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FORECASTING THE GERMAN BIGHT'S MORPHODYNAMICS: DEVELOPMENT OF A TOOL FOR LONG-TERM COASTAL MANAGEMENT

Bert Putzar[1], Sandra Wappelhorst[2] and Andreas Malcherek[3]

ABSTRACT

With the development of sophisticated modeling systems for coastal applications and the increased computer power in the last decades, long-term simulations of coastal zone morphodynamics on high resolutions grids can be carried out within a reasonable time frame. The modeling system can be used to represent the complex system interrelations and thus providing a basis for measures that can be conducted to reach an efficient coastal management. This article describes the development of a coupled numerical model for the German Bight, representing an area of great economic, ecologic and social importance. First result of long-term (100 years) and medium-term (10 years) simulations for a selected area are presented.

1. INTRODUCTION

The German coastal zone is characterized by diverse ecosystems and a wide variety of natural re- sources. It serves as a habitat for animals and plants and provides settlement areas for humans. The coastal zone is faced with major changes due to natural processes and human uses. The latter refer for example to urban developments, the expansion of ports and industries, constructions for coastal protection, agriculture, tourism and environmental pollution from the landside and on the sea it is mainly fishing, raw material production, the laying of pipelines and cables, shipping, military use and atmospheric contamination. These human uses compete directly with the requirements of flora and fauna (Lütkes & Schuchardt 2006).

The above-mentioned aspects are also subject to the mainly natural processes of morphodynamics. Morphodynamic processes like erosion and sedimentation can be a high risk for coastal habitats and residential areas. Therefore, it is crucial to take into account morphodynamic aspects when developing strategic visions or policies for the management of the coastal zone. For example, the economic success and ecological viability of infrastructure projects on coasts or estuaries, such as coastal protection, port development or the utilization of land for tourism, highly depend on the reliable prediction of morphodynamic processes. Morphodynamical changes like coastal erosion or reorganization of dune islands can risk these infrastructures and lead to land losses, flooding, the collapse or failure of coastal buildings or disruption of the shipping channels.

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To face these potential impacts, it is important to identify and predict these long-term changes in an early stage in order to assess and implement appropriate strategies and measures for the sustainable development of the coastal zone. Thus, significant risks for the people living there like usage conflicts, failure of the coastal protection or disruption of the shipping can be minimized. In this context, numerical simulation systems are a helpful tool to model the complex reality and to analyze different scenarios. This allows decision makers to derive recommendations for action and strategic visions for future developments.

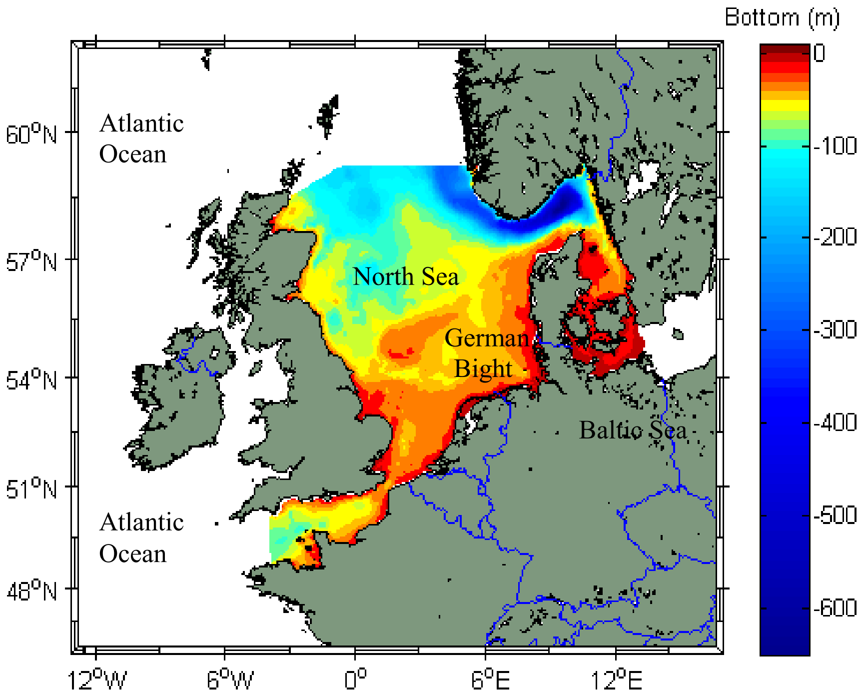
This article introduces a newly-developed coupled numerical model to simulate the long-term morphodynamic evolution of the German Bight. Simulations were carried out over a period of 100 years and over a period of 10 years. First results are shown for the inner German Bight with focus on the mouth of Elbe River and Weser River.

2. THE GERMAN BIGHT

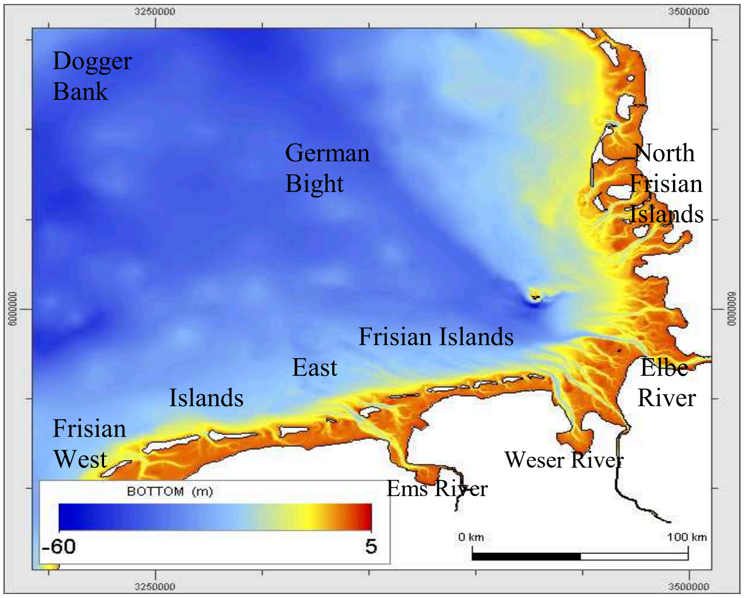
The German Bight is a large bay located in the South-East of the North Sea (Figure 1a), bounded by the Dutch, the German and the Danish coastline. With an average water depth of approximately 30 m, the German Bight is relatively shallow in contrast to the North Sea, which has an average water depth of about 100 m and a maximum value in the Norwegian Trench of about 725 m. Larger areas with maximum depths up to 60 m are located in the central part (Figure 1b). The Dogger Bank, a large shallow area, is a natural boundary to the adjacent part of the North Sea in the north-westerly and westerly direction. The water depths in this area are between 20 m and 30 m.

The morphology is characterized by the barrier island systems of the Frisian Islands, the intertidal area of the Wadden Sea, and three main estuaries of the River Elbe, the River Weser and the River Ems (Figure 1b).

The tidal wave enters through the English Channel and the northern connection to the Atlantic Ocean, causing a tidal range between three and four meters. The semidiurnal M_2-tide dominates and induces a 12.25-hour rhythm of ebb and flow. Exposed to the prevailing westerlies, storm surges and high waves contribute to the morphodynamic evolution of the coastal area.



(a) Geographical position of model domain.



(b) Bathymetry of the German Bight (year 2006).

Figure 1 Overview over the model domain, bathymetry and sediment distribution

Figure 2 shows the sediment distribution of the upper stratum of the sea floor. The classification used here is based on the Udden-Wentworth scale and the median grain diameter d_{50}. The sediment distribution is a result of deposition during the Quaternary, the geological youngest period of Earth's formation, and relocation of these sediments by tide and wind-induced waves. Very fine sand and Medium sand predominate in the upper stratum. Sediments with a larger d_{50} do not occur significantly in the German Bight. On contrast, one can find partially wide areas with cohesive sediments, indicated with coarse silt in Figure 2. Examples are the area south-easterly of the Island of Heligoland or the Wadden Sea.

Due to the geological development, the sediment available for sediment transport is in general limited by a non-erodidable horizon, the basis of Holocene sediments. The sediment thickness varies between a few meters around the East Frisian Islands and approximately 15 m in the south-easterly part of the German Bight and the area of the North Frisian Islands (Zeiler et al. 2008).

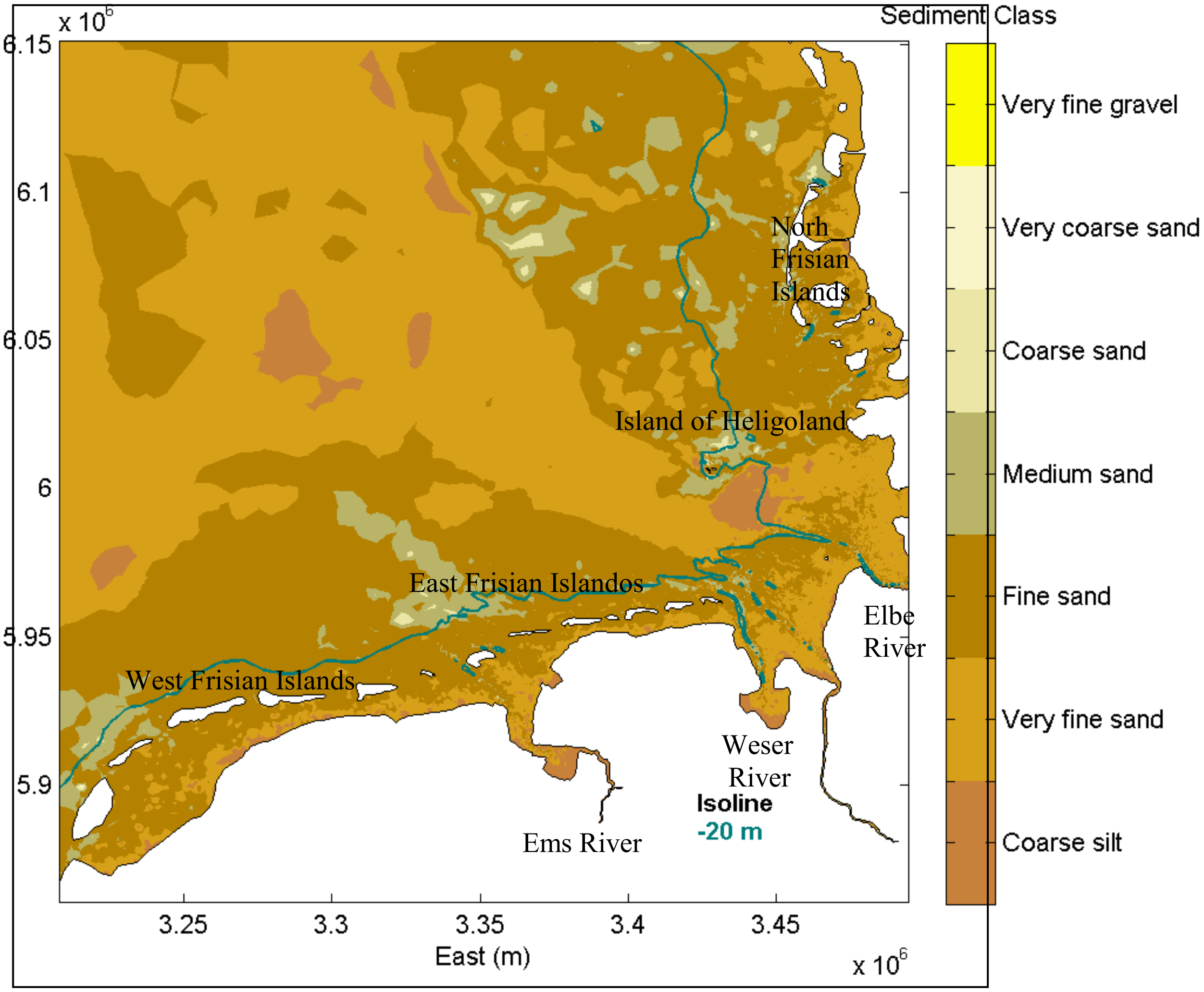


Figure 2 Sediment distribution in the German Bight.

3. SIMULATION MODEL

To simulate the long-term morphodynamic evolution of the German Bight, a coupled numerical model was developed basted on the Finite-Element system TELEMAC (Hervouet, J.M. & Bates, P. (2000)). The simulation model can take into account the tide-induced and wind-induced forces on the Hydrodynamics to calculate depth-averaged velocities in the model domain. Based on two-dimensional velocities, the sediment transport as bed load and suspended load is modeled. The effect of waves is considering by calculating the wave-induced bed shear stress. According to the integrated modeling approach of the TELEMAC system, all models use the same Finite Element grid.

3.1 Hydrodynamic Model

The TELEMAC-2D (Electricité de France 2010b) code solves the depth-averaged free surface flow equations as derived first by Barre de Saint-Venant in 1871. The main results at each node of the computational mesh are the water depth and the depth-averaged velocity components. It can take into account, among others, the following phenomena: propagation of long waves with non-linear effects; influence of Coriolis force; influence of wind, turbulence and bed shear stress and intertidal flats. For the simulations the Elder turbulence model and a constant Coriolis factor for the whole domain are applied. Special care was taken to model tidal flats. Thanks to newly developed algorithm, an edge based advection scheme that avoids negative water depths and ensures mass conservation was applied.

3.2 Wave Climate Model

The sea state was modeled with the TOMAWAC (Electricité de France 2011) software. It is a third- generation wave model to calculate the wave propagation in coastal areas and the sea state by solving the evolution equation of directional spectrum of wave action in each spatial node on a finite element mesh. It takes into account: wind-generated waves; energy dissipation by white capping; non-linear interaction by triplets and quadruplets of frequency; energy dissipation by bottom friction and wave dissipation by wave breaking. TOMAWAC provides wave parameters like mean period, peak frequency and mean direction to the morphodynamic model SISYPHE.

3.3 Morphodynamic Model

The morphodynamic model SISYPHE (Electricité de France 2010a) is used to simulate sediment transport and the evolution of the bed by solving the Exner equation. It calculates the sediment trans- port rates based on the depth averaged velocities and the water depth and calculates bed load. Several sediment transport formulae for bed load and total load under current and combined current-wave flow are implemententent, e.g van Rijn, Einstein-Brown, Meyer-Peter-Müller, Bijker or Bailard (Electricité de France 2010a). Suspended load is calculated by solving the depth-averaged transport equation for each sediment fraction. The bed composition can be modeled with several sediment fractions and can consist of non-cohesive and of cohesive sediment fractions. The vertical discretisiation is based on an active layer approach. SISYPHE can take into account phenomena like gravitational sediment transport, waves etc.

3.4 Model Coupling

The hydrodynamic model TELEMAC-2D and the morphodynamic model SISYPHE are coupled in a direct way. At each simulation time step, the hydrodynamic model calculates the depth-averaged flow field and the water depth. These results are passes to SISYPHE. After calculating sediment transport and the resulting bed evolution, the updated bed level and the new bed roughness $k_s = 3d_m$, where d_m denotes the mean diameter, are passed back to TELEMAC-2D.

The mean period, peak frequency and mean direction are calculated a priori with TOMAWAC and saved into a binary file. For simulations with wind and wave influence, the TOMAWAC file is read and the sea states are interpolated at every time step according to the actual simulation time matching the wind field from TELEMAC-2D.

3.5 Grid, Boundary and Initial Conditions

The simulation domain covers the North Sea, the English Channel and the adjoining area to the Baltic Sea, as illustrated in Figure 1a. The unstructured finite element mesh consists of nearly 70000 triangular elements and is applied to all simulation models.

At the open boundaries to the Atlantic Ocean tidal elevations are imposed. 14 harmonics extracted from the FES2004 ((Lyard et al. 2006)) tidal data are applied. Hourly wind field data is obtained from Deutscher Wetterdienst for the years from 1996 until 2006. The whole structured data is interpolated on the unstructured simulation grid. Fresh water inflow is considered for the Elbe River with 870 m^3/s (BLF 2010), the Ems River with 80.1 m^3/s (NLWKN 2006) and the Weser River with
324.0 m^3/s (NLWKN 2006). These values represent the multi-annual mean discharge. In case of simulations with wave influence, the sea state computed a priori by TOMAWAC is used to calculate the wave orbital velocity within the morphodynamic model SISYPHE.

The bed composition of the sea floor is modeled by one cohesive fraction and six non-cohesive fractions. For each sediment fraction a characteristic grain diameter was defined, which read as followed: Coarse silt ($d=4.7 \times 10^{-5}$ m), Very fine sand ($d=9.4 \times 10^{-5}$ m), Fine sand ($d=1.875 \times 10^{-4}$ m), Medium sand ($d=7.5 \times 10^{-4}$ m), Coarse sand ($d=1.5 \times 10^{-3}$ m) and Very fine gravel ($d=3 \times 10^{-3}$ m). Figure 2 shows the initial sediment distribution in term of sediment classes. The initial thickness of available sediment is set to a fixed value of 20 m.

The initial bathymetry for the year 1996, the year 2006 and the sediment distribution are obtained from an advanced data-based model, providing high-resolution data for every node of the computational grid. Initial values for the velocities and the free surface elevation are set to zero for each simulation.

4. RESULTS

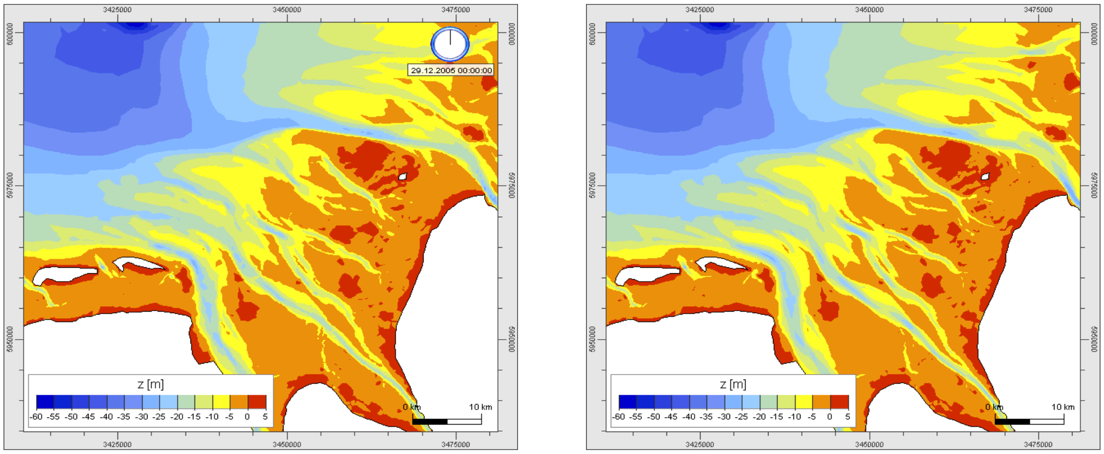
In the first development stage, simulations were carried out for a long-term period of 100 years, starting from 2006, and a medium-term period from 1996 to 2006. The long-term simulation was carried out solely with tide forcing and one sediment fraction ($d=3.75 \times 10^{-4}$ m) to obtain a reference state of the German Bight and to test model stability. For the medium-term simulation different transport formulae for current and combined current-wave flow have been applied. The results indicate the influence of wave-induced sediment transport and the significance of the formula used. For a better representation, not the whole German Bight is shown, but the main focus is on the mouths of the estuaries of Elbe River and Weser River.

4.1 Long-term Simulations over 100 Years

The results for the bed level and bed evolution are illustrated in Figure 3. During the simulation period the large scale morphology does not change much. Comparing the initial state (Figure 3a) and the bed level after 100 years (Figure 3e); one can recognize that the deeper parts show no significant change. Only tidal channels migrate and lead to a local variation of the morphology.

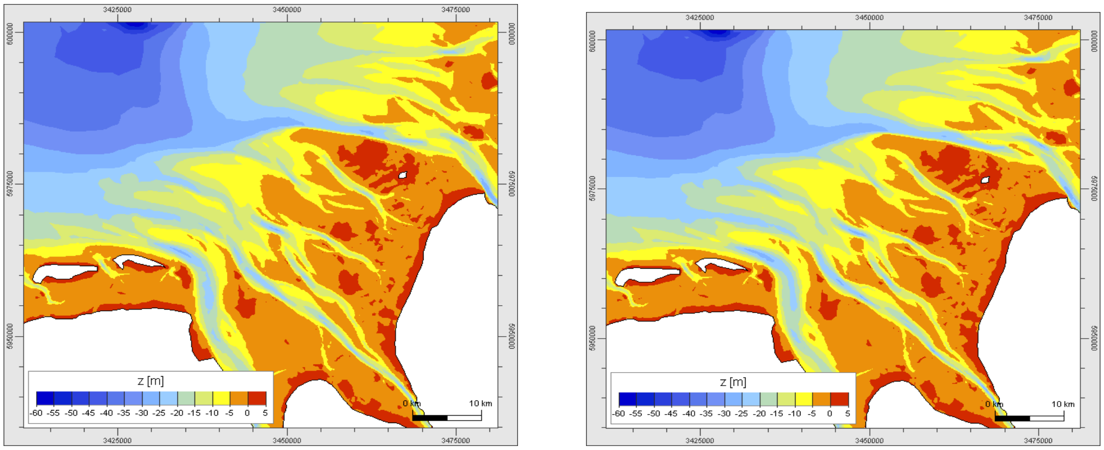
The bed evolution, illustrated in Figure 3f, is in a range of −19.6 m and 19.7 m. The largest values can be found in the tidal channels of the Elbe River (Position P1), the Weser River (Position P2) and the Jade (Position P3). In general, it can be observed that the channels migrate in a north- easterly direction. On the tidal flats and the areas below the −20 m isoline the bed evolution is – compared to the tidal channel migration – relatively small.

The results indicate that due to tide forcing the sea floor adapts slowly in a uniform manner and that significant bed evolutions take place only in tidal channels.



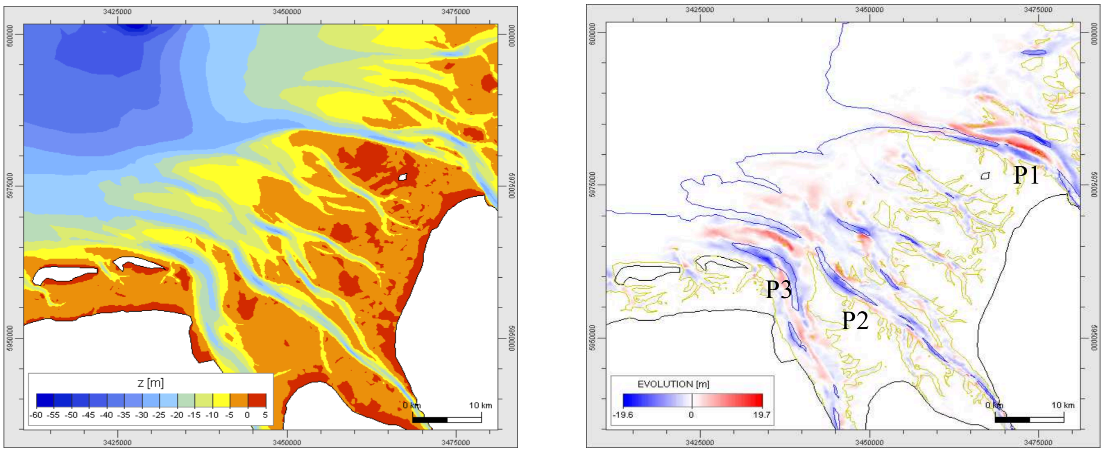
(a) Initial bed level.

(b) Bed level after 25 years.



(c) Bed level after 50 years.

(d) Bed level after 75 years.



(e) Bed level after 100 years

(f) Bed evolution after 100 years;
isolines: yellow -2m, blue -20 m.

Figure 3 Long-term simulation results with tide forcing only and one sediment fraction.

4.2 Medium-term simulations over 10 Years

The tide-driven simulation shows that sediment transport takes places in the intertidal creeks and channels, whereas the morphology of tidal flats remain mostly unaffected. To investigate the influence of wind and waves on the sediment transport, simulations over a period of 10 years with four different transport formulae under tide, wind and wave forcing were carried out. The simulation period covers the years 1996 until 2006. The initial sediment distribution consists of seven sediment fractions (Figure 2) and the thickness of the active layer is calculated as three times the mean grain diameter. The simulation setup is according to the applied sediment transport formula: tide forcing only– van Rijn; tide and wind forcing–van Rijn; tide, wind and wave forcing–Bijker and tide, wind and wave forcing–Bailard.

Figure 4 shows the results of four simulations for a period of 10 years. Here, the simulated bed evolution is compared with a reference bed evolution. The reference bed evolution is obtained from the simulation with tide forcing only (Figure 4a). As expected, the morphodynamics takes place mainly in tidal channels. With the same sediment transport formula (van Rijn) but with additional wind forcing, one can see only small differences in bed evolution in a range of −0.64 m to −0.79 m. The difference between the bed evolution computed with Bijker and the reference bed evolution is illustrated in (Figure 4c). The results indicate that taking waves into account leads to a different erosion and deposition pattern. A much more significant difference shows the simulations results with the Bailard formula. Figure 4d shows that in contrast to the Bijker formula waves have not only a local influence but also the large-scale erosion and deposition pattern changes significantly.

The results for simulations with different forcing show on one hand that the wind influence is comparatively small and that waves can change the erosion and deposition pattern significantly. The combination of periodic and stochastic impacts generates a more dynamic sediment transport and can result in large-scale bottom evolutions. On the other hand the simulated morphology is largely influenced by the transport formula chosen. Two different sediment transport formula for combined current-wave flow show considerably different erosion and deposition pattern.

5. CONCLUSIONS

This article introduces a numerical model for long-term morphodynamic simulations of the German Bight, with the aim to provide a tool for sustainable coastal management. A first analysis of long- term and medium-term simulations show reasonable results and provide a first insight into the system behavior of the German Bight. In the next stage further calibration of the model is necessary to obtain more reliable results. Furthermore, simulations with tide and waves over a period of 100 years should be carried out.

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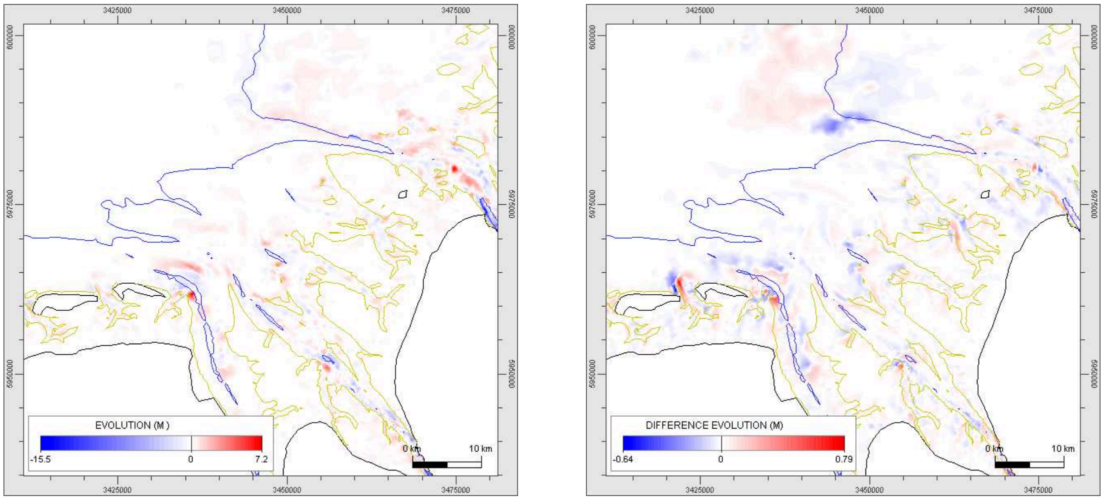
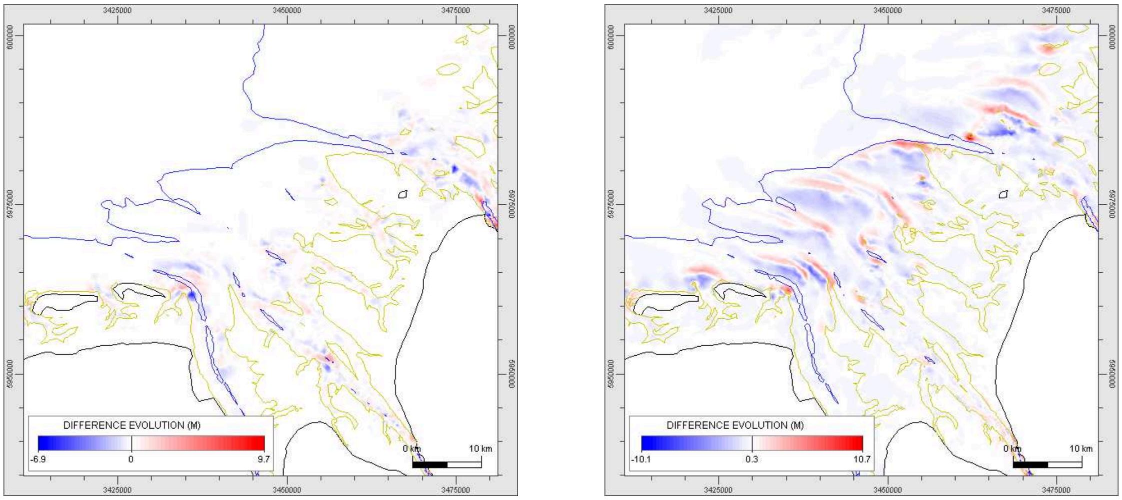


(a) Reference bed evolution with tide forcing wind forcing only, transport formula van Rijn. (b) Difference bed evolution with tide and wind forcing, transport formula van Rijn.



(c) Difference bed evolution with tide, wind and wave, transport formula Bijker (d) Difference bed evolution with tide, wind and wave, transport formula Bailard.

Figure 4 Results for simulations with different forcing (tide, wind and wave) and seven sediment fractions over a period of 10 years. Figure 4b to Figure 4d show the difference in bed evolution compared to the reference bed evolution in Figure 4a (note the scale). Isolines: yellow −2 m, blue −20 m.

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