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Modelling of Suspended Matter Transport from the Oder River

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ABSTRACT

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In order to quantify the riverine sediment flux to the Arkona Basin, the transport pathways and fate of fine-grained suspended matter discharged from the Oder River from October 1996 to October 1997 were simulated using the MIKE3 modelling system, including a cohesive sediment transport module. Results indicate that about 550,000 regular tons of sediment are transported to the Arkona Basin annually. There is some indication that transport is episodic and mainly governed by wind events. There is a general tendency for the sediment transported from the Oder to be diverged into a pathway either to the north towards the Arkona Basin (2/3) or to the east towards the Bornholm Basin (1/3) over time-scales of several months. Primary sedimentation along a vertical transsect from the mouth of the Oder River to the Arkona Basin generally takes place in the form of easily resuspended fluffy material. Critical shear stress for the resuspension of this fluff is 0.02 N/m^2. Generally, such thresholds are exceeded 5–6 times per month in shallow water (D <10 m) and 1–2 times per month in deep water (D >10 m) during wind events normally only lasting a few hours. Vertical sedimentation fluxes measured in shallow water are less than 10 $g/m^2/day$ during short periods with calm weather. A comparison with average rates of 80–115 $g/m^2/day$ measured during 3-month observation periods indicates that the resuspension rate in shallow water is about 8–10 times higher than the primary sedimentation rate. The shallow water areas above the 20 m isobath are non-depositional areas acting as temporal deposits for sediment transported from the Oder River through Pomeranian Bay to the Arkona Basin or the Bornholm Basin.

ADDITIONAL INDEX WORDS: *Baltic Sea, Pomeranian Bay, modelling, fine-grained sediment, sediment fluxes, pathways, yearly net transport.*

INTRODUCTION

The background concentration of suspended sediment in the western Baltic Sea is generally very low (1–3 mg/l) (POHL *et al.,* 1998; YEMELYANOW and PUSTELNIKOV, 1975), but there are still large areas of deposition in the Bornholm and Arkona Basins (EMEIS *et al.,* 2001). The primary sources are the discharge of sediment from the large rivers, erosion along the Baltic coastline, as well as primary production (POLLEHNE *et al,* 1995). The Oder River sediment discharge is not exactly known, but it is anticipated that some 425,000 tons are discharged annually (LEIPE *et al.,* 1998), equivalent to a mean concentration of suspended matter of 25 mg/l.

This study presents the results of a 3D modelling exercise carried out in order to describe and quantify the pathways and fluxes of suspended matter from the Oder River to the Baltic Sea. The MIKE 3 modelling system (DHI, 1998) was used, including a full 3D description of the hydrodynamics (HD) coupled with an environmental module describing the transport and fate of cohesive material (MT) (JACOBSEN, 1997). The influence of the suspended sediment on the hydrodynamics is related to changes in density and kinematic viscosity of the fluid. The settling velocity of the material is important in describing the transport processes because of its impact on how and where the sediment is transported and deposited. Cohesive sediment is characterised by bio-geochemical properties which change the physical properties of the primary particles by allowing them to flocculate and form large aggregates with settling velocities much higher than individual particles (KRONE, 1978; BURT, 1986; PEJRUP, 1988; EDELVANG, 1996). It has been shown both in the laboratory (MANNING and DYER, 1999) and in field studies (MIKKELSEN, 2001) that turbulent dissipation governs the size of the flocculated material. This is accounted for in the MT module by relating the settling velocity to both the shear stress and the suspended matter concentration. This paper describes the results of the model simulations calibrated against in situ measurements and compared with NOAA AVHRR satellite images.

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STUDY AREA

Pomeranian Bay is situated in the southern part of the Baltic Sea, bordered to the southeast by the Polish coast and to the southwest by the German coast (see Figure 1). The northern boundary is the 20 m isobath marking the borderline between the shallow Pomeranian Bay and the deeper Arkona Basin (SIEGEL *et al.*, 1999). The Oder is the fifth largest fresh water source to the Baltic Sea, discharging some 16–18 km^3 of water annually into the Pomeranian Bay. The bay is a relatively shallow area with depths of between 10 to 15 m (see Figure 2). There is little tidal influence in the Baltic with a maximum tidal range of approximately 0.3 m. Wind, bathymetry and water transported into the area from the north and east govern the hydrography of the Pomeranian Bay.

The water circulation in the Pomeranian Bay is primarily wind-driven (SIEGEL *et al.*, 1999; BESZCZYNSKA, 1999). Westerly winds blow for about three-quarters of the year, easterly winds prevail in spring. This has a strong bearing on the fluxes to and from the Arkona Basin. Four measuring stations were selected within the area representing different depths along a south to north transect from the Oder to the Arkona Basin. ODAS Tonne (54°04.85′N; 14°09.52′E) at a depth of 16 m was selected as the main station. At this site, a tripod equipped with sediment traps, an Aanderaa current meter and a transmissometer was deployed. This station was previously used by the ODER project (ODER PROJECT MEMBERS, 1995). The locations of the other stations are: Nordperd Rinne (54°21.94′ N; 13°51.72′ E) at a depth of 20 m; Tromper Wiek (54°36.06′ N; 13°45.64′ E) at a depth of 25 m; and the Arkona Basin (54°56.14′ N; 13°49.95′ E) at a depth of 47 m.

METHODS

3D Modelling

A 3D model was used, because the water column is often stratified in the study area. The period 1 October 1996 to 1 October 1997 was selected as the simulation period covering an entire hydrologic year. The model bathymetry consists of 14 km^2 grid cells covering an area of some 18,000 km^2; three-quarters of which is covered with water (Figure 2). The German and Polish coasts border the model area with the Oder as the sole freshwater source. There is an open boundary towards the eastern Baltic Sea framed to the north by the island of Bornholm. The northern boundary is almost closed with a small opening between the southern tip of Sweden and Bornholm. To the west, the tip of Rügen closes the opening towards the Danish Straits connecting the Baltic with the North Sea. The boundary conditions are extracted from a 3D regional model covering parts of the Baltic Sea and Danish waters (FEHMARN BELT, 1998). The model was calibrated against measurements conducted during dedicated cruises and past studies (*e.g.*, LILJEBLADH and STIGEBRANDT, 1996; SIEGEL *et al.*, 1999).

The MIKE 3 modelling system used for this specific study consists of the MT module coupled to the basic MIKE 3 HD module computing the hydrodynamics. The HD module is a generalised 3D modelling system using the Reynolds-averaged Navier-Stokes equations in three dimensions for solving the full non-linear equations of continuity and conservation of momentum in three dimensions. The solution includes the effects of turbulence and variable density together with the conservation equations for salinity and temperature (for a complete description, see DHI (1998)). The MT module is developed as a separate module linked to the hydrodynamic module. It solves the advection-dispersion equations to account for the passive transport and spreading of suspended sediment as well as the sediment transport process equations to account for settling, deposition, consolidation and erosion. The suspended sediment is characterised by its concentration and settling velocity in the MT model. Up to 12 types of bed layers can be selected depending on the system being modelled. The bed layers are characterised by their thickness, density and shear strength (critical shear stress for erosion). In this study, the seabed mainly consists of sand covered by a thin layer of fluff (STOLZENBACH *et al.*, 1997), which is only temporarily deposited on the bed during calm weather, with residence times from one day to two weeks (LAIMA *et al.*, 1999). Therefore, only one bed layer was specified to account for the fluffy layer. Fluff is a low-density substance with a high organic content containing fine-grained sediment particles deposited on the seabed.

During the period 1 October 1996 to 1 October 1997, five cruises were conducted in the area. On each of these cruises, the critical shear stress of the fluff layer was determined experimentally (see Table 1). The method was to collect undisturbed sediment cores along the transsect from the Oder outlet to the Arkona Basin using a hydraulically dampened boxcorer (LUND-HANSEN *et al.*, 2001). Critical shear stress was determined using the LABEREX chamber (LUND-HANSEN *et al.*, 1999) on board the ship. The principle in this method is to increase the shear stress until critical shear stress is reached, which is determined by measuring the light attenuation in the chamber. The critical shear stress varied from about 0.024 N/m^2 at the shallow water station to about 0.016 N/m^2 in the Arkona Basin; it was consistent for all five cruises. The LABEREX chamber was calibrated using Laser Doppler Anemometry (LUND-HANSEN *et al.*, 1999).

The initial sediment bed is assumed to have a constant density of 1,150 kg/m^3. Critical shear stress for erosion of this layer is generally set at 0.02 N/m^2 in accordance with field measurements for the area (see Table 1). Erosion is determined from PARTHENIADES (1986) [Formula 1]

$$E = E_0(\tau_b - \tau_{ce})/\tau_{ce} \quad \text{for} \quad \tau_b > \tau_{ce} \qquad [1]$$

where E_0 = bed material parameter, τ_b = bed shear stress and τ_{ce} = critical shear stress for erosion.

Consolidation of the bed, which is described in the model as a transfer of sediment between the bed layers, is not included in the model because the residence time of the fluffy material is relatively short. The critical shear stress for deposition (the value below which the suspended sediment will settle) was estimated to be 0.1 N/m^2. Deposition is simply determined from [Formula 2]

$$D = C_b\, W_{50} \qquad \text{for } \tau_b < \tau_{cd} \qquad [2]$$

where C_b = suspended sediment concentration at the bottom,

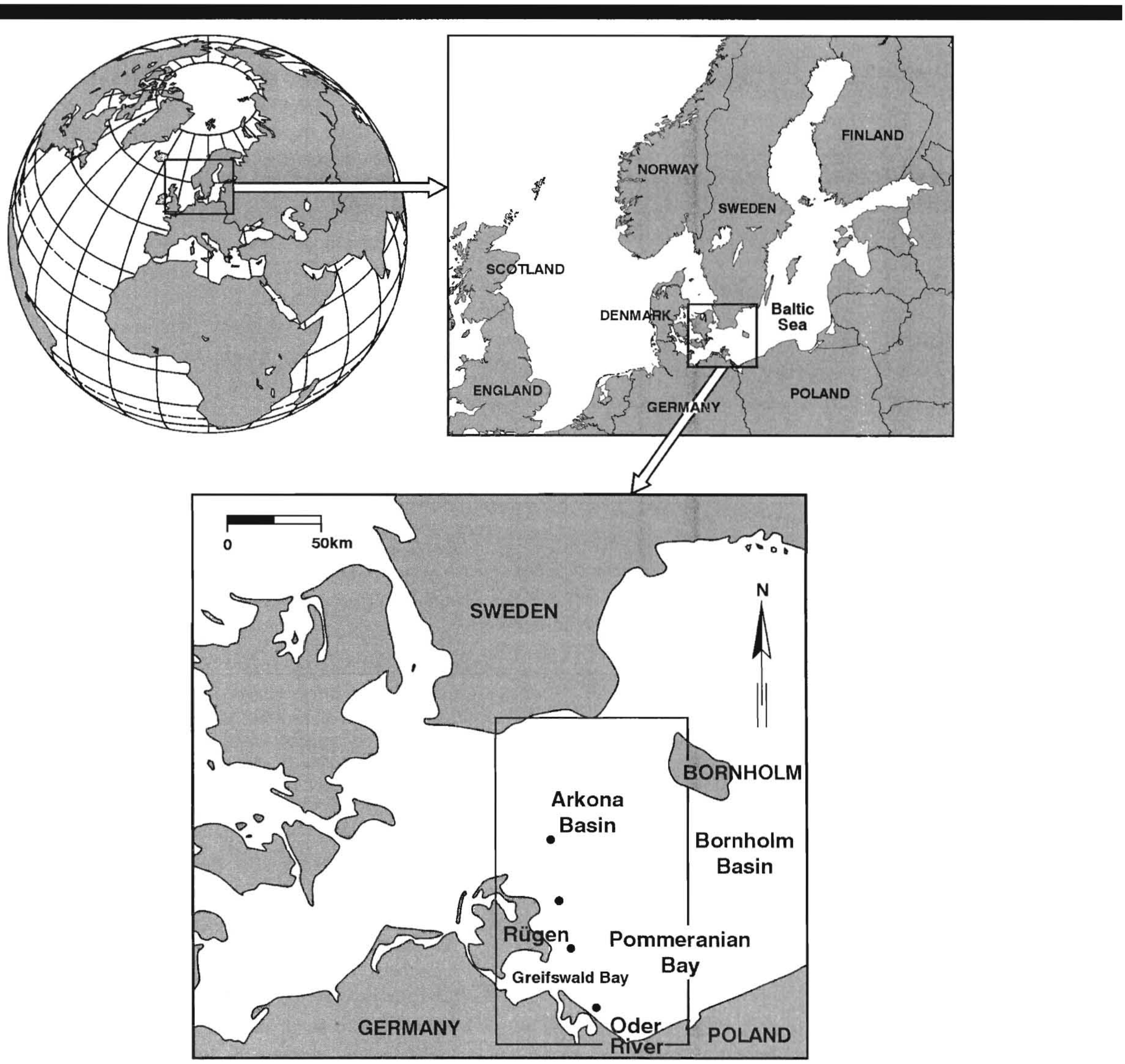

Figure 1. Study area in the southern Baltic. Modelling area framed □. The four measuring stations marked with dots ●.

W_{50} = median settling velocity. A background suspended sediment concentration of 1 mg/l was applied to the whole area. This was a conservative assumption based on measurements from other parts of the Baltic Sea system (EDELVANG, 1998; POHL *et al.*, 1998; YEMELYANOW and PUSTELNIKOV, 1975). The Oder River discharge was taken as monthly mean values from BALTIC SEA ENVIRONMENT PROCEEDINGS (1986). The suspended sediment load was estimated to have a mean value of 25 mg/l based on LEIPE *et al.* (1998). The settling velocity of the suspended sediment was given a mean of $13*10^{-6}$ m/s for primary particles, equivalent to a particle diameter of 4 microns for mineralogical material at 20°C. This is in the low range of the values given in JÄHMLICHH *et al.*, submitted; CHRISTIANSEN *et al.* (submitted) for the suspension in general. The reason for this is that a relatively large percentage of the material discharged from the Oder is assumed to be organic material with a low density; the density of organic matter is close to the density of sea water allowing the material to remain in suspension. Flocculation was included in the model calculations using a settling index of 1.37 as originally established by BURT (1986) on Thames sediment. The settling index describes the relation between the median settling velocity and the suspended sediment concentration [Formula 3]

$$W_{50} = k\ C^{m} \qquad [3]$$

where W_{50} is the median settling velocity, k is an empirical constant, C is the measured suspended sediment concentration and ^{m} is the calculated index. This means that in the model, settling velocities will increase with increasing concentration.

Satellite Image Processing

HRPT (High-Resolution Picture Transmission) data from the NOAA-14 provided by NOAA-SAA (1999) were used in

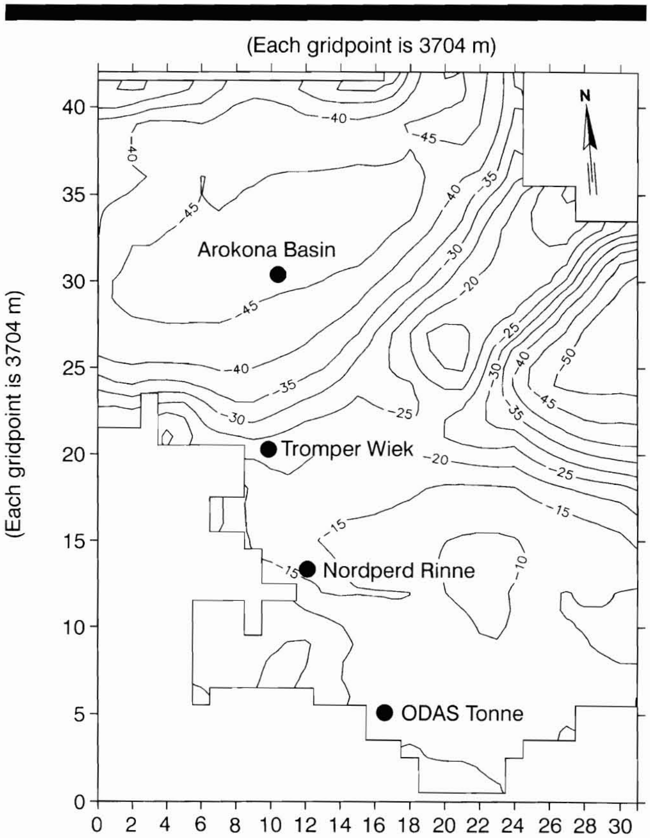

Figure 2. Model area with a grid spacing of 3704 m; Name and location of the four measuring stations marked with ●.

this study. In order to analyse the hydrodynamic processes, the Multi Channel Sea Surface Temperature (MCSST) in the satellite images was selected as an indicator of the freshwater plume from the Oder River. The plume feature derived from the satellite image processing was then compared to the predicted plume in the MIKE 3 simulations described by the salinity variation. The comparison between MCSST and simulated salinity is used only as an indicator of the plume from the Oder River. The distribution of the suspended sediment concentration derived from the simulations was compared to the water column reflectance (WCR) from the Advanced Very High Resolution Radiometer (AVHRR). No correlation algorithm between sea truth data and WCR was computed, as no data were available on the specific dates when images were available. The highest reflectance values were used to give a qualitative, spatial description of the shapes of the most turbid suspended matter gradients without proposing any quantitative distributions. Lower WCR values were grouped together in order to avoid false interpretations of results influenced by effects other than suspended matter. The comparisons on the selected dates may include AVHRR images of both WCR and MCSST or only one of these, depending on the quality of the individual scenes. This is not commented on further in the description of the various incidents.

Rectification of the images was done using orbital parameters (GOODRUM *et al.*, 1999) and they were adjusted to a geo-

Table 1. *Listing of variables.*

	Model Simulation	Measurement
Thickness of initial bed layer (m)	indefinite	—
Density of bed layer (kg/m^3)	1500	1200–2365
Critical shear stress for erosion (N/m^2)	0.02	0.019
Critical shear stress for deposition (N/m^2)	0.01	—
Background concentration (mg/l)	1	1–3

reference (a coastline map), which provides absolute accuracy at the sub-pixel level. Visible and near infrared data were calibrated to % albedo by applying a time degradation algorithm and sun-angle normalisation. This is carried out automatically by the Copenhagen Image Processing System (CHIPS) software (HANSEN, 1999) using the method described by RAO and CHEN (1996). The brightness values for the thermal channels were calculated using the in-flight calibration data provided in the HRPT. The table with the calibrated values incorporates the non-linear corrections following the NOAA AVHRR calibration in the NOAA user guides (KIDWELL, 1998; GOODRUM *et al.*, 1999). The digital levels measured by the sensor are thereby converted to Satellite-received Infrared Radiation Intensity. Various tests were applied to validate the images and to eliminate clouds following the procedure described in STOWE *et al.* (1991), which is applied for ocean daytime overpasses. After the algorithms had been applied to the images, they were remapped into a UTM31 projection performing the nearest pixel technique.

Sea Surface Temperature Retrieval

With the objective of correcting the atmospheric attenuation caused mainly by the absorption of water vapour, the pixels that survived all the tests were transformed by the Split window proposed by MCCLAIN *et al.* (1985) corrected for NOAA-14 AVHRR. In this way, the Multi Channel Sea Surface Temperature (MCSST) was obtained. The NOAA 14 coefficients were found in KIDWELL (1998). The standard error of the MCSST was found to be 0.57.

Total Suspended Matter Retrieval

Temperature images are very useful in showing general oceanographic flow patterns, whereas the reflectance in the visible and near infrared channels (0,58–0,68 μ and 0,72–1,10 μ) is useful for analysing other environmental processes. Some of the optical characteristics of the sea vary as a function of the pigment concentration or coloured sediment, which produce a higher absorption, while other sediments produce a higher reflectance. This can be used as a good indicator of the distribution of the total suspended matter (TSM). Wherever the TSM concentration was high enough, AVHRR visible and near infrared channels were used to map the TSM distribution in the model area. TSM was retrieved using the difference between the two visible channels in a method developed for coastal areas and inland waters (LI *et al.*, 1998; STUMPF and PENNOCK, 1989). The corrections were developed according to the methodology proposed by VIOLLIER *et al.* (1980) for the Coastal Zone Color Scanner adapted for

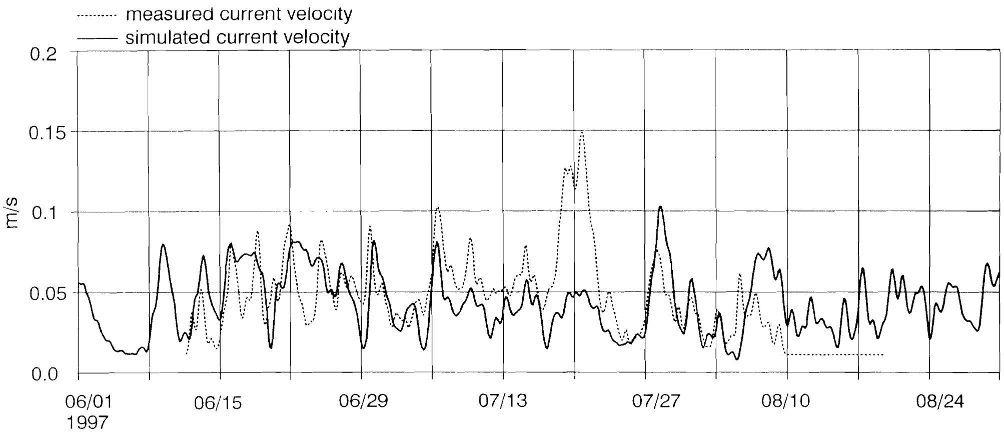

Figure 3. Comparison between measured and modelled bottom current velocities at ODAS Tonne.

AVHRR (PRANGSMA and ROOZEKRANS, 1989; SPITZER *et al.*, 1990). In order to describe the shapes produced by TSM concentration gradients at the surface, the corrected algorithm values were assumed to be a useful indicator, as no in situ measurements were available to quantify TSM distribution.

In situ Measurements

A tripod system with a height of 2 m consisting of a stainless steel frame equipped with five sediment traps, a transmissometer and an Aanderaa current meter was deployed at the ODAS Tonne station. Sediment traps consist of stainless steel tubes closed at the lower end. The tubes are 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, 0.7, 1.05, 1.4 and 1.75 m above the seabed. Divers closed off the openings of the sediment traps with caps before retrieving the tripod onboard the ship. Poison or brine solutions were not used in the traps to prevent degradation of organic matter and zooplankton grazing on trapped phytoplankton. This is because the application of poison in sediment traps may cause over-trapping, killing intruding animals not to be considered part of the passive sediment flux.

The transmissometer (DST PC 9202) placed 0.5 m above the seabed measured the light attenuation of a 630-nm wavelength beam over a distance of 0.5 m. The Aanderaa (RCM 8) current meter measured current speed, conductivity and temperature 1 m above the seabed. The weight and composition of the material collected in the sediment traps was determined; the water was filtered through pre-weighed GF/F WHATMAN filters (0.7 μm retention) and dried for 24 hours at 60°C before weighing.

Bottom shear stresses relating to currents were computed from the Aanderaa current meter measurements (taken1.0 m above the bottom) based on the definition of the logarithmic velocity profile. Bottom shear stresses relating to waves were calculated using Airy's wave theory to estimate near-bottom maximum orbital velocity CERC (1975) and computing threshold grain-sizes for given orbital velocities according to KOMAR and MILLER (1973). The vertical variation of suspended matter concentration was measured during each cruise by collecting water samples from different water depths using a depth-integrated water sampler of the Niskin type. The sampled water was filtered using pre-weighed GF/F WHATMAN filters (0.7 μm).

RESULTS AND DISCUSSION

Current Velocities at ODAS Tonne

Figure 3 shows a comparison between measured and simulated current velocities 1 m above the bottom at the ODAS Tonne station. There is a good agreement between the measured and the simulated current velocities for the period 11 June to 11 August 1997. The measured current velocities vary between 0.01–0.15 m/s with a mean value of 0.05 m/s, whereas the modelled current velocities vary between 0.01–0.13 m/s with a mean value of 0.04 m/s. In Figure 4, the variation in current velocities for the entire modelling year from 1 October 1996 to 1 October 1997 shows current velocities that reach maximum velocities in November 1996 and June and September 1997 during periods of strong westerly winds with speeds above 10–15 m/s. However, there is a general tendency for the model to underestimate peak values of current speed; this is especially true for the period 18 to 23 July, when measured current velocities are about twice to three times as high as the simulated velocities (see Figure 3). The reason for this difference is that high current and wave stresses dominated the area between 17 and 22 July related to a period with wind speeds of 10–12 m/s from the northeast (see Figure 4) combined with an exceptional flood from the Oder lagoon (MATTHÄUS *et al.*, 1998; LAIMA *et al.*, 1999). The model is unable to reproduce the flood incident due to lack of specific data. In this context it is important to remember that the model represents mean values with each point representing an area of some 14 km^2 compared to the point measurements.

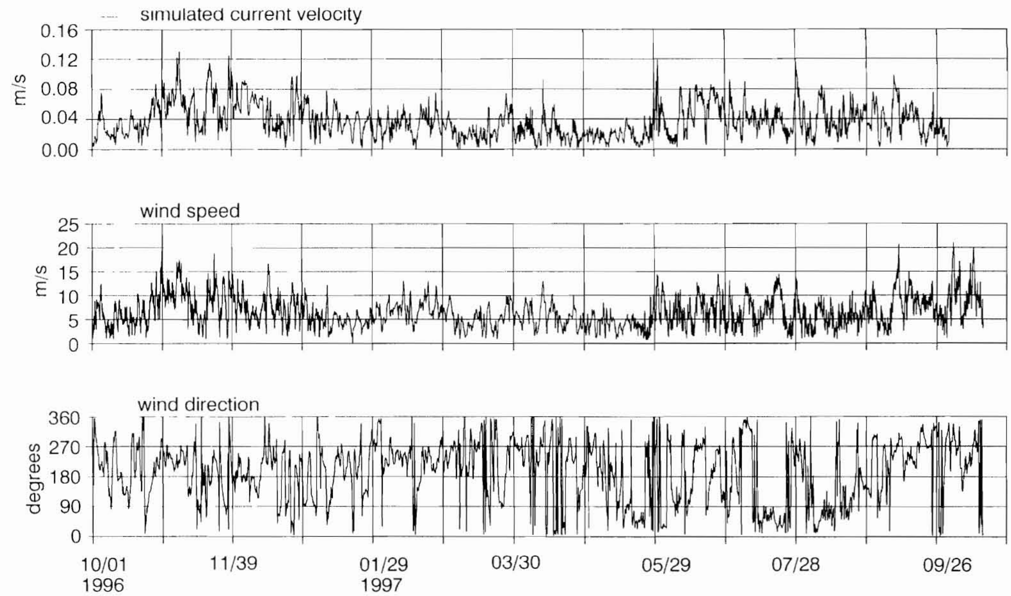

Figure 4. Wind speed and direction from HIRLAM data compared to simulated yearly variation in bottom current velocities at ODAS Tonne.

Variation in Suspended Sediment Concentrations

The highest simulated suspended sediment concentrations occurred from November 1996 to February 1997 with values varying between 1–12 mg/l (Figure 6). In this period, there was a tendency for high resuspension frequency related to westerly winds with speeds above 10 m/s. The spring of 1997 was a calm period experiencing minimal variation in suspended sediment concentrations. This is succeeded by a period with higher suspended sediment concentrations (June to September 1997) caused both by wind events and by the major Oder flood at the end of July. The simulated yearly variation in suspended sediment concentration at the four measuring stations is compared to point measurements during four different cruises. The measured values are relatively low because fair weather conditions prevailed during the cruises. In October 1996, both measured and simulated values were approximately 1 mg/l representing the background concentration. In March 1997, the measured and simulated values were also approximately 1 mg/l except for the ODAS Tonne station, where a suspended sediment concentration of 5 mg/l was measured compared to a simulated value of 3 mg/l. In June 1997, all measured values were low ($\approx$ 2 mg/l) whereas the simulated values varied between 2 mg/l for the Arkona Basin to 5 mg/l for Nordperd Rinne. The discrepancy is explained by the fact that this cruise was conducted after strong westerly winds with wind-speeds up to 15m/s, which caused resuspension (Figure 5). The decrease in suspended sediment concentration is less marked in the simulation compared to the in situ data. This could indicate that the effect of flocculation on the settling of suspended material is underestimated in the model. JÄHMLICH *et al.* (1999) showed that near-bottom flocculation after resuspension events enhanced the settling fluxes of organic carbon. In August 1997 there was again a relatively good correlation between the measured and simulated values.

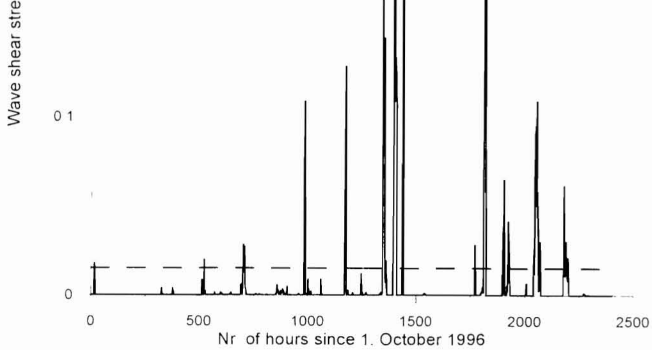

Figure 5. Wave-induced shear stresses at the bottom at ODAS Tonne. Treshold shear stress for resuspension is shown with hatched line.

Validation of Model Results Against Satellite Images

A comparison was made with selected NOAA AVHRR satellite images in order to validate the model results. Images were obtained from various dates representing the most common wind conditions for the Pomeranian Basin: easterly and

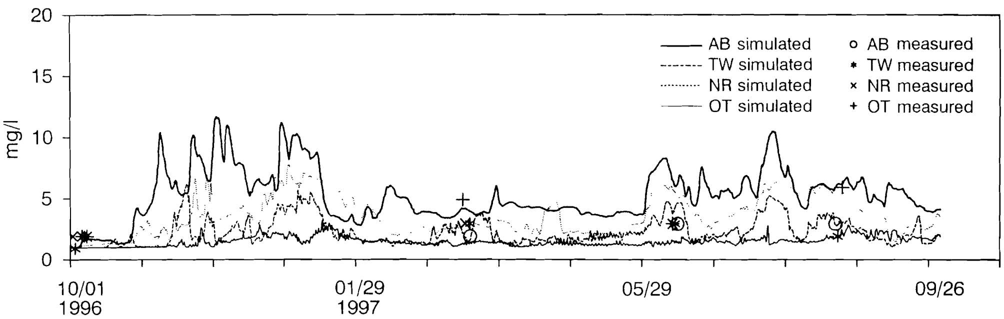

Figure 6. Simulated yearly variation in suspended sediment concentration at the four measuring stations compared to point measurements.

westerly winds. During westerly winds, the water from the Arkona Basin enters the Pomeranian Bay creating a current that moves to the east carrying Oder River discharge as well as water from Greifswald Bay. A characteristic plume of water appears along the Polish coast if the wind continues to blow in this direction more than a few days. During easterly winds, the plume along the Polish coast is broken and the Oder River and Greifswald Bay discharges are moved to the North along the coast of Rügen entering the Arkona Basin.

Easterly Wind Pattern Characteristics

A jet along the German coast is established after a few days of wind blowing from the east (see Figure 7 a). This jet comes from southeast of Pomeranian Bay carrying the sediment-rich and warmer/colder water from the Oder River and turns to the North due to the coastal shape and bathymetry. The jet follows a pathway along the transect from ODAS Tonne, Nordperd Rinne, Tromper Wiek ending in the Arkona Basin. This is illustrated in Figures 7 a & b, which compare the model simulation of salinity with the satellite image of MCSST (Figure 7 a) and the TSM distribution simulation with the WCR in the image from 13/08/1997 (Figure 7 b).

Figure 8 illustrates the influence of northeasterly winds on the Oder discharge depicted by salinity and MCSST on 11/06/1997. Surface currents push the discharge from the Oder River and Greifswald Bay to the west along the German coast. A high gradient of temperature and salinity occurs perpendicular to this coast. This is because the jet along the Polish coast is broken due to the mixing process with the water coming from the east and the up-welling cells of colder water, which are due to the offshore Ekman transport. At the end of 09/06 and 10/06 the wind turned to the west. This change still does not affect the surface plume shapes in Pomeranian Bay, but produces an eddy south of the Arkona Basin. The model simulations reproduce this eddy and the other features as observed when comparing the satellite images to the model results.

Westerly Wind Pattern Characteristics

A WCR image from 26 April 1997 was selected to show the TSM distribution during a typical westerly wind situation in the satellite image compared to the model simulation (Figure 9). The wind blew from the west for four days (21 to 25 April 1997) producing a surface current to the east resulting in a movement of the water masses from the Pomeranian Bay and the coast of Rügen to the east along the Polish coast. The onshore Ekman transport pushes the warmer, low salinity waters along the Polish coast resulting in temperature and salinity gradients appearing parallel to the coast. SIEGEL *et al.* (1999) interpreted this as a dynamic feature, not just as an effect of the heating of shallow coastal areas. The WCR image agrees well with the model simulation.

Horizontal Distribution and Flux of Suspended Matter in the Pomeranian Bay

Simulated fluxes of water and sediment are given in Table 2 for the modelling year 1996–97: the northern boundary represents transport to the Arkona Basin, the eastern boundary represents transport towards the Bornholm Basin (See Figure 1 for definition of boundaries). The total amount of sediment being transported is, of course, a function of the boundary conditions given in the model, including sediment discharged from the Oder and the background concentration of 1 mg/l in the entire area. Therefore, the figures given are relative in the beginning. Accumulated total water fluxes over a number of cross-sections were calculated based on the simulated current velocities and water levels. There is a yearly flux of some 370 km^3 of water directed to the east towards the Polish coast due to the westerly wind. In the opposite direction there is a westward transport of about 470 km^3 including part of the fresh water discharge supplied by the Baltic rivers. The net water flux across the eastern boundary is thus 100 km^3 directed into the Pomeranian Bay from the east. At the northern boundary there is a water flux of about 540 km^3 northward bound into the Arkona Basin and a corresponding southward flux of some 420 km^3. This gives a net water flux of 120 km^3 to the Arkona Basin including discharge from the Oder (17 km^3) and the water crossing the eastern boundary (100 km^3).

The simulated yearly flux of sediment is also calculated for the Pomeranian Bay. Across the eastern boundary there is a sediment influx of 630,000 tons compared to 1 million tons in the opposite direction, thus giving a net flux of 370,000 tons to the Bornholm Basin. Across the northern boundary there is a northward bound flux of some 930,000 tons of sediment

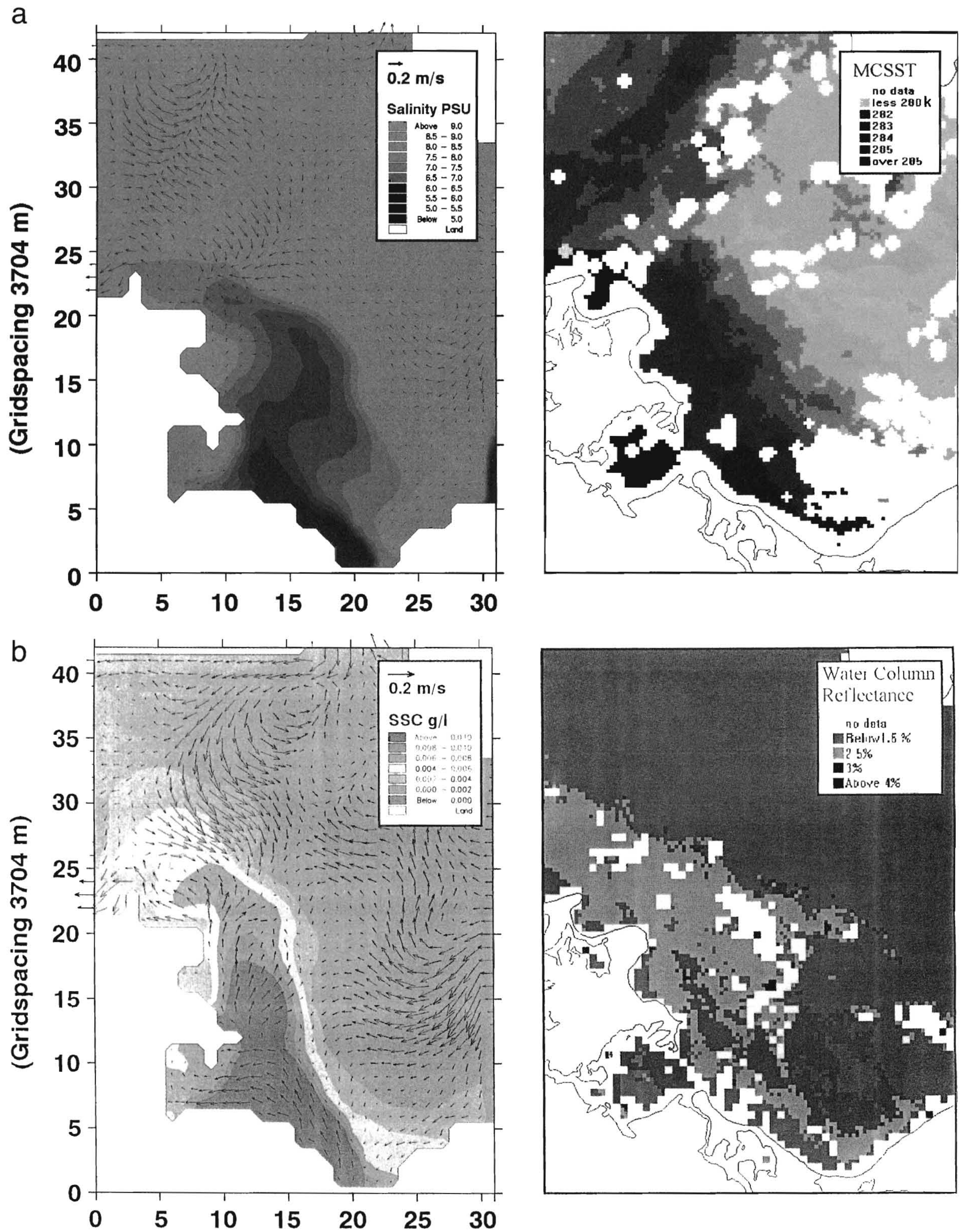

Figure 7. a) 13 August 1997: Comparison between MCSST (NOAA AVHRR) and salinity (MIKE 3). b) 13 August 1997: Comparison between WCR (NOAA AVHRR) and suspended sediment concentration (MIKE 3).

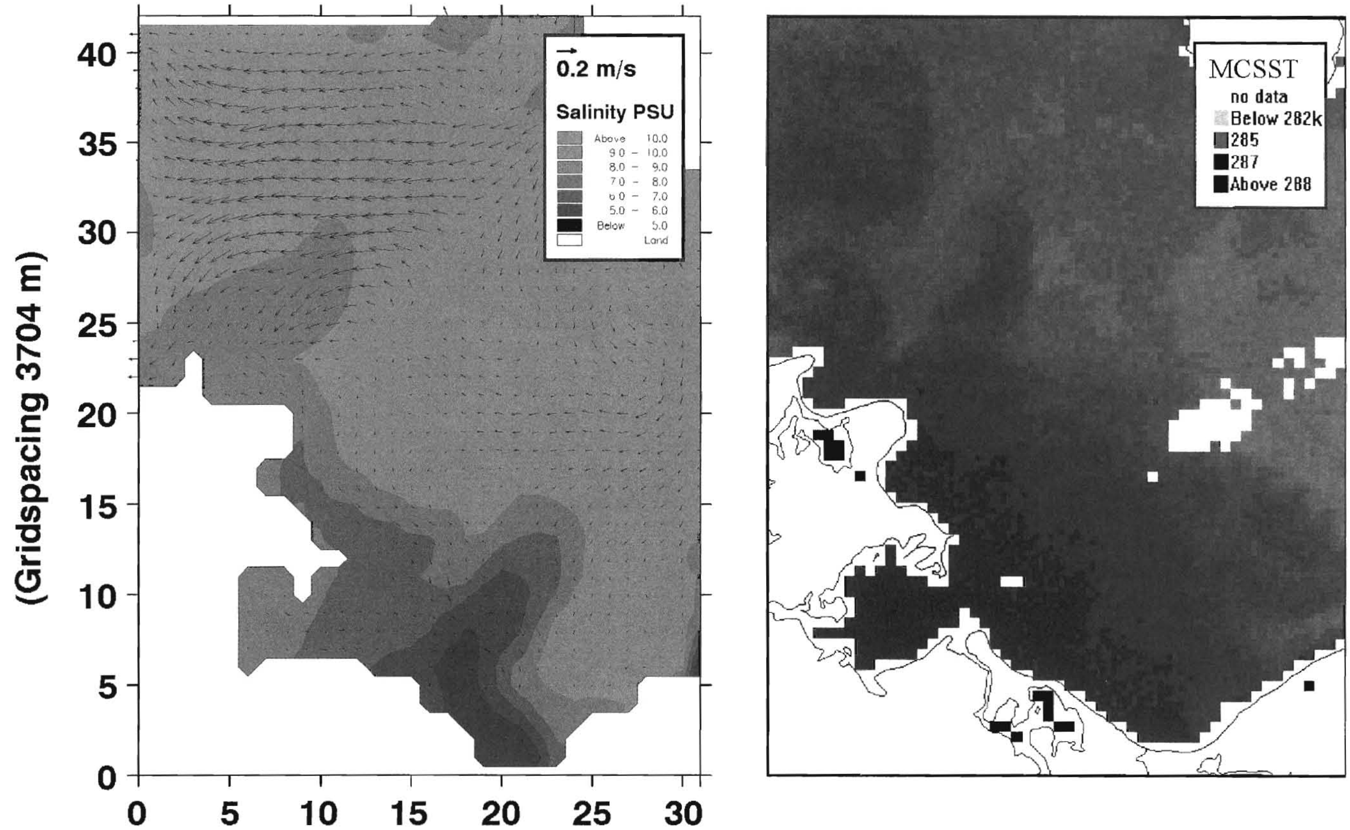

Figure 8. 11 June 1997: Comparison between MCSST (NOAA AVHRR) and salinity (MIKE 3).

compared to a southward flux of 380,000 tons giving a total net flux to the Arkona Basin of 550,000 tons. The overall interpretation of the horizontal flux budget is that there is a general export of sediment from the Pomeranian Bay across both the northern and eastern boundaries. This includes sediment discharged from the Oder River and primary production, which is not accounted for, as well as supplies from the eastern and northern Baltic amounting to about the same as the sediment discharged from the Oder.

Vertical Fluxes of Suspended Matter in the Pomeranian Bay

The net vertical flux of suspended matter in shallow water is a product of primary sedimentation and frequent resuspension governed by waves and currents. In the present study using data from ODAS Tonne, wave-induced orbital velocities resulted in bottom shear stresses above the threshold for resuspension 17 times during a 4-month summer period in 1997 and 16 times during a 4-month winter period in 1996–1997 (Figure 5). Current-induced resuspension occurs with almost the same frequency (Figure 10). However, a general observation is that most current-induced resuspension episodes coincide with wave-induced resuspension episodes. As described in VINCENT *et al.* (1981), parts of this coincidence may be due to additional pumping of the current meter rotor by near bottom wave orbital movements. However, a visual inspection of the current speed recordings does not show signs of such periodicity. Enhanced sediment transport may take place when current movements are enhanced by wave motion (OPEN UNIVERSITY 1989). The combined effect of current and wave-induced shear stresses is an enhancement of the current-induced shear stress on the bottom by the waves without a linear relationship (HEATHERSHAW 1989). Generally, the effect is most pronounced at current stress values close to the threshold for resuspension. This means that resuspension of fine material may take place in shallow water even more often than indicated by Figure 5 and Figure 10. Such a suggestion corroborates the findings in CHRISTIANSEN *et al.* (submitted). They showed that, due to flocculation, settling velocities were increased at this site and the residence time for suspended matter in the water column only 1–2 days.

The wind is a very important factor in near-bottom dynamics in the area, which is in accordance with findings by MORHOLZ (1998). Because of the high near-bottom energy level, the shallow water parts of the Pomeranian Bay (above the 20 m isobath) are non-depositional on time scales longer than 1–2 weeks and act as temporal stores for the sediment transport. In deeper areas, wave-induced resuspension in particular appears much less frequently. During a 4-month observation period, the number of resuspension events was cal-

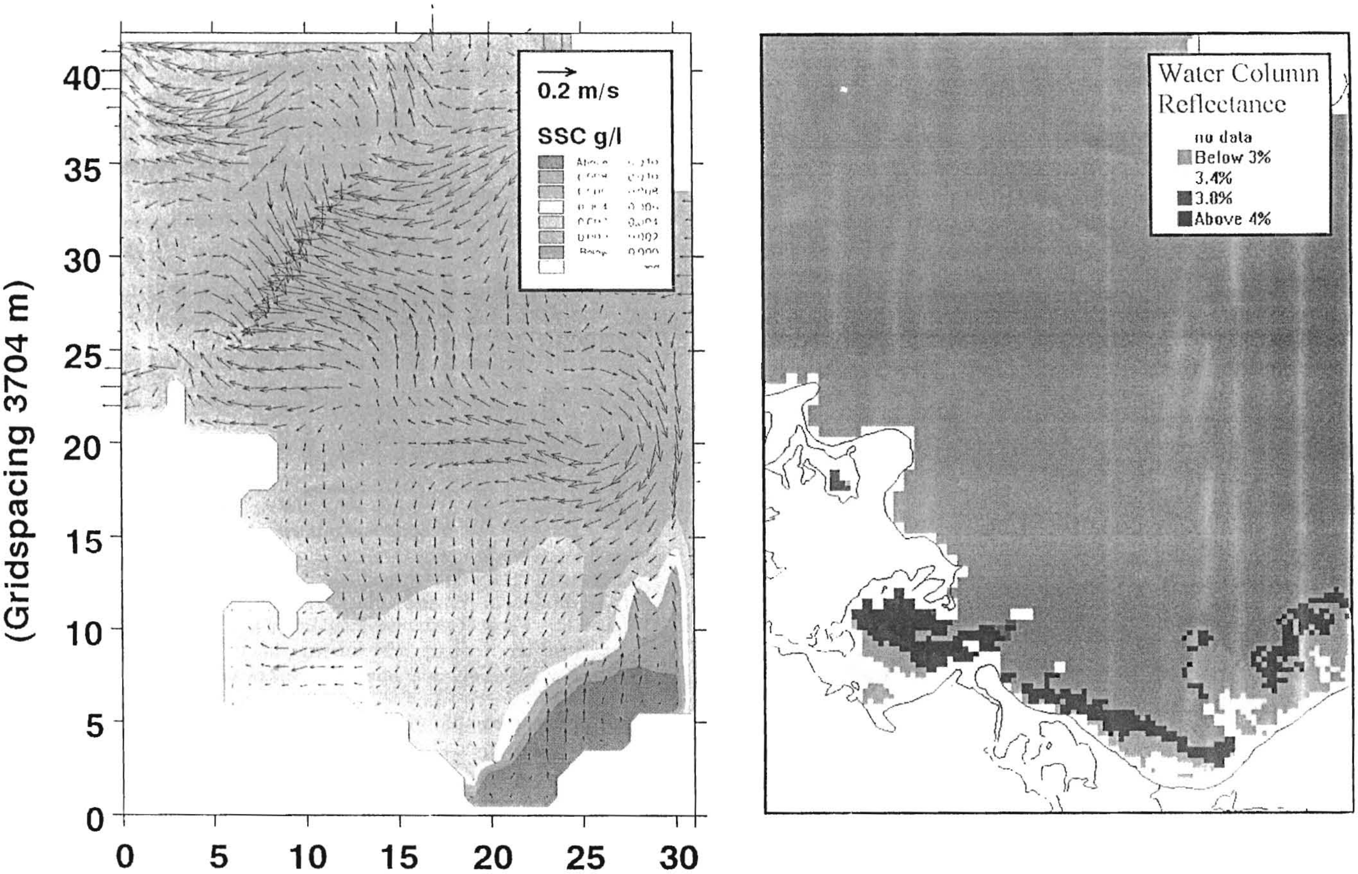

Figure 9. 26 April 1997: Comparison between WCR (NOAA AVHRR) and suspended sediment concentration (MIKE 3).

culated at 6 and 3 at depths of 26 m and 47 m, respectively (see Figure 5). Thus, resuspension events at the Arkona station do not necessarily coincide with the events at the stations along the transect from ODAS Tonne to Tromper Wiek (see also Figure 6 showing the yearly variation in suspended matter at the 4 stations). In this way the deeper areas become depositional. This is especially true for the Arkona Basin, whereas the station at Tromper Wiek is situated in a transition zone between erosion/deposition areas (SHIMMIELD *et al.*, 1999).

The sedimentation fluxes measured with sediment traps on the tripod deployed at ODAS Tonne during short periods of calm weather are less than 10 g/m^2/day (Figure 11), which may be taken to represent primary sedimentation. In a 16 m high water column, the average total particulate matter content per square meter ranges from 32 g to 192 g using data from LUND-HANSEN *et al.* (1999). This means that with no supply during calm weather, the water column could be emptied of suspended matter within 3–19 days. Sedimentation fluxes measured during 2–3 month observation periods show average rates of 80–115 g/m^2/day, indicating that the resuspension rate in shallow water is about 8–10 times higher than the primary sedimentation fluxes in the first 1.75 m above the bottom. This is in accordance with earlier findings by VALEUR *et al.* (1995a & b) and PEJRUP *et al.* (1996) showing resuspension rates up to 10–50 times the primary fluxes in Danish coastal waters. Resuspension rates near the bottom (0.35 m above the bed) are much higher with rates up to 225 g/m^2/day recorded during 2–3 month observation periods. It is important to note that observations made during June–August 1997 include effects of the Oder River flood event in July 1997.

CONCLUSION

The full 3D hydrodynamic modelling system MIKE 3 simulated one year of suspended sediment transport from the Oder River to the Arkona Basin. Generally, model simulations of current velocities and suspended matter concentrations at the bottom show good agreement with the in situ measurements at the ODAS Tonne station during a 3-month period. However, there is a general tendency for the model to underestimate peak values of current speeds, which is explained by the difference in scale between an in situ measurement at a specified point and the simulated value representing a grid of 14 km^2. The simulated variation in suspended sediment concentration also compares well with measured values at the selected measuring stations. Measured

Table 2. *Simulated fluxes from the Pomeranian Bay to the adjacent basins.*

Simulated Fluxes Per Year	Directed Eastward	Directed Westward	Net Transport − Into Bay + To Bornholm
water (m^3)	3.7×10^{11}	4.7×10^{11}	-1.0×10^{11}
sediment (ton)	1.0×10^{6}	6.3×10^{5}	$+3.7 \times 10^{5}$
	Directed Northward	Directed Southward	Net Transport − Into Bay + To Arkona
water (m^3)	5.4×10^{11}	4.2×10^{11}	$+1.2 \times 10^{11}$
sediment (ton)	9.3×10^{5}	3.8×10^{5}	$+5.5 \times 10^{5}$

values are generally very low, because fair weather situations prevailed during cruises. It appears that the simulated decrease in suspended sediment concentration is less marked than the measured decrease indicating the effect of flocculation may be underestimated in the model simulations.

NOAA AVHRR satellite images have been used to validate the general trends in the simulated distribution of suspended matter at the surface. The model is able to reproduce the dynamic features of both westerly and easterly wind situations with respect to water discharge as well as sediment discharge from the Oder including the more complicated eddy features.

The flux of sediment from the Oder River to the Arkona Basin is in the order of ½ million tons, which accounts for about half of the material transported by horizontal fluxes. Measurements of vertical fluxes show that they are governed by current as well as wave-induced resuspension events with the latter having the major influence on specific events. Generally, the resuspension rate is shown to be about 10 times higher than the primary sedimentation flux of between 80–115 g/m²/day. Shallow areas with water depths less than 20 m are primarily erosional, whereas deeper areas are depositional.

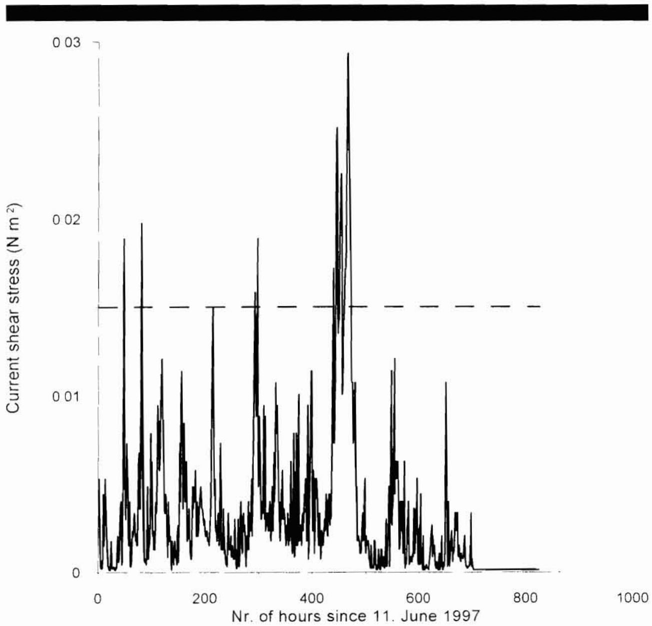

Figure 10. Current induced sheer stress at ODAS Tonne from 11 June to 19 August 1997. Threshold shear stress for resuspension is shown with hatched line.

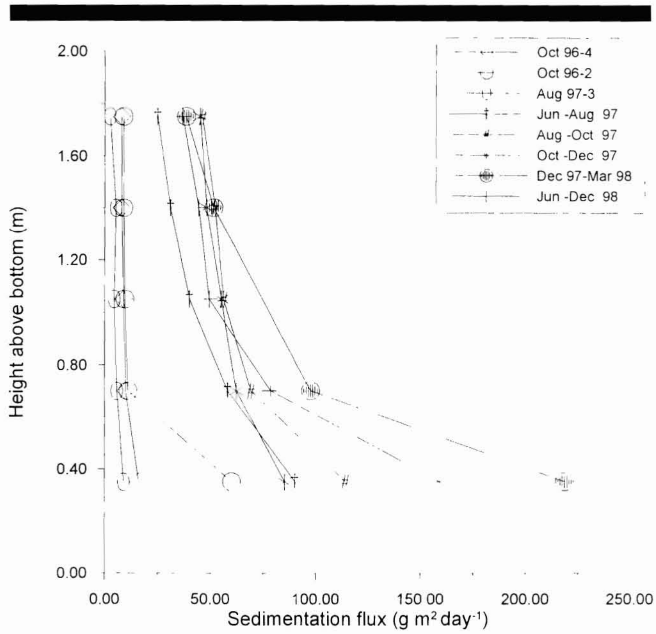

Figure 11. Vertical sedimentation fluxes at ODAS Tonne.

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