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Die Küste, 69 PROMORPH (2005), 311-337

Morphodynamic Response to Natural and Anthropogenic Influences in the Dithmarschen Bight

By Jort Wilkens and Roberto Mayerle

Summary

In this paper a validated process-based model for the simulation of medium-scale morphodynamics (Wilkens, 2004; Wilkens and Mayerle, 2004; Junge et al., in this volume) is applied to investigate the significance of both natural and anthropogenic influences in the central Dithmarschen Bight on the German Wadden Sea coast. Medium-scale morphodynamics are here defined as changes on the scale of tidal channels, tidal flats and sand banks.

Simulations involving the activation of one or more natural driving forces due to e.g. tidal action, swell waves, wind and locally-generated wind waves were carried out covering a two-year period. A definition of the strength and character of these forces, i.e. associated with tidal range, wave heights and directions, wind velocity and direction, was based on the conditions that were found to be representative for medium-scale morphodynamics (Wilkens, 2004). By comparing the resulting morphological changes it was possible to determine a distribution of the significance of each of the investigated forces. It could be shown that tidal action plays an important role over the entire study area whereas swell influences only the western-most part, and the effects of locally-generated waves are significant mainly in the centre. Typical behaviour of medium-scale morphological features could be related to one or more of these forces.

The influence of storm events on the morphodynamic model results was investigated on the basis of a 'real time' hindcast of a well-documented severe storm in the south easterly part of the German Bight. The boundary conditions were determined with the aid of a sequence of nested and coupled models for flow, waves and sediment transport, starting from a model for the entire North Sea. This approach yielded hydrodynamic results that were in good agreement with available water level and wave measurements. The computed medium-scale morphological changes due to the storm event were found to be rather limited with respect to the average yearly changes.

The computed morphological changes under medium-scale representative conditions were found to be clearly different in character from average medium-scale changes and less than 10 % of computed yearly changes in terms of magnitude. The influence of two land reclamations in 1972 and 1978, respectively, was assessed by evaluating the model results of three consecutive morphodynamic simulations each covering a period of approximately ten years. An analysis of volumetric changes in the inner Meldorf Bight, from which land was reclaimed, showed a tendency towards the development of a new dynamic equilibrium of its medium-scale morphodynamics.

Zusammenfassung

In diesem Beitrag wird ein validiertes, prozess-orientiertes Modell für die Simulation mittelskaliger Morphodynamik (Wilkens, 2004; Wilkens and Mayerle, 2004; Junge et al., diese Ausgabe) beschrieben, mit dem die Signifikanz der natürlichen und anthropogenen Einflüsse in der zentralen Dithmarscher Bucht im Deutschen Wattenmeer untersucht werden soll. Mittelskalige Morphodynamik ist hier definiert als Änderungen in der Größenordnung von Prielen, Watten und Sandbanken.

Simulationen deckten einen Zeitraum von 2 Jahren ab, unter Berücksichtigung einer oder mehrerer natürlicher Antriebskräfte, d.h. Tiden, Wellen und Wind. Durch Vergleiche der morphologischen Änderunge konnte bestimmt werden, in welchen Gebieten welche Antriebskräfte am bedeutendsten waren. Es wurde gezeigt, dass die Tide im gesamten Gebiet einen signifikanten Einfluss auf die Morphodynamik hat; Dünung ist jedoch nur im äußersten Westen von Bedeutung und örtliche Windsee spielt in der Mitte des Gebietes eine Rolle. Die typische Dynamik der mittelskaligen morphologischen Einheiten konnte mit einer oder mehreren Antriebkräften in Beziehung gesetzt werden.

Die Bedeutung von Sturmereignissen wurde auf der Basis einer ‚Echtzeit'-Simulation eines ausführlich dokumentierten Sturmes in der südöstlichen Deutschen Bucht untersucht. Die Randbedingungen wurden bestimmt mit einer Kette von gekoppelten Modellen für Strömung, Wellen und Sedimenttransport, wobei mit einem Modell für die ganze Nordsee angefangen wurde. Dieser Ansatz lieferte hydrodynamische Ergebnisse welche eine gute Übereinstimmung mit verfügbaren Wasserstands- und Seegangsdaten zeigten. Die berechneten mittelskaligen morphologischen Änderungen waren relativ klein im Vergleich zu den mittleren jährlichen Änderungen.

Die berechneten morphologischen Änderungen zeigten ein unterschiedliches Verhalten im Vergleich zum durchschnittlichen mittelskaligen Verhalten, wobei die Änderungen im Umfang weniger als 10 % der jährlichen Änderungen mit mittelskaligen repräsentativen Randbedingungen betrugen. Der Einfluss von zwei Landgewinnungsmaßnahmen wurde mittels einer Volumen-Analyse der Modell-Ergebnisse dreier aufeinander folgender morphodynamischer Simulationen für Zeiträume von je etwa zehn Jahren untersucht. Es wurde eine Tendenz zu einem dynamischen Gleichgewicht der mittelskaligen Morphodynamik in der Meldorfer Bucht festgestellt.

Keywords

Morphology, Medium-Scale, Morphodynamics, Modelling, Dithmarschen Bight, Meldorf Bight, Tidal Flats, Tidal Channels, Storm Event, Land Reclamation, PROMORPH, DELFT3D

Contents

1. Introduction

The present paper describes an investigation of the forces responsible for driving morphological evolution in the central Dithmarschen Bight, a tidally-dominated bight located in the southeast part of the German Bight. A calibrated and validated medium-scale morphodynamic model (WILKENS, 2004; WILKENS and MAYERLE, 2004; JUNGE et al., in this volume) was applied in the investigation. Medium-scale morphodynamics are here defined as changes on the scale of tidal channels, tidal flats and sand banks.

Various medium-scale conditions were defined for forcing the model over a simulation period of two years. By subsequent intercomparison of the model results it was possible to identify several areas with different dominating forces. The observed morphological changes from 1977 to 1999 are correlated to these dominant forces. The complex interactions between individual morphological features, such as e.g. tidal channels, tidal flats and shoals, were analysed considering the dominance of either tidal action, wave action or a combination of both. In addition, morphological development was interpreted in the context of land reclamation undertaken at the beginning of the investigation period, i.e. in 1972 and 1978. Considering the good performance of the applied morphodynamic model as well as the underlying individual process modules for flow (PALACIO et al., in this volume), coupled flow and waves (WILKENS et al., in this volume), and sediment transport (WINTER et al., in this volume), this study provides a good insight into the distribution of the governing processes in the investigated tidal flat area.

2. The Central Dithmarschen Bight

The Dithmarschen Bight, located between the Eider and Elbe estuaries in the southeast part of the North Sea, contains of a number of tidal channels and tidal flats. The bathymetry of the Dithmarschen Bight is shown in Fig. 1. The two major channels Norderpiep and Suederpiep join in the middle of the bight and continue as the Piep channel towards the east, which subsequently spreads over the shallow Meldorf Bight. Maximum water depths in the channels are of the order of 20 m, and up to 15 m near the western edge of the outer tidal flats, e.g. at Tertiussand.

The mean grain sizes of bed material mainly lie in the range of 80 µm to 200 µm whereas the grain diameters of much finer suspended sediment lie between 10 µm and 90 µm. The hydrodynamics of the area are characterised by a tidal range varying between 3.0 m and 3.5 m and maximum wave heights of up to 3.5 m along the western edge of the bight and 0.5 m in

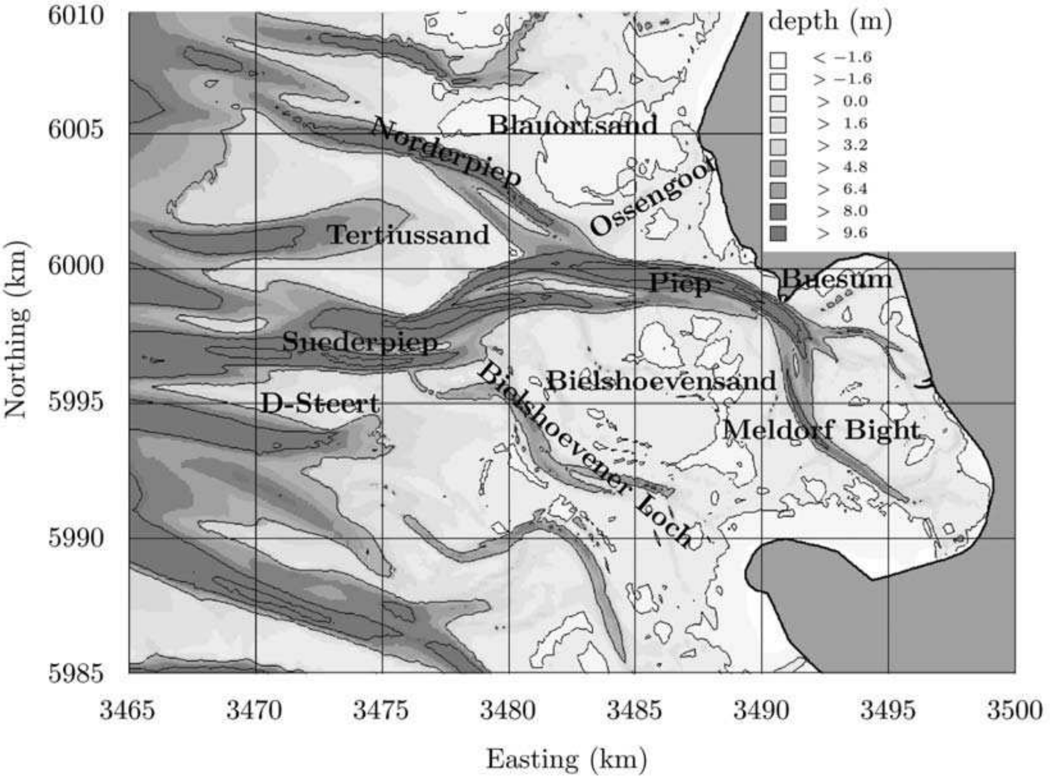


Fig. 1: Bathymetry of the central Dithmarschen Bight in 1977, indicating the main morphological features (WILKENS, 2004)

the eastern part. About 50 % of the study area is exposed during normal low tide. Applying the classification by Hayes (1979), the outer western part falls within the 'slightly tidally-dominated' and the more sheltered eastern part within the 'highly tidally-dominated' classifications, considering mean values of tidal range and wave heights, as indicated in Fig. 2.

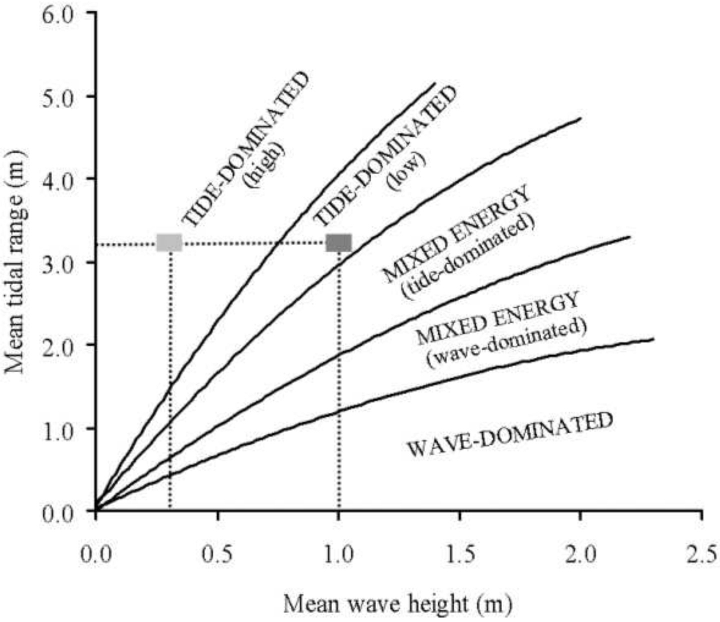


Fig. 2: Classification of tidal areas according to Hayes (1979) for mean tidal range and wave height conditions. The dark and light grey boxes indicate the western and eastern parts of the Dithmarschen Bight, respectively (Wilkens, 2004)

As shown in Fig. 3, two dikes were constructed in 1972 and 1978, respectively, along the eastern boundary of the Meldorf Bight for the purpose of land reclamation. As a result of land reclamation (11.5 km² in 1972 and a further 22.5 km² in 1978) the area of the Meldorf Bight was reduced by approximately 40 %, thereby decreasing the drainage area of the Piep tidal channel.

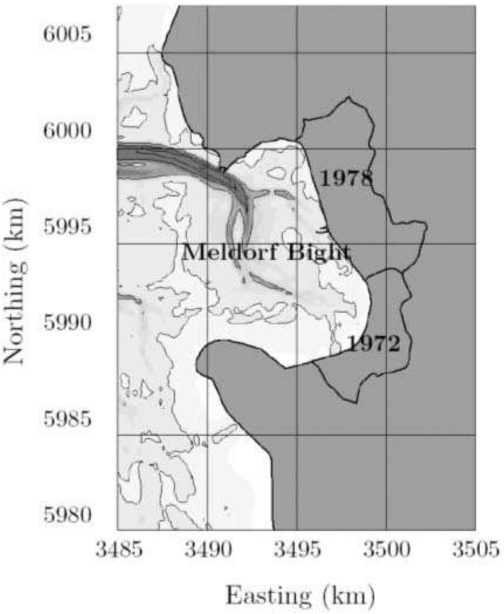


Fig. 3: Dike constructions in the Meldorf Bight in 1972 and 1978 (Wilkens, 2004)

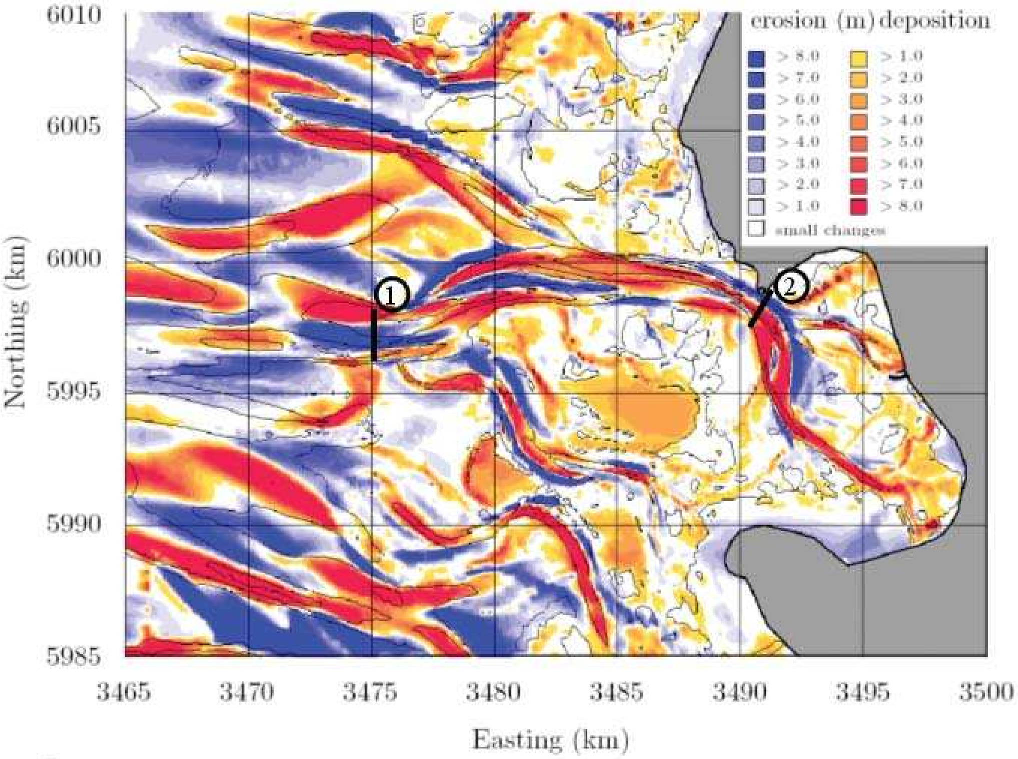


Fig. 4: Sedimentation and erosion in the Dithmarschen Bight between 1977 and 1999. Isolines shown for 1977 bathymetry (WILKENS, 2004). Transects of Figs. 5 and 6 are indicated (1 and 2 respectively)

Fig. 4 shows the observed morphological changes from 1977 to 1999 based on bathymetric measurements carried out by the Federal Maritime and Hydrographic Agency (BSH) in Hamburg and the Office of Rural Developments (ALR) in Husum. The changes on the eastern tidal flats should be interpreted with caution, however, as the density of bathymetric measurements in these areas is sparse. As clearly evident in the figure, the morphology is fairly dynamic. This may be related to the high tidal range and strong wave action along the edge of the outer tidal flats. The observed changes in depth of up to 8 m are mainly due to the migration of channels, flats and shoals. The western edge of the Tertiussand tidal flat is seen to retreat, with transportation of (part of) the eroded material towards the east. The expansion of this tidal flat towards the south and northeast is seen to cause further changes to the Norderpiep and Suederpiep channels. The Norderpiep migrates towards the northeast, as evidenced by parallel stretches of sedimentation and erosion.

Near the 3475 km Easting line the Suederpiep (transect 1 in Fig. 4) shows accretion along its northern bank combined with erosion in the middle of the channel. As may be seen in Fig. 5, this erosion is mainly characterised by a reduction in the size of the submerged bar in the middle of the channel. Erosion of the two sub-channels on either side of the bar is limited due to the presence of a layer of consolidated, fine-grained material ('Dithmarscher Klei', see ASP NETO, 2004; RICKLEFS and ASP NETO, in this volume). The presence of the 'D-Steert' shoal just south of the Suederpiep channel prevents this channel from migrating southwards. This shoal also shows a landward migration, indicated by erosion on its western side and sedimentation on its eastern side. Increased meandering is evident at the S-shaped bend in the Suederpiep east of the 3475 km Easting line while erosion is observed along the northern bank bordering Tertiussand.

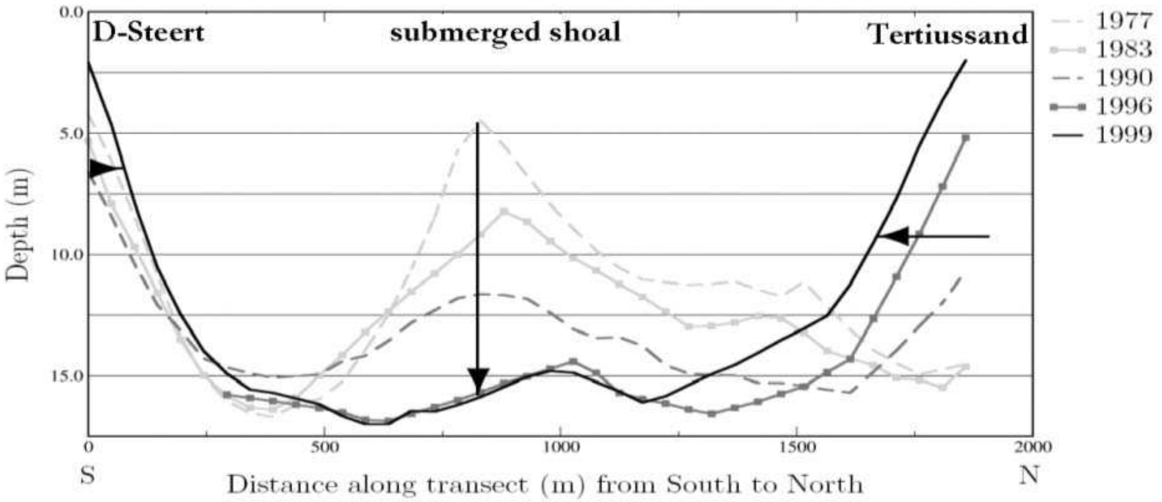


Fig. 5: Changes in the Suederpiep channel profile near 3475 km Easting

The parallel stretches of sedimentation and erosion in the Suederpiep indicate the northward migration of the submerged shoal in this channel. This is accompanied by accretion along the southern channel bank. Eastward of the merging of the Norderpiep and Suederpiep a general decrease in the channel depth is observed. This may be related to the reduced discharge owing to the decreased size of the drainage area resulting from land reclamation in the Meldorf Bight. Near Buesum, where the Piep bends towards the south, meandering of the channel occurs due to sedimentation along the inner bank and erosion on the north-eastern side of the channel. The harbour protection structures at Buesum are seen to limit the north-eastward migration of the channel bank on this side. As the 'Dithmarscher Klei' layer outcrops in the middle of the channel (ASP NETO, 2004; RICKLEFS and ASP NETO, in this volume) the channel cross-section can only be maintained by a steepening of the north-eastern bank, as shown in Fig. 6 (transect 2 in Fig. 4). An eastward migration of the Piep channel is observed south of Buesum. This is accompanied by an overall sanding-up of the minor channels in the Meldorf Bight with general accretion on the tidal flats in this area. It is likely that both effects are a result of the reduced drainage area caused by land reclamation.

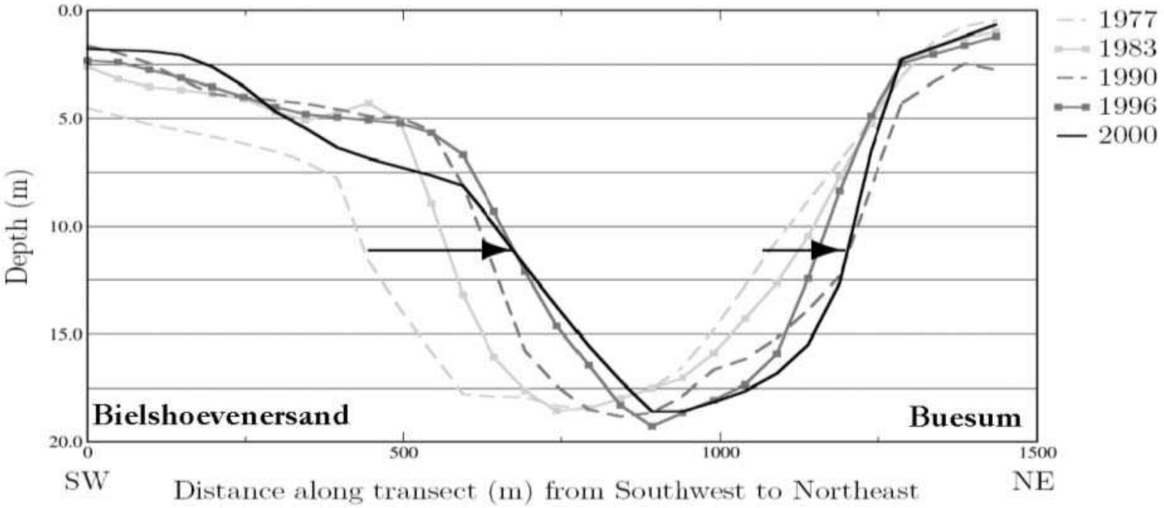


Fig. 6: Changes in the Norderpiep channel profile near Buesum

3. The Morphodynamic Model

The morphodynamic model applied in this investigation was calibrated and validated on the basis of over 20 years of bathymetric measurements. The morphological evolution during medium-scale periods of up to ten years was simulated to evaluate and improve model performance. A comparison between model results and measurements was made on the basis of a visual comparison of sedimentation and erosion patterns as well as a volumetric analysis of several sub-domains. This is described in detail in WILKENS (2004) and JUNGE et al. (in this volume). The model was set-up using the Delft3D modelling system developed by Delft Hydraulics in the Netherlands (ROELVINK and VAN BANNING, 1994).

Following coupling of the process modules for flow, waves and sediment transport, the morphodynamic 'shell' was defined. Input filtering and model reduction is performed in the morphodynamic shell. Forcing of the model with respect to representative tidal, wave and wind climates conditions is determined in the input filtering procedure. These conditions are imposed on the open boundaries of the process modules, i.e. the free surface and the lateral boundaries towards the open sea. Model reduction is achieved by morphodynamic time-stepping, i.e. the results of a single tidal cycle are extrapolated over a varying time step based on model stability criteria. These approaches significantly speed up morphodynamic simulations while conserving realistic model results of good quality. For details the reader is referred to WILKENS (2004) and JUNGE et al. (in this volume).

4. Dominant Medium-Scale Processes

The dynamics of the central Dithmarschen Bight are not directly influenced by the discharges of the rivers Elbe and Eider as extensive tidal flats separate these systems from the study area. Even under storm conditions there is no evidence that an interaction takes place over these shallow areas. The possible driving forces for morphological evolution are thus restricted to tidal action, wave action and the effects of wind. Wave action may be present due to incoming swell from remote areas or as a result of local wave generation. Wind effects may include the afore-mentioned wind-induced wave generation as well as the forcing of wind-driven currents. The enhanced wave action and currents may initiate additional sediment transport and change the patterns of sediment dynamics.

Model sensitivity studies have shown that although wind-driven currents may develop on the shallow tidal flats, the effect of wind-driven currents on medium-scale morphodynamics is rather limited. Attention was thus focussed on the morphodynamic significance of tidal action, swell and locally-generated waves in the present study.

These forces and their effects may interact. For example, sediment brought into suspension by wave action may be transported by tidal currents. This interaction may result in significant morphological changes which would not otherwise have occurred through wave action or tidal currents alone. It was thus important in the model investigations to carefully consider which processes should be included in or excluded from the simulations in order to properly assess the significance of each of the processes under examination.

5. Model Investigations and Results

Several morphodynamic simulations were carried out covering a period of two years. This period was determined to be sufficiently long to make initialisation effects negligible relative to the changes induced by the imposed forcing on a medium scale. Moreover, the computation time required for a two-year simulation was found to still lie within practical limits. The initial bathymetry for these simulations was based on bathymetric measurements made in 1977. This bathymetry also formed the initial bathymetry for calibrating the morphodynamic model, thus enabling the results of a variety of sensitivity and calibration simulations to be confidently used for a more conclusive interpretation of the results of the simulations discussed in the following.

A comparison of computed sedimentation and erosion patterns served as a means of assessing the model performance. In the first instance a reference simulation was performed in which representative conditions determined from model calibration and validation simulations were imposed. The sedimentation and erosion patterns resulting from this reference simulation are shown in Fig. 7.

In the western part of the domain relocation of sediment can be seen both in the channels and on the tidal flats. The largest changes are generally along channel banks, indicating a change of slope or a migration of these banks. Towards the east, a gradual limitation of morphological changes to the channels is evident. In the Meldorf Bight east of Buesum (see Fig. 1) only slight sedimentation near the channels is seen, accompanied by erosion in the Piep channel.

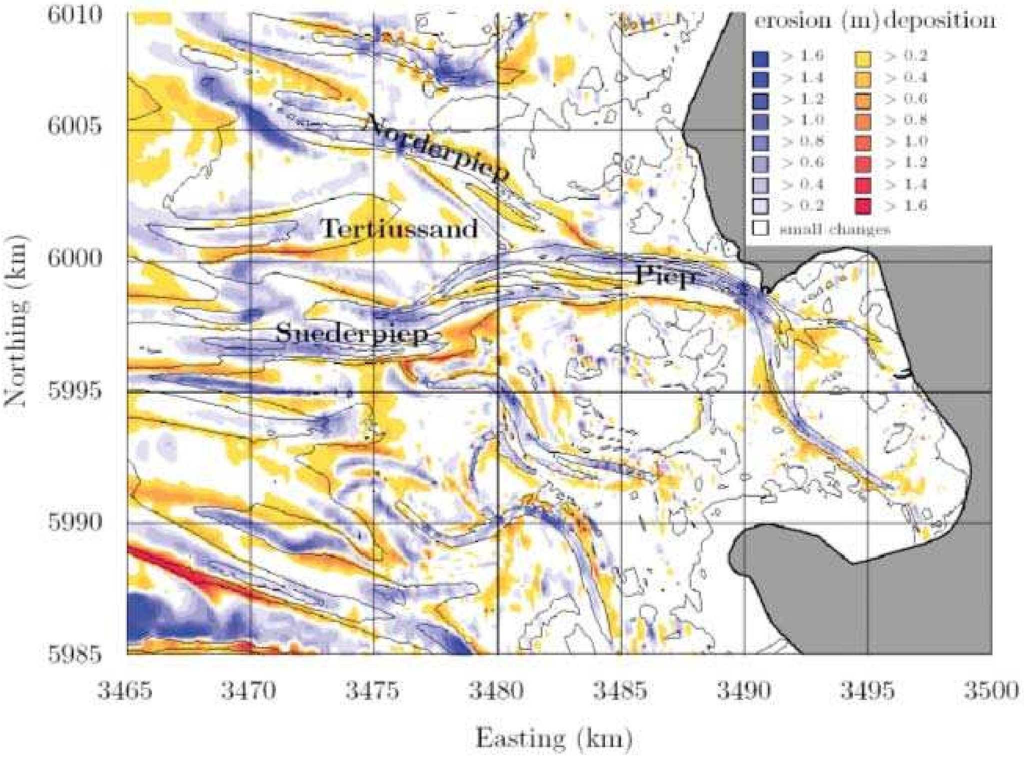


Fig. 7: Computed morphological changes from 1977 to 1979 based on morphologically representative tidal, swell and wind conditions (WILKENS, 2004). Isolines shown for 1977 bathymetry

5.1 Significance of Tidal Effects on Morphodynamics

With swell and wind forcing excluded from the boundary conditions in the morphodynamic simulation, the morphological changes shown in Fig. 8 result. These are caused by the tide alone and are characterised by high erosion in significant parts of the tidal channels and deposition of sediment on the tidal flats. The most prominent differences are indicated by the letters A to D in Fig. 8.

In order to compare the results of both simulations the positive and negative differences between the final bathymetries were represented using a graded colour scale, as shown in Fig. 9. Blue areas indicate that the computed sea bed is lower for the simulation without wind and swell than for the reference simulation (negative differences). It should be noted that the colour scale of Fig. 9 differs from that of the sedimentation and erosion plots of Fig. 8.

At location A the stretch of high erosion is replaced by accretion. The channel running through the Tertiussand tidal flat (see Fig. 1) shows enhanced erosion compared with the reference simulation results. At location B to the south of this channel overall accretion is observed, which is contrary to the erosion computed in the reference simulation. The southward expansion of Tertiussand near location B is no longer evident. At location C near the eastern edge of Tertiussand a progression of this tidal flat towards the northeast no longer occurs in the simulation without swell and wind action. The stretch of erosion given by the reference simulation is now replaced by sedimentation. An extension of Tertiussand towards the west also occurs due to increased deposition. In the neighbouring channels Norderpiep and Suederpiep a slight increase in erosion can be seen. Sedimentation at location D is found to decrease when wind and swell effects are excluded. This indicates that when swell and wind are absent as driving forces, the channels are larger than in the reference case.

From Fig. 9 it is clearly seen that the differences between the results of the two simulations are more pronounced in the western part of the study area. This result is in keeping with the fact that this area is closest to the seaward boundary and is thus mostly affected by wave action. In contrast to the latter, only small differences are found in the sheltered part of the investigation area to the east of the 3485 km Easting line. A general deepening of the tidal channels is observed throughout the study area whereas the submerged bars in the larger channels show accretion. The development or extension of a number of secondary channels is found to occur at various locations on the adjacent tidal flats.

Summarising the results, it is concluded that pure tidal forcing tends to enhance the development of channels as well as bars and tidal flats. The tidal currents are concentrated in the channels, where they encounter the least resistance due to bottom friction. This means that relatively high shear stresses develop in the channels, thus causing them to deepen. In contrast to this, accretion tends to occur in the remaining shallow areas where shear stresses are far lower. Moreover, the absence of wave attack along the western tidal flats enables them to extend in the seaward direction. Owing to the virtual absence of differences between the simulation results in the most easterly part of the study area it is concluded that this part is tidally-dominated.

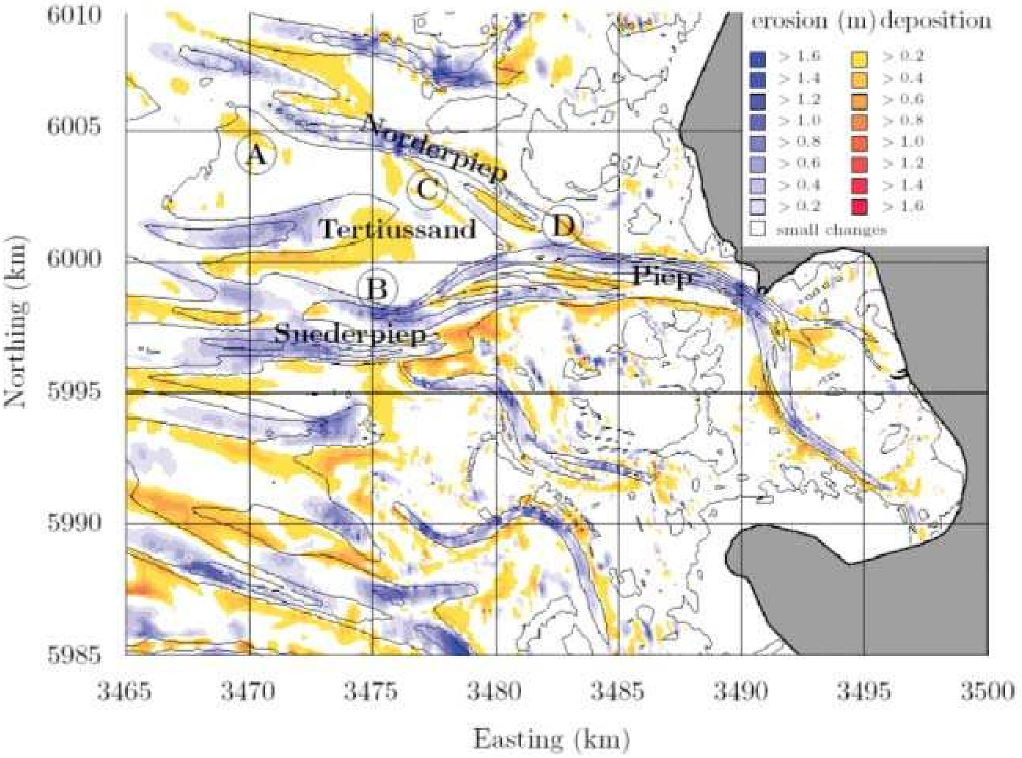


Fig. 8: Computed morphological changes from 1977 to 1979 – tides only. Isolines shown for 1977 bathymetry

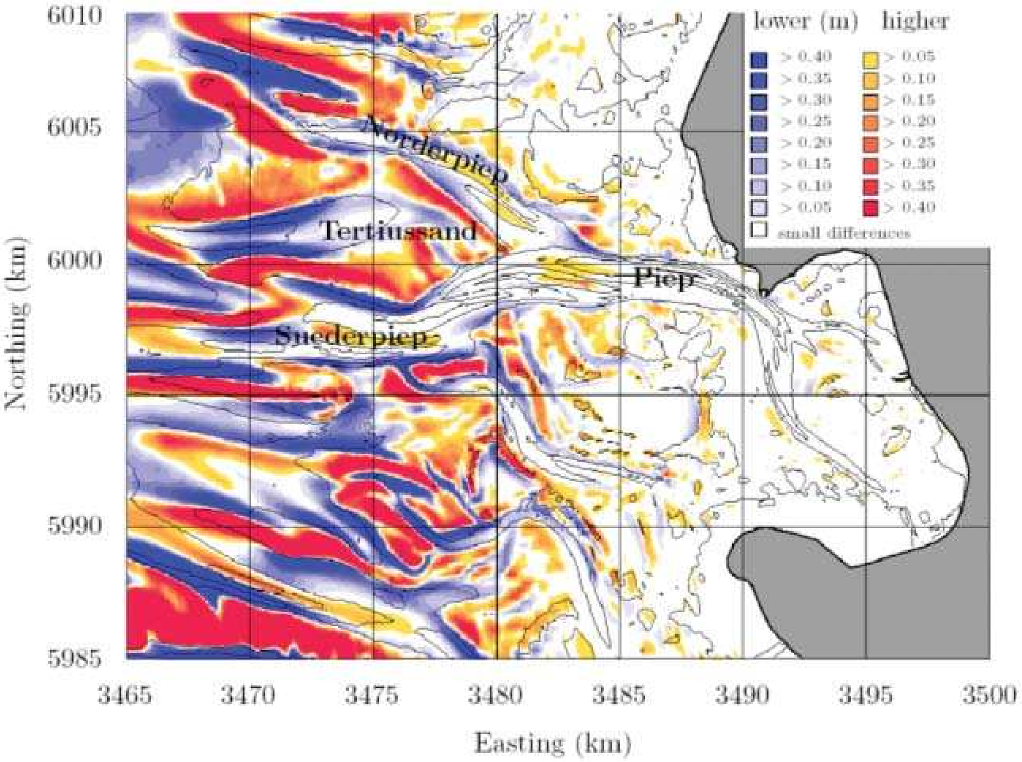


Fig. 9: Differences between the final bathymetries of the reference simulation and the simulation without imposed swell and wind conditions. Negative differences between the latter and former are indicated in blue. Isolines shown for 1977 bathymetry

5.2 Significance of Swell Effects on Morphodynamics

In order to evaluate the significance of imposed swell conditions the results of the simulation without swell (i.e. with tidal and local wind forcing only) were compared with the results of the reference simulation. Similar to the previous investigation, the resulting sedimentation and erosion patterns were compared. These are shown for the simulation without swell in Fig. 10. Adopting the same graded colour scale representation as in the previous subsection, the differences in the final bathymetries are shown in Fig. 11.

As may be seen in Fig. 10, the erosion near location A is now replaced by accretion. Near location B on the north-western side of Tertiussand a similar effect is observed; compared to the reference simulation, in which erosion was computed at this location, a large patch of sedimentation is now evident. The narrow stretch of erosion along the Norderpiep channel computed in the reference simulation is now reduced in size. In the Norderpiep itself far more erosion is computed in the simulation without swell. The progression of the edge of Tertiussand in the north-eastern direction is not distinguishable in Fig. 10. Less erosion is seen directly east of location C while the erosion computed in the reference simulation west of location C has completely disappeared. The southward migration along the southern edge of Tertiussand obtained under reference conditions is no longer present in the results of the simulation without swell.

Differences between the final bathymetries (Fig. 11) are only found in the western part of the study area. It is also noted that the part of the study area in which differences now occur (approximately along the 3480 km Easting line) is shifted further westward compared to the simulation results with tidal forcing only (cf. Fig. 9).

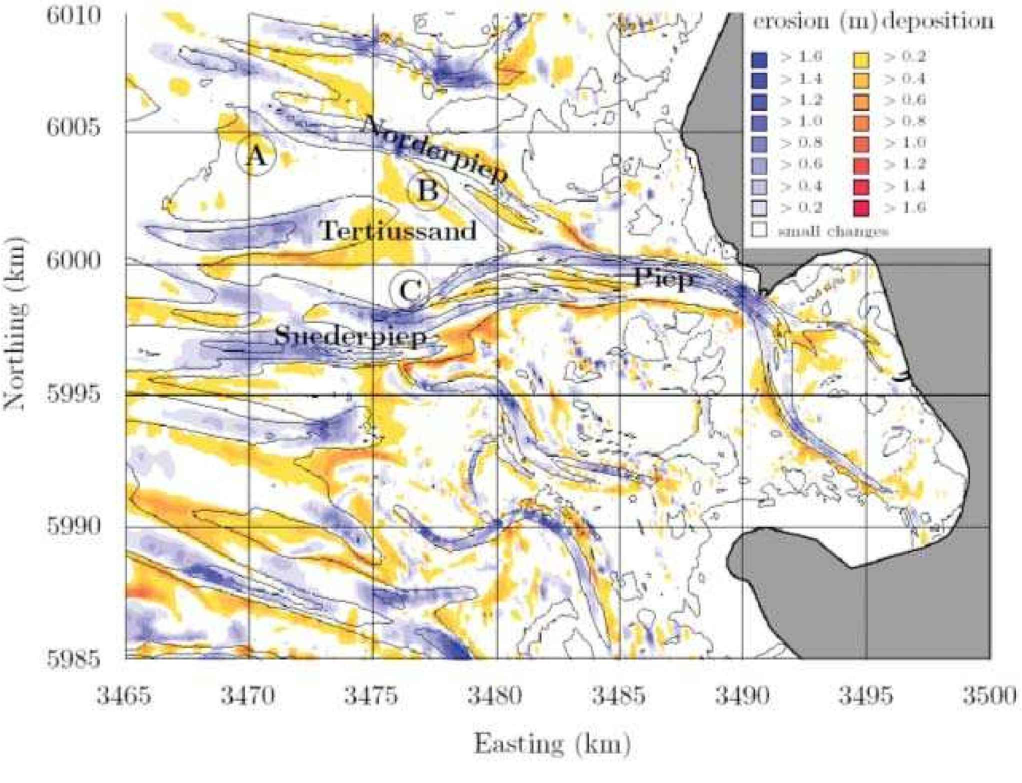


Fig. 10: Computed morphological changes from 1977 to 1979 (without swell). Isolines shown for 1977 bathymetry

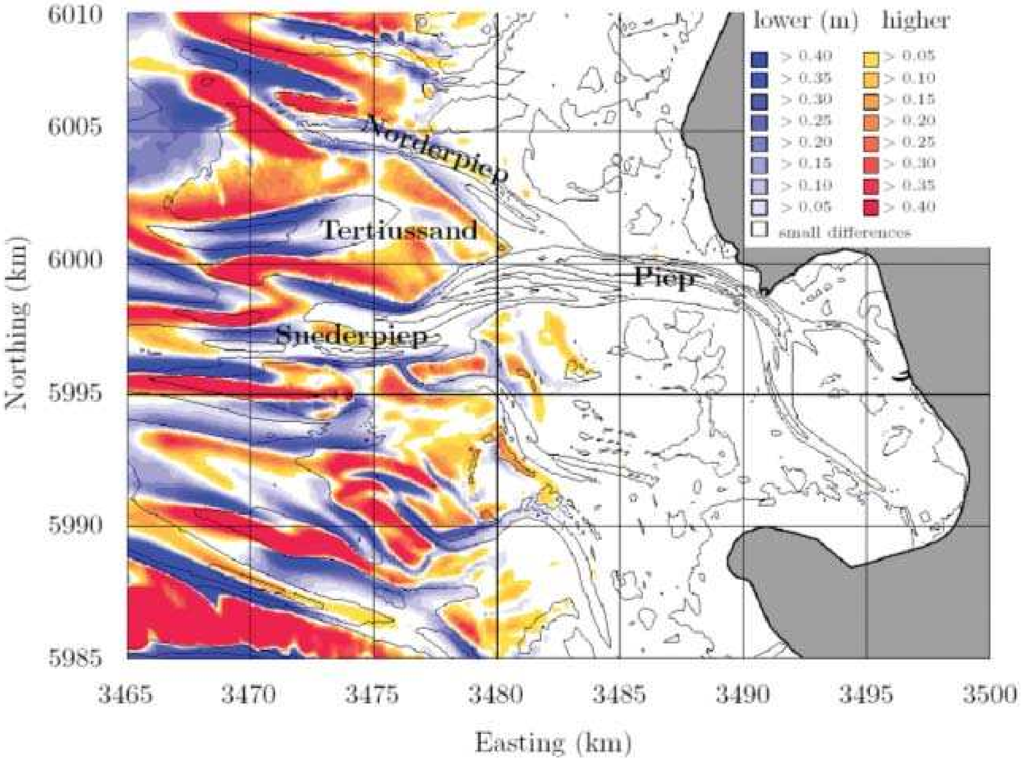


Fig. 11: Differences between the final bathymetries of the reference simulation and the simulation without imposed swell. Negative differences between the latter and former are indicated in blue. Isolines show for 1977 bathymetry

Summarising the results, it may be concluded that swell mainly influences the morphodynamics of the western part of the investigation area, particularly in the region of Tertiussand and its adjacent channels. This result is not surprising, as it is known from observations that most swell waves break on the outer tidal flats. The effects of swell are mainly evidenced by a reduction in height of the shallower areas combined with a reduction in depth of the neighbouring deeper areas. It would appear that sediment is stirred up by swell mainly in the wave-breaking zones where depths decrease rapidly, and then transported to deeper areas by tidal and wave-induced currents.

5.3 Significance of Local Wind Effects on Morphodynamics

In order to investigate the significance of local wind on the morphodynamics of the study area a simulation was carried out in which the local wind was greatly reduced compared to the representative conditions imposed in the reference simulation. It was necessary to impose a very mild wind climate for stability reasons, especially regarding swell wakes behind dry shoals or tidal flats. As local wind conditions are imposed in both the flow and wave modules, the reduced wind climate affects wind-induced currents as well as local wave generation. Further effects may be expected due to influencing of the incoming swell waves. The resulting sedimentation and erosion patterns over the two-year simulation period are shown in Fig. 12. Fig. 13 shows the differences between the final bathymetries of the reference simulation and the simulation without local wind. As before, the areas coloured in blue indicate negative differences in seabed levels between the simulation without local wind and the reference simulation.

The main differences on Tertiussand are the slightly lower depositions near locations A and B, and the reduced erosion along its north-western and south-eastern edges. Several less pronounced differences are found along the main channels. The Norderpiep shows less sedimentation along its north-eastern bank while the Suederpiep exhibits less sedimentation along its southern bank. A comparison of the final bathymetries shown in Fig. 13 reveals that the differences are mainly confined to the middle of the investigation area. Furthermore, these differences are much smaller than those observed in the difference plots of the previous Sections (cf. Fig. 9 and Fig. 11).

Summarising the results, it is concluded that local wind has a relatively limited effect on the morphodynamics of the study area, being mainly restricted to the middle of the domain between the 3475 and 3485 km Easting lines. The fact that the model results on the eastern tidal flats bordering the Piep channel are not appreciably different indicates that the fetch in these areas is too small to produce significant wind-induced currents or local wave generation. Although this is true for the imposed representative tidal cycle, it is noted that this may not be true for significant water level set-up during storm surges. In the middle of the study area, however, where water depths are greater and fetches are longer, the above-mentioned wind-induced currents and waves do become important with regard to morphological evolution. Further towards the west, the influence of the local wind is again very limited. It would appear that the dominance of swell in this area is so large that the presence or absence of local wind does not significantly affect the model results.

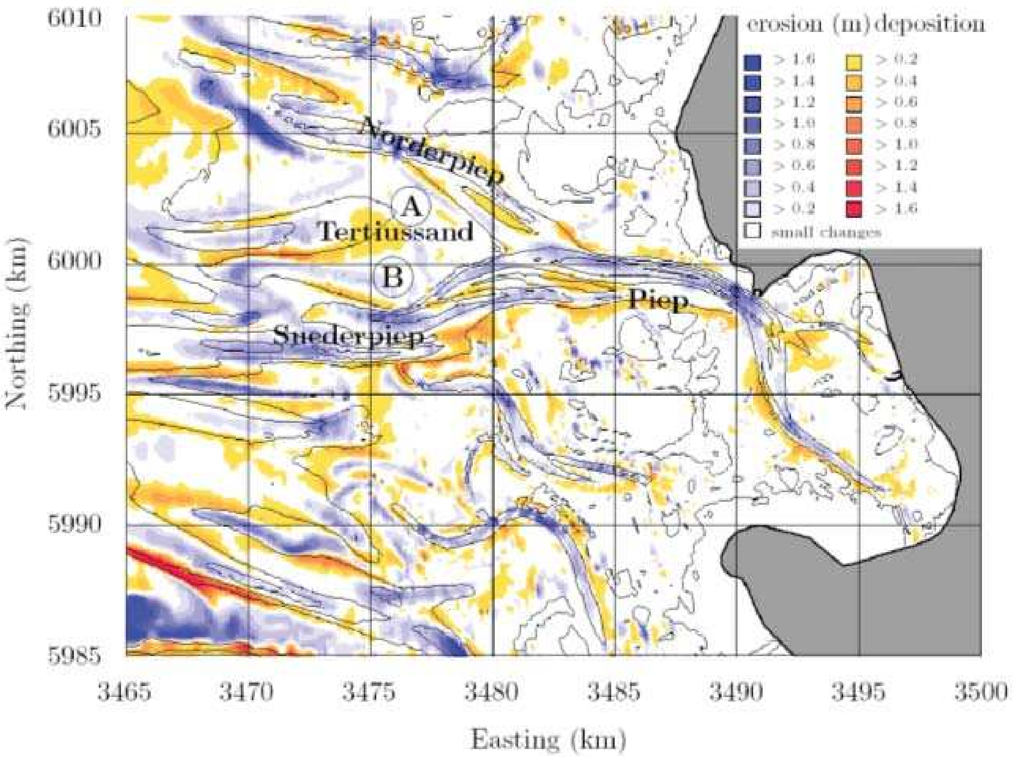


Fig. 12: Computed morphological changes from 1977 to 1979 (without wind). Isolines shown for 1977 bathymetry

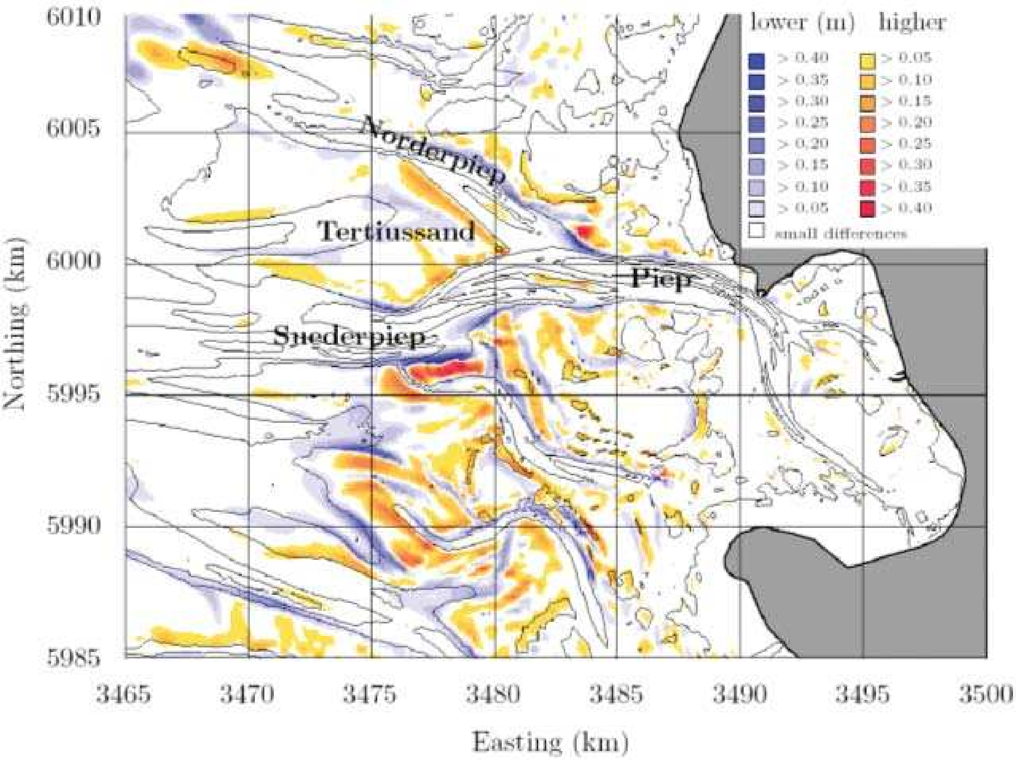
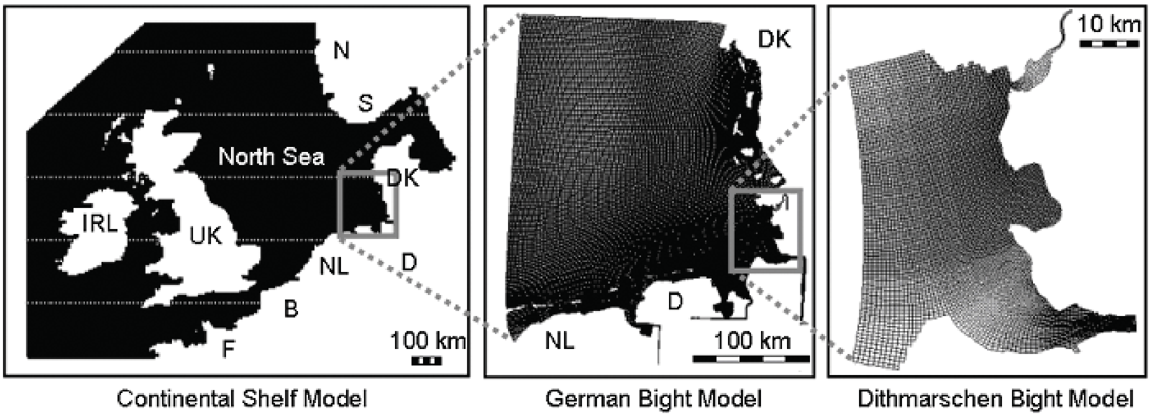


Fig. 13: Differences between the final bathymetries of the reference simulation and the simulation without imposed wind. Negative differences between the latter and former are indicated in blue. Isolines shown for 1977 bathymetry

5.4 Significance of Storm Events on Morphodynamics

In order to evaluate the significance of storms on the morphodynamics, an approach somewhat different from the afore-described approach has been used. To represent the hydrodynamic conditions during a storm the wind conditions over the entire North Sea have been taken into account. The nesting sequence of Fig. 14 was applied to generate open boundary conditions for the Dithmarschen Bight Model, where these wind conditions were imposed in each of the models.



Continental Shelf Model German Bight Model Dithmarschen Bight Model

Fig. 14: Nesting sequence from the Continental Shelf Model towards the Dithmarschen Bight Model

The wind data have been taken from the synoptic PRISMA model (LUTHARDT, 1987). Starting from the German Bight Model, the flow models have been coupled to modules for waves and sediment transport. Nesting was applied for both modules to provide open boundary conditions for the Dithmarschen Bight Model. Morphodynamic updating has been limited to the latter model, leading to model results concerning the morphological changes induced during the considered storm period.

The morphological impact of the storm event has been compared to computed morphological changes over an entire year on the basis of morphologically representative boundary conditions (WILKENS, 2004; JUNGE et al., in this volume).

5.4.1 The Storm Event Anatol

The storm event selected for the evaluation was the relatively well-documented storm "Anatol" in the beginning of December 1999 that formed one of the most severe storms of the last decade (DWD, 2000). Anatol was a typical low pressure area that moved from west to east across the central North Sea and caused strong onshore winds combined with a storm surge of approximately 2.7 m above MHW at Buesum (refer to Fig. 1). The wind fields in Fig. 15 show the path and intensity of the storm across the North Sea. It shows increasing wind speeds after December 3rd, 09.00 UTC, with a gradual shift in direction from west-southwest to west. When the low pressure centre passes the wind velocities reach their maximum value of approximately 30 m/s (11 Beaufort) and the wind direction is west-northwest. Once the low pressure area has passed the wind velocities decrease and the direction changes back to west.

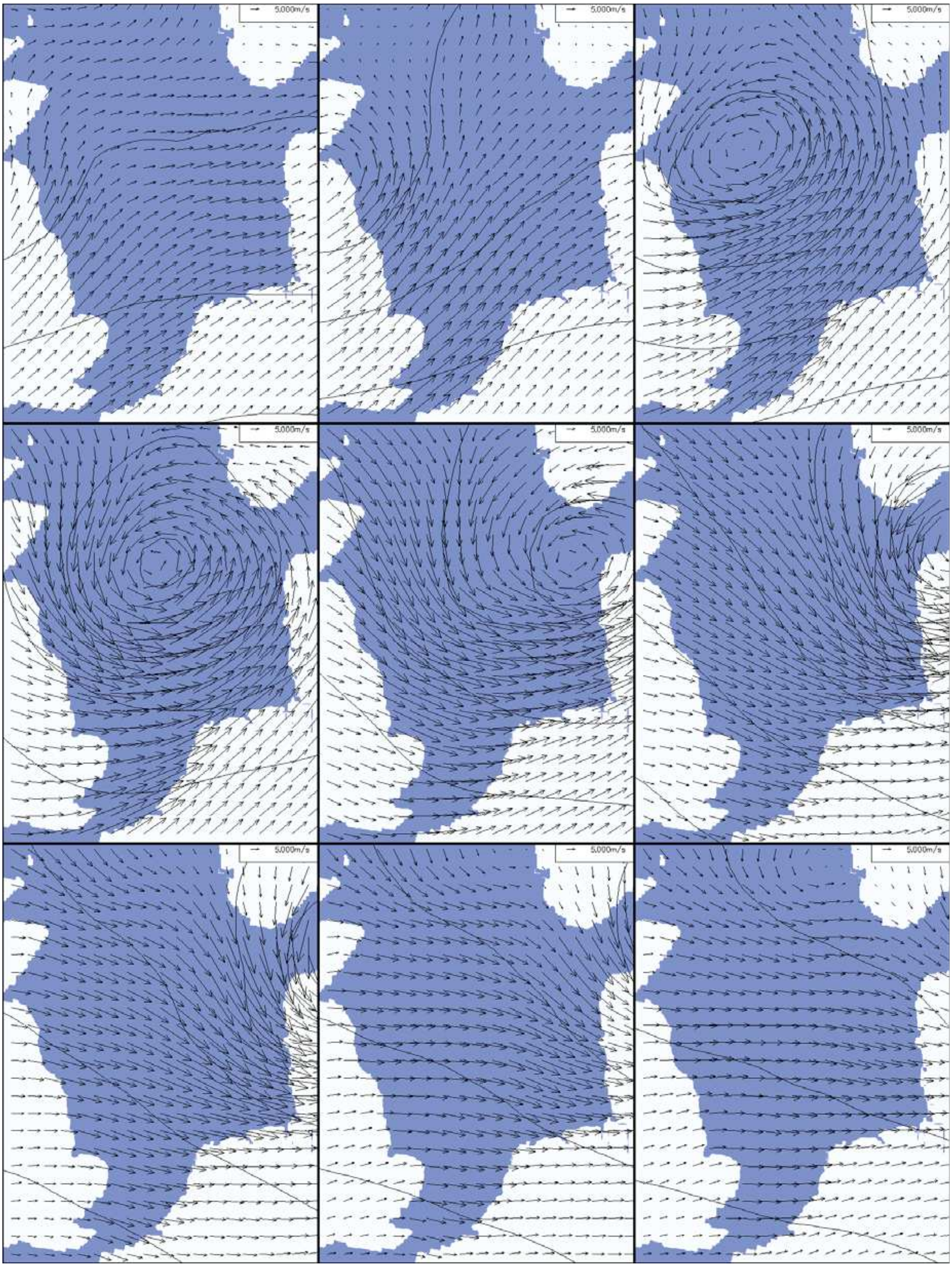


Fig. 15: Wind velocity fields over the North Sea during the storm Anatol in 3-hour intervals from 3 December, 03.00 until 4 December, 03.00 UTC (WILKENS, 2004). Based on synoptic data from the PRISMA model (LUTHARDT, 1987)

5.4.2 Hydrodynamics

Several records of wave heights and water levels were available during Anatol for the locations shown Fig. 16 (wave data from the Federal Maritime and Hydrographic Agency (BSH) in Hamburg and water level data from the Office of Rural Development (ALR) in Husum). The wave measurements were made outside the model domain of the Dithmarschen Bight model and have therefore only been compared to the results of the German Bight wave model. The observed and modelled wave heights are shown in Fig. 17. An under-prediction between 0.5 and 1.0 m can be seen around the peak wave heights; in general the wave heights are reproduced rather well, however. It should be noted that a stationary wave model has been used in this study, inherently leading to discrepancies as for a model domain with the extension of the German Bight an instationary model would generally be preferred. However, the results were deemed to be suitable for the purpose of this study.

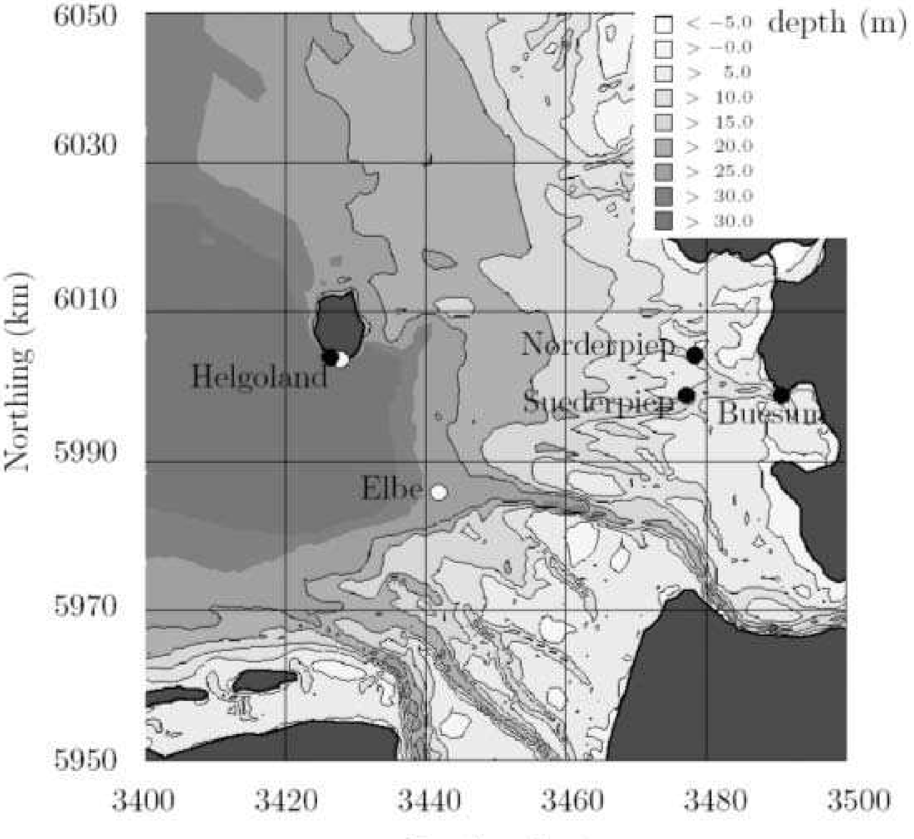


Fig. 16: Location of the wave buoys (white) and water level gauges (black)

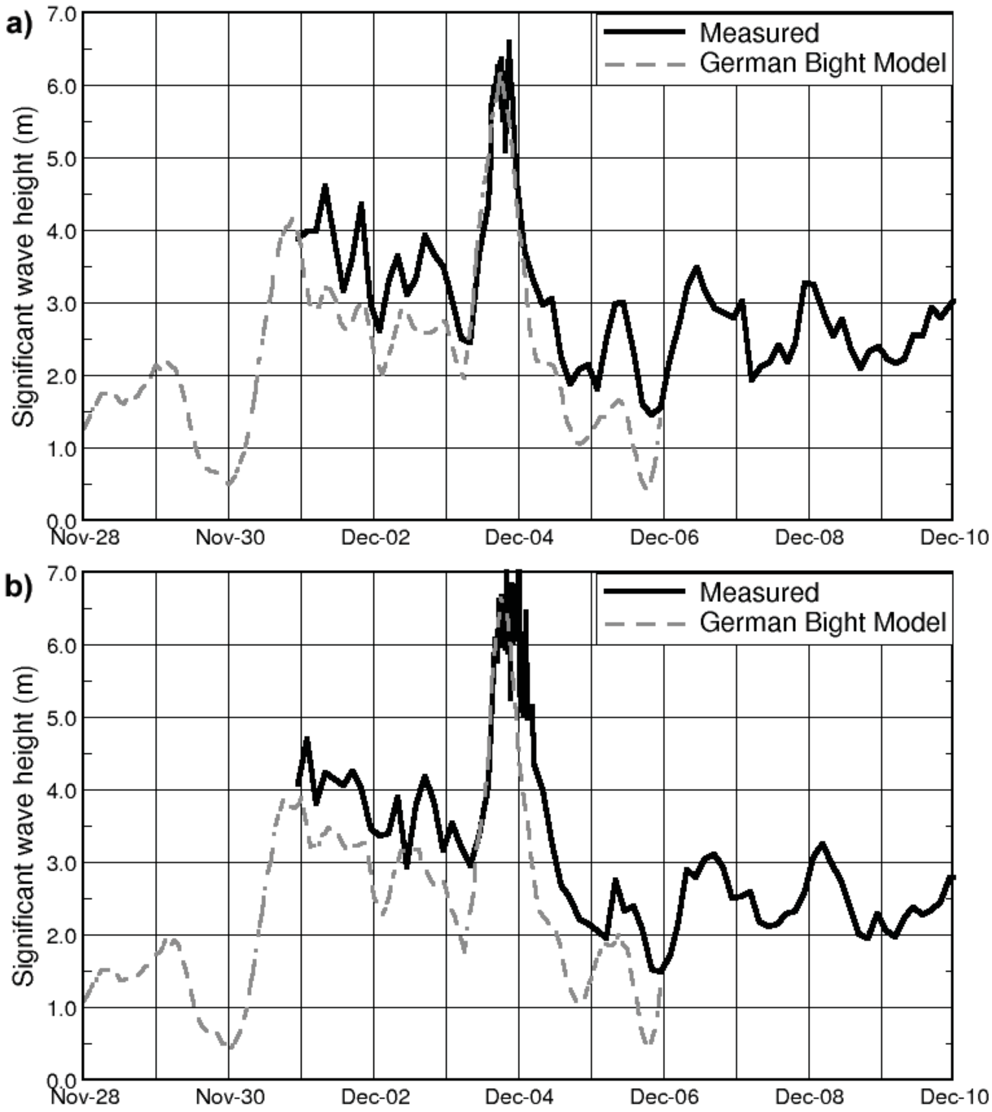


Fig. 17: Observed and computed wave heights at the a) Helgoland and b) Elbe buoys, using the German Bight model

Comparisons of the observed and computed water levels are shown in Fig. 18. It is seen that the storm surge is reproduced very well. Differences can be seen mainly for some of the troughs in the water level records and in some phase lags. The largest phase lag can be noted for the Suederpiep (Fig 18c). As one may see, the measured water level signal at this location is clearly ahead of those near Buesum and in the Norderpiep. Such a phase lag is especially unlikely between the Norderpiep and Suederpiep, both gauges being located at a similar distance from the edges of the tidal flats. The authors therefore suspect that an error occurred in the data processing for the Suederpiep data. The peak values of approximately 4.5 m are captured rather accurately, thus yielding the right volumes that enter and leave the study area apart from the normal tidal prisms.

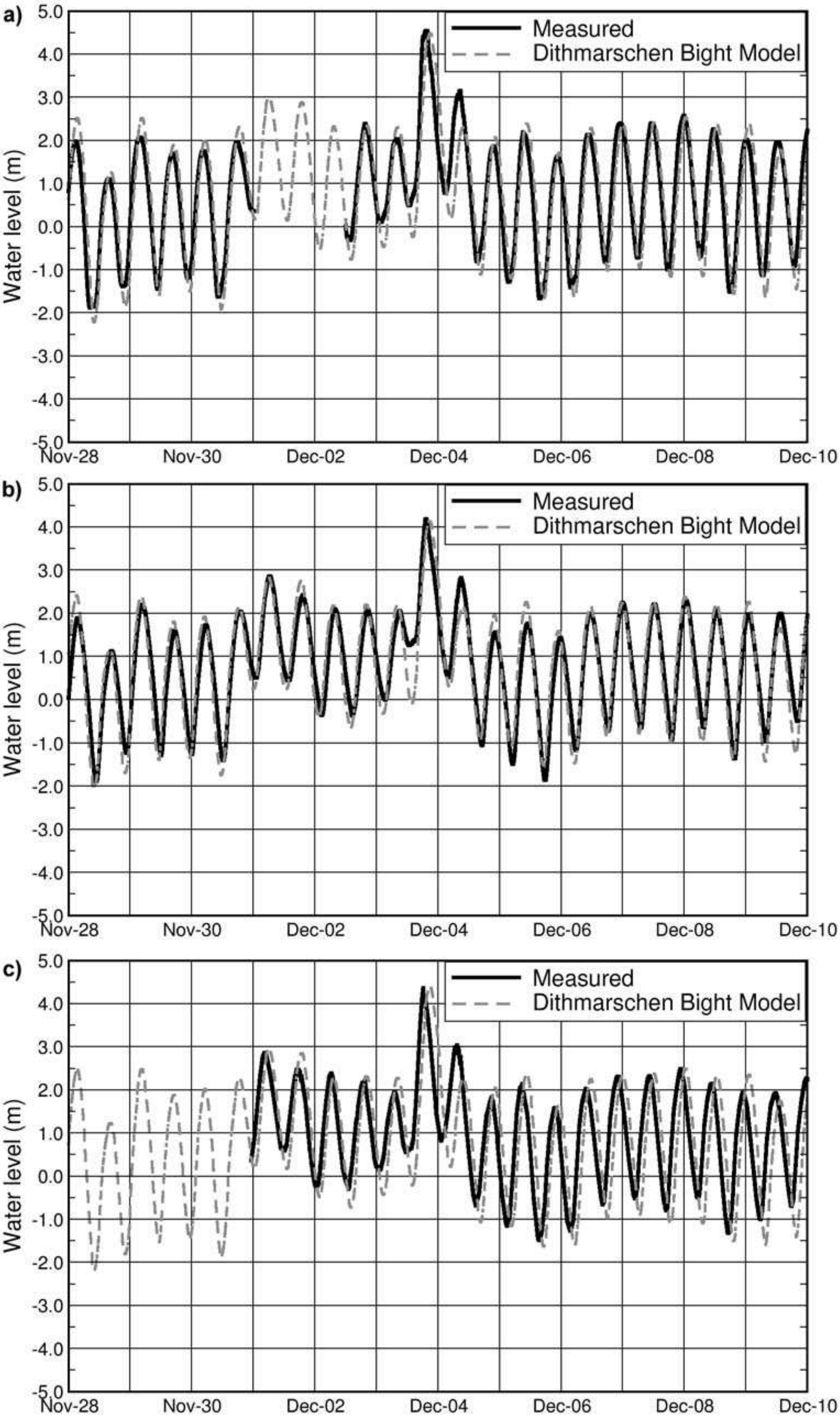


Fig. 18: Observed and computed water levels at gauge stations a) near Buesum, in the b) Norderpiep and c) Suederpiep, using the Dithmarschen Bight model

5.4.3 Morphodynamics

The bed load and suspended load transports were computed on the basis of the above presented hydrodynamic model results. The model settings were taken from the validated medium-scale morphodynamic model (WILKENS, 2004; JUNGE et al., in this volume). The total simulation of the storm event was built up of a sequence of sub-simulations of one hour. In each sub-simulation the sequence of hydrodynamic, sediment transport and morphodynamic models has been executed, where the final results of each were used as initial conditions for the subsequent one. This led to a smooth morphodynamic simulation over the period from 30 November 0.00 UTC until 6 December 0.00 UTC. A warming-up period of five days was considered, preceding this simulation. The resulting patterns of sedimentation and erosion are shown in Fig. 19.

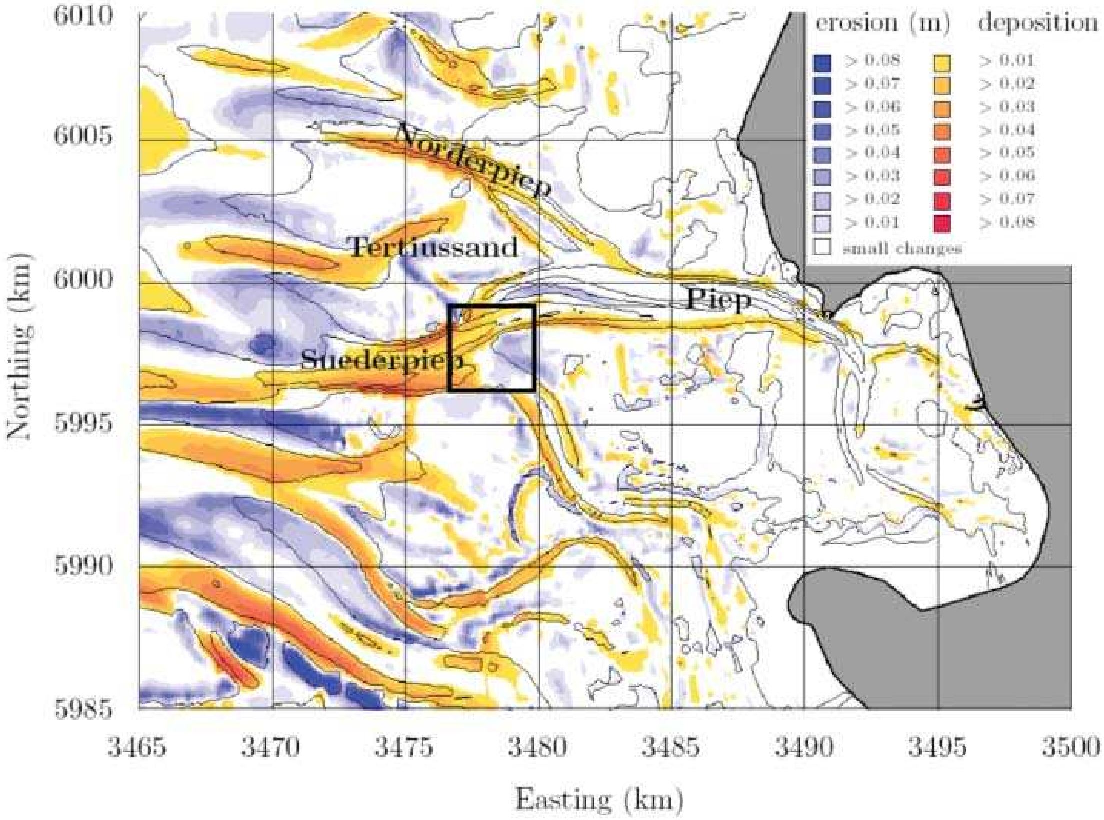


Fig. 19: Computed sedimentation and erosion during the storm period of six days (WILKENS, 2004). The square indicates the area investigated by WINTER et al. (2005)

The computed maximum morphological changes in the study area are within a range of approximately 40 mm over the six day-period, being notibly lower than expected for such a storm. Relatively strong sedimentation occurs in the channels Norderpiep and Suederpiep, as well as in the sub-channel on the western side of the tidal flat Tertiussand. Erosion is seen at the western side of the tidal flats and shoals, caused by the incoming swell waves. The sediment that eroded from these shallow areas was deposited in the neighbouring channels. In the channel Piep stretches of sedimentation can be seen along its banks. Interestingly, the storm event has little to no impact on the eastern part of the domain even though a storm surge of approximately 2.7 m above MHW occurred, which caused stronger currents and higher waves even in the shallower parts of the domain.

To assess the impact of the storm, the resulting morphological changes have been compared to those computed for an entire year with morphologically representative boundary conditions. These representative conditions were found to be optimal for computing the medium-scale morphodynamics in the calibration of the morphodynamic model, considering periods of ten years. The results of the simulation of the one-year period are shown in Fig. 20. It should be noted that the scaling of the graded colours differs by a factor of ten.

In general, a deepening of the tidal channels is seen, accompanied by stretches of accretion along the channel banks and on the majority of the submerged shoals in the channels Norderpiep, Suederpiep and Piep. The centre of Tertiussand shows sedimentation and the surrounding areas of this tidal flat show slight erosion. At the western edges of the tidal flats extended patches of sedimentation can be found. The mediocre imposed wave climate is thus too mild to cause a retreat of these tidal flats. The eastern part of the Piep and the Meldorf Bight show significant changes, with deepening of the channels and accretion in the shallower areas.

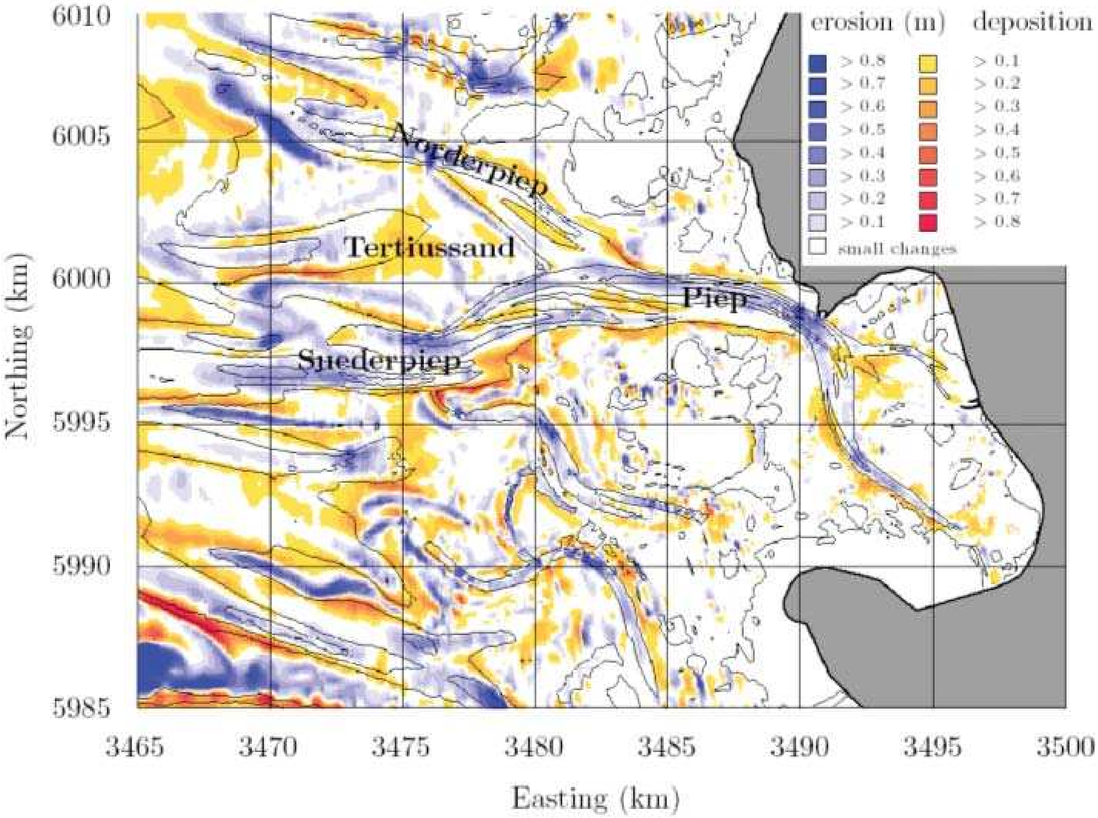


Fig. 20: Computed sedimentation and erosion for a one- year period with representative conditions (WILKENS, 2004)

Comparison of Fig. 19 and Fig. 20 shows that the magnitude of the computed morphological changes over an entire year is a factor ten larger than those computed for the storm event. The horizontal distribution of the areas of sedimentation and erosion is rather different, however. The severity of the imposed waves, their intrusion into the study area due to the storm surge and the current velocities induced by the increased water level changes at the beginning and end of the surge are the causes for these differences. Evidently, the simulated storm has a rather different impact on the area than the averaged, representative conditions. Elevated areas are eroded and deeper areas are filled up. The computed impact of the storm event is limited, however, with maximum changes generally below 0.05 m.

WINTER et al. (2005) presented an evaluation of the storm Anatol for a small scale area (4 km^2) at the southern bank of the Suederpiep on the basis of high resolution multi-beam echo sounder data. Three cross-sectional profiles, measured approximately one month before and two and a half months after the storm, respectively, were compared. This revealed local sedimentation in the channel up to 0.3 m and erosion of the tip of the tidal flat in the Southeast up to 0.25 m over a period of three months including the storm Anatol. For large parts of the investigated profiles the changes were below 0.10 m and therefore within the mentioned measurement accuracy. However, their results do evidence that locally larger morphological changes can occur than those seen in the model results presented here. With the limited spatial resolution of the medium-scale model it was not possible to reproduce these local changes. A model grid and bathymetric data with a higher resolution and perhaps a three-dimensional approach would be necessary for modelling such small-scale morphological changes.

6. Synthesis of the Results

Considering the findings of the previous section in combination it may be concluded that both the tide and swell have a large influence on the medium-scale morphodynamics of the study area. It has been shown that the tide is mainly responsible for initiating, maintaining, extending and migrating tidal channels, shoals, bars and flats. Without the influence of waves and, less significantly, local wind, these morphological features tend to become more pronounced. Along the mutual borders of these features, restrictions on their further extension naturally become established. When swell is introduced into the morphodynamic simulation, an equalising of these morphological features takes place. High-lying areas tend to erode whereas tidal channels tend to become partly filled with sediment. Furthermore, swell is found to be the main driving force responsible for the expansion of Tertiussand in the north-easterly and southerly directions as well as for erosion along its western extremity. Although local wind and wind-generated waves are shown to have a less pronounced influence on medium-scale morphological evolution, their influence cannot be ignored altogether.

The simulation of the storm event showed that even severe swell and wind conditions in combination with a storm surge do not significantly affect the eastern part of the domain. The exposed tidal flats and neighbouring channels in the west are indeed altered by such events. In contrast to general medium-scale trends in the morphodynamics, shallow areas are eroded and channels show sedimentation. However, the model results suggest that the extent to which the medium-scale morphology is changed by a single storm is generally less than 10 % of yearly bathymetrical changes. On a much smaller morphological scale larger changes may occur.

The afore-mentioned findings do not fully comply with the dominance of hydrodynamic forces on morphodynamic evolution, as would be expected according to the classification of HAYES (1979) given in Fig. 2. Instead of being only slightly tidally-dominated, the western part of the study area should rather be defined as a mixed-energy zone, as swell plays an important role in the development of the investigated Tertiussand tidal flat as well as (indirectly) its adjacent channels. As the deep channels Norderpiep and Suederpiep are also maintained in the reference simulation, a tidally-dominated mixed-energy description appears to be more appropriate. It has already been shown that swell and local wind effects have no appreciable influence on the results of the morphodynamic simulations presented for this part of the area of investigation. It is thus concluded that a classification of the eastern part of the study area as highly tidally-dominated (see also Fig. 2) agrees well with model results.

In overall terms it may be stated that the application of a validated morphodynamic model provides a valuable insight into the underlying morphodynamic driving forces and serves as a powerful tool in this respect for verifying and improving initial estimates based on empirical assumptions.

7. Morphological Response to Land Reclamations

The morphological changes calculated from field surveys in the Meldorf Bight presented in Section 2 indicate a general filling-up of the tidal (sub-)channels and an accretion of the tidal flats. Although the results for the tidal flats must be interpreted with caution due to the relatively poor data availability, a net import of sediment into the Bight is evident. This is most likely directly related to the land reclamations of 1972 and 1978 which led to reduced drainage area of the main Piep channel. Bearing in mind that the Meldorf Bight is highly tidally-dominated, as concluded in Section 6, the average import of sediment in the medium-term is relatively independent of the wind and wave climates. It should be noted that this is not necessarily true for storm conditions, which were not included in the analysis discussed in the previous section as only more moderate, representative conditions were considered.

The morphological response to land reclamation in the Meldorf Bight was investigated by performing simulations with the presented morphodynamic model. The medium-scale character of this model does not allow for a proper representation and analysis of the small-scale channels and gullies in detail. However, the model may be used to evaluate the behaviour of the Meldorf Bight as a whole. The study was thus limited to an evaluation of the relative changes of the wet volume below mean sea level (approximately German Normal Null). Any changes in the morphology above mean sea level were thus ignored, which is justified by the poor data coverage of especially the higher tidal flats.

These relative volumes are defined as:

$$V_{rel,i} = \frac{V_i}{V_{1977}} \times 100\ \%$$

with:

$V_{rel,i}$ relative wet volume of the Meldorf Bight below MSL in year *i*
V_{1977} wet volume of the Meldorf Bight below MSL in 1977
V_i wet volume of the Meldorf Bight in below MSL year *i*

Based on the simulation results of the validated morphodynamic model the relative volumes were determined for the periods 1977–1987, 1990–1999 and 1999–2009. These three periods were investigated for calibration, validation and model prediction, respectively, as discussed in WILKENS (2004), WILKENS and MAYERLE (2004) and JUNGE et al. (in this volume). For each period the model bathymetry at the beginning of the simulation was updated to comply with bathymetric measurements of the respective starting year in order to prevent excessive deviations from actual morphological developments (WILKENS, 2004). The relative volume was computed each year for the area shown in Fig. 21.

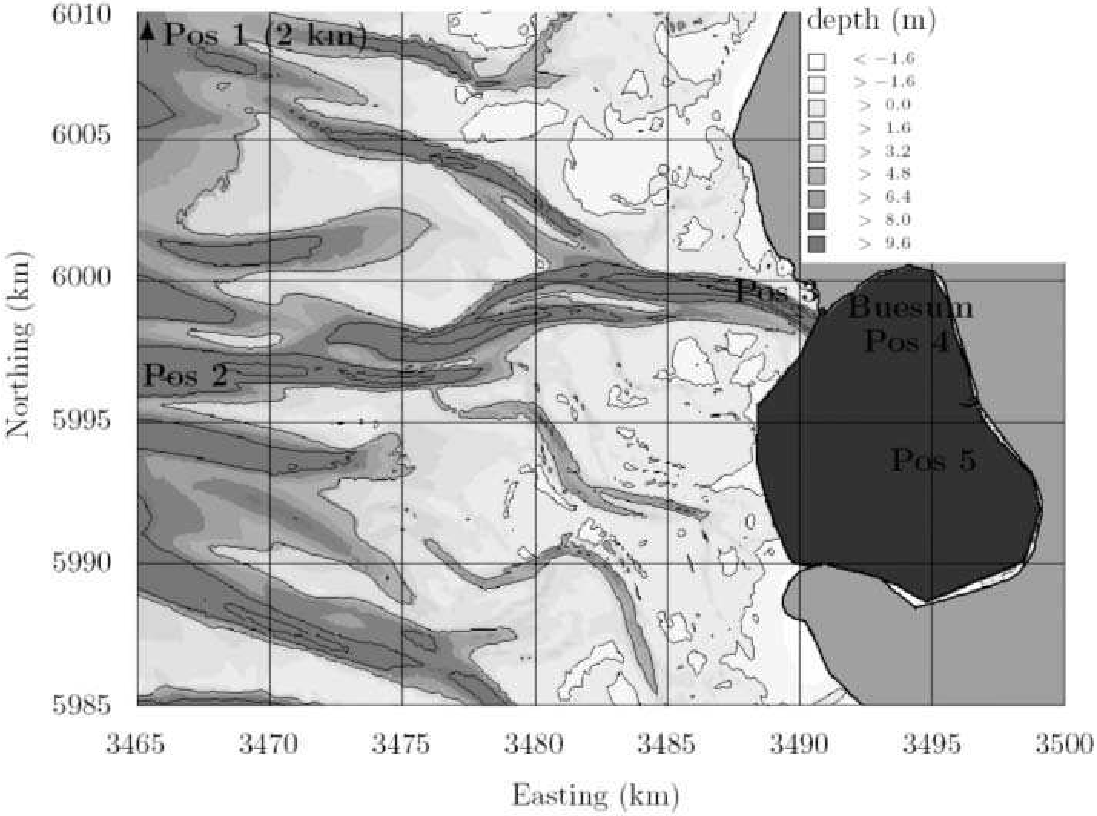


Fig. 21: The Meldorf Bight, as considered in the volumetric analysis

The results of the volumetric analysis are shown in Fig. 22. The values based on measurements indicate a gradual decrease in the wet volume of approximately 30 % between 1977 and 1999. The first 20 % of this reduction occurred between 1977 and 1990, followed by a clearly less-pronounced decrease during the subsequent decade. The decreasing rate of volume reduction during the latter period might indicate the approach to a state of (dynamic) equilibrium. However, the fluctuations over the investigation period do not permit any definite conclusions in this respect. The results of the three model simulations yield volume decreases of 7 %, 4 % and 0 % of the 1977 volume, respectively. An approach to actual bathymetric changes could only be achieved by updating the bathymetry at the beginning of each simulation according to corresponding observations. A perfect fit between the model results and the observed morphological evolution was not expected, however, since the morphodynamic model and its validation were based on the central tidal channel system rather than the inner Meldorf Bight. Nevertheless, the model results clearly predict a decrease in the wet volume and, more interestingly, a reduction in the rate of volume changes with time. The results of the model simulation from 1999 to 2009 predict a fairly stable wet volume in the Meldorf Bight, indicating that a state of equilibrium has been reached.

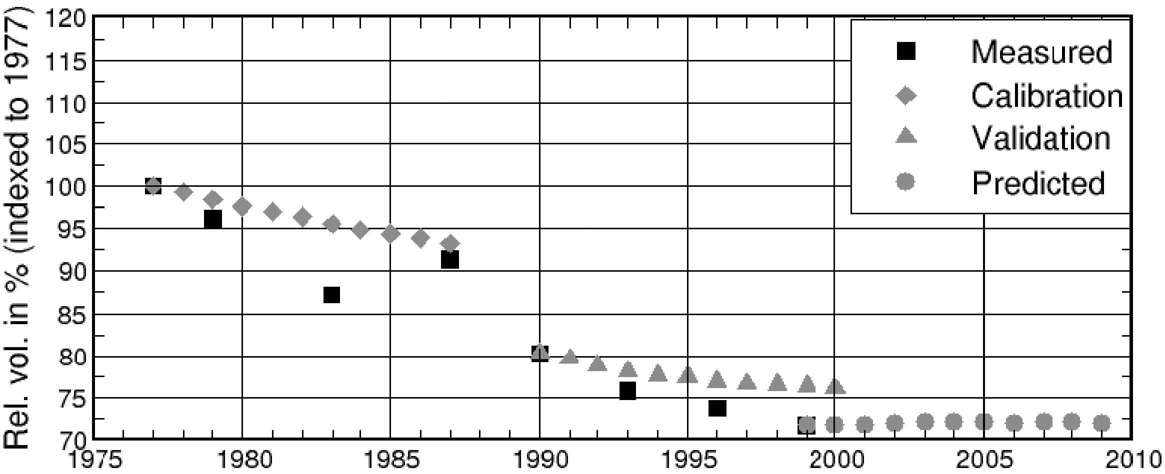


Fig. 22: Relative wet volume of the Meldorf Bight (WILKENS and MAYERLE, 2004)

Once the morphodynamics in the Meldorf Bight have attained a new equilibrium state, the import of sediment due to land reclamation will have come to an end. This new equilibrium state may well have an impact on the future development of the seaward tidal flats and channels, as they will no longer need to supply sediment to the Meldorf Bight in this respect. Independent of the latter, other processes may of course still lead to sediment exchange between both areas, e.g. the import of sediment to adapt to a rising mean sea level. As such, a state of dynamic equilibrium in the Meldorf Bight would appear to be a more realistic description.

Since the rates of volumetric changes were not reproduced too well in quantitative terms, the model in its current form cannot be used to draw conclusions about the adaptation time of the Meldorf Bight to land reclamations. However, the decrease in the observed wet volume reduction and the fairly stable volume predicted by the model for the simulation period 1999 to 2009 do indicate that the Bight is reaching, or has already reached, a new state of dynamic equilibrium.

8. Conclusions

The present study has shown that the validated morphodynamic model is a useful tool for investigating the driving processes responsible for morphological evolution in the study area. The fact that the individual process-based modules for tides, waves and sediment transport as well as the overall morphodynamic model were calibrated and validated increases the trustworthiness of the model results and the conclusions drawn from them. When applying the model for such studies, however, it is important to bear in mind the temporal and spatial scale for which the model has been validated.

On the basis of the model studies carried out in the present investigation it was concluded that the outer tidal flats are only slightly tidally-dominated whereas swell has a relatively high influence along the seaward boundary of the study area. This deviates from the well-known classification by HAYES (1979), according to which a highly tidally-dominated characterisation would follow. In the central part of the study area close to the junction of the Norderpiep and Suederpiep channels into the Piep channel the morphology was shown to be sensitive to locally-generated waves and tidal action. Further eastward, the morphodynamics are purely dominated by the tides and thus comply well with HAYES' classification.

The significance of storm conditions was shown to be rather limited in the morphodynamic model results on the medium-scale. The rather different character of the effects does make storm events a significant force that should be represented either individually or as part of the morphologically representative conditions in medium-scale morphodynamic modelling. Since storms generally cause morphological changes differing from the medium-scale trends, the representative conditions should induce morphodynamics that represent the combined effects of long periods with mediocre conditions and short periods with quite different severe conditions, without resolving these individually.

The land reclamations in the Meldorf Bight were found to cause an imbalance between local hydrodynamics and morphology, which is compensated for by a net import of sediment. The latter thus represents an additional forcing mechanism in the study area. Due to the limited database and the medium-scale character of the applied model it was only possible to draw weak conclusions regarding the response of the morphology to dike constructions. Both measurements and model results showed a clear tendency towards a reduction in the wet volume at a diminishing rate with respect to time. Although the model results indicate relatively stable conditions after 1999, the trend in observations suggests a further slight decrease. Considering the model results in combination with observations, it is anticipated that the morphology is reaching, or has already reached, a new state of dynamic equilibrium commensurate with the current dimensions of the drainage area.

9. Acknowledgements

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