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The concept of “representative tides” in morphodynamic numerical modelling

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Abstract

Process based numerical modelling of coastal morphodynamics involves model and data reduction schemes in order to cope with computational limitations. Model reduction, on the one hand, may involve the discretisation of the interactive multi-dimensional diverse natural system into a reduced set of coupled process- simulation modules. Data reduction schemes, on the other hand, are used to parameterise processes: The use of schematised open boundary conditions, which are considered as representative in terms of their cumulative morphological effect, is a concept known as “morphological” or “representative” boundary condition. Recent model applications show realistic tendencies in terms of depositional and erosional areas. On the other hand, the reproduction of characteristic changes in morphology such as the migration of bars, banks and channels is only occasionally captured. Using field data on observed morphological impact of a single storm event and numerical model data, it is demonstrated that the concept of representative tides may lead to simulations of morphological development lacking natural dynamics. Instead, morphodynamic models should be applied with open boundary conditions

that consider the variation in tidal and meteorological forcing, rather than characteristic single tides.

Introduction

Coastal evolution is driven by the continuous interplay of meteorological, hydrodynamic, sedimentdynamic, and morphological processes at a variety of spatial and temporal scales. In the recent past, numerical models have gained ground in improving our understanding of natural dynamics and the assessment of consequences of human impact: If the relevant physical processes are known and expressed in mathematical formulations, numerical models can be developed to simulate coastal processes on a discrete grid (Wyatt et al. 2003; Lesser et al. 2004). Whereas process-based hydrodynamic models are being widely applied and successfully validated for the prediction of currents and water levels at engineering time and length scales, sediment-dynamic and morphodynamic models must still be considered to be in the process of development. Considerable uncertainty must therefore be anticipated when uncalibrated models are being applied (Davies et al. 2002). Sediment transport models can be tuned to hindcast measured sediment concentration or fluxes at single positions but typically suffer from insufficient input of field data for spatially and temporally resolved calibration and validation (Winter et al. in press).

To allow for the computation of coastal morphological evolution on time-scales of years to decades, and length scales of some tens of kilometres, substantial model and input data reduction schemes are essential because the full-scale direct simulation of all involved processes is not feasible. The distinction of the inherent time scales between hydrodynamic and morphodynamic processes leads to model reduction options (*tide averaging*): Assuming that the morphological evolution takes place on much larger timescales than the underlying hydrodynamic processes, the bed level can be considered invariant (quasi-steady) throughout a typical hydrodynamic cycle (wave, tide). The hydrodynamics, sediment transport, and bed evolution can thus be calculated successively in separate computational modules. The repeated feed-back of the new bottom topography (morphological time step) into the hydrodynamic and transport computations results in a dynamic simulation of the bed evolution. Further model reduction can be achieved by increasing the morphological time step (*elongated tide*) either by an extrapolation of the computed bed evolution (*morphological factor*) or by methods which avoid the time-consuming re-computation of the hydrodynamics after every transport and bed-evolution step (*continuity correction*) (De Vriend et al. 1993; Latteux 1995; Roelvink 2006).

Furthermore, a filtering of input data is applied to save computational resources: The commonly accepted and applied concept of using *representative boundary conditions* for flow and wave models is based on the assumption that the long-term effect of natural tidal forcing can be approximated by a small number of tidal boundary conditions, if their cumulative effect on the morphology is close enough to the effect of the real signal throughout the whole period (Latteux 1995). This tidal input filtering procedure typically involves a (long-term) morphodynamic reference simulation and several computations of the cumulative effect of different single tides. The specific single harmonic that - if continuously applied - produces similar morphological effects as the reference simulation is taken as representative and used for the forcing of the morphodynamic computation (Cayocca 2001; Hirschhäuser et al. 2001; Mason and Garg 2001; Wilkens 2001). Winter (in press) bases the choice of representative tides on observed rather than on simulated reference morphodynamics. However, these authors then find single or double ‘representative’ tides – typically ranging on the order of 2 to 10% higher than the mean tidal range - which reproduce the morphodynamic effect of the reference data to best possible extent.

Morphodynamic modelling systems which simulate the interaction of flow and sediment transport and subsequent morphological evolution, often perform well in terms of sedimentary budgets: For meso-scale applications, published examples show partly realistic results in the assignment of depositional and erosional tendencies. On the other hand, most models show significant limitations in the reproduction of morphodynamics and only occasionally capture the observed horizontal migration of bars, banks and channels. These shortcomings apply as much to quasi-steady two-dimensional models as to more sophisticated fully integrated three-dimensional models (e.g. Hirschhäuser and Zanke 2002; Grunnet et al. 2004, Lesser et al. 2004).

The purpose of this paper is to demonstrate that the concept of representative tides in morphodynamic modeling of natural processes cannot be upheld. Based on field data and numerical model experiments, the importance in natural variability for the coastal evolution is stressed out.

Materials and Methods

This study is based on field data and numerical model simulations. Echo sounder data have been compiled for the analysis of the morphological evolution of a 4 km² study area in the German Wadden Sea, located in the south-eastern North Sea (Fig. 1). Successive datasets show the dynamics of a tidal inlet section facing the open North Sea at 54.1°N/ 8.67E. Mean water depths range from 25 m in the channel to 3 m at the channel banks. In order to relate the observed morphodynamics to external driving forces, water level time-series have been used, which indicate storm surge events by extremal values.

Simulation data of three numerical models have been used. Large scale hydrodynamics in the North Sea are computed with a model covering the European Continental Shelf, which is described below. Additionally results of morphodynamic simulations with nested smaller scale models of the Eider estuary and the Meldorf Bight on the German North Sea coast are shown.

Field Data

The annual variation in morphology of the study area has been described on the basis of data obtained from routine observations by the relevant German authorities: Digital bathymetrical data provided by the German Federal Maritime and Hydrographic Agency (BSH), Hamburg, cover surveys of April/May 1998, May/June 1999, August 2000, and April 2001. The echo-soundings were provided as reduced sets of data points with an approximate spacing of 150 m. Data as obtained from BSH is vertically referenced to Normal Null (NN), approximately equal to mean sea level (MSL) and horizontally defined in Gauss-Krueger coordinates.

In addition five successive surveys between May 1999 and February 2000 have been carried out by the GKSS Research Centre using Research Vessel “Ludwig Prandtl”. Bathymetry was recorded with a multibeam echo sounder (Kongsberg SIMRAD EM 3000) coupled with a RTK (Real Time Kinematic) GPS and a motion sensor to compensate for ship movement. The data density is about 30 depth values per square meter, the horizontal data accuracy is 20 cm and vertical accuracy is about 10 cm. Campaigns were carried out in the weeks 22, 26, 36,44 of the year 1999 and week 3 of the year 2000.

To assess the morphological evolution of the area in terms of hydrodynamic forcing, water level data from Cuxhaven tidal gauge is used. The high water levels have been extracted to locate high-energy storm flood events, which appear as distinct peaks in the time-series. According to German BSH classification an event is called "storm-flood" if the water level exceeds MHW (mean high water) by more than 1.5 m. Water levels above MHW + 2.5 m are classified as "severe storm flood". The MHW of Cuxhaven is 1.55m above MSL.

Numerical Models

To simulate hydrodynamic scenarios in the North Sea, we applied the Delft3d-FLOW modelling system (Roelvink and Van Banning 1994) to set-up a hydrodynamic numerical model of the

European continental shelf sea (ECSSM). The spherical grid covers the region between 13W/48N and 13E/62N with a resolution of 2.5 nm (1/24°) in the latitudinal and 3.75 nm (1/16°) in the longitudinal direction. For three-dimensional simulations, ten layers form a vertical sigma-coordinate grid. The model bathymetry was adopted from another modelling system (Kleine 1994) and additionally interpolated from sea floor topography derived by satellite altimetry and digitized sea-charts (Smith and Sandwell 1997). At the free surface, the model is forced by climate data fields (wind, atmospheric pressure). At the lateral open boundaries the model is driven by water level conditions derived from a global tidal model (Egbert et al. 1994). These harmonic open boundary conditions (10 astronomical constituents) are corrected for atmospheric pressure to account for the inverted barometer effect. The model quality has been validated on measured water levels from tidal gauges throughout the model domain. A comparison between measured and computed tidal harmonics (only tidal forcing) for a station close to the study area exemplarily is given in Fig 2. Model simulations considering also wind and pressure at this station, result in a variance explained by 95% (n= 19000) and a mean squared error in water-level height of 0.05m. The model is applied to study tide and climate forced hydrodynamics, the impact of extreme events (e.g. Diesing et al. in press), and the generation of boundary conditions to smaller scale nested local models.

Such a local model has been defined for the area of bathymetric measurements described above. Driven by water level conditions as computed by the ECSSM model, the local model of the Meldorf Bight (MBM) spatially is higher resolved: The curvi-linear computational grid features a variable resolution of 100 – 800m to allow for a detailed simulation of the hydrodynamics in the area of interest at low computational cost.

Additionally model simulation results from a small scale numerical model of the Eider estuary at the German North Sea coast have been further analysed. This model was set-up comprising coupled computational modules for the simulation of currents, sediment transport and bed evolution. Details on the set-up, calibration and validation of the model are given in Winter (2002) and Winter (in press). Here the quality of morphodynamic simulations has been evaluated and related to characteristics of the applied open boundary conditions. The model quality was derived by calculating the squared correlation r^2 between measured and computed morphological differences:

$$r^2 = \frac{\sum_i (x_i - \bar{x})^2 (y_i - \bar{y})^2}{\sum_i (x_i - \bar{x})^2 \sum_i (y_i - \bar{y})^2}$$

In which x_i is the morphological difference measured at the position i, and y_i is the morphological difference calculated at the same position. $\bar{x}, \bar{y}$ are the averaged morphological differences of all positions of the according datasets.

Results

Observed morphodynamics

The three-year evolution of the study area shows a general flattening trend of the tidal channel and erosion of the protruding spit. This is exemplified by three cross-sectional depth soundings plotted in Fig. 3: The annual sedimentation in the tidal channel in the first two years is of the order of 0.6m. Although the northern channel banks also accrete at the same rate, the horizontal retreat of the spit by about 100 m / year is accompanied by erosion of about 0.5 m. The differences in bathymetry reveal comparatively small changes between summer 2000 and spring 2001.

Five successive surveys between May 1999 and February 2000 offer additional information on the evolution of the study area: From June until September 1999 hardly any changes occurred. Apart from a local deepening of the channel, also in the following two-months no significant morphological changes were observed. The last dataset of February 2000 then indicates the filling of the channel and erosion of the spit with similar magnitude as the annual rates (Fig. 4).

The main hydrodynamic events in the period of 1998-2001 can be identified as extreme maxima and minima in the high water time-series from Cuxhaven tidal gauge (Fig. 5). Maximum water levels are usually caused by the combination of high tides and the set-up by strong north-westerly winds. In 1998 a storm flood in October 27 and in 1999 two main storm flood events in February 5 and December 3 occurred. Around October 21, 1999 exceptionally strong winds from south easterly directions caused very low high water levels (negative surge). On January 30, 2000 another storm flood occurred. Compared to the preceding winters of 1998/1999 (4 storm floods) and 1999/2000 (5 storm floods) the winter season 2000/2001 was calmer as only two events happened (Axer et al. 2005).

Numerical model sensitivity studies

Tidal variation

Two simulations of tidal hydrodynamics have been carried out with the MBM model, embedded into the ECSSM model. The simulations cover a full neap-spring tidal cycle in early December 1999. First the model was applied considering astronomical forcing only. Exemplarily the tidal dynamics at two positions are visualised in Fig. 6 in terms of summed current velocities (tidal ellipses). The diversity of the curves underlines the variability of current directions and -magnitude in the course of the neap-spring cycle. Additionally a simulation of the same period, now considering the impact of wind-, pressure and large scale water level set-up is shown. The simulation includes the period of a storm flood event (3.-4. December). Although the absolute current velocity magnitudes do not exceed those of the first simulation, a distinct change in variability is observed when taking into account meteorological forcing.

Sensitivity of morphodynamic models to boundary conditions

Based on the morphodynamic simulations of Winter (2002), the effect of different single tide boundary conditions has been assessed. Several simulations had been carried out that each involved the calculation of a one year morphological evolution of the Eider estuary. Each simulation was driven at the open boundaries by water level time series of a different reiterated single or double tide. These individual simulations were evaluated in terms of the similarity between calculated and observed morphodynamic changes by the explained variance (r^2) a measure of similarity in shape. The simulations produced varying goodness of fit, however no trends could be detected: No significant correlation between the quality of simulation and tidal characteristics, such as the mean water level, the tidal range, the high water level or the low water level was observed (Fig. 7).

Discussion

The concept of representative boundary conditions for morphodynamic numerical modelling is applied under the assumption that certain single tides may provide a characteristic forcing which can lead to realistic morphological evolution. However, field data and numerical model experiments provide evidence that the natural variability in forcing is crucial for coastal evolution.

The comparison of successive bathymetric datasets illustrates significant morphodynamic characteristics of a tidal inlet in the German Wadden Sea. The data show progressive sedimentation in the deep tidal channel and erosion of a shallow region over a three year period. Monthly data in relation to hydrological records reveal that the morphological evolution is not continuous, but takes place in steps. It is shown that a number of extreme events such as storm floods or extremely low high-water levels occur throughout the time of investigation. Although no data are available which explicitly describe the impact of a single event on the local bathymetry in the course of a single storm, the resultant bathymetric changes of low energetic periods can be compared to the impact of high energetic events: It is obvious that during the calm period of June-September 1999, hardly any morphological changes took place. By contrast, a similar period characterised by a series of exceptionally low (negative) water levels partly resulted in distinct changes: The outer region (channel and toe of spit) was deepened whereas the flanks and shallow regions were not significantly affected. The subsequent period between two measurement campaigns covered several storm-flood events (November 1999-February 2000). During this period, bathymetric changes occurred, which coincide with the observed annual morphodynamics. It thus becomes clear that the different forcings (storm floods or extreme low high water) seem to partly result in similar (erosion of the spit) and partly in opposing dynamics (filling or deepening of the channel).

Model results visualised in terms of tidal ellipses illustrate the natural variability of tidal currents over neap-spring cycles. Clearly the tidal ellipses, and hence the morphodynamic forcing directions, continuously change, even in response to astronomical tidal forcing alone. This variability is amplified when taking extreme events into account, as shown by the considerable hydrodynamic dicrepancies between average tidal forcing and a storm surge event.

The dependency of morphological evolution on the natural variability in forcing, is also confirmed by the analysis of other model simulations. Sensitivity analysis of regional scale sediment transport models had shown that inherent sediment transport model parameters, as the grain size, settling velocity or bottom roughness, mainly influence the amplitude of computed sediment dynamics and thus the quantity of transported sediment. In contrast, the shape and characteristics of sediment transport patterns are mainly controlled by the driving hydrodynamics (Winter and Mayerle 2003; Winter et al. in press). Thus, in terms of morphodynamic simulations in tidal areas based on cumulative rates of sediment transport where absolute rates may cancel out, local hydrodynamics are the significant processes. Furthermore, morphodynamic simulations carried out to test the sensitivity of a model to different single tides used as boundary conditions showed no significant correlation of single tide characteristics to model quality. This demonstrates that the quality of a morphodynamic simulation does not depend on attributes of a specific tide. This is also confirmed by recent numerical experiments of Roelvink (2006), who modelled the morphological evolution of an idealised tidal inlet. He showed that only by avoiding the concept of representative tides, the evolution of an initially flat bathymetry to complex morphological patterns such as channels and intertidal shoals was possible.

Conclusions

The reported limitations in numerical model quality when simulating coastal morphodynamics with process based coupled numerical models are found to be related to the concept of "representative boundary conditions".

It was shown that the observed natural morphological evolution of a tidal channel in the German Wadden Sea, is composed from small changes during normal meteorological conditions and significant morphodynamics in high energetic periods.

The natural variability in forcing has been exemplarily visualised by tidal ellipses of a neap-spring tidal cycle with and without meteorological forcing. The difference in change of direction and magnitude to the uniformity of a reiterated single tide is obvious.

Numerical experiments on the effect of tidal conditions at the open model boundaries do not show a dependency of the morphodynamic model quality on hydrological parameters of a single tide.

It is concluded that natural variability in forcing as well as single events, their chronology and their variable combination rather than special characteristics of reiterated tides is leading to natural coastal evolution.

It becomes clear that in the case of the selection of a specific boundary condition capable in simulating any short term morphodynamics cannot be suitable to reproduce annual trends. On the other hand any boundary condition that by coincidence may reproduce similar morphodynamics as being measured for one distinct period (hindcast) should not be considered applicable for others (forecast).

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Figures

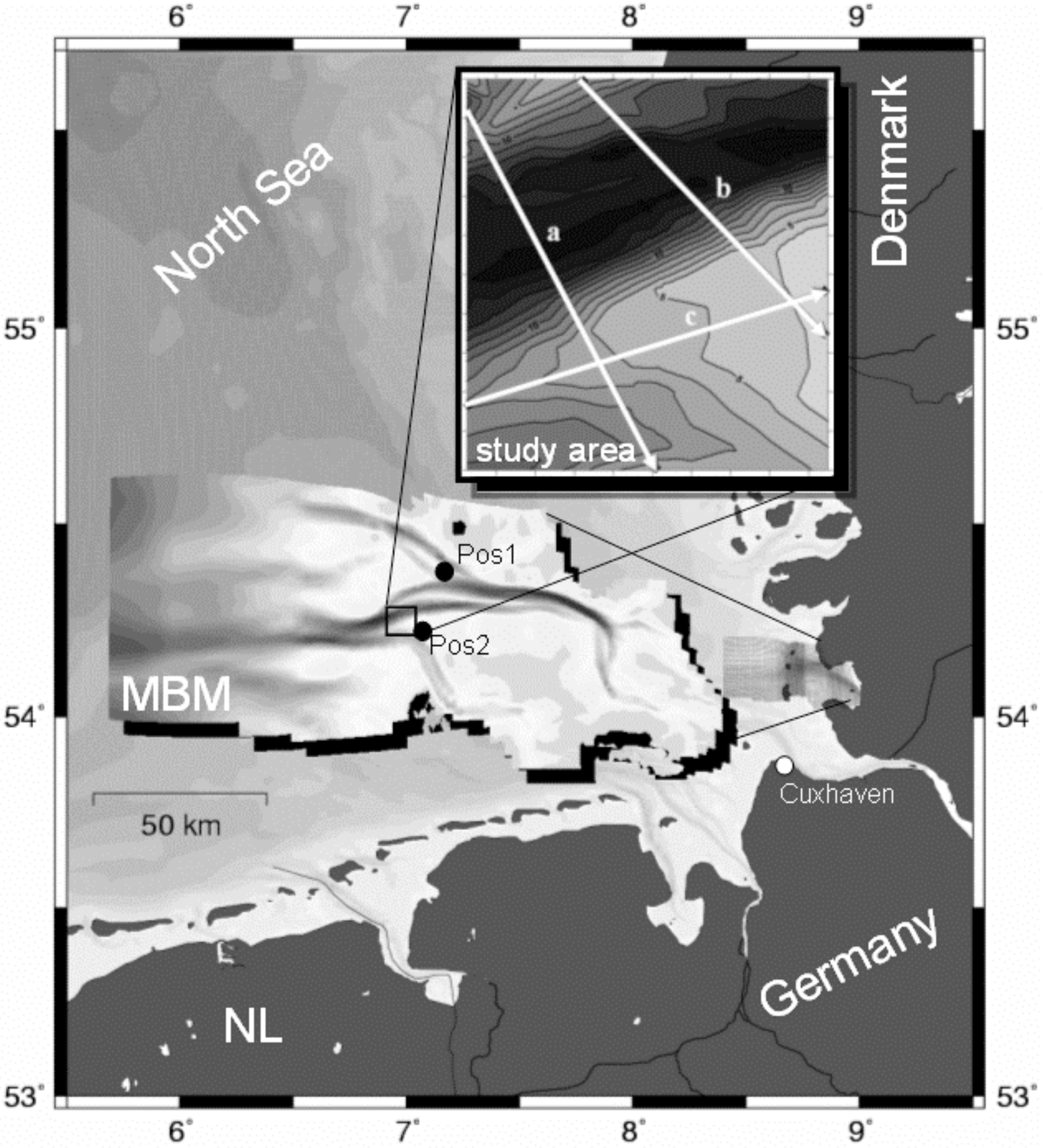


Fig. 1 Map of the German North Sea coast indicating, a zoom into the MBM model bathymetry and the study area, and the location of transects a, b, and c.

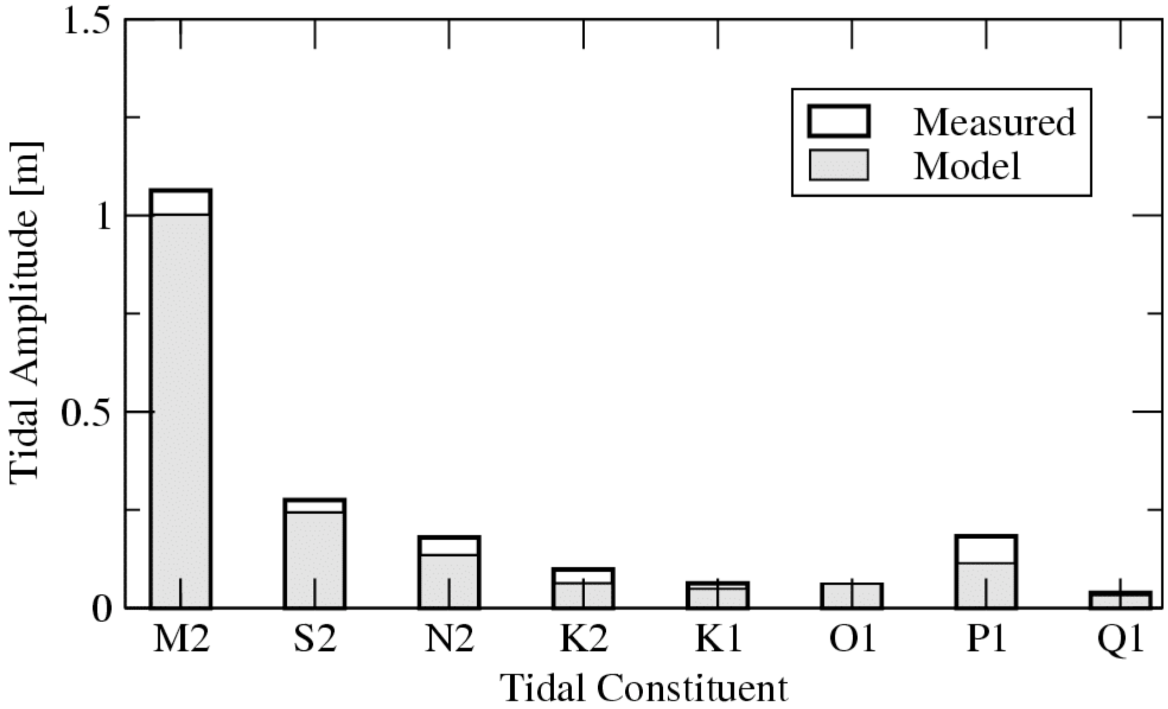


Fig. 2 Water-level amplitudes of station Helgoland near the study area in the German Bight. Shown are results for the eight main tidal constituents as analysed from tidal gauge records and numerical model simulations.

Fig. 3 Depth data as obtained at the times of the annual BSH measurements. For the location of the transects a,b,c see Fig. 1

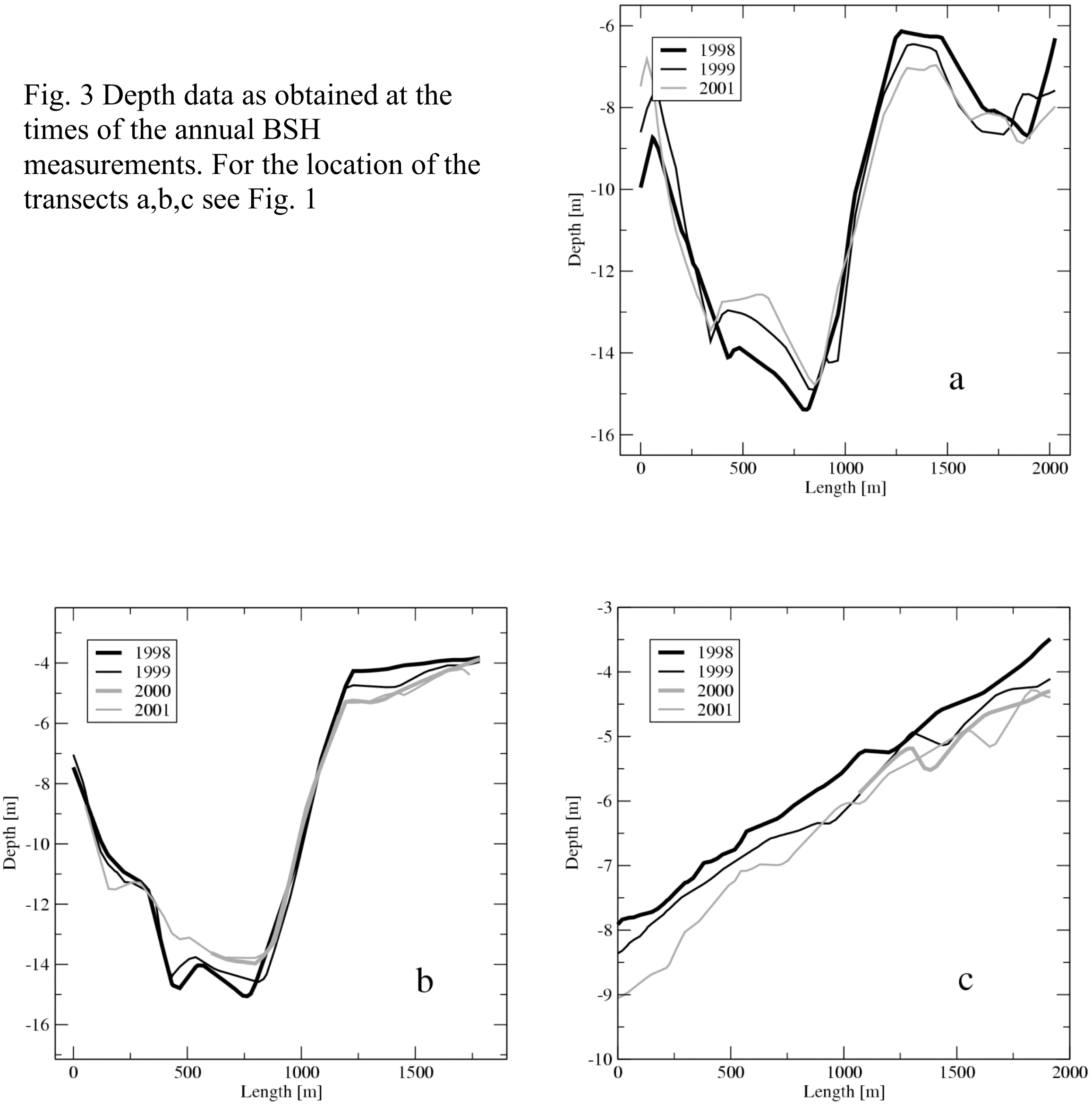
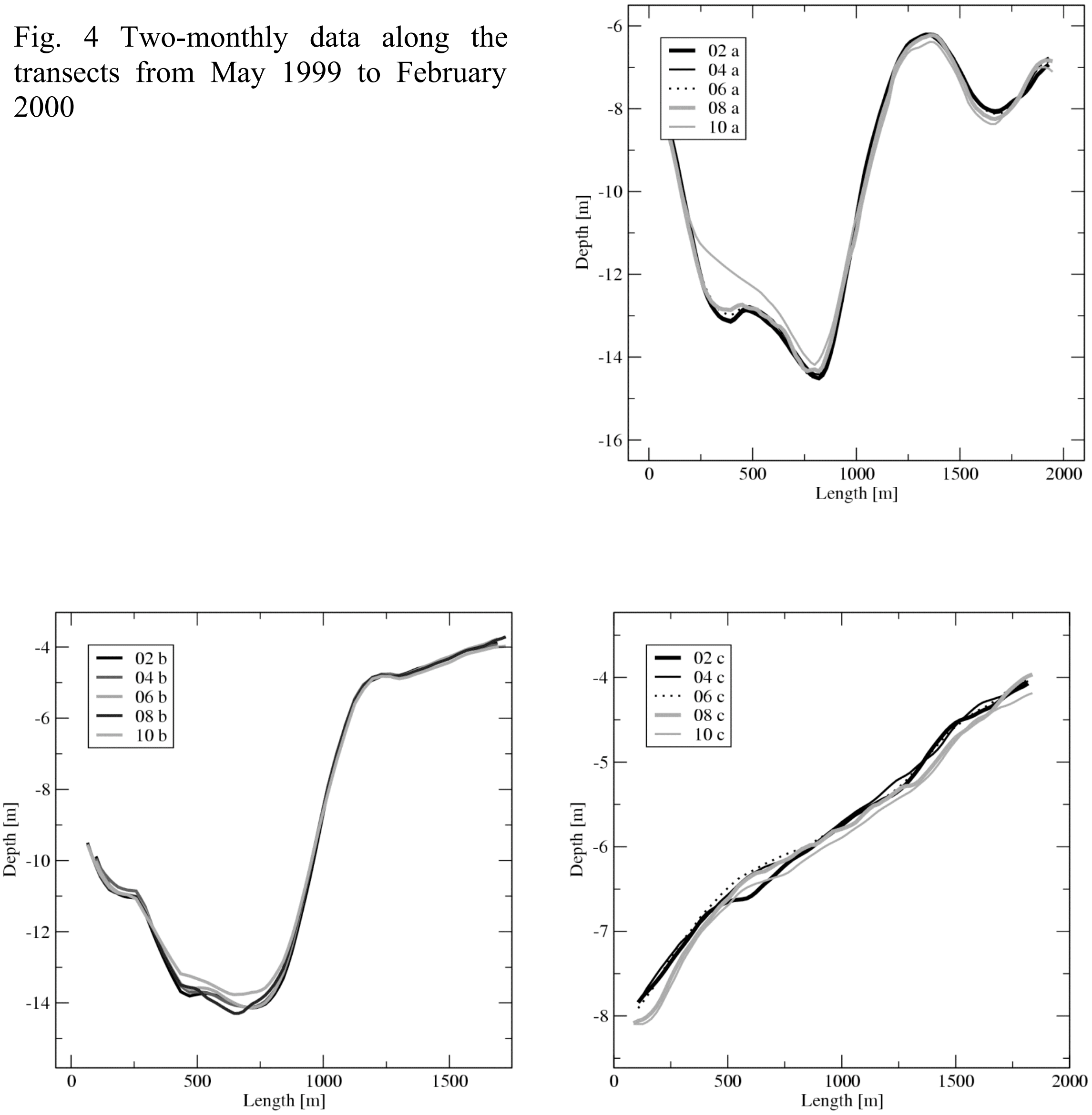


Fig. 4 Two-monthly data along the transects from May 1999 to February 2000



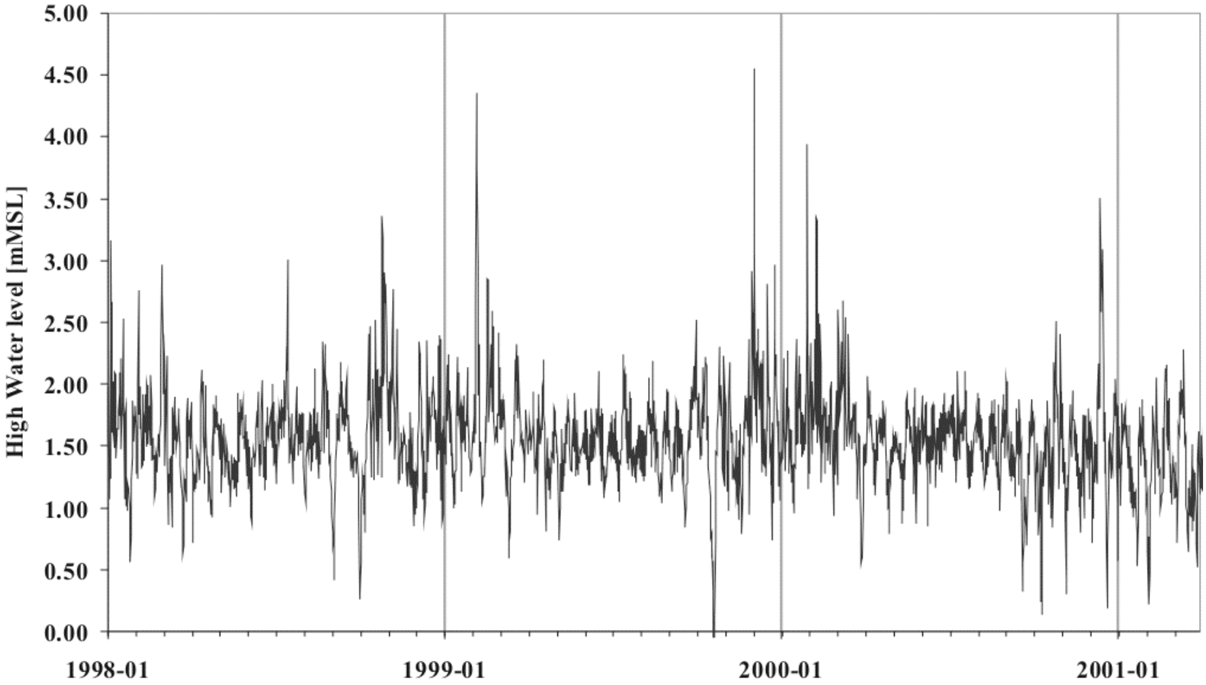
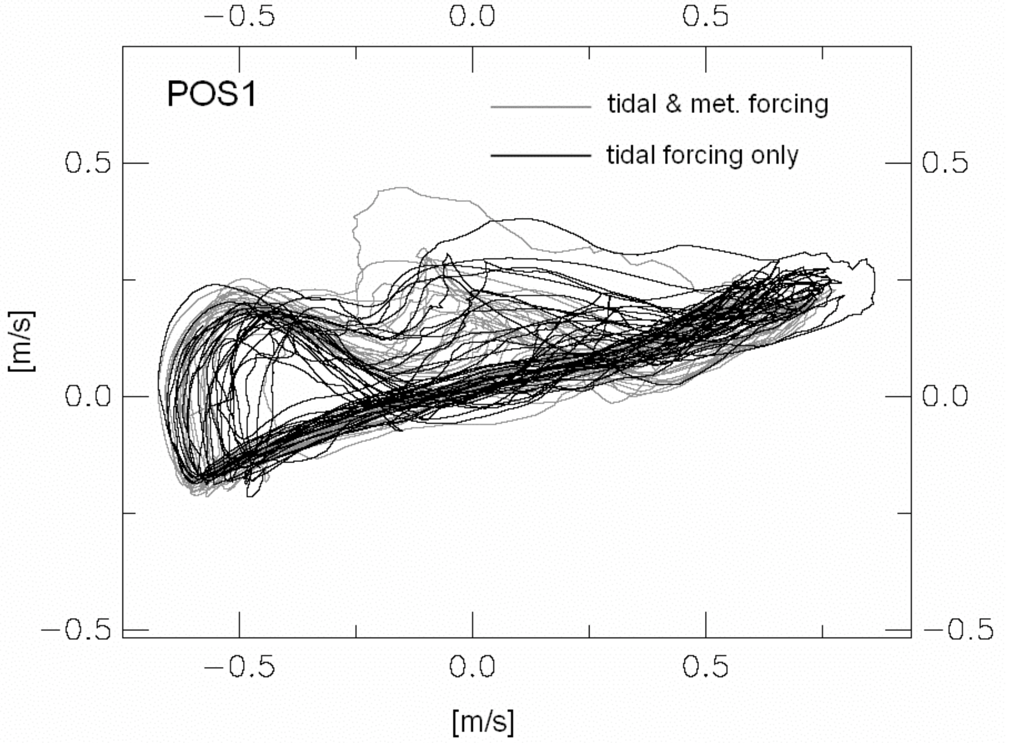
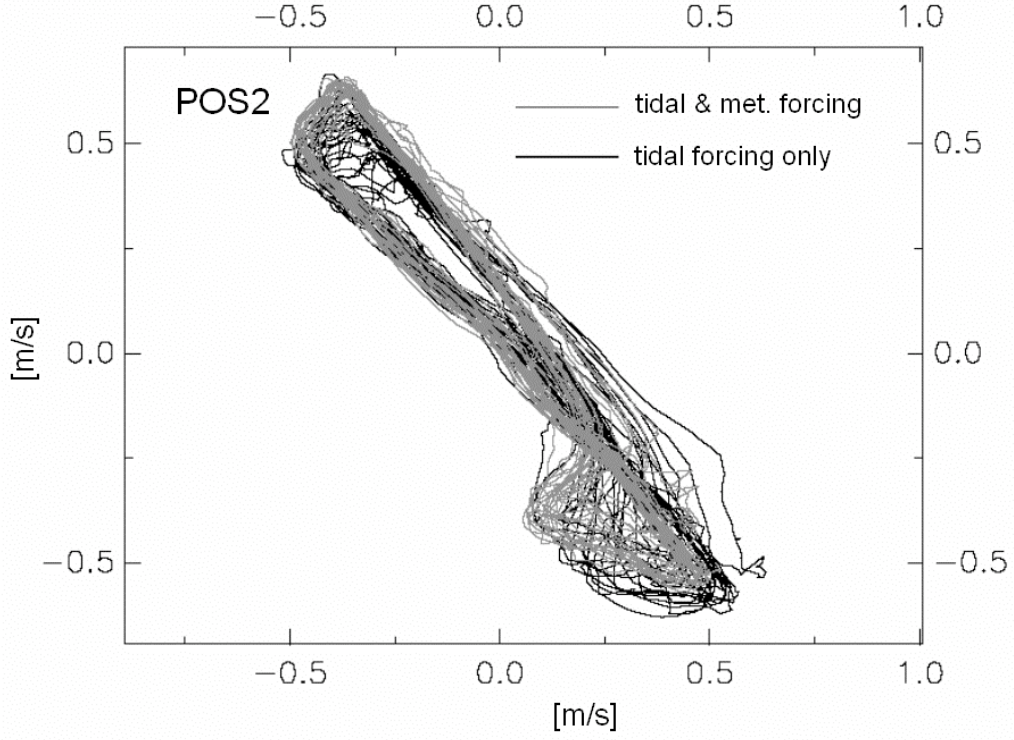


Fig. 5 High-water levels at Cuxhaven tidal gauge (see Fig. 1)

Fig. 6 Natural variability of hydrodynamic forcing shown by the tidal dynamics at two positions (Pos1 and Pos2 as marked in Fig. 1) shown as summed current velocities (tidal ellipses)





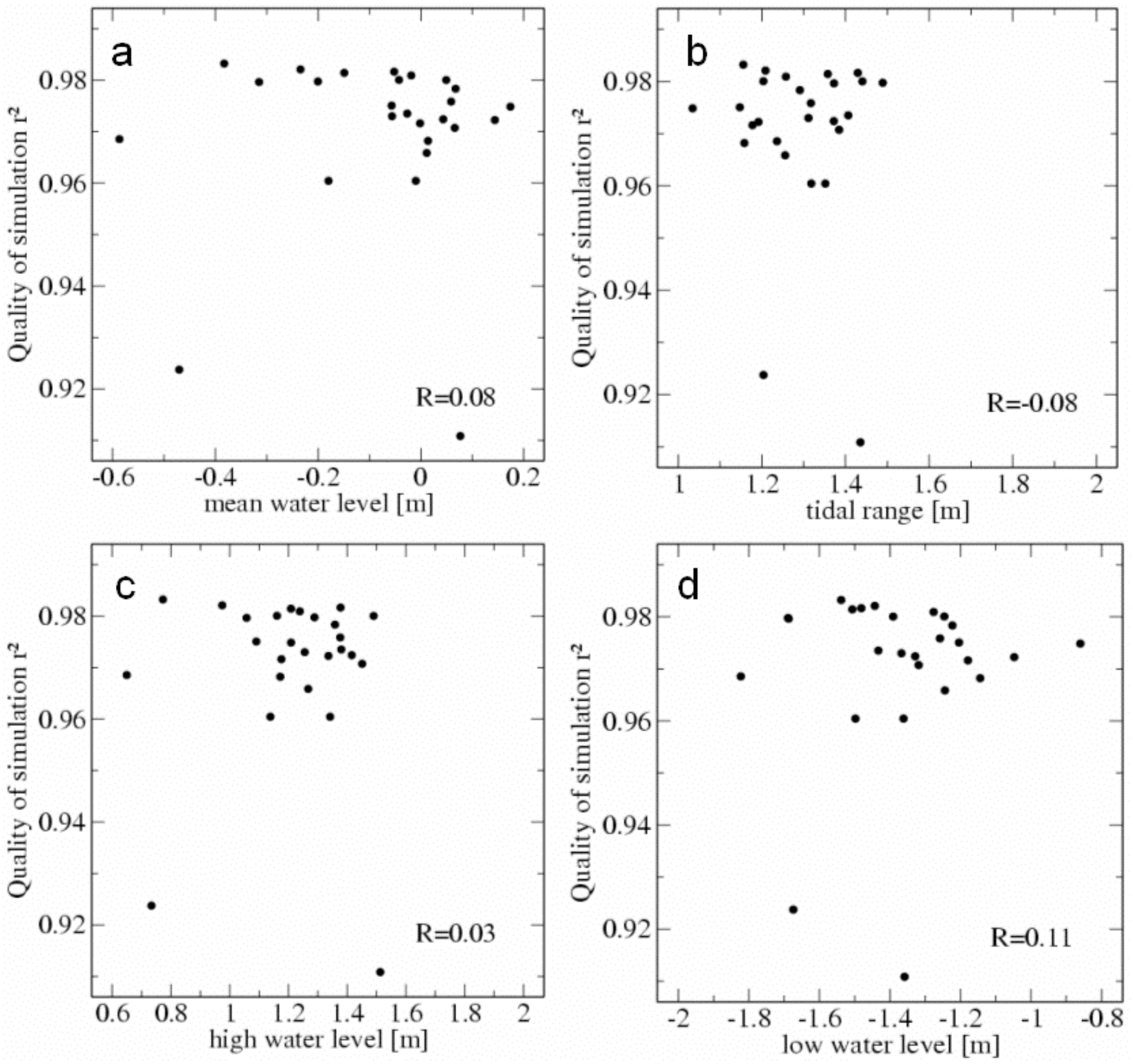


Fig. 7 Effect of different tidal parameters on the quality of simulations: a Mean water level, b tidal range, c high water level, d low water level