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Proceedings of the 7th International Conference on HydroScience and Engineering

Philadelphia, USA September 10-13, 2006 (ICHE 2006)

ISBN: 0977447405

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EFFECT OF STORM EVENTS ON THE MORPHODYNAMICS OF A TIDALLY-DOMINATED COASTAL ENVIRONMENT

Talal Etri[1] and Roberto Mayerle[2]

ABSTRACT

A state-of-the-art process-based model is applied to hindcast morphological developments resulting from severe storms in a study area on the German North Sea coast. The applied morphodynamic model is based on coupled flow, wave and sediment transport models via a bed evolution model. Owing to the complex geomorphological conditions in the study area, a curvilinear grid with an enhanced grid resolution of about 20m along the coastline was implemented. The effectiveness of the model for simulating morphological changes during storm conditions is demonstrated by a qualitative comparison of model results with measurements. This comparison yields good agreement regarding trends and the order of magnitude of bed elevation changes. Comparisons among the modelled morphological changes resulting from severe storms in the study area serve to improve our understanding of the dominating processes during storm events. The bed elevation changes in the study area due to storms were found to be of the order of several decimetres. It was also found that sudden increases in westerly wind speeds in conjunction with neap tides result in enhanced erosive activity.

Keywords: Short-term morphodynamics; storms; tidal flats; Dithmarschen Bight; North Sea;

1. INTRODUCTION

The effect of storm events on morphodynamics is still poorly understood due to a lack of suitable field data. Despite the fact that the driving forces can nowadays be measured and modelled fairly well, very little is known about the morphological developments resulting from storm events. Besides the fact that bathymetric measurements are expensive, it is very difficult to obtain the necessary field data immediately before and after a storm event. With the recent advancements in numerical models applied to coastal areas, however, simulations of wave-induced currents, sediment transport and bed elevation changes have been successfully carried out, thus offering an alternative means of improving our understanding of the underlying physical processes. In this paper a high resolution process-based model is applied for simulating three severe storm events in the German North Sea. These include the storms in January 1976 and January 1994 as well as the well-documented storm “Anatol” at the beginning of December 1999. Comparisons of the morphological changes during these storm events are analysed under consideration of the different driving forces.

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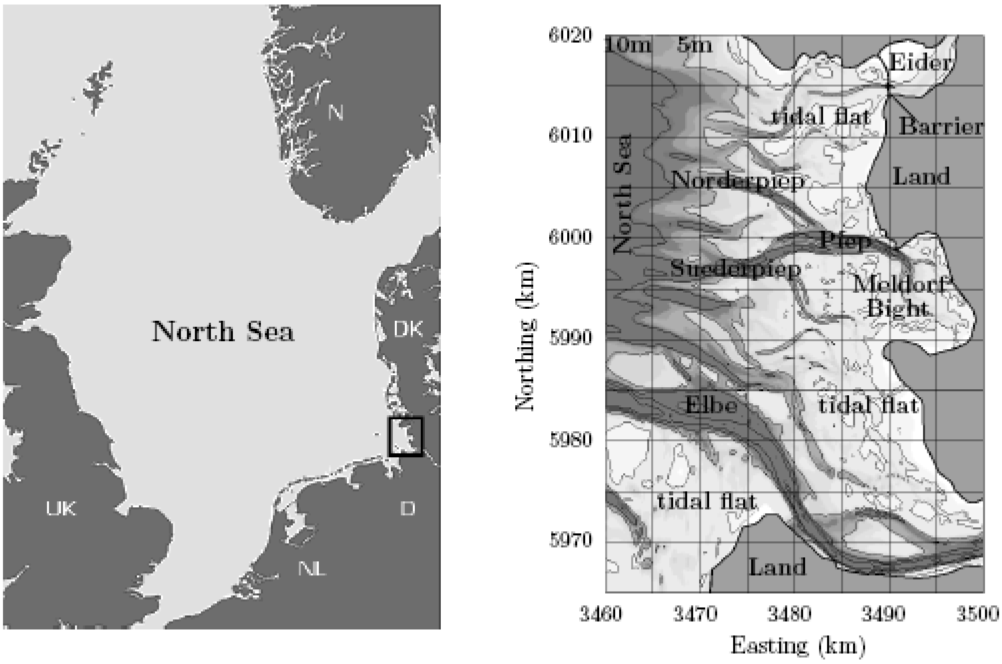
2. INVESTIGATION AREA

The investigation area is the central Dithmarschen Bight on the German North Sea coast (Fig.1). The study area is located about 100 km north of Hamburg between the Eider and Elbe estuaries. The morphology of the study area is dominated by tidal flats, tidal channels and sandbanks over the outer region. Maximum water depths in the channels are of the order of 23m, and approximately 50% of the study area is intertidal. The hydrodynamics and sediment dynamics of the study area are driven by the combined effects of tides, waves and wind-induced currents. Under average conditions the tidal influence is predominant. The semi-diurnal tide has a mean tidal range of 3.2m, varying between 2.4m at neap tides and 4.2m at spring tides. Westerly winds (SW-W) prevail in the study area. Wave heights in the outer region are about 0.8m, with wave-breaking along the outer margins of the area of interest. Maximum current velocities in the tidal channels are of the order of 2m/s. The temporal and spatial variations of current velocities are strongly influenced by the complex bathymetry (see Fig 2). Storm surges can result in water level setups of up to 5m, favouring wave propagation into normally shallow regions. The surficial sediment in the tidal channels and on the tidal flats consists mainly of sands with varying proportions of silt and clay. The grain sizes of the material transported in suspension are up to 5 times smaller than those of mobile sediments on the seabed.



(a) North Sea (b) Dithmarschen Bight

Fig. 1: Location of the investigation area

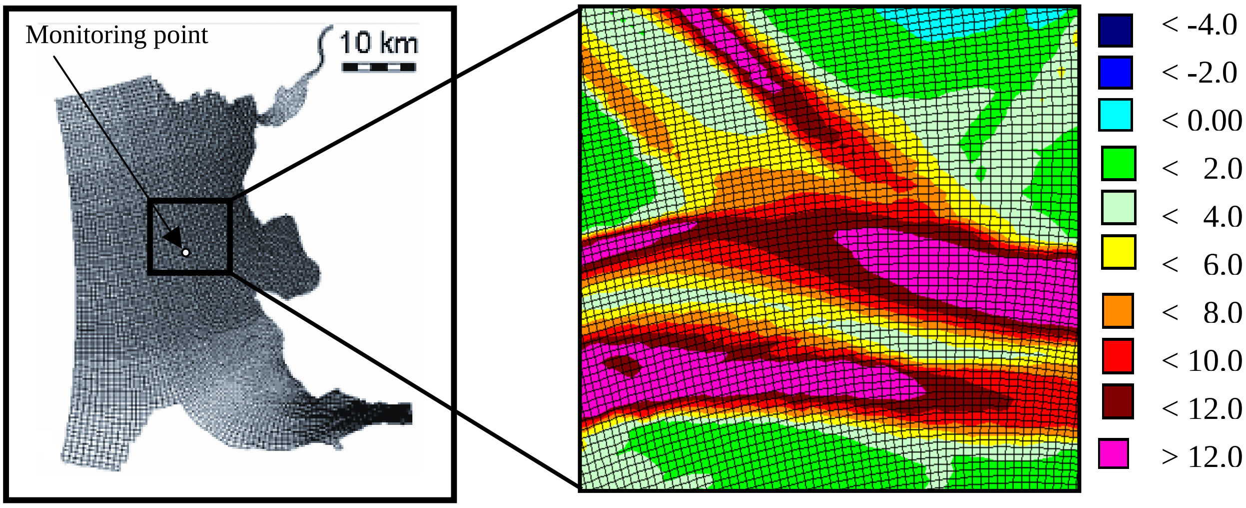
3. PROCESS-BASED MORPHODYNAMIC MODEL

The state-of-the-art two-dimensional depth-integrated process-based model implemented in this study was developed on the basis of the Delft3D Modelling System (Roelwink and Van Banning, 1994). The model covers an area of about 1600 km^2 (Fig. 2a). The model for simulating short-term morphological evolution was created by coupling the process-based models for flow, waves and sediment transport via the bed evolution model. The set-up procedure, results of sensitivity studies for the main numerical and physical parameters, and the calibration and validation of the models against field data are fully documented by e.g. Palacio et al. (2005), Wilkens et al. (2005), Winter et al. (2005) and Wilkens and Mayerle (2005). The simulations of water levels, current velocities, waves and sediment transport were shown to be in good agreement with observations.

In order to correctly represent hydrodynamic conditions during storms, wind conditions over the entire North Sea were taken into account. Therefore the wind data were determined using the synoptic PRISMA model (Luthardt, 1987). The wave model is based on the SWAN wave model (Booij et al., 1999; Ris et al., 1999). The transport model computes sediment dynamics based on the flow and wave parameters determined from the hydrodynamic models. The bed load is derived from the algebraic formulation proposed by Bijker (1971). As the high velocity gradients and small grain sizes of the sediment transported in suspension result in considerable lag effects with respect to local current velocities, the suspended sediment concentration and transport were computed by solving the advection diffusion equation with appropriate bed boundary conditions. The pick-up function proposed by Bijker (1971) was used for non-cohesive sediment material.

The open-sea boundaries for the flow and wave models were obtained according to the nesting sequence shown in Fig. 3. Flow conditions along the open-sea boundaries of the investigation area were obtained by nesting the Dithmarschen Bight Model (DBM) in the German Bight Model (GBM), which in turn is nested in the north-west European Continental Shelf Model (CSM). The open-sea boundary conditions for waves were obtained by nesting the DBM in the larger GBM. The GBM wave model is forced by wind only, neglecting incoming wave energy through the open-sea boundaries (Mayerle et al., 2005). From a sensitivity study it was concluded that the extra computational costs of additionally nesting the GBM in the CSM for improving wave boundary conditions were not justified due to only slight differences in wave parameters along the boundary of the DBM (Wilkens et al., 2005). In the simulations of morphological changes in the study area for the considered storm events, morphodynamic updating was limited to the DBM model.

In this study a higher resolution grid was set up with about 173,000 cells and a grid spacing ranging from 20m near to the coast to as much as 340 m in the outer regions. Short-term morphodynamic simulations were carried out continuously using the Bijker (1967) approach for estimating wave-current interaction and bed shear stresses.



(a) Dithmarschen Bight (b) Grid detail (depth in m)

Fig. 2: Computational grid of the Dithmarschen Bight Model

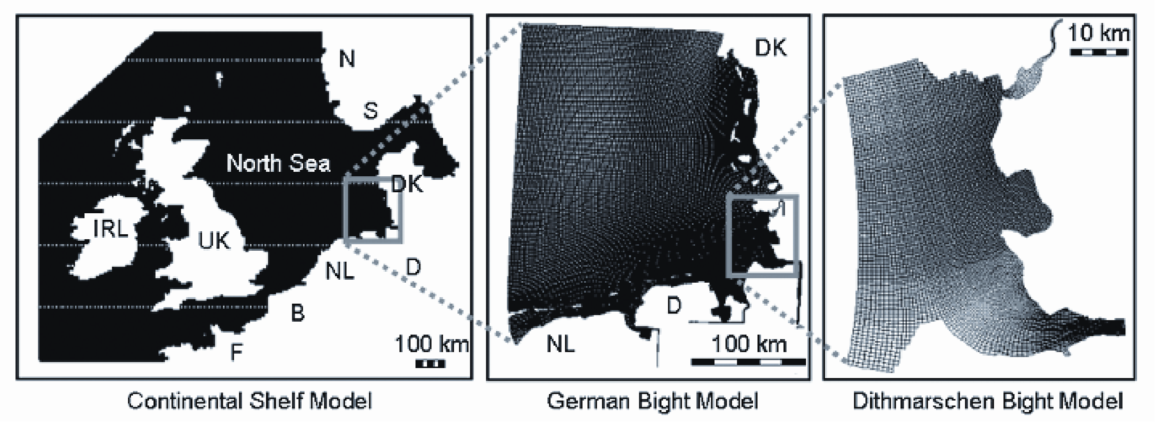


Fig. 3: Nesting sequence from the Continental Shelf Model to the Dithmarschen Bight Model

4. SELECTED STORMS

In order to study the effects of storm events on the morphodynamics of the investigation area, three storm events were selected, namely, the storms of January 1976 and 1994, and December 1999 (Anatol). These storms were selected owing to their historical significance and the amount of destruction caused. Table 1 shows the main characteristics of the selected storm events. Figs. 4 to 7 show the temporal variations of wind speed and direction, significant wave heights, water levels and current velocities, respectively, during the storms in the middle of the study area, as indicated in Fig. 2. The wind data were obtained using the PRISMA interpolation model (Luthardt, 1987). Hydrodynamic data were obtained by means of the nesting sequence shown in Fig. 3. These storms were typical low-pressure areas moving from west to east across the central North Sea, causing strong onshore winds combined with a strong surge. Wind speeds during the selected storms ranged between 20 and 28 m/s, with a mainly westerly wind direction during the 1994 and 1999 storm events. Higher wind speeds and waves occurred during the storm Anatol in 1999.

Table 1: Characteristics of the selected storm events

Storm event	Max wind speed (m/s)	Tidal range (m)	Storm surge (m)	Specification at sea[3]	Probable height of waves (m) (in the open sea, remote from the coast)[3]
January 1976	20	3.5 Spring	4.4	Moderately high waves of larger wavelength	5.5
January 1994	22	3.2 Spring	4.6	High waves	7.0
December 1999	28	2.6 Neap	4.4	Very high waves	9.0

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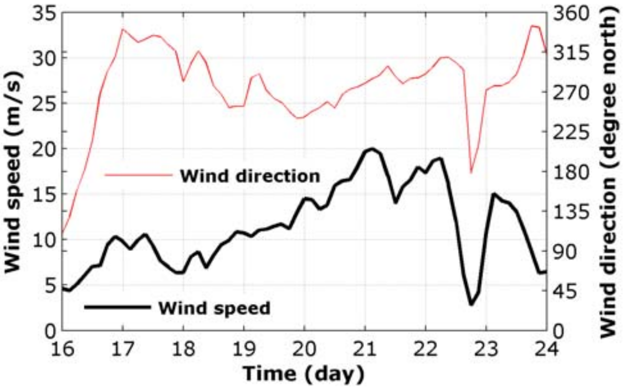
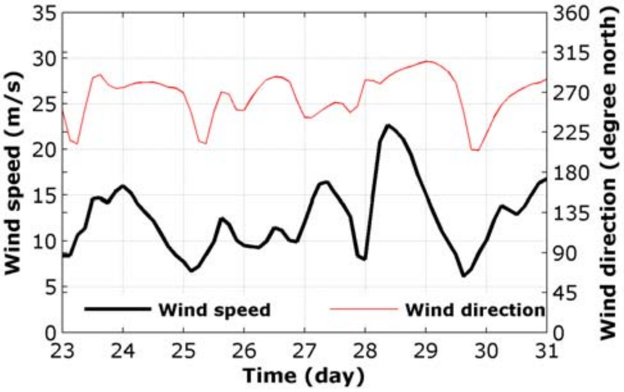
[3] According to the Met Office, UK

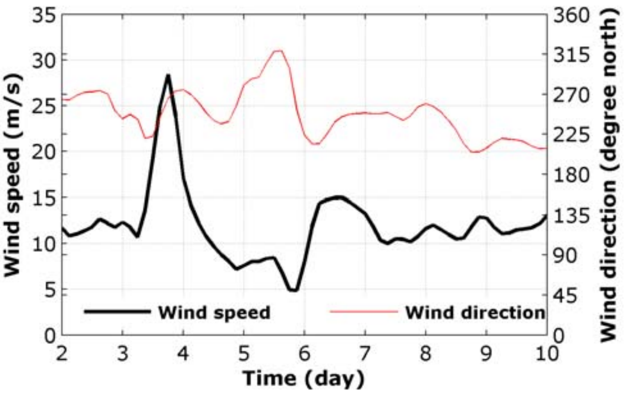
It is pointed out that the increase in wind speed during the January 1976 storm was gradual, as opposed to the sudden increases observed during the storms in January 1994 and December 1999. Moreover, the January 1976 and January 1994 storms occurred in conjunction with a spring tide, as opposed to a neap tide in December 1999.



a) January 1976

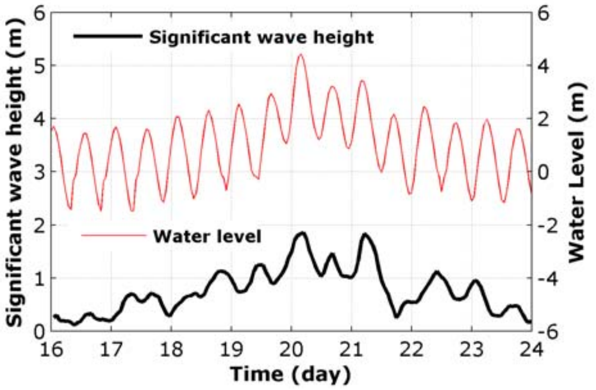


b) January 1994

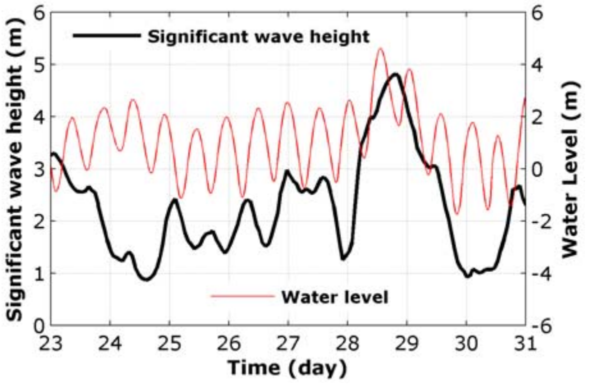


c) December 1999

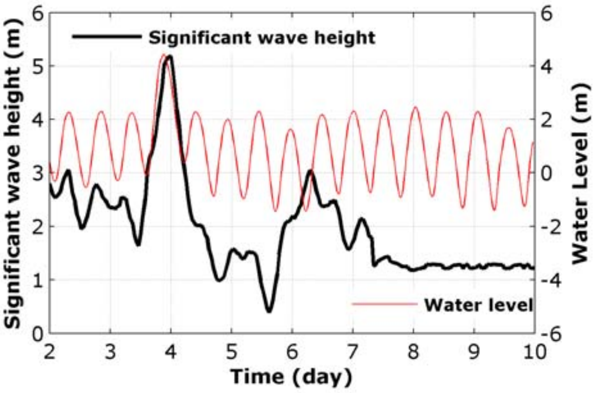
Fig. 4: PRISMA winds



a) January 1976

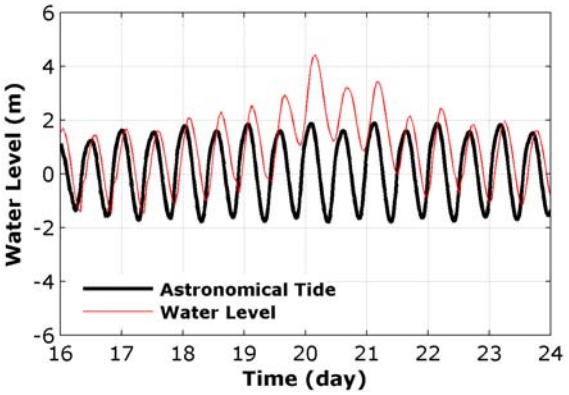


b) January 1994

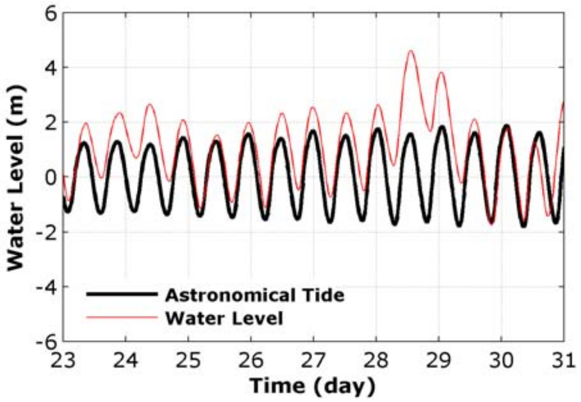


c) December 1999

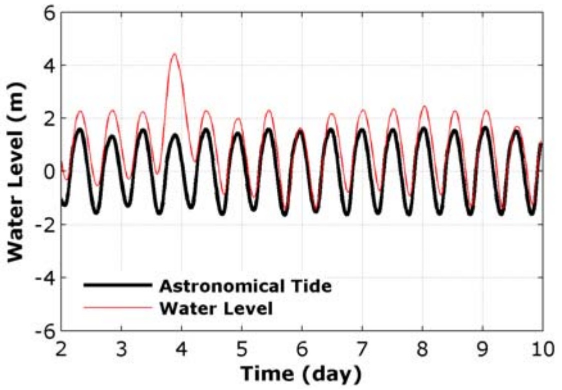
Fig. 5: Modelled wave heights



a) January 1976

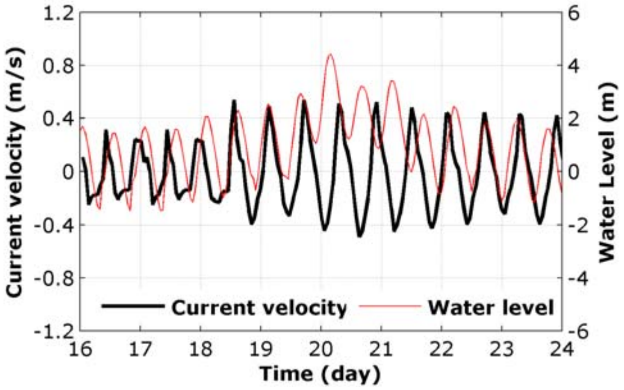


b) January 1994

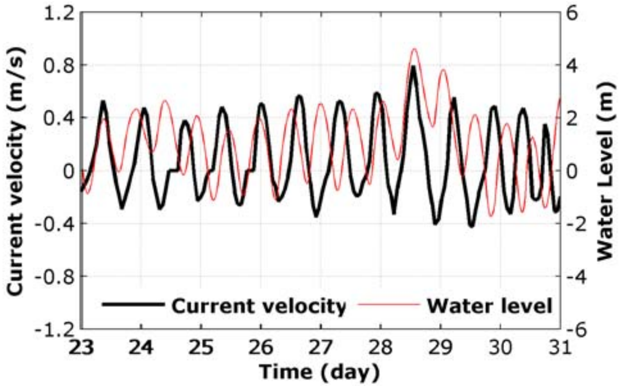


c) December 1999

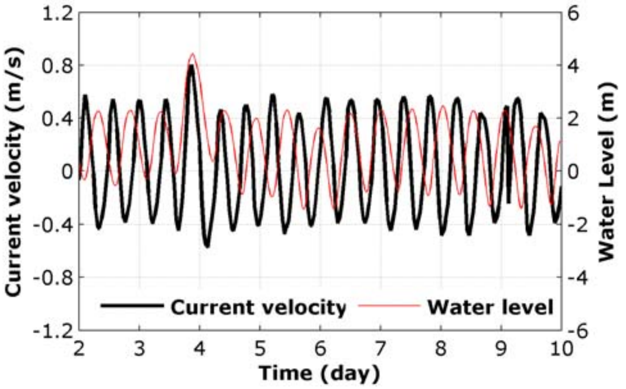
Fig. 6: Modelled water levels



a) January 1976



b) January 1994



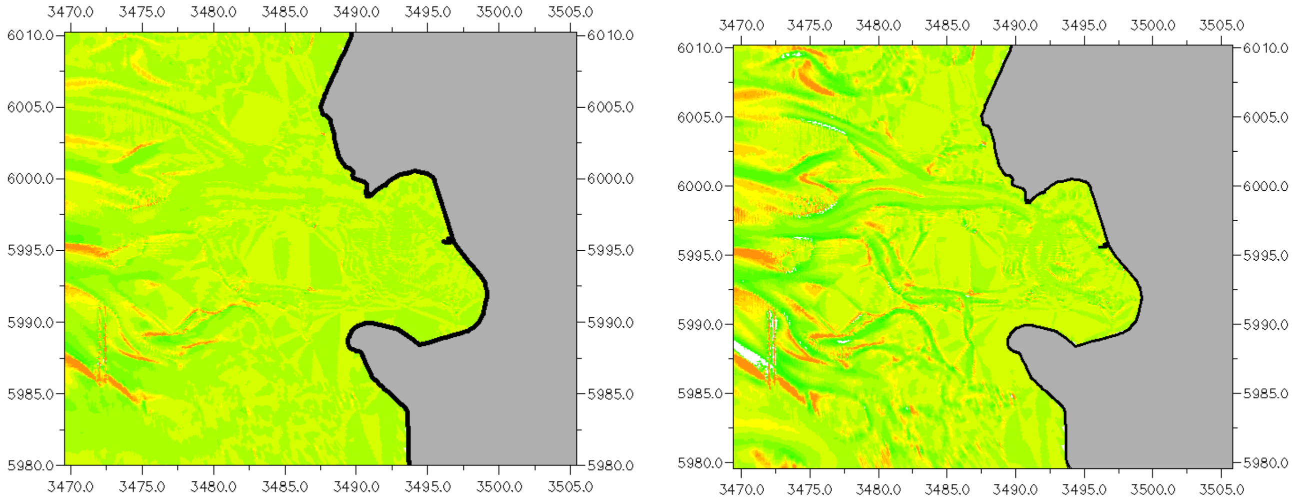
c) December 1999

Fig. 7: Modelled current velocities

5. SIMULATIONS AND RESULTS

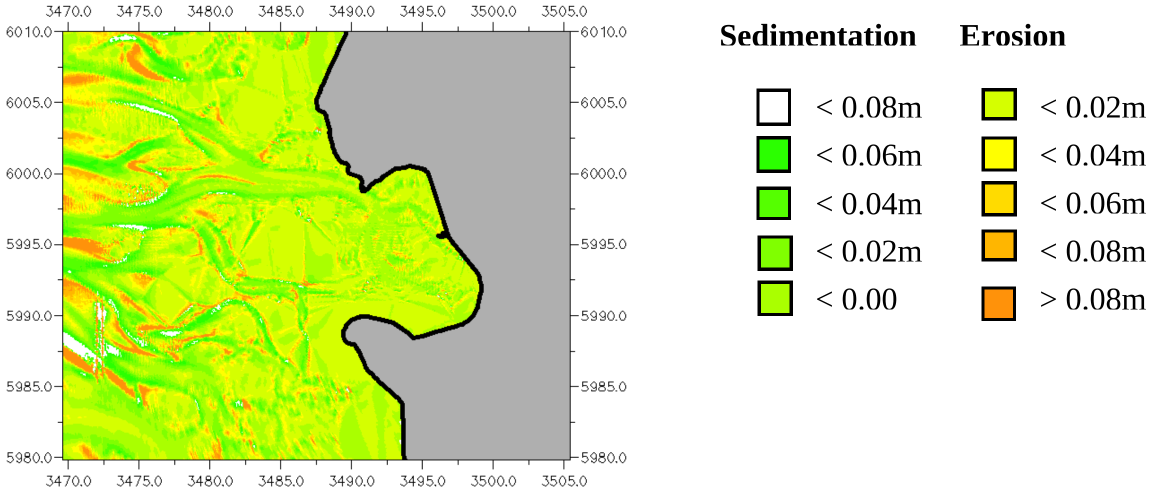
Morphodynamic model simulations covering the selected storm periods were carried out using forced water levels, waves and winds. In order to permit direct comparisons between the results, the same bathymetry (1999) was used initially. The simulations commenced a few days before the storms and covered a period of 15 days. The temporal variation of winds, wave heights, water levels and current velocities during the storms are shown in Figs. 4 to 7, respectively.

The spatial variations of bed elevation changes due to the storms are shown in Fig. 8. It can be seen that erosion takes place primarily in the most exposed areas along the sandbanks and tidal flats predominantly in the outer region accompanied by material deposition in the tidal channels. The changes in bed elevation were found to be of the order of few decimetres. Moreover, it is seen that higher erosion occurs during the December 1999 storm.



a) January 1976

b) January 1994



c) December 1999

Fig. 8: Bed level changes resulting from three storm events

The resulting morphological changes were evaluated according to changes in the wet volume below a reference level integrated over five large areas (listed 1 to 5 in Fig. 9). These areas consist of an exposed sandbank (Tertiussand), three tidal channels (measurement area, Norderpiep and Suederpiep) in the central part of the domain, and a tidal channel (Piep) in the relatively sheltered part of the domain. The bathymetric data for the year 1999 used at the beginning of the simulations was taken as the reference bathymetry in this analysis as follows:

$$V_{rel,i} = \frac{V_i}{V_{1999}} \times 100 \ \%$$

Where: $V_{rel,i}$ = Relative wet volume below MSL of the sub-domain in year i.
V_{1999} = Wet volume below MSL of the sub-domain in 1999.
V_i = Wet volume below MSL of the sub-domain in year i.

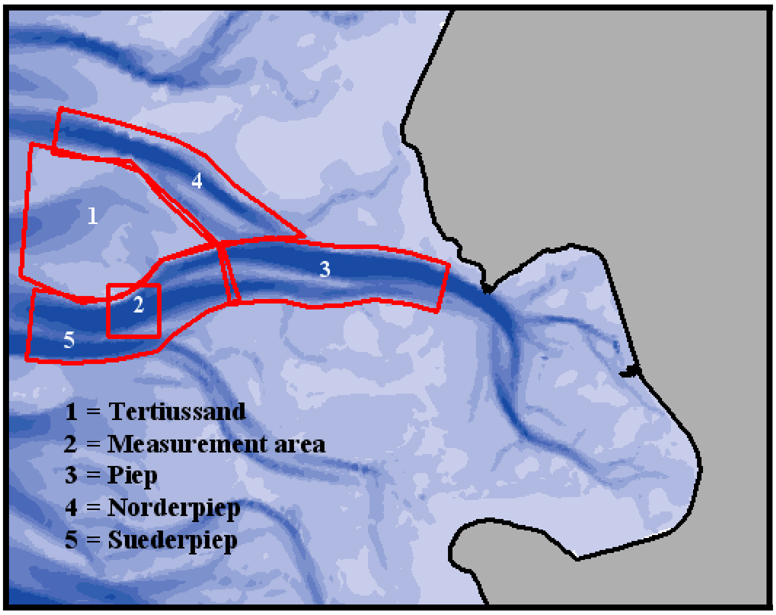
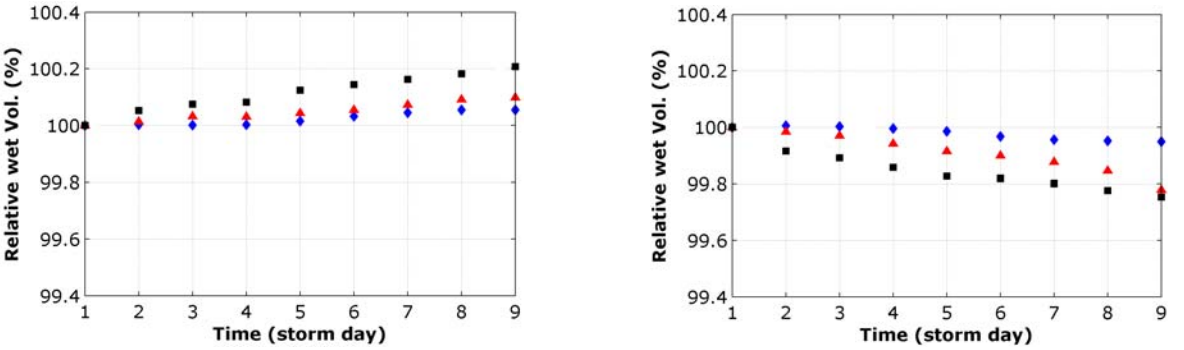
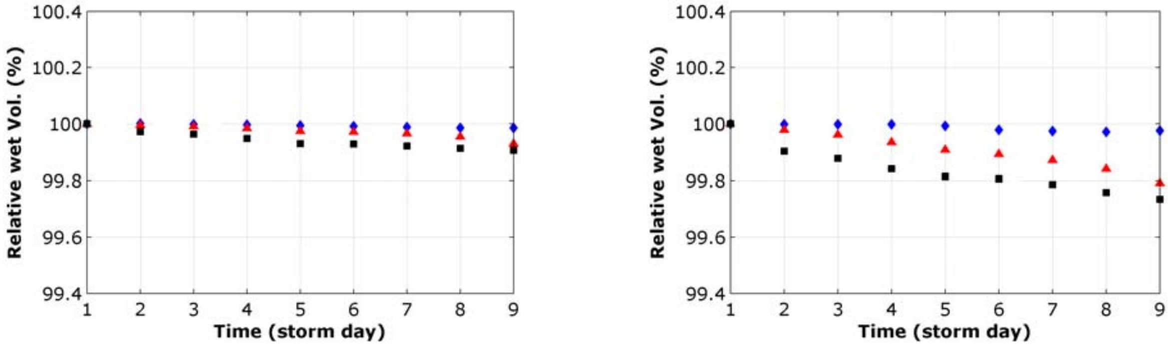


Fig. 9: Location of the sub-domains for bathymetric analysis

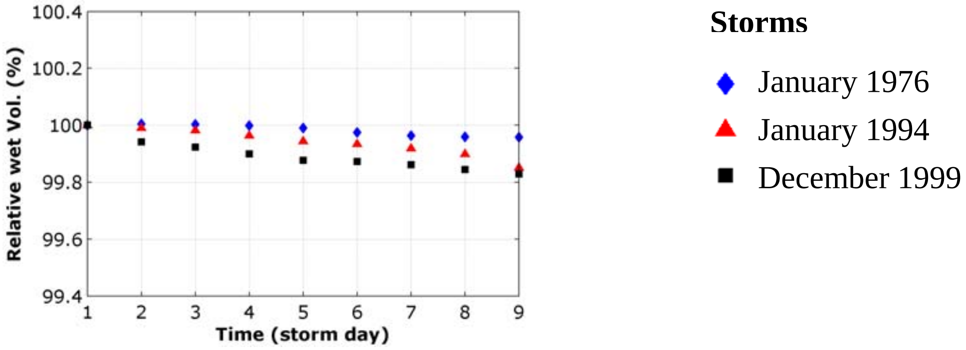
Comparisons of the modelled volumetric changes over the five areas for the three storm events over the simulation period are shown in Fig. 10. The results indicate erosion of the sandbanks accompanied by deposition in the tidal channels. As is evident from Fig. 10, the least and the most significant morphological changes occurred during the storms of January 1976 and December 1999, respectively. This is probably due to the gradual increase in wind speed and higher water levels during the January 1976 event as opposed to the sudden increase in wind speed combined with low water levels in December 1999. The bed elevation changes during the January 1994 storm lie about midway between those resulting from the other two events. Although this storm, which occurred during a spring tide, is also characterised by sudden changes in wind speed, the maximum wind speeds are lower than during the storm Anatol in December 1999.



a) Sub-domain 1 - Tertiussand b) Sub-domain 2 – Measurement area



c) Sub-domain 3 - Piep d) Sub-domain 4 - Norderpiep



e) Sub-domain 5 - Suederpiep

Fig. 10: Relative wet volumes referred to the beginning of the storm event

The simulated changes in bed elevations were found to be about 0.09 m at the edges of the exposed sandbank (sub-domain 1) as a result of the storm Anatol. The trends and order of magnitude of the morphological developments are in close agreement with the results of an analysis by Winter et al. (2005) based on high-resolution multi-beam echo-sounder data collected during the storm Anatol. An evaluation of the bathymetrical changes was carried out for a small-scale area (4 km^2) along the southern bank of the Suederpiep tidal channel (Sub-domain 2 in Fig. 9). This study revealed local sedimentation in the measurement area of up to about 0.6 m and erosion of the tip of the tidal flat to the south-east by as much as 0.5 m over a period of three months, which included the storm Anatol. The model results, that have been obtained from the Anatol simulation at the same measurement area (Sub-domain 2), were about 0.2 m sedimentation and 0.1 m erosion over two weeks period of time.

Over large parts of the surveyed profiles, however, the bed elevation changes were found to be below 0.1 m. Although the changes in bed elevation based on measurements available before and after the storm event occurred over a period of three months, the results permit a rough assessment of the trends and orders of magnitude of the modelled morphological changes.

6. CONCLUSIONS

The effectiveness of a process-based morphodynamic model for hindcasting bed elevation changes during extreme storm events is demonstrated for a tidally dominated area on the German North Sea coast. Good agreement in trends and order of magnitude was obtained between computed and observed morphological changes. Simulations were carried out for three of the most severe storms observed in the area. The results show a tendency towards erosion of the more exposed sandbanks and tidal flats, and deposition of the eroded material in the tidal channels. The morphological changes during the storm events were found to be of the order of few decimetres. The results of the simulations serve to improve our understating of the underlying physical processes during storm events. It was found that sudden increases in westerly wind speeds in conjunction with neap tidal conditions result in the highest erosive activity in the area, whereas gradual changes in wind speed combined with spring tides leads to lower morphological activity.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support of the German Ministry of Education and Research throughout the research project “Modelling of Medium-term Wave climate in the German North Sea (MOSES)”. We also extend our thanks to Dr. Ian Westwood for reviewing and proofreading the draft manuscript.

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