TIDAL ASYMMETRIES, WATER EXCHANGES AND SEDIMENT TRANSPORTS IN THE EAST FRISIAN WADDEN SEA

J.-O. Wolff & B. W. Flemming

Introduction

The East Frisian Wadden Sea is characterised by a chain of barrier islands with associated inlets which connect the tidal basins with the North Sea (see Fig. 1). The major physical controls are provided by the tides and meteorological forces (wind, radiation, and freshwater fluxes). Extreme events like storm surges or winter ice coverage episodically throw the system into disarray in terms of hydrodynamics, sediment redistribution, and benthic ecology (Flemming, 2002). In addition, man-induced morphological changes in the form of land reclamation and dike construction had profound effects on a time scale of several centuries.

Recent observations and numerical model runs suggest that the channels in the East Frisian Wadden Sea are ebb-dominated, i. e. transport through the inlets between the islands is characterised by a strong time-velocity asymmetry with considerably steeper gradients during ebb phase. Together with seasonal temperature variations, this has implications for the transport of sediments through the inlets and their distribution in the back-barrier basins (Krögel & Flemming, 1998). These short- and medium-scale events are further complicated by the current rate of sea-level rise amounting to about 18 cm per century.

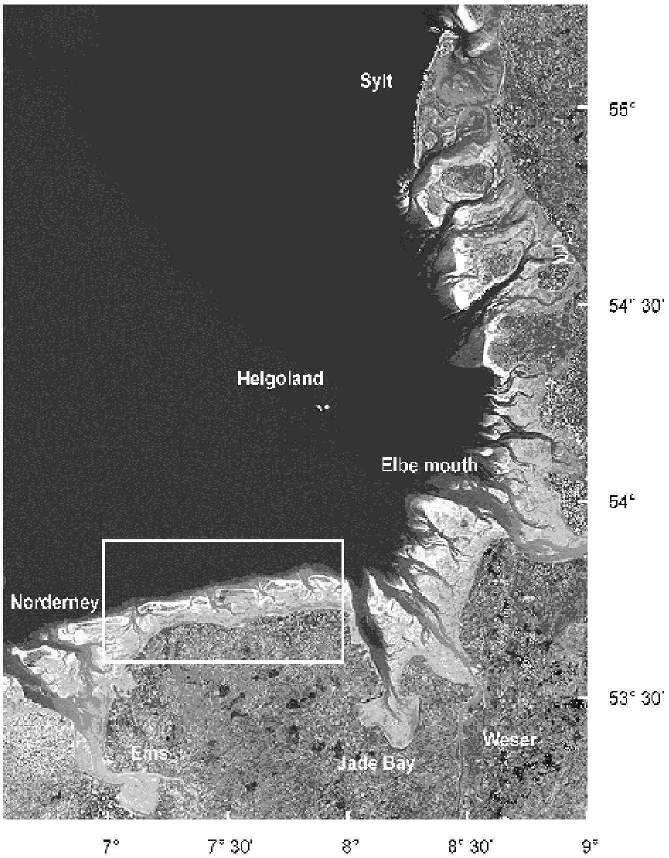

Fig. 1. The German Bight and the East Frisian Wadden Sea (in the inner rectangular frame). Picture from Landsat 5/TMAP, courtesy of GKSS.

The tidal signal exerted in the Atlantic Ocean propagates into the North Sea and finally influences the currents in the tidal basins of the East Frisian Wadden Sea. The simple hydrodynamics of flooding and flushing of a tidal basin are reasonably well understood and documented in the literature. However, it is the combined process of a highly turbulent flow over complex topography with the equally complex nature of the sediment response which so far eludes a complete general understanding, let alone a thorough quantitative description.

We aim at a better understanding of the hydrodynamics and the resulting sediment dispersal in the back-barrier region. To achieve this, a complex hydrodynamic model was coupled with a sediment transport module validated on the basis of observed sediment characteristics and dynamics in the field. With the commissioning of a measuring pile located in the inlet area between the islands of Langeoog and Spiekeroog (see Fig. 2), the investigations will concentrate on the extrapolation of local *in situ* measurements over larger areas of the East Frisian Wadden Sea.

Hydrodynamic numerical modelling and comparison with observations

The numerical studies are based on a relatively new model, the General Estuarine Transport Model (GETM) originally developed by Burchard & Bolding (2002). As demonstrated in Stanev *et al*. (2003a, b), this model is quite appropriate for a simulation of the hydrodynamic situation in the Wadden Sea. In the following, we will briefly list some of the most important characteristics of the model, in particular those which are of utmost importance for a simulation of the relevant physical processes in our model area.

GETM is a 3-D primitive equation numerical model (Burchard & Bolding, 2002) in which the momentum and continuity equations are supplemented by a pair of equations describing the time evolution of the turbulent kinetic energy and its dissipation rate. The first application of this model in the East Frisian Wadden Sea is described in Stanev *et al*. (2003b), and we refer to this paper for more details about the model presentation, its set-up and forcing, as well as first results of the simulations and model validations against observations. Here we will only present some aspects of particular interest. A special feature of GETM is its ability to adequately treat dynamics in deep inlets and channels as well as on the intertidal flats, the latter falling dry during part of the tidal cycle. This is achieved by introducing a "drying corrector" which reduces the influence of some terms in the momentum equations in situations of very thin fluid coverage on the intertidal flats. In the present simulations, the areas where the water column is thinner than D_{min} = 2 cm are considered dry. In the interval between D_{crit} = 10 cm and D_{min}, the model physics is gradually switched towards friction domination by reducing the effects of horizontal advection and Coriolis acceleration. For a water coverage greater than 10 cm, the full physics is included.

In the horizontal, the model domain is resolved in equidistant steps of 200 m, and the horizontal matrix includes 324×88 grid points in the zonal and meridional directions, respectively. In order to reduce the number of land points in the model area, the region bounded by the rectangular frame in Fig. 1 was rotated by 9^o (cf. North arrow in Fig. 2). In the vertical, the model uses terrain-following co-ordinates. The vertical discretisation consists of 10 equidistant layers extending from the bottom $z = -H$ to the sea surface ζ. Because ζ changes continuously during the model integration, the thickness of the water column D becomes a function of the sea-level, i. e. the vertical discretisation changes with time (of particular importance is the fact that the tidal range is similar or greater than the mean depth of the tidal basins). In our model area, the coarsest vertical resolution (in the deepest channels) is about 2 m. In the limiting case when the thickness of the water column approaches D_{min}, the resolution is about 2 mm. The model is forced at the open boundaries with sea-level data from the operational model of the German Federal Maritime and Hydrographic Agency (Bundesamt für Seeschifffahrt und Hydrographie, BSH). The BSH model is a 3-D prognostic model (DICK *et al*., 2001) for the North Sea and the Baltic Sea with a rather coarse resolution of 10 km. Embedded in this is a higher-resolution model for the German Bight which has a grid spacing of 1.8 km. STANEV *et al*. (2003b) demonstrated that the forcing signal of the BSH operational model compares very well with pile measurements (GKSS) in the tidal inlet between the islands of Baltrum and Langeoog (in terms of phase and amplitude). Small differences are to be expected due to the transformation of the tidal signal through friction in the inlet and on the shallow tidal flats.

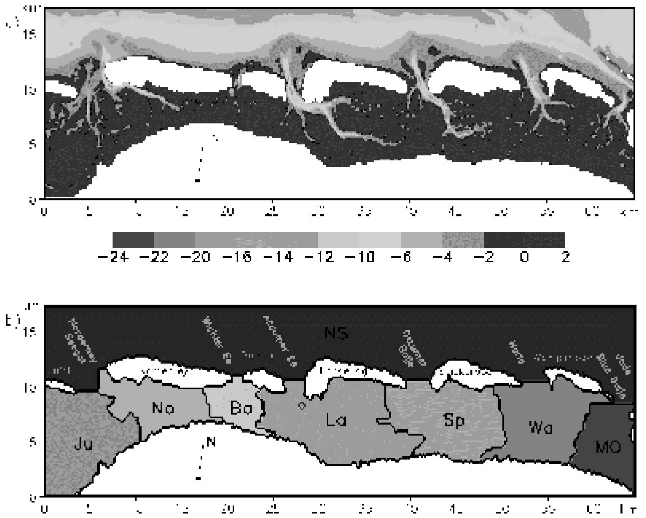

Fig. 2. a) Topography in m below mean sea level, b) individual tidal basins named after the islands in front of them (see STANEV et al., 2003b for details).

The fact that the BSH sea-level data were independently verified by the data from the pile station gave us confidence to investigate temporal and spatial signals in the back-barrier areas using our high-resolution model in combination with the BSH sea-level forcing. A further independent source of observational data came from ship campaigns during which velocities across this tidal inlet (Accumer Ee) were measured using an ADCP. As shown in STANEV *et al*. (2003b), the transport through the inlet, inferred from the ADCP data and measured sea-level, correlates reasonably well with the modelled transport and sea-level, especially during spring tide conditions. Thus, whereas the phase of the modelled sea-level is almost perfectly simulated, the amplitudes are slightly underestimated. During neap tide conditions we observe a small phase shift, i. e. the model signal is slightly ahead of the observations. A number of factors can be responsible for this effect, but one major process, which has been ignored in these simulations so far, is wind forcing. It is nevertheless very encouraging that the trends of the sea-level and transport signals are very close to the observed trends, indicating that the main physical processes are well represented by the numerical model. Especially the asymmetry in the transport signal, as shown both by the simulations and the observation, stimulated us to investigate the dominant processes in the tidal basins with regard to nonlinear effects (see STANEV *et al*., 2003b). These nonlinear effects and their potential impact on the distribution of sediments in the tidal flats are discussed in more detail further in this paper and in Stanev *et al*. (2003, in prep.).

Water exchange and residence time in a tidal flat

The exchange of water between the open ocean and coastal seas has a pronounced impact on the entire oceanic system. This exchange is quite vigorous in areas characterised by complex bathymetry and sometimes controls the evolution of the bathymetry itself. One such region is the East Frisian Wadden Sea. With a tidal range of 2.6 - 3 m, this coastal sector would be classified as upper mesotidal (HAYES, 1979). About 10^8 m³ of water is transported four times a day through the narrow tidal inlets connecting the North Sea with the back-barrier basins. The width of the inlets ranges from 1 - 3 km. Although the exact volume transport through the individual inlets is still uncertain, some estimates based on our numerical model and the available topography are provided in STANEV *et al*. (2003b). Given those uncertainties it is even more difficult to estimate flushing or residence time.

In order to estimate the residence time of water particles in the tidal basins, a 3-D Lagrangian tracer model was developed and coupled to GETM (WOLK, 2003). As an example the simulations were carried out in the tidal basin of Langeoog, which is connected to the North Sea by the tidal inlet Accumer Ee. Up to 180.000 particles were distributed according to the water depth at the starting point of the simulations and followed through 18 tidal cycles. Once a particle had left the model area through its open boundaries, it was no longer tracked, and the time it had spent in the basin was allocated to its starting gridbox. Finally, all those values were averaged and a mean residence time was computed for each gridbox (see Fig. 3). Less than 5% of the particles did not leave the area, and the run time of the model was taken as an estimate of their residence time. Particles initially located in the vicinity of the open boundaries and those in the tidal channels have the shortest residence times (less than about 2 tidal cycles). The longest residence times are found close to the coast, behind the island of Langeoog and on the very shallow flats in the centre of the basin (up to 20 tidal cycles, or 10 days).

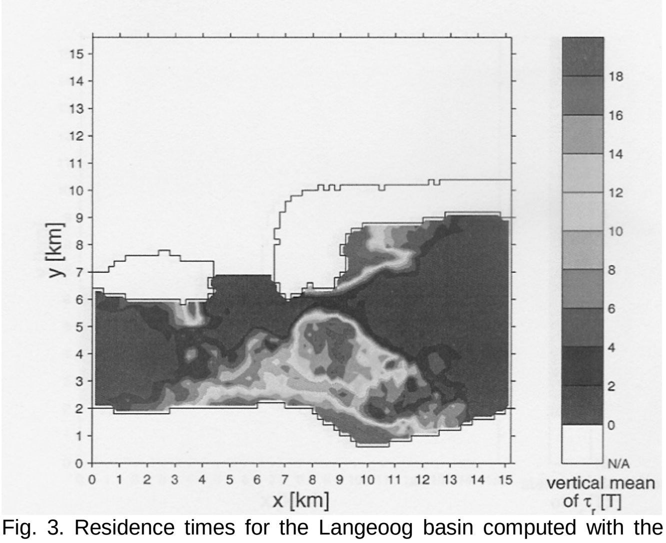

Fig. 3. Residence times for the Langeoog basin computed with the Lagrangian tracer model. Units are in M_2 tidal cycles T=12.42 h (from WOLK, 2003).

Although these simulations give some insight into the water exchanges between the tidal basins and the open sea, a more important question is related to the temporal evolution of the transport which we will address in the following section.

Tidal asymmetries

In a series of papers we analysed the temporal variability of the tidally induced signals of sea-level and transport through the inlets (Saleck, 2002: Stanev *et al*, 2003a, b, c, in prep.; Stanev and Wolff, this volume). Starting from the observation that the tidally induced transport through the inlets shows a distortion in a way that the time between slack water and maximum ebb currents is significantly different from the time between slack water and maximum flood current (see Fig. 4) a simple theory was developed that helps to explain this phenomenon.

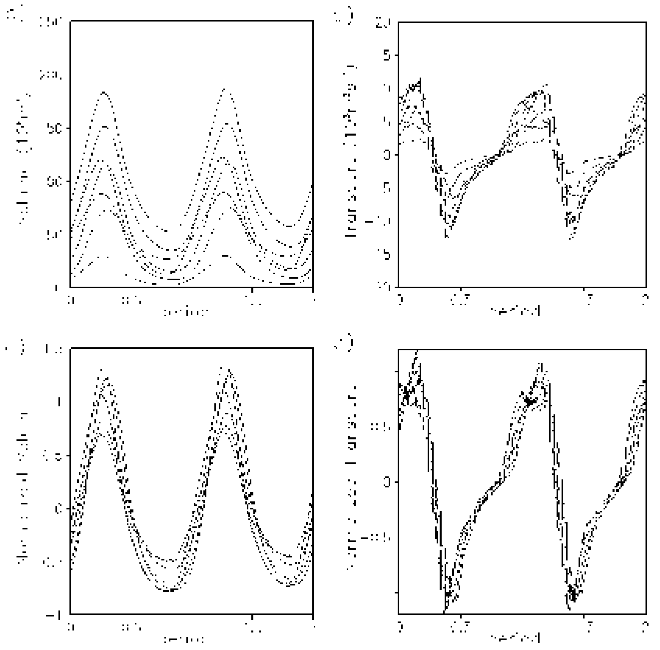

Fig. 4. a) Basin volumes in 10^6 m^3 and b) transports in 10^3 m^3s^{-1} through the various inlets as defined in Fig. 2b. c) and d) are as a) and b) but normalised by their respective mean values (see Stanev *et al*., 2003a for details). Positive values for the transports are landward currents (flood).

Considering the most basic situation of an inlet/bay-system driven by a sea-level gradient between the open ocean and the bay only two equations are needed to describe the response of the transport through the inlet forced by the sea-level signal in the open ocean, i. e. a momentum equation which describes the action of the pressure gradient force on the water particles and the continuity equation which relates the volume transport through the inlet to the sea-level change in the bay (for more details see Stanev & Wolff, this volume and references therein). Non-linear effects enter this otherwise well-known system (Helmholtz oscillator) due to the consideration of a depth-depending area of the tidal flats and the depth-depending cross-sectional area of the tidal inlets both influencing the instantaneous volume transport and its time evolution. The "hypsometric" control, i. e. the influence of the variable area of the tidal flats with the tidally induced sea-level change can be seen in Fig. 5. Depending on the slope of the topography in the tidal flat the time evolution of the transport through the inlet during flood is delayed according to

$$\frac{d}{dt}V = \varepsilon\omega\cos(\omega t) + \varepsilon^2\omega\frac{1}{2}\sin(\omega t) \qquad (1)$$

where V is the normalised excess volume, ω the forcing frequency and ε a parameter controlling the steepness of the vertical side walls in the basin. Eq. 1 simply states that the nonlinearity due to the sloping side walls generates harmonics in the transport with twice the frequency.

Sediment dynamics

Since the import of sediment from remote sources is insufficient to compensate the deficit created by sea-level rise, the East Frisian Wadden Sea is a strongly transgressive depositional system. In the course of sea-level rise, sediment is thus eroded on the upper shoreface and transported into the back-barrier basins. As a result, the whole barrier island system slowly migrates landwards as it accretes vertically, the rate being dictated by the volume of the deficit created by sea-level rise (Flemming, 2002). The migration rate currently amounts to about 100 m per 10 cm sea-level rise.

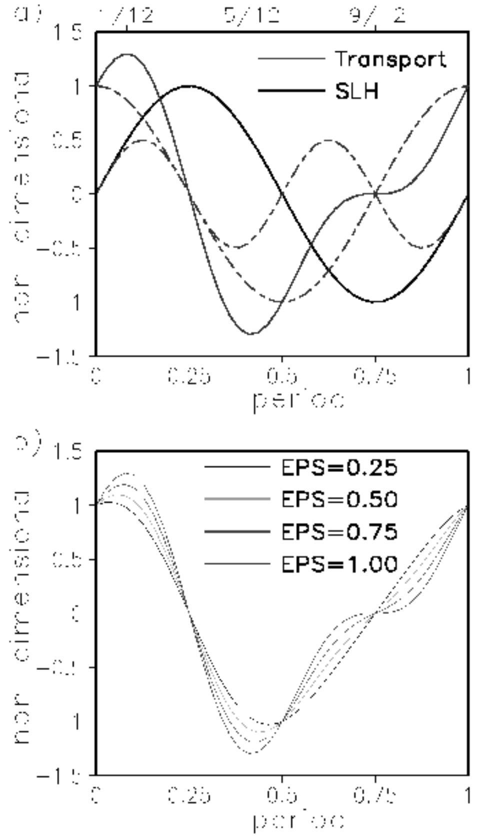

Fig. 5. a) Sea-level height and inlet transport for ε=1. The dashed lines are the 2 terms on the right-hand-side of Eq. 1. b) Normalised transports for various values of the steepness parameter ε. Higher values of ε indicate less steep side walls.

Over the last millennium, this natural transgressive response of the system was severely obstructed by man in the form of land reclamation and dike construction. As a result, the size of the original Wadden Sea was reduced by as much as 50% in some places (Mai & Bartholomä, 2000). The physical obstruction imposed by the dikes had two major effects. On the one hand, the areas of the tidal basins, and hence the volumes of the associated tidal prisms, were greatly reduced. On the other hand, average energy levels along the shoreline increased, thereby truncating the natural sedimentary facies succession, as a result of which the finer-grained end-members (mud flats, salt marshes) were eliminated (Flemming & Nyandwi, 1994; Chang *et al*., this volume). In the course of continued sea-level rise, increasingly coarser sediment facies will hence be squeezed out along the dike (Flemming & Bartholomä, 1997).

Based on this conceptual geological model (Fig. 6), which is supported by numerous observations world-wide, we postulate that most of the imported suspended particles must eventually be eliminated from the system, simply because the accommodation space is not available. The overall fluxes of suspended matter per unit time, the periods of predominant import and export, and the dynamic conditions controlling resuspension and net export are still poorly understood.

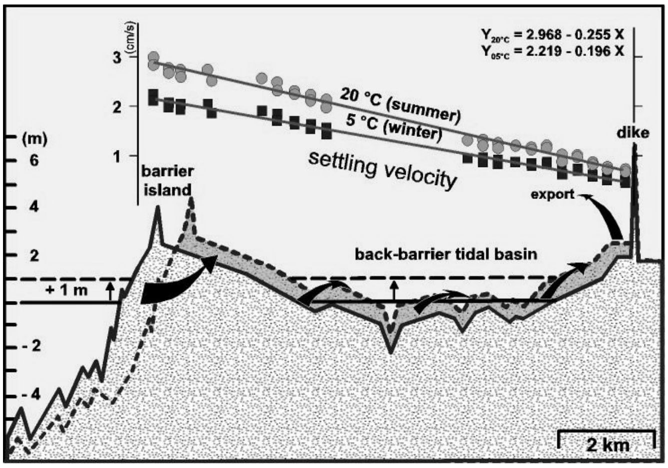

Fig. 6. The conveyor-belt model of import and export of sediment in the course of transgression in the presence of a landward obstruction (dike) as a function of particle settling velocities along the energy gradient.

In the course of sediment flux studies over recent years using calibrated ADCP measurements and pump sampling, it was established that under fair and moderate weather conditions (up to about Bft 6), there appears to be either no or a net import of sediment into the tidal basins (SANTAMARINA CUENO & FLEMMING, 2002). Considering the net export hypothesis for suspended matter outlined above, one must therefore assume that export conditions are created during stormy weather, although it is unclear whether this occurs regularly during the winter season, or only episodically during severe storm surges. Since ship-based observations are not possible during severe storms, this questions is hoped to be solved by continuous measurements at the recently erected pile station. At the same time, the nature of the suspended matter is being investigated in order to distinguish between single and aggregated particles, in particular. This is achieved by comparing *in situ* particle-size spectra using a laser particle sizer (LISST-100ST), and size spectra disaggregated particles collected by pump sampling and analysed in the laboratory. First results indicate that aggregates are predominately composed of particles >8 µm in size, whereas larger suspended particles mainly comprise single, non-aggregated particles (cf. XU, 2000; JOERDEL *et al*., this volume). The energy-gradient model is also supported by the fact that artificial sedimentation ponds created along the dike mainly contain coarser silt-size and less finer silt- and clay-sized particles (CHANG *et al*., this volume).

Sediment transport in the East-Frisian Wadden Sea is being modelled using the three-dimensional, hydrodynamic k-epsilon GETM model, coupled with a sediment transport module (BRINK-SPALINK *et al*., this volume). The implemented sediment-related processes include advection, vertical mixing, settling, and deposition and erosion of sediment. The model is run using different grain sizes which are classified in two groups: non-cohesive sediments with grain diameters larger than 63 µm (sand) and cohesive sediments with grain sizes smaller than 63 µm (mud), part of the latter fraction having the property of forming aggregates resulting in higher settling velocities. This is accounted for by a settling velocity which is dependent on the suspended sediment concentration. The distribution of sediment types shows patterns similar to the ones found in observations. Sediment dynamics in the back-barrier basin is highly asymmetrical due to the ebb dominance of the channels and the flood dominance of the tidal flats. As a result, sediment transport processes are also very sensitive to different meteorological events. Modelling therefore included simulations with variable wind forcing in order to be able to compare storm events with calm weather conditions, both at spring and neap tides.

Fig. 7 shows the time *versus* depth diagram for mud and sand over three tidal cycles around spring tide at a position in the tidal channel of Otzum (Otzumer Balje) just south of the west end of the island of Spiekeroog (for more details see Brink-Spalink *et al*., this volume). Sand is transported near the bottom with maximum concentrations when current velocities are highest. It vanishes from the water column during slack water, whereas large amounts of the mud stay in suspension. The maxima of mud concentrations are shifted with respect to the maxima of sand in suspension indicating that mud is still eroded and accumulates in the water column, while sand already settles down and is being redeposited. The highest mud concentrations are reached approximately one hour after the highest current velocities. The response of the sediments to different wind strengths and wind directions has been studied by BRINK-SPALINK et al. (this volume). Whereas for no-wind and low-wind (3 Bft) conditions no net sand transport occurs and mud is even exported from the inlet, both mud and sand is being accumulated when strong winds are active from north-west.

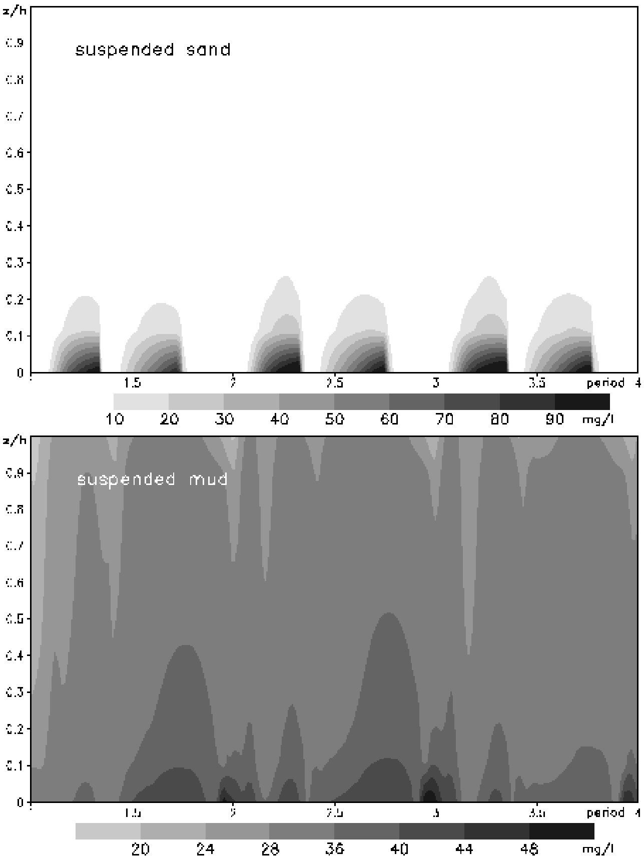

Fig. 7. Time *versus* depth diagrams for sand in suspension (top) and mud in suspension (bottom) at a position in the Otzumer Balje around spring tide.

Swell

Surface gravity waves can have a profound influence on the morphology in coastal areas due to their ability to mobilise sediments and their influence on the suspended material due to enhanced levels of turbulence. Furthermore, a detailed knowledge of their energy distribution is essential for the design of coastal projects, because they determine to a great degree the geometry of beaches and the slope of tidal channels etc. In a preliminary study GETM was used to drive a spectral wave model, i. e. the K-model (see e. g. SCHNEGGENBURGER, 1998). This one-way coupled model was applied to the Wadden Sea area in front of and behind the two islands of Baltrum and Langeoog (see Figs. 2 and 9) mainly because of the availability of data from the GKSS from pile stations and ship surveys. Four different wind scenarios were chosen to represent maximum wind speeds in sufficiently different wind directions in order to study the most dramatic influences of the currents on the distribution of wave energy (see WERFT, 2003, for more details). In Fig. 8 it is shown that the spectral energy density of the surface gravity waves shifts to shorter wavelengths when currents are considered (depending on the direction of the tidal current compared to the direction of the wind). In this situation the spectrum also broadens and the significant wave height increases.

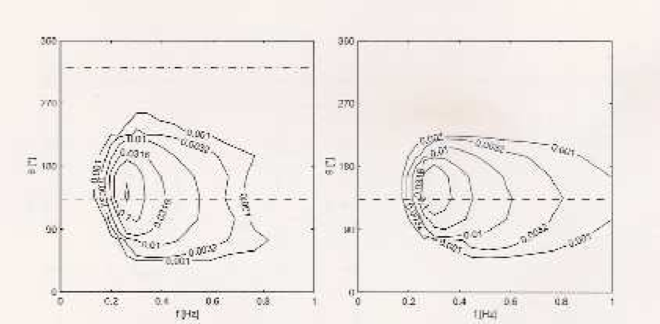

Fig. 8. Frequency-direction energy density spectra at the pile position in the inlet between Baltrum and Langeoog islands (Accumer Ee) for a north-westerly wind with currents (left) and without currents (right) three hours after high tide (from WERFT, 2003). Spectral energy densities are given in m^2Hz^{-1}.

For waves travelling in the direction of the tidal currents the situation is reversed. Wave energy is shifted to longer wavelengths, and the spectrum is narrower than in the situation where no currents are considered in the wave model. Fig. 9 shows the field of the current (velocity and direction, top panel) for the case of the north-westerly wind, the fields of significant wave height and wave direction for the situation where the currents are considered in the wave model (middle panel) and the case without currents (lower panel). These snapshots are shortly before high tide. For the case with currents included the significant wave height is increased in front of the islands and in the tidal inlet. Wave-induced orbital velocities for the computed significant wave heights can reach speeds similar to the tidal flow in the tidal inlets, thus having an influence on sediment processes. There are only very small changes detectable on the tidal flats. The shadowing effect of the islands is clearly visible.

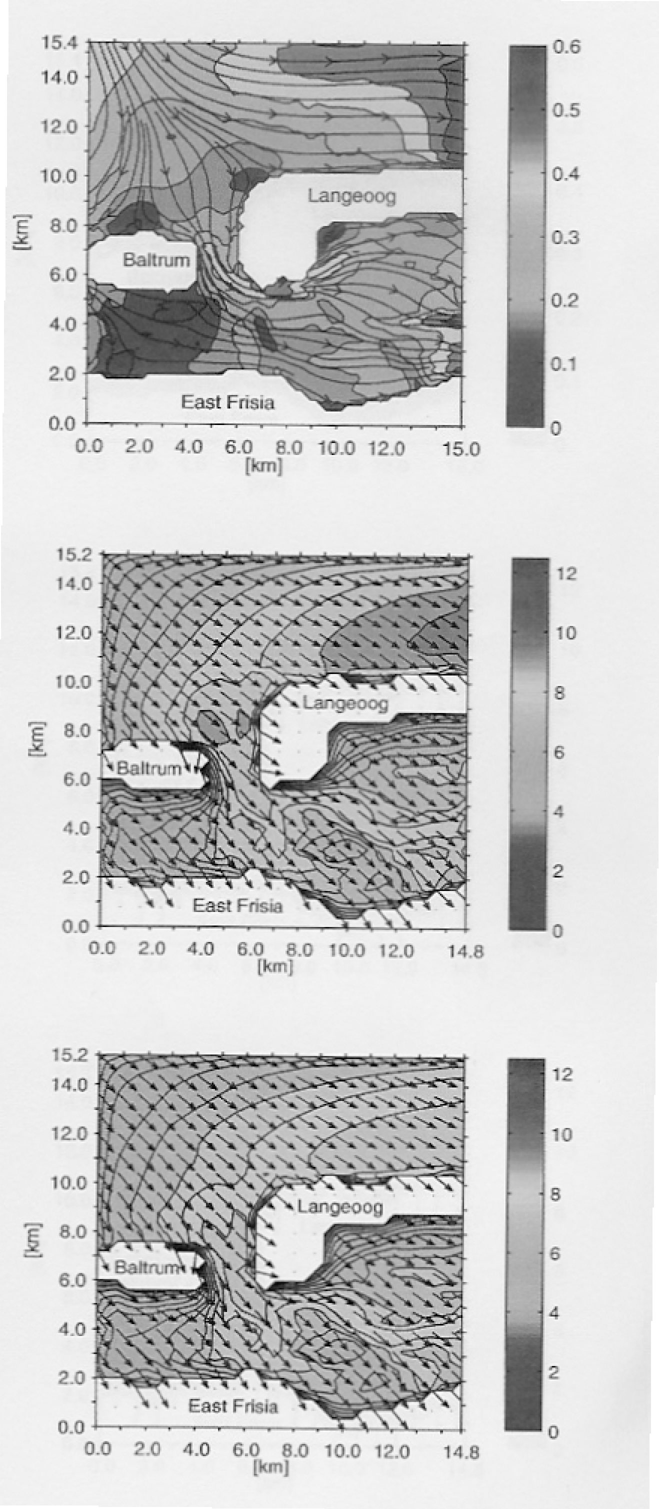

Fig. 9. Top panel: Current speeds and directions in m/s. Middle panel: Significant wave height with currents included (units are 0.1 m). Arrows indicate wave direction. Lower panel: same as middle panel, but without the effect of tidal currents (from WERFT, 2003).

Summary and outlook

The principle aim of our work is a better understanding of the hydrodynamics and the resulting sediment dispersal in the back-barrier region. To achieve this, a complex hydrodynamic model was coupled with a sediment transport module validated on the basis of observed sediment characteristics and dynamics in the field. With the commissioning of a measuring pile located in the inlet area between the islands of Langeoog and Spiekeroog (see Fig. 2), the investigations will concentrate on the extrapolation of local *in situ* measurements over larger areas of the East Frisian Wadden Sea. We believe that the most important hydrodynamical processes in this part of the German Wadden Sea are now reasonably well understood and captured by the numerical model. To further increase the realism of the simulations we plan to increase the horizontal resolution of the model and start to study thermohaline processes. The temperature and salinity distribution in the waters of the Wadden Sea can be highly variable due to incoming solar radiation on dry and wet areas and their different heat absorption capacity, due to heavy precipitation or strong evaporation and controlled freshwater inputs through sewers draining the coastal land areas of East Frisia. Furthermore, we would like to study the impact of extreme events, like storm floods and winter ice conditions, which normally have a dramatic influence on the distribution of sediments and the biological and geochemical processes in the Wadden Sea. This concentrated effort to understand the full complexity of the physics, chemistry and biology of one of the most unique coastal areas on this planet is a challenge that will keep us busy for a long time. The rewards of this research initiative will undoubtedly be of benefit not only for the scientific mind, but for all people living with and from such coastal areas and those who just come to enjoy a healthy and cared for environment.

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[1]J.-O. Wolff & [2]B. W. Flemming, [1]Universität Oldenburg, Fakultät V - Mathematik und Naturwissenschaften, Institut für Chemie und Biologie des Meeres, Postfach 2503, D-26111 Oldenburg, Germany, Phone: +49 441 7985343; fax: +49 441 798 3404; [2]Senckenberg Institute, Division of Marine Science, Schleusenstrasse 39a, D-26382 Wilhelmshaven, Germany. Phone: +49 4421 947540; fax: +49 4421 947550; e-mail: wolff@icbm.de.