Impact of winter storms on sediment dynamics in the East-Frisian Wadden Sea (southern North Sea)

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Keywords: European winter windstorms, sediment transport, Wadden Sea, observations and modelling

ABSTRACT

Introduction

The East Frisian Wadden Sea is characterized by a chain of barrier islands with associated inlets which connect the tidal basins with the North Sea. The major physical controls are provided by the tides and meteorological forces (e.g. 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).

Sedimentological evidence indicates a net export of suspended fine sediments with the following chain of arguments: Since the import of sediment from remote sources is in-sufficient 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.

Over the last millennium, this natural transgressive response of the system has been severely obstructed by man in the form of land reclamation and dike construction. As a result, the size of the original Wadden Sea has been reduced by as much as 50 % in some places (Mai and Bartholomä, 2000). The physical obstruction imposed by the dikes has had two major effects. On the one hand, the areas of the tidal basins, and hence the volumes of the associated tidal prisms, have been greatly reduced. On the other hand, average energy levels along the shoreline have increased, thereby truncating the natural sedimentary facies succession, as a result of which the finer-grained end-members (mud flats, salt marshes) have been eliminated (Flemming and Nyandwi, 1994).

In the course of continued sea-level rise, increasingly coarser sediment facies will hence be squeezed out along the dike (Flemming and Bartholomä, 1997). Based on this conceptual geological model (see Fig. 1), which is supported by numerous observations world-wide, it is postulated 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.

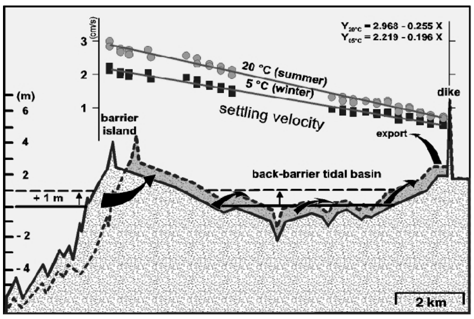

Figure 1: reaction of a tidal system to sea level rise and cross shore distribution of sediment settling velocity.

Considering this 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. Because ship-based observations are not possible during severe storms, this questions was addressed by continuous measurements at a pile station (see Fig. 2). From this pile station, we obtain important data

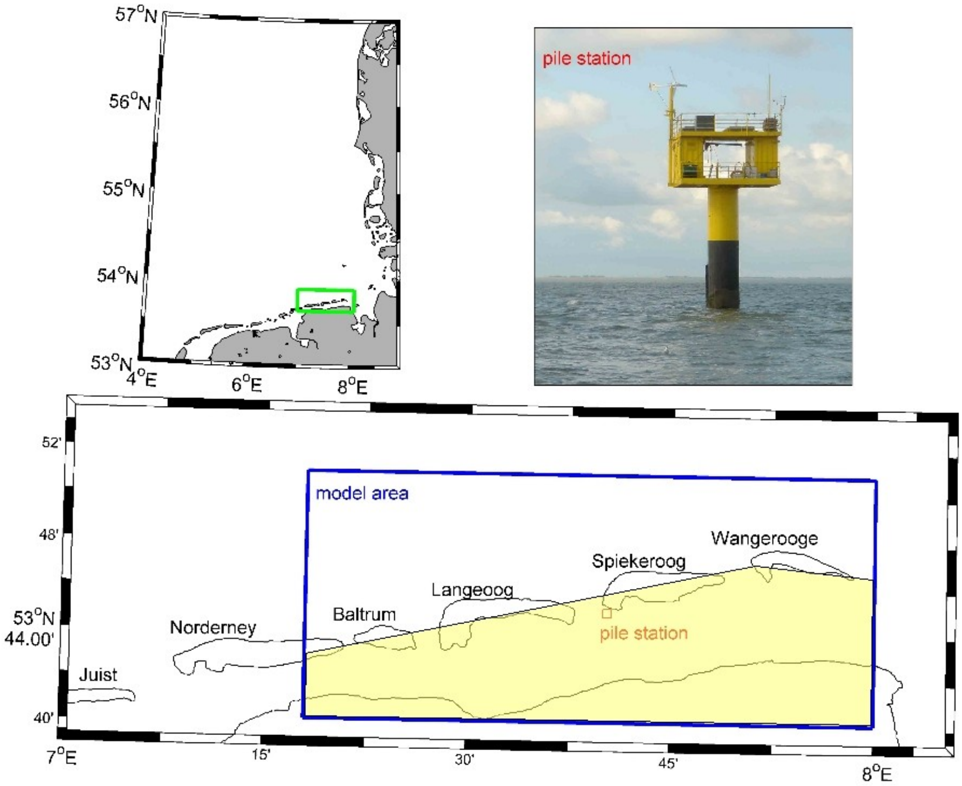

Figure 2: The considered model area as part of the southern North Sea. Furthermore, the pile station operated by the research group 'BioGeoChemistry of Tidal Flats' is shown on the figure top right. The sediment budgets are calculated for the yellow tidal basin area.

like wind speed, water velocity, significant wave hight or suspended sediment concentration during normal weather conditions and storm surges.

In the winter season of 2006/2007 the southern North Sea endured three major storm surges (NLWKN, 2007). The storm surge on the 1st of November 2006 ranges in amongst the class of the three highest sea levels ever recorded along the Lower-Saxionian coastline over the last 100 years (1906, 1962, 2006). Storm "Britta" started to build up sea level from about mid-day of the 30th of October to midnight when the strongest built-up occurred until about 6 am with wind speeds measured at the pile station of up to 100 km/h and a local sea level of more than 2 m above mean high water at the pile station (see Fig. 3). Maximum currents measured at the pile station where above 1.8 m/s.

Under normal weather conditions, there are some processes leading to an accumulation of (fine) sediment in the tidal basins. Here, stokes drift due to wave effects and the effects of settling lag and scour lag could be mentioned (see e.g. Bartholdy, 2000).

During extreme events like storm surges, we face conditions characterized by gale-force winds, much increased sea levels and associated swell. All these factors increase the erosion of sediments at the sea floor in the tidal inlets and on the tidal flats. Smaller sized particles, having also smaller sinking velocities, are therefore kept for a longer time in suspension. This situation potentially leads to an export of smaller sediment classes to the North Sea leaving behind sediments of larger size fractions behind the barrier islands in the East-Frisian Wadden Sea.

In detail, we want to test this hypothesis with our model by considering the effects of increased sea level and enhanced wind speeds. We explicitly mention that wave effects are not considered in this model study, although we believe in their great importance for sediment dynamics in tidal flat systems.

Model

For the high-resolution numerical simulations of the hydrodynamics we have used the General Estuarine Transport Model (GETM, Burchard and Bolding, 2002).

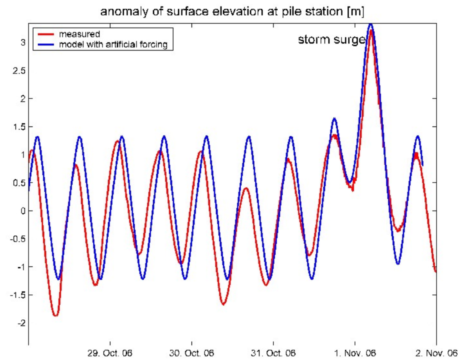

Figure 3: Anomaly of surface elevation at the pile station. Red: the measured elevation during the storm surge in November 2006. Blue: the artificial elevation used in the model with storm surge forcing (scenarios S2 and S3).

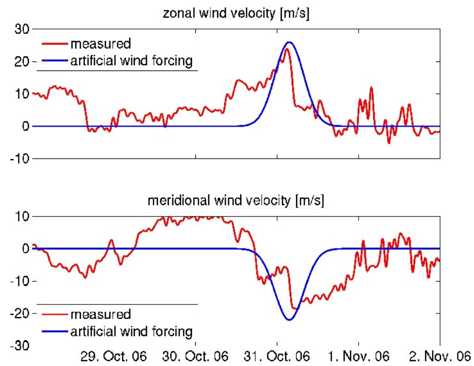

Figure 4: Zonal and meridional wind speed 10 m above sea level. Red: measured at pile station. Blue: artificial wind speeds used for model scenario S3.

GETM is a prognostic three-dimensional hydrodynamical model especially suited for shallow coastal regions under the influence of tidal currents where substantial areas are prone to drying and flooding during a normal tidal cycle. The model is based on the horizontal momentum equations and the continuity equation with two prognostic equations for the turbulent kinetic energy and its dissipations rate influencing the vertical eddy viscosity coefficient. These equations describe the purely dynamic situation. Coupled to GETM is a suspended particulate matter (SPM) model. The sediment module is based on a diffusion-advection equation with an additional sinking velocity, which is calculated using the formula of Soulsby (1997) with a fluid viscosity adopted to a water temperature of 4°C. We consider 5 non-cohesive sand fractions with diameters between 40µm and 200µm. Sediments are eroded from the bottom, if a critical bottom shear stress is exceeded. The sediment deposits, if the bottom stress of the fluid is below a critical value. As we consider non cohesive sediments, these critical shear stresses increase with particle diameter and are calculated with the formula of Soulsby and Whitehouse (1997). The complete model set-up (including forcing, boundary conditions and parameterizations) and comparisons with obsvervations is described in more detail in Wolff et al. 2008 in prep.) .

To investigate the response of the sediment system under normal and extreme weather situations we use an artificial surface elevation at the open boundaries (with the period of the M2-tide) and artificial wind speeds.

These forcing functions have realistic magnitudes as can be seen from Fig. 3 and Fig. 4. We simulate the water elevation of the storm surge by adding a Gaussian elevation peak at the end of the forcing period to the M2 tidal signal. We consider three different model scenarios by starting with M2 tidal forcing only and than adding first the artificial sea-level and than wind forcing (see Table 1).

scenario	boundary forcing	wind forcing
S1	M2-tide	no
S2	M2-tide + storm surge	no
S3	M2-tide + storm surge	yes

Table 1: overview over the different model scenarios.

Results and Conclusions

In Fig. 5, we show that our model captures the right order of magnitude and dynamic of suspended sediment concentration in the water column during the storm surge even with these simplified forcing functions (scenario S3).

For normal conditions (no storm surge, scenario S1) there is a slight accumulation of all sediment fractions in the tidal basin area (yellow area in Fig. 2), which is demonstrated in Fig. 6.

From Fig. 6 it is also evident that the increase of the water level leads to a loss of sediment during storm surges (scenario S2). This loss is even higher, when the wind is switched on (scenario S3). For scenario S3, the highest loss is obtained for the smallest sediment fraction (see Fig. 7).

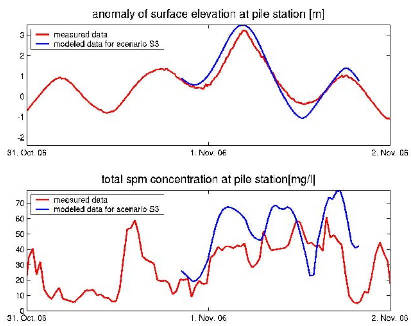

Figure 5: Comparison between measured (red) and modeled (blue) data at pile station. Top: anomaly of surface elevation. Bottom graph: total suspended sediment 9 m above ground.

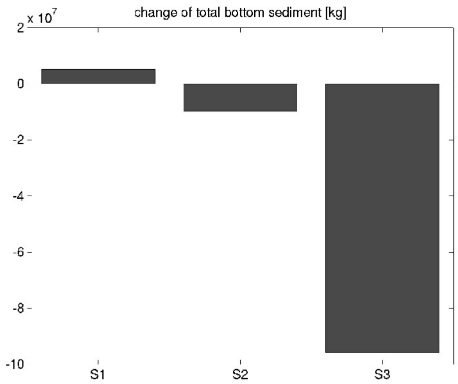

Figure 6: Change of total bottom sediment during the storm surge period in the tidal basin area for the different model scenarios. A positive change means accumulation of sediment.

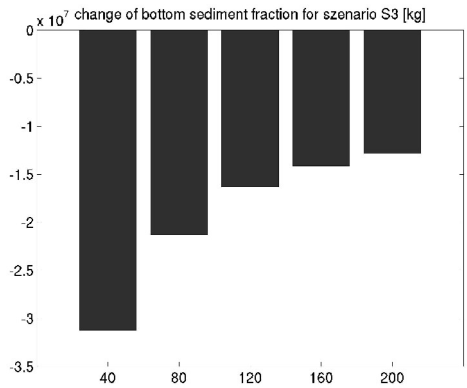

Figure 7: Change of bottom sediment fractions in the tidal basin area during the storm surge period for scenario S3.

The estimated loss of total sediment during a storm surge in the considered area is of the order of 10^7 - 10^8 kg. Our model results seem to confirm the above mentioned hypothesis of increased loss of the fine sediment fraction during storm surges.

After all, we would like to point out again that these results are obtained without the consideration of wave effects, which might be very important for sediment dynamics in tidal flat systems. This is planned for future work.

Acknowlegdements:

We thank Joanna Staneva and Ulf Gräwe for helpful discussions concerning the numerical simulations with GETM. Thomas Badewien provided us with the data from the pile station and helped us with the evaluation of the model results. Furthermore, we thank the *Bundesamt für Seeschifffahrt und Hydrographie (Federal Maritime and Hydrographic Agency, BSH)* for providing topography data.

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