in Table 3 suggest that in general the decreasing aluminium contents are most probably due to the increasing portion of organic carbon and thus a dilution of mineral matter by organic matter. This observation is corroborated by the study of Jonsson & Carman (1994). They observed a more than 1.7-fold increase in sediment organic matter content between the late 1920s and the late 1980s. The same was observed in the Gotland Deep (Neumann et al. 1997, Kunzendorf & Christiansen 1998, Christiansen et al. 2000).

However, because of the low density of organic matter (slightly higher than 1.0 g cm^{-3}) compared to mineral matter (on average 2.6 g cm^{-3}), the greater accumulation of organic matter does not lead to a strong increase in bulk sediment accumulation rates.

4.3. Recent and long-term sedimentation

Different methods have been applied in the past to evaluate sedimentation rates in the Baltic Sea. Ignatius et al. (1971) used the average thickness of dry matter deposited in the Gotland Basin during the last 7000 years and estimated a sedimentation rate of 1 mm yr^{-1}. Later, ^{210}Pb dating was applied by numerous authors, who obtained recent sedimentation rates of 1.0 to 1.3 mm yr^{-1} (Niemistö & Voipio 1974) or slightly higher (Suess & Erlenkeuser 1975, Suess 1978, Niemistö & Voipio 1981). The latter value is in good agreement with the average sedimentation rate observed in this study for the past 100 years: 0.93 $\pm$ 0.67 mm yr^{-1}. Such observations have led to the conclusion that 'the rate of sedimentation has been surprisingly uniform for several thousand years' (Ignatius 1981). This conclusion can be supported by the present work, as demonstrated in Fig. 6. It displays the thickness of the mud layer (after P. Bonacker 1996, unpublished) that has accumulated since brackish water conditions were established in the

Baltic Sea 7000 years BP (Winterhalter 1992). Comparison of both subfigures makes it evident that the spatial patterns of sedimentation rates have not changed significantly during thousands of years. Accumulations of 1 to 7 m in 7000 years account for an average linear sedimentation rate of 0.14 to 1.0 mm yr^{-1}. Short-term variability, however, is concealed.

4.4. Spatial variability of sedimentation and near-bottom hydrography

A closer look at the variability of the linear sedimentation rates observed in the present study and their distribution patterns reveals strong spatial variation reflecting the hydrographic conditions in the deep water (compare Fig. 8 and Fig. 7). LSR in the range from 0.17 to 3.0 mm yr^{-1} were observed in this study.

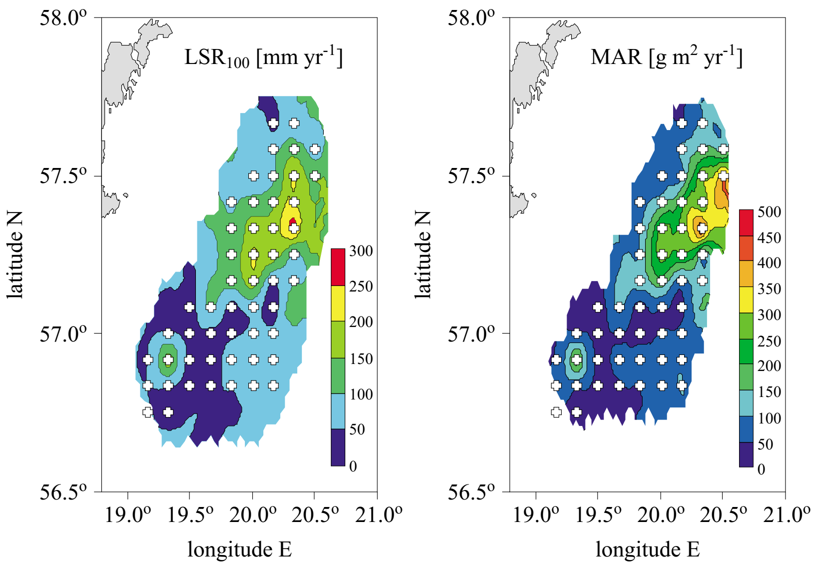

Fig. 8. Spatial patterns of Linear (LSR_{100}) and Bulk Sediment Accumulation Rates (MAR)

The observed non-uniform distribution of both LSR and MSR (Fig. 8) indicates specific hydrographic conditions leading to different rates. Empirical measurements of near-bottom currents are rare, e.g. Hagen & Feistel (2001) and Hagen & Feistel (2004). Hence, near-bottom velocities were calculated from a 3-D model. The data were applied to study their possible impact on the observed spatial distribution of sedimentation rates.

The model simulation comprised a period of 23 years (1970 to 1993). The mean circulation is basically characterised by an anticlockwise current pattern with average velocities of 1 to 3 cm s^{-1}. Maximum near-bottom current speeds of up to 50 cm s^{-1} occur at the slopes. The low model current velocities in the area below 150 m water depth do not exceed the threshold for the resuspension of even fluffy material (the skin friction velocity is permanently < 0.5 cm $^{-1}$s). Hence, erosion of material is unlikely and undisturbed laminated sediments may accumulate (see Fig. 7).

Comparing the maximum current velocities with the distribution map of LSR and MSR presented in Fig. 8 it becomes evident that the highest rates occur in the NE part of the study area, where the near-bottom current velocity is strongest. The strong currents and mean northward transports at the eastern margin lead to an import of large amounts of suspended matter, which sinks rapidly to the seafloor in the adjacent deep basin, resulting in high accumulation rates there.

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