Observation- and Modelling of Morphodynamics in Sandy Coastal Environments

Habilitationsschrift

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Fachbereich Geowissenschaften

der Universität Bremen

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Bremen, 2011

Summary

The topic of sandy coast morphodynamics involves the mutual influences of coastal topography, local sedimentology, the driving meteorological and hydrodynamic boundary conditions, flora and fauna, and the activities of human beings: The latter as direct actors through coastal constructions and other interventions, as indirect actors through possible contributions to global change, but also as receiving agents - as living individuals confronted with the forces of the sea.

The general aim of coastal research is to gain an as comprehensive as possible understanding of the different systems and their interaction in order to be able to evaluate their current state, assess their stability, explain past changes (in the geological record), and predict future developments under different conditions. Such systems dynamics involve a large bandwidth of spatial and temporal scales: from the microscopic interaction of turbulent fluid motions with single particles to meso-scale tidal dynamics of subaqueous bedforms to macro-scale seasonal adaptations of beach profiles or the meandering of tidal channels, to the mega-scale evolution of shorelines and shelf systems over decades to centuries.

The process of understanding involves a continuous feedback of observations, abstractions, mathematical formulations, model development (ranging from conceptual models to mathematical formulations of processes, and to complex, process-based numerical modelling systems), and the testing of models on the basis of observations, new abstractions, and so forth. In the case of the morphodynamics of sandy coasts, the interaction of the physical processes involved in hydrodynamics, sediment dynamics, and their mutual adjustment to changing bed topographies seem most relevant, although biogeochemical processes play a (commonly underrated) additional role.

This discourse presents an extended summary of the current state in the continuous process of gaining knowledge on coastal morphodynamics. It focuses on the dynamics of tidal channels and their main roughness elements: subaqueous compound bedforms. Methodological approaches involved are field measurements and numerical modelling, which are introduced and discussed.

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1 Introduction

Land and sea meet in the coastal zone - it is '*the part of the land most affected by its proximity to the sea and that part of the ocean most affected by its proximity to the land'* (Hinrichsen, 1998). Coasts are among the most dynamic environments on the planet because here terrestrial and marine processes continuously interact over a broad bandwith of spatial and temporal scales. In its vast variety of geographical forms, ecological richness, physical relations, and economical values the coast has for eons fascinated humankind from casual admirers to dedicated scientists of various disciplines who try to understand the interaction of the complex processes controlling the evolution of coastlines and ecosystems under natural forcing and anthropogenic influence.

With increasing human exploitation, coastal zones in particular have come under increasing socio-economic pressure. The exploitation potential of the land-sea interface in terms of settlement, traffic, constructions, harbour development, tourism, fisheries, offshore structures, etc., goes along with severe impacts on the natural environment. Past experiences have shown the vulnerability of marine systems, e.g. in the form of large-scale responses to small-scale coastal engineering interventions (Capobianco et al., 1999; Pilkey and Dixon, 1998), and the disastrous effects of extreme events (Pilkey and Young, 2005; Schiermeier, 2005). The often detrimental effects of human interferences with the coast have led to the development of management strategies which aim at a sustainable development of coastal zones based on detailed knowledge of the natural systems, the underlying processes, and their response to external forcing.

Various coastal systems can be defined which encompass the interaction, interrelation, and interdependency of their associated entities:

- **Socio-economic systems** that link demographic and economic characteristics of a wide variety of coastal management issues such as, for example, environmental protection, coastal constructions, recreation, exploitation of natural resources.

- **Ecosystems** on micro-, local- and regional-scales that involve interdependent organisms such as plants and animals within the same habitat, and which are linked together through nutrient cycles and energy flow, and are individually and together influenced by chemical and physical factors of their environment.

- **Physical systems** that describe the dynamics of acting forces and their effects. The main entities of these systems encompass driving hydrodynamic processes, resulting transports, and their geomorphologic effects.

The above systems are characterised by their parts and composition, their drivers, processes and output, and their interconnectivity: The various parts of a system, and also the different systems by themselves, have functional and structural relationships between each other. These may be analysed as closed structures, but must take into account environmental aspects that act across the system boundaries.

Definition of Morphodynamics

The above-mentioned physical systems can be understood as primary drivers of the other systems. The interplay between hydrodynamics (meteorological forcing, short waves and wave-, wind- and tide-induced currents) and sediment dynamics (erosion, transport, deposition and resulting morphological change) both drives and is influenced by coastal morphology. The main processes are commonly schematised as a looped series of fluid motion, sediment transport, and topographic change. The commonly cited work of Wright and Thom (1977) termed the '*mutual adjustment of fluid dynamics and topography involving sediment transport'* as **morphodynamics**.

This scheme, however, can be misinterpreted as a closed system, tending towards a stable equilibrium because the most crucial external drivers (the open boundary conditions) are not mentioned. This certainly does not hold in natural systems that are continuously exposed to unsteady forcing. De Vriend (1991) understands the term morphodynamics more generally as the *'dynamic behaviour of alluvial boundaries'*. The dynamic behaviour is the result of the feedback loop of hydrology, sediment transport and resulting bed evolution driven by time-variant or stationary boundary conditions (Figure 1).

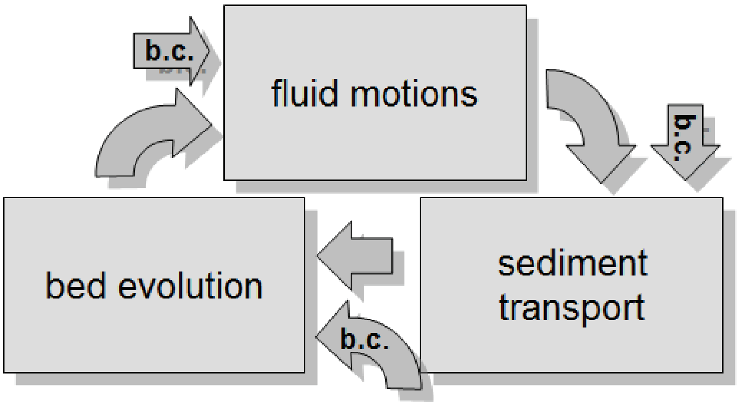

Figure 1: Scheme of coastal morphodynamics: Loop of the mutual adjustment of fluid motions, topography and sediment transport under the influence of conditions at the system boundaries (b.c.).

The morphodynamic scales

The morphodynamic loop described above holds on several temporal and spatial scales: Kraus et al. (1991) classified morphodynamics into micro-, meso-, macro-, and mega-temporal and -spatial scales. In that sense, micro scales cover the interaction of waves, turbulence and single grains, and the formation of small ripples on the seabed, or the formation and destruction of flocs and aggregates in less than seconds to minutes on millimetre to centimetre length scales. Meso-scales cover processes acting on meters to kilometres in minutes to months. However, a further differentiation of the meso-scale into a small-scale (decimenters to tens of meters; minutes to days) and a large-scale (hundreds of meters to kilometres; days to months) seems appropriate in this context (Figure 2). Thus, small-scale morphodynamic processes comprise the formation, dynamics and hydraulics of bedforms such as small dunes or scours produced in the instantaneous response to tide- or wind- and wave-driven currents. The large meso–scale, for example, covers the migration of large dunes in tidal channels or the adaptation of beach profiles to storm conditions. Sediment pathways, tidal channel migration, or the vertically oscillating behaviour of tidal flats cover macro-length (kilometres) and -time scales (months to years). Mega-scale morphodynamics, in turn, comprises coastal features exceeding 10 km in length and dynamics over decades to centuries. Finally, sub-regional and regional morphodynamics (mega-spatial scale >10 km) occurs within macro- to mega-time scales (Kraus et al., 1991). The morphodynamics on yet larger scales, e.g. the Holocene evolution of coastlines or the formation of barrier islands, are beyond the scope of this discourse and are therefore not covered here.

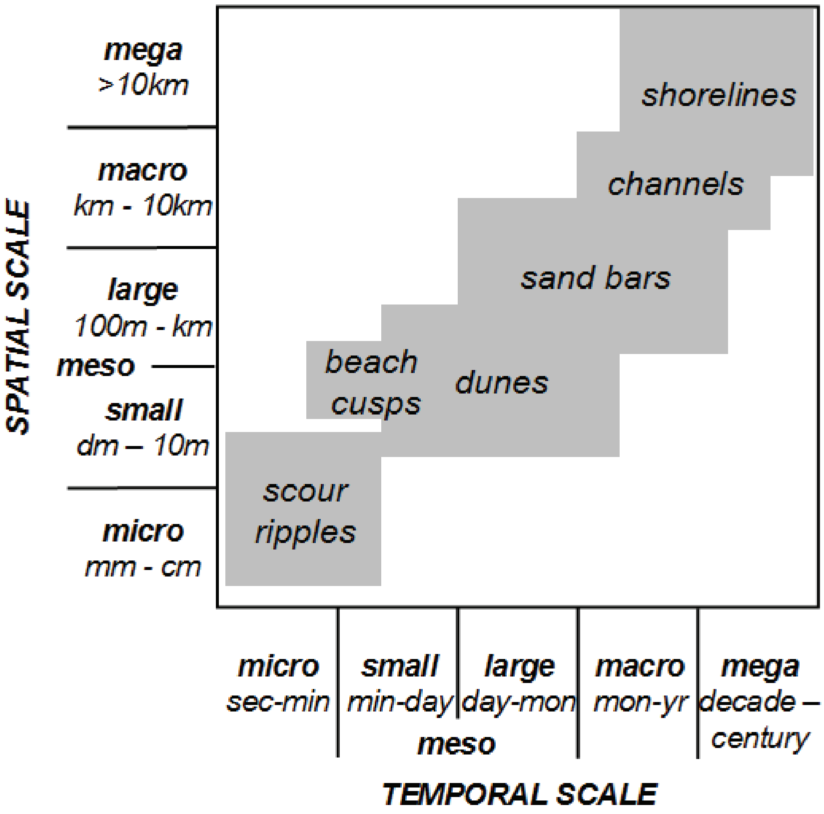

Figure 2: Spatial and temporal scales and typical coastal morphological features.

Cowell and Thom (1997) group time scales at which coastal processes operate into four classes: **Instantaneous time scales** involve the evolution of morphology during a single cycle of the forces that drive morphological change (waves, tides) from a few seconds to many days or weeks. **Event time scales** are concerned with coastal evolution as a response to forcing processes operating across time spans ranging from that of an individual event through seasonal variation from a few days to many years. **Engineering time scales** describe coastal evolution under natural forcing and its response to human impact from a few months to decades. **Geological or geomorphological time scales** operate over decades to millennia and cover the evolution of landforms in response to long-term mean trends in the forces (sea level, climate).

It should be noted, that the above classifications draw rather arbitrary lines through a continuous time-space system. The listed features certainly rely on processes over different scales which interact and depend on each other. Scientific understanding of morphodynamic systems thus not only requires the study of processes and interactions according to the spatio-temporal equilibrium, but also the bridging of temporal and spatial process scales and classifications.

Understanding the system

The visualisation and interpretation of coastal morphodynamics are commonly based on time-series of morphological states. The inter-comparison of data of different times for the same area reveals a residual morphological evolution between the states. Topographic ('dry morphology') and bathymetric ('wet morphology') data usually are derived from land- or ship-based surveying (Ehlers, 1988) or remote sensing products like aerial photography, lidar or satellite altimetry (Chu et al., 2006; Kroon et al., 2007; Niedermeier et al., 2005).

Observed morphological changes can often be directly related to external (e.g. hydrodynamic) forcing factors. Beach erosion due to storm wave action, scouring around offshore foundations, or the breaching of dikes in a storm surge are examples of **forced behaviour**, also called 'hydrodynamic templates'. In contrast to the obvious direct effect of the forcing agent to morphology, **freely- or self-organised behaviour** describes cases in which no obvious relation between assumed forcing factors and observed patterns can be recognised. Patterns like bed ripples, dunes, or features like beach cusps and rip currents are often related to and explained by self-organisation. Obviously, the analysis of coastal morphodynamics requires more than just information on morphological states: The description of the relevant drivers is of prime importance. However, coherent hydro- and sediment dynamics are only rarely measured simultaneously with the morphological measurements and a completely synoptic analysis, i.e. the simultaneous observation of all relevant parameters of a multi-dimensional morphodynamic system, is certainly not feasible.

The evaluation of modern coastal systems, the reconstruction of past stages, and the prediction of possible future developments require an understanding of the underlying processes and their interaction. The physics of morphodynamic processes are highly non-linear and many elements and their coupling are still unclear. Some parts are understood in a deterministic way (i.e. they can be derived from first principles), e.g. fluid dynamics in principle can be calculated by numerical solution of the Navier-Stokes equations (NSE). However, limitations in computational power and uncertainties in the initial and boundary conditions can only be overcome by simplified parameterisations and thereby reduce the theoretically possible direct simulation to an approximation. Other relevant processes are far less well understood than the hydrodynamic system: The stability of the fluid-bed interface is a two-phase problem, which as yet has no deterministic solution. However, based on theoretical and empirical considerations, a wide range of modelling approaches have been formulated to relate, interpolate, extrapolate and interpret measured data and to simulate system states. These models may comprise conceptual, empirical, data-driven stability concepts and numerical process-based approaches. Empirical relationships have been formulated for the description of boundary-layer properties of the fluid and bed (Nielsen, 1992), critical stages of erosion and deposition (van Rijn, 2007a), sediment transport on the bed and in suspension (van Rijn, 2007b), and the formation of bedforms of various sizes (van Rijn, 1984; Yalin, 1964). If these are embedded in a system of computational modules for the calculation of fluid motions and bed evolution, a simulation of morphodynamics is theoretically possible. However, by definition, any empirical relationship is only valid for the system under consideration and the range of observations it is based upon; thus, application to other environments requires calibration and validation based on local field data. Thus, the current state of the art in understanding the morphodynamics of any system requires both: The analysis of field data and the utilisation of model approaches.

Purpose

This discourse introduces 13 selected peer-reviewed publications of the author (10 first authorships) dealing with the observation and modelling of morphodynamics in sandy coastal environments. It shows the integration of state-of-the-art numerical model concepts and field observations into coastal morphodynamics research. It focuses on the large- to macro-scale morphodynamics of tidal channels and small to large current-generated structures: Subaqueous compound bedforms. Methodological approaches involved are field measurements and numerical modelling, both of which are introduced and discussed below. The following chapter 2 focuses on the observation and analysis of coastal morphodynamics on the small to large-scale (bedforms) and the macro-scale (inlets, channels, estuaries). Chapter 3 introduces different modelling approaches and numerical modelling strategies, and provides examples of macro-scale process based numerical models. Important shortcomings of the models are discussed. Chapter 4 places the publications into the general context of coastal morphodynamics. In the final chapter an outlook on ongoing and future research activities is given which addresses the integration of the results of small-scale field observations with macroscale models.

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2 Observation of coastal morphodynamics

The analysis of coastal morphodynamics is usually based on data of successive bathymetric stages of the domain under investigation, which on a large variety of spatial and temporal scales allows the visualisation of their residual evolution (Figure 3). Bathymetric data commonly are derived by ship based hydro-acoustic mapping. This involves data acquisition by the deployment and recording of echo-soundings and positioning, the filtering of raw data for errors, the correction of data for ship movement and water depth, and the projection of data to common coordinate systems and reference levels (Cohen, 1980). In the recent past, positioning and measuring techniques and post-processing software tools have undergone significant advances, leading to the possibility of spectacular high-resolution imaging of the seafloor by multi beam echo-sounder (MBES) technology (Lurton, 2002; Winter, 2006b). Other methods to derive high-resolution information on the micro-scale bed evolution involve stationary measurements by optical methods such as stereo-photogrammetry (Briggs, 1989), laser distance sensors, and acoustically fixed or profiling pencil beam sonars (Van Rijn, 1986).

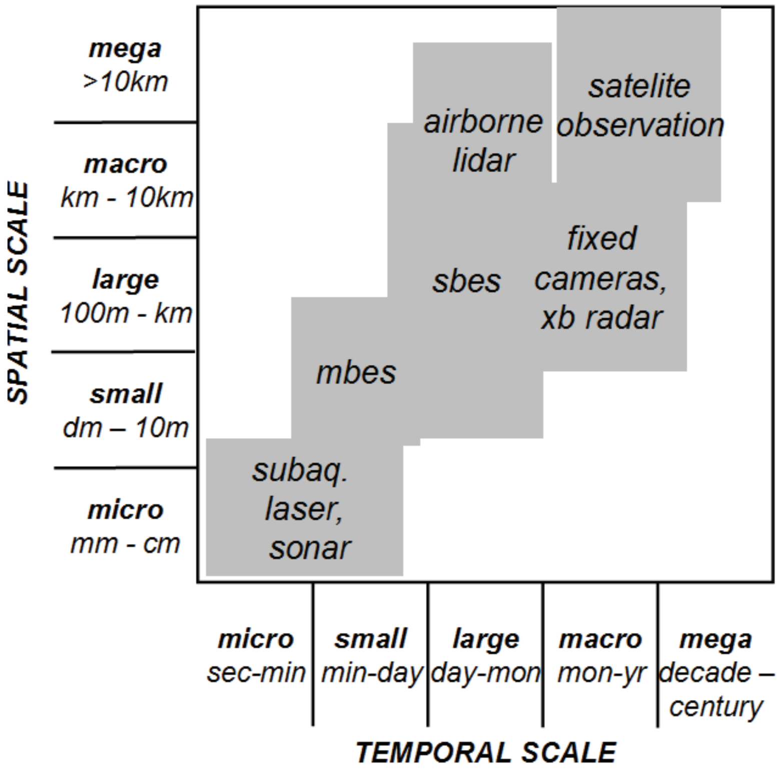

Figure 3: Scales and measuring techniques: In which *mbes* are multi-beam echo sounders, *sbes* are single beam echo sounders, and *xb radar* refers to x-band radar

For meso- to macro–scale observations, long-exposure camera images of wave patterns (Aarninkhof, 2003; Bryan et al., 2008) or radar facing the nearshore (Serafino et al., 2010; Ziemer et al., 2004) are analysed. Airborne remote sensing by photogrammetry (Lane et al., 2003), lidar (Finkl et al., 2005; Irish and White, 1998; Jones et al., 2007a; Notebaert et al., 2009), or radar (Niedermeier et al., 2005) are applied for dry and shallow water areas. Mega-scale morphodynamics are usually derived from satellite observations (Chen and Chang, 2009; Ryu et al., 2008). The analysis of mega-scale morphodynamics also requires the exploitation of old pre-digital data sources such as historical sea charts (Homeier et al., 2010) or the geoscientific analysis of the sedimentary record (Behre, 2002; Streif, 2002).

Despite the fact that modern instruments deliver high-quality digital data, which can be processed electronically, the semi-automatic nature of field data acquisition, and the pre- and post-processing of high-resolution data requires considerable manual effort which easily exceeds the time required for the acquisition of the measurements. After data acquisition and post-processing, geo- and time-referenced data (x,y,z,t) are obtained that describe the topography (elevation of sea bed). Successive measurements of the same domain can then be compared to reveal the residual bathymetric evolution between the times of measurements. Commonly, the irregularly spaced raw bathymetric data are interpolated on structured or unstructured grids to form digital elevation models (DEM). Several different gridding and data interpolation algorithms are available, and these should be carefully chosen and evaluated for the required purpose (Heritage et al., 2009; Rayburg et al., 2009; Saffet, 2009). DEMs then allow the direct comparison of different datasets at the same discrete points. Methods for the visualisation and analysis of bathymetric change involve the comparison of longitudinal or cross-sectional depth profiles (transects) or depth contour lines (isobaths) recorded at different times. Characteristic features can then be recognised and followed through time. By subtraction of DEMs of two different stages difference maps are generated which allow a spatial quantification of measured residual deposition and erosion. Morphodynamic analysis by the animation of bathymetric evolution is another option (Smith et al., 2000), but the discrepancy between the large spatial extent of the whole coastal system and the relatively small but complex changes of its parts leads to considerable uncertainty in detection and interpretation.

2.1 Observation of micro- to meso-scale morphodynamics

As mentioned above, the modern high-resolution MBES bathymetry reveals features and morphodynamic processes that could not be resolved by former techniques. Examples are manifold and comprise the detection and quantification of scour dynamics (Noormets et al., 2006), bedforms (Ernstsen, 2002; Ernstsen et al., 2006) and other morphological features (Li and King, 2007; Roberts et al., 2005). Rhythmic patterns such as aeolian dunes are among the most fascinating geomorphologic features on our and other planets (Claudin and Andreotti, 2006). As a product of the interaction of a deformable bed and the forcing hydrodynamics, subaqueous bedforms have been a phenomenon fascinating the scientific community for more than a century (Ayrton, 1910; Darwin, 1883; Dyer and Huntley, 1999; Flemming, 2000; Fredsøe, 1974; Hulscher et al., 1993; Kennedy, 1963; Kennedy, 1969; Liu, 1957; Sumer and Bakioglu, 1984; Yalin, 1976). Despite the simplicity in form, their ubiquitous nature and the multitude of applied methods and approaches, a satisfactory formulation of the underlying physical principles has remained elusive and probably still needs many more years of dedicated research (cf. Kennedy, 1963). As bedform nomenclature is a matter of controversy between different schools, the terms "sandwave" or "dune" – which both have been understood purely descriptive by some researchers (cf. Ashley, 1990) but process-related by others (Yalin, 1976) – are avoided here in favour of the term "bedforms". Important reviews of the state of knowledge on subaqueous bedforms are given in other works (Allen, 1968; Best, 2005; Dalrymple and Rhodes, 1995; McLean, 1990).

As an example, Figure 4a shows a map of compound bedforms in the Grådyb tidal channel (Danish Wadden Sea, off Esbjerg harbour) in which the primary (large) forms are in the order of some hundred meters in length and several meters in height. Smaller, secondary features in the order of some tens of meters in length and some decimetres in height are super-imposed. Tertiary bedforms (ripples) may also exist but cannot be sufficiently well resolved. Repeated ship-based multibeam echo-sounder surveying of the centre of the main navigational channel over several hours reveal the morphological adjustment of the bedforms (shown in Figure 4b as an example of a compound dune of 100 m length and 3.5 m height) to the tidal currents. It can be observed that the upper parts of the compound dune shows horizontal oscillatory motions in the order of several meters over a tidal cycle, whereas the deeper trough region seems stable. The large forms can also be recognised over longer time periods, and show considerable residual migration (Ernstsen et al., 2011).

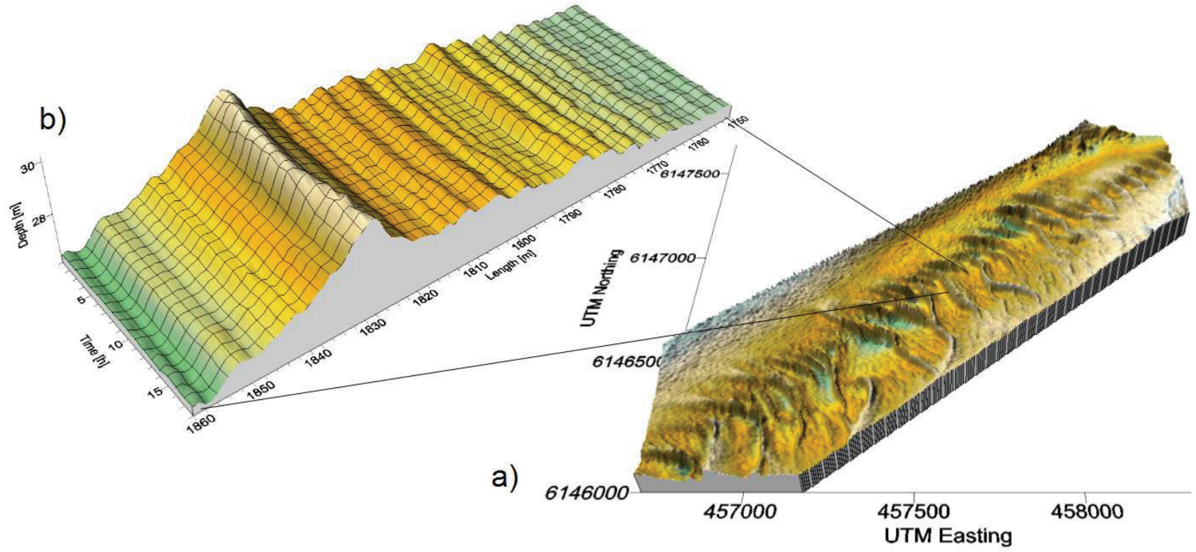

Figure 4: Compound bedforms in the Gradyb tidal channel (Danish Wadden Sea, North Sea coast) recorded in 2002. a) Map of the inlet channel at 0.5 m resolution. A series of large (= 200 m long) bedforms can be seen. b) Detail of the temporal evolution of one compound bedform repeatedly measured over a period of 16 hours.

The analysis and quantification of bedform dynamics require objective and automated methodologies to minimise errors in the recognition of the super-imposed small dunes and thus the allocation of dynamic properties to specific elements. In analogy to the processing of time-series (e.g. wave or tidal sea-level analysis), different methods may be applied for an objective description, dimensioning, and subsequent parameterisation of bathymetry in the presence of subaqueous bedforms: Simple manual detection of morphological properties (e.g. defining the positions of troughs and crests), and recognition of individual forms; automated detection of bedform characteristics in the spatial domain; spectral analysis of bedform profiles by Fourier transformation and wavelet analysis, and two dimensional Fourier transformation of bedform fields.

Analysis in the spatial domain

Common approaches for the description and analysis of bedform morphology and migration mainly consider triangular-shaped elements by linear interpolation between manually detected crest and trough positions (Hoekstra et al., 2004; Simons et al., 1965). Such procedures, however, do not allow a sufficiently realistic approximation of the complex bathymetric patterns found in tidal domains. Instead, all the features resolved by the measurement technique should be taken into account, which makes the manual recognition of bedforms subjective and very work intense (Ernstsen et al., 2005). Van der Mark and Blom (2007) proposed a bedform tracking tool in which geometric variables of individual bedforms are determined by zero-upcrossing of detrended and smoothed bed elevation profiles. This method is semi-automatic and still requires the subjective input of the moving average filter. Ernstsen et al. (2010) extended this procedure by an objective estimation of the size of the moving trend line to track and quantify secondary bedforms.

Spectral analysis

Spectral analysis can be used to decompose patterns and detect their (time- or) space-frequency features (Jain and Kennedy, 1974; Winter and Ernstsen, 2007). The spectral decomposition of measured bed profiles into a set of harmonic constituents by Fourier transformation has already been suggested by Nordin and Algert (1966) who used auto-covariance and spectral density analysis to overcome the simplistic description of bedforms as triangular-shaped bodies. Furthermore, Robert (1988) applied semivariograms as a statistical method for the investigation of roughness properties of bed profiles obtained from field work and laboratory experiments. More recent studies use a spectral method to describe changes in the height, length, and shape of wave-generated ripples which are considered to be the product of an energy transfer process (Davis et al., 2004).

The high accuracy of modern instrumentation allows the application of spectral methods also to bathymetric field data. Winter and Ernstsen (2007) applied a spectral decomposition of bed elevation profiles over compound bedforms of the Grådyb tidal inlet in the Danish Wadden Sea. Two profiles, measured at high and low water were decomposed by Discrete Fourier Transformation (DFT) into two sets of harmonic waveforms individually described by their amplitudes, wavelengths and phases. A comparison of individual waveforms along the two profiles thus reveals their specific spectral evolution in time. The change in size could be determined by the difference in amplitude, while the migration distance of the individual spectral components can be calculated from the difference in phase. Figure 5 shows an example of the derived migration distances of all waveforms.

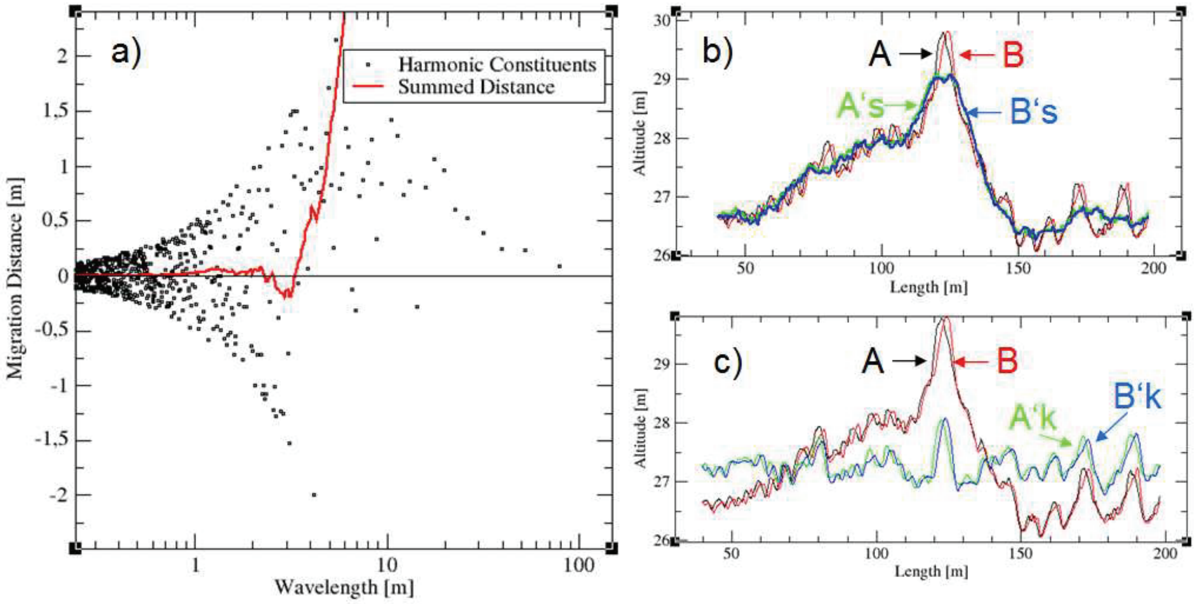

Figure 5: a) Decomposition of two compound dune bed profiles at high water (A) and low water (B) reveal migration distances by the differences of component phases. b) Recomposition of waveforms considered static A's and B's; c) Recomposition of waveforms considered kinematic A'k and B'k.

Numerical noise is shown by positive and negative migration distances for constituents of small wavelengths. The summed distances of wavelengths smaller than two meters thus oscillate near zero. These waveforms of indifferent migration and those featuring a migration distance of less than 0.25 m were considered as being on average static. By contrast, waveforms that show larger migration distances were considered mobile (kinematic). The recomposition of the classified harmonic constituents for the part considered stable is given in Figure 5b and the kinematic part in Figure 5c. While the stable constituents sum up to a roughly triangular shaped body which is considered not to move during the ebb time period, the recomposition of the kinematic constituents exposes the migrating forms as being approximately ten meters in length and up to one meter in height.

The spectral decomposition of the bathymetric signal into harmonic waveforms of different frequency clearly has great potential for bedform analysis and modelling (see section 3.1). However, Fourier transformation assumes a periodicity of the analysed signal, a feature which does not necessarily hold for bathymetric profiles and which therefore results in considerable noise in the component spectrum.

Wavelet analysis

Non-periodical sequences like bedform profiles can be analysed by wavelet transformation (Klees and Haagmans, 2000). The manner by which information about the spatio-temporal evolution of spectral characteristics can be derived has been shown by Cataño-Lopera et al. (2009) for laboratory-scale features. Fraccascia et al. (2011) carried out continuous wavelet transforms of bathymetric data recorded over seven years (from 2002 to 2009) along a 1600-m-long transect over natural compound bedforms in the Grådyb tidal inlet. Following the methodology proposed by Torrence and Compo (1998) for time-series analysis, characteristic wavelengths of the compound bedforms and their temporal evolution were analysed. It was shown that the observed bedforms are composed of four dominant wavelengths. This discrete spectrum was recognized throughout the eight years, confirming an observation by Winter and Ernstsen (2007) based on Fourier analysis. Although wavelet analysis can reveal interesting features such as the discrete spectrum composing bedforms, it must be complemented with other methods to derive information on bedform geometry. So far only single profiles have been inter-compared. Although seemingly feasible, to the best knowledge of the author, no studies have yet applied two-dimensional wavelet transformations of compound bedforms.

2D spectral analysis

The above methods describe the analysis of one-dimensional bathymetric profiles. The procedures thus require the a-priori subjective judgement on the choice and extraction of the "right transect". In the case of current-generated bedforms, profiles normal to the bedform crests are commonly used if the data allow this choice (not possible for single-beam echo-sounder profiles). Morphological characterisation and the objective derivation of bedform orientation and dimensions by using 2D spectral analysis have been shown by Lefebvre et al. (2011). The spectra descriptors calculated for a series of sub-regions for a domain with a high variance in bedform occurrence showed characteristic elements of that particular region. In combining spectral parameters of the sub-regions into an area-wide map, a differentiation into representative morphological elements was achieved.

2.2 Observation of macro- to mega-scale morphodynamics

Measuring campaigns that are carried out by research institutions are usually restricted by temporal and financial limitations. As a consequence, the scientific focus is commonly constrained to spatially limited study areas and the analysis of "snapshots" of the system. Long-term monitoring of coastal morphology for academic interests alone is hardly possible, although notable exceptions exist (e.g. COAST3D in the Netherlands, Coastal DUCK in the USA). However, governmental agencies often carry out extended coastal monitoring programmes. A wide range of meteorological, hydrographical, physical, biochemical and morphological parameters are thereby routinely measured at particular locations and varying time intervals. However, because such programmes are usually undertaken for other than scientific interests, the choice of locations and range of parameters measured often do not fully satisfy scientific requirements. Bathymetric surveys of German waters, for example, are carried out by the Federal Hydrographic Agency (BSH) and the local Waterways and Shipping Agencies (WSA) in fulfilment of governmental responsibilities for the navigability of waterways. Their data acquisition and processing schemes are optimised for the assessment of morphological states in these particular areas to support decisions on necessary measures to guarantee safe navigation, e.g. the dredging of shoals considered as shipping hazards. This implies frequent surveys of the waterways in contrast to rare observations in areas of less socio-economic interest. At least agreement has been reached on coordinated actions by these authorities for synoptic bathymetric data acquisition (Wulff, 2005), which makes it a very valuable source of information on the state and dynamics of the meso- to mega-scale morphological coastal systems occurring in these areas.

For the visualisation and analysis of morphodynamics, the irregularly-spaced raw bathymetric data are gridded to structured or unstructured grids to form digital elevation models (DEM). Different states can then be inter-compared over time at the same discrete points. By the subtraction of DEMs generated for different time slices, bathymetric difference maps are produced which allow a spatial quantification of measured residual deposition and erosion. An example is shown for the outer Jade and Weser tidal channels in the German Bight in Figure 6a in which the residual erosion (negative) and deposition (positive) patterns for a 21-year time interval are visualised. The long and slim features aligned parallel to each other with alternating positive and negative values reveal residual channel migration. Obviously, large areas of the domain could not be taken into account because either in 1984 or 2005 no data was available for comparison, thus highlighting a major disadvantage of this method. It must be emphasized here that seemingly small values in residual differences do not necessarily mean that little instantaneous transport took place at these locations.

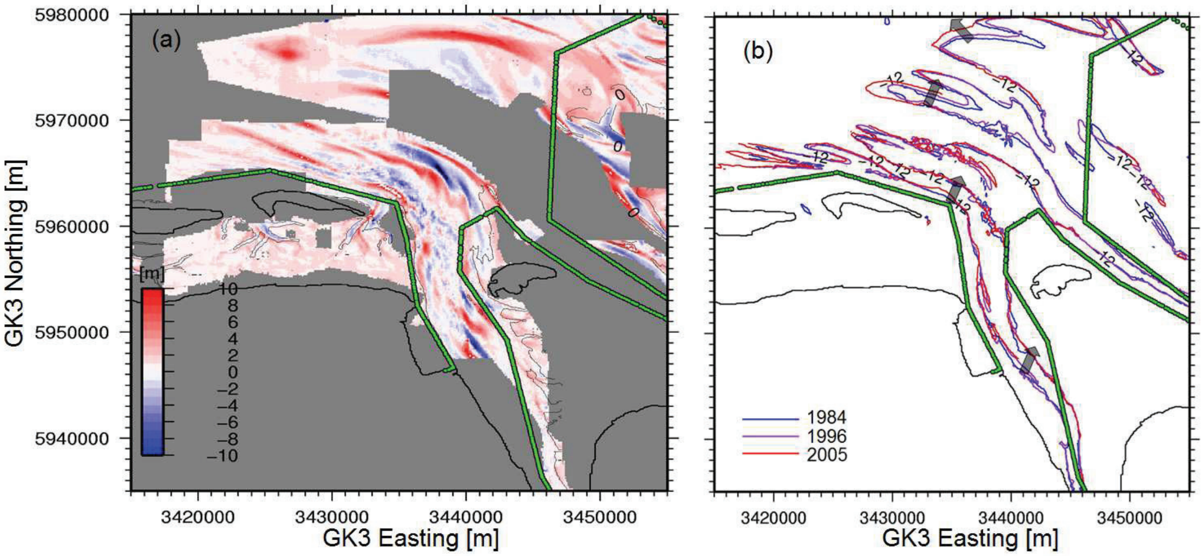

Figure 6: Morphological evolution of the Jade-Weser tidal channels based on BSH datasets between 1984 and 2005. Coordinates are in the equidistant Gauss-Krueger system. (a) Bathymetric differences between 1984 and 2005; negative values represent residual losses of material, areas without data are grey. (b) Comparison of the 12 m isobath calculated for the years 1984, 1996, and 2005; arrows depict preliminary interpretation of possible trends.

Bathymetric change between more than two states may also be visualised by comparison of longitudinal or cross-sectional depth profiles or depth contour lines of different times. In this way, characteristic features can be recognised and followed through time. This procedure, however, limits the analysis to either one cross-section or one (or a few) depth levels as shown in Figure 6b where the 12 m isobaths derived from 1984, 1996 and 2005 datasets are, for example, shown for the outer Jade-Weser region. A comparison of these lines allows the identification of possible trends; however, the four-dimensional morphodynamic system cannot be derived by interpretation of isobaths only.

The analysis of larger areas and the initialisation of numerical model bathymetries usually require the compilation of data of different origins and periods into one DEM. Commonly the most recent (or best quality) data is gridded first which is then successively complemented by older (or less reliable) data for the remaining regions. To avoid interpolation problems at the overlapping areas of different datasets Milbradt et al. (2005) present a higher-order algorithm for a spatio-temporal interpolation between datasets.

The macro-scale morphodynamics of the German Bight have been subject of several studies, especially with respect to tidal flats. Several authors have provided detailed descriptions of the morphology and dynamics of tidal flats (e.g. Albers and von Lieberman, 2010; Bartholomä and Flemming, 1997), tidal inlets and barrier islands (Flemming and Davis, 1994), estuaries (Gönnert, 1996; Winter, 2006a), the offshore (Hüttemeyer et al., 1999), and the shelf (Diesing et al., 2006) of the German Bight. Commonly, these studies focus on confined areas but some extensive compilations for larger areas are also available (Ehlers, 1988; Niemeyer et al., 1995; Schüller, 1991). For the southern German Bight - from the Ems to the Elbe - Homeier et al. (2010) have recently analysed numerous charts and maps spanning four centuries (1650-1960), compiling these into a consistent mega-scale picture. Winter (2011) gives an overview of the mega-scale morphodynamics of the whole German Bight at meso-scale resolution. A simple parameter is defined for the quantification of coastal morphodynamics based on bathymetric data of various times and variable spatial extent: The bed elevation range (BER) takes into account bathymetric data from the period 1982-2008 and is shown for the German North Sea coast (Figure 7). The parameter BER is the envelope of the bed evolution and may be understood as the morphodynamic spatial domain in which the morphological evolution takes place. The compiled data shows the highest morphological activity in the outer estuary tidal channels of the East Frisian coast and along the northwest coast. Considering the known distributions of tidal currents and wave energy along the German Bight coastline, it was suggested that the main morphodynamic drivers along the East Frisian coast are the tidal currents, whereas the high morphologic activity along the northwest coast can be viewed as being forced by waves.

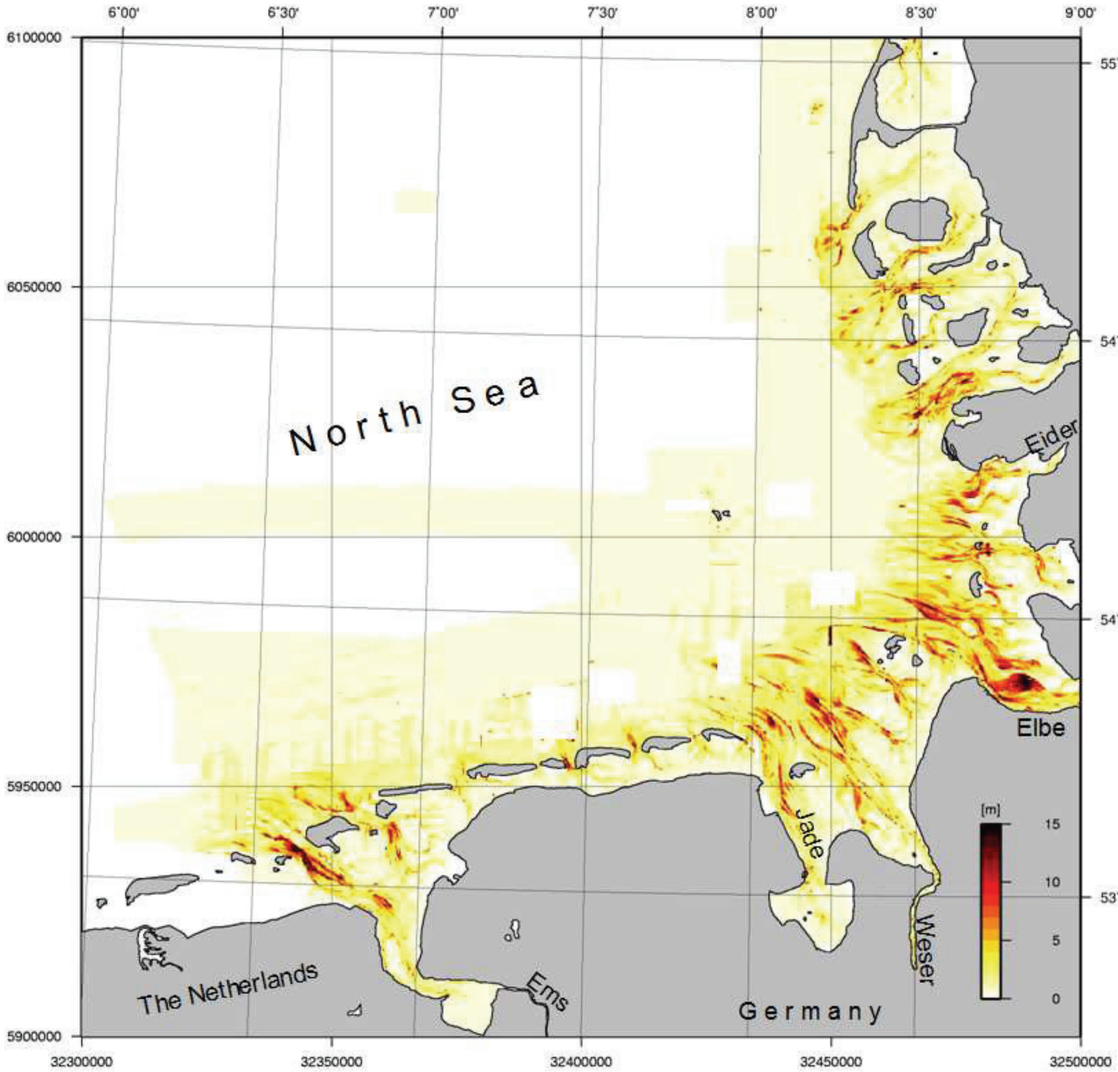

Figure 7: Macro-scale morphodynamics of the German North Sea coast as imaged by the bed elevation range BER. Positions are given in UTM32 (ETRS89) and geographic coordinates (WGS84).

2.3 Summary

Coastal morphodynamics are observed across several spatio-temporal scales. Although observation technology has greatly advanced, it is still mostly limited to a focus on residual morphologic changes. The morphodynamics are thus decoupled from the dynamic processes (hydrodynamics, sediment transport). Bathymetric measurements constitute time slices in a continuously changing environment. Interpolation between surveys is possible if sufficient data (spatial and temporal resolution) are available. For a comprehensive analysis of coastal morphodynamics, however, all relevant processes should be known. As the simultaneous measurement of the coherent hydrodynamic and sediment dynamic properties is not feasible at all relevant time and length scales in the field, other approaches are needed: Dedicated laboratory model experiments on the bed-fluid interface can focus on physical processes under controlled boundary conditions. In addition, mathematical models can be introduced to serve as higher-order tools for the spatio-temporal inter- and extrapolation of field data and scenario analysis.

3 Morphodynamic modelling

A **model** is commonly defined as being a *'representation of essential system aspects with knowledge being presented in a workable form'* (Van Waveren et al., 1999). A model can thus be a simplification or interpretation of data (e.g. a Digital Elevation Model), a conceptual view, a physical representation (e.g. a down-scaled prototype in a laboratory flume experiment), or a description of a system based on mathematical formulations. The latter mathematical models span wide ranges of objectives and complexity. Mathematical model concepts may be data oriented (only based on interpretation of measured data) to fully process oriented (deterministic models based on physics). Empirical relationships or neural networks are examples of purely data driven models. Soft hybrid models, which use process-oriented numerical modules in a neural network environment, and numerical models with data assimilation are intermediate concepts. Fully deterministic models describe the physics of a system by formulations which are based on first principles and are solved by direct numerical simulation (DNS). Models may also be classified into their domain of application (e.g. hydrodynamic, ecological, morphological, meteorological models), their spatial dimension (e.g. one-dimensional (1D), two-dimensional depth-averaged (2DH), three-dimensional (3D)), or practical application (e.g. to answer academic, scientific, administrative, or commercial questions).

The term **modelling** can be understood to encompass the process of model design, the development, the model set-up, the model calibration and validation, and the application of models. **Simulation** or **model experiment** are similar terms which may be used to describe the process and product of modelling a system under certain sets of parameters and boundary conditions. This chapter introduces mathematical model concepts and leads to a description of 2DH and 3D process-based morphodynamic numerical models. Model and data reduction schemes are introduced and the modelling procedure is briefly described. Some morphodynamic model applications are discussed and common shortcomings are highlighted.

3.1 Morphodynamic model concepts

Non-mathematical representations of system behaviour can be called **conceptual models**. These may include schematised and simplified visualisations of complex processes, flow charts or diagrams representing inter-relations between processes or model entities. They may stand alone to interpret or explain observed features if fundamental knowledge on the underlying processes is limited. Conceptual models also form a crucial first step in the development and application of more complex models. Prominent examples of conceptual models are the sequence of beach morphological states as defined by Wright et al. (1985), delta sediment dynamics such as the one by Kana et al. (1999), the response of the East Frisian Wadden Sea to sea-level rise by Flemming and Bartholomä (1997), or the estimated large-scale sediment transport pathways in the German Bight described by Sündermann and Klöcker (1983). A conceptual model in which the formation of saddle shaped subaquous dunes in a tidal channel was explained by inter-action of currents, sediments and local bathymetry has been suggested by Ernstsen et al. (2005).

Behaviour oriented models are built from mathematical expressions or rules derived from experiments, experience or conjecture, but not directly from first-order principles. Often dimensionless variables are defined (e.g. the Shields parameter) and equations are found as a best fit function between parameters. Examples for **empirical models** on coastal morphology include the relation of temporal scales T (time), spatial scales L (length) and Z (depth) through a transport rate $q=ZL/T$, in which typical values for q were found to be in the range 10^{-5} to 10^{-6} m²/s. This holds for environments of sufficient sediment supply and current strength and may also be used to estimate the largest spatial scale at which coastal morphology can adapt to sea-level rise (Dronkers, 2005). Other examples are the Bruun rule for coastal retreat (Bruun, 1962) or the Dean Rule for shoreface slope (Dean, 1990). A well established empirical relationship between the tidal inlet cross-sectional area A and the tidal prism P (at spring tide) was given by O'Brien (1931) as $A=cP^n$ with the exponent n in the order of one and a constant c in the order of 10^{-4}. Alternative empirical relationships between inlet cross-section and tidal prism are inter-compared by Stive and Rakhorst (2008). Other behaviour oriented concepts include the geometric fitting of log-spiral curves to embayed beach planforms, which have led to widely accepted assessment and prediction options for beach equilibrium states (Silvester and Hsu, 1997). A diffusion type behaviour model of beach profile change is described by de Vriend et al (1993a). Winter and Ernstsen (2007) formulate a dynamic 1D behaviour model to analyse bedform super-imposition based on empirical equations and a spectral decomposition of compound tidal bedforms.

Ranging in complexity between empirical formulations, which describe static equilibria between state variables, and numerical solutions of the full set of fundamental equations, **cellular automata models** are tools to simulate the spatial and temporal evolution of some system properties. These properties are defined for and communicate on discrete grids. The system behaviour here is assumed to be governed by a given set of abstract rules. Conceptual ideas, empirical formulations or simplified fundamental processes may be coupled and expressed in communication rules which drive the interaction between cells. Two dimensional cellular models have, for example, been constructed to explain self-organized formation of beach cusps (Werner and Fink, 1993), barchan dunes (Zhang et al., 2010), braided rivers (Murray and Paola, 1994), or the long-term morphodynamics of shoreline evolution due to waves (Ashton et al., 2001).

In principle, **complex process-based** models are based on the theoretical understanding of the underlying physical processes. The governing equations are set as partial differential equations from the fundamental physical laws such as conservation of mass, momentum, and energy. If approximated by numerical approaches, the **direct numerical simulation** (no parameterisation and turbulence sub-models) of the Navier-Stokes equations, which describe the motion of fluids, is possible. However, in that case all spatial and temporal scales of the hydrodynamics (flow and turbulence) must be resolved – down to the smallest dissipative scales of turbulence. The required very high grid resolution and very small time-steps of simulations lead to very high computational demands. The direct simulation of processes relevant to the topic of coastal morphodynamics is thus reduced to boundary layer studies at small scales and relatively low Reynolds numbers (Ferziger and Perić, 2001). The application of direct numerical simulation to coastal morphodynamic scales is therefore not feasible yet. The direct simulation of flow structures in combination with **discrete element methods** or **smoothed particle methods**, however, are very promising lines of research – in particular when considering the increasing computational resources expected to be available in the future (Papista et al., 2011; Schmeeckle and Nelson, 2003).

Stability concepts

Many morphologic patterns observed in the coastal environment can be related to instabilities produced by the flow response to seabed perturbations: Sand dunes, ripples, beach cusps, rip cells, breaker bars, meandering and braiding channels, tidal flats, and sand banks all have in common that their characteristic wavelengths are not evident in the external driving conditions. For highly idealised topography and for a limited range of spatial and temporal scales, morphodynamic feedbacks can be solved analytically. **Linear stability analysis** aims at the initial response of a system to an infinitesimal perturbation of a basic equilibrium state. In this initial phase the perturbation is considered so small that the flow pattern is hardly changed. The flow response is assumed to react linearly – and can thus be formulated by linear equations which can, in some cases, be solved analytically. The linear approximations do not hold for large growth rates in which the importance of nonlinear processes increases (e.g. flow separation, gravity induced down slope transport, shift from bed load to suspended load at ripple crests). Linear stability models thus indicate the 'initial tendency' to pattern formation starting from small fluctuations of certain equilibrium. This initial tendency involves the shape and horizontal length scales of the pattern but not its amplitude (Nemeth et al., 2002). Dronkers (2005) gives an example of the growth of an initial perturbation, which expands exponentially and migrates depending on the phase difference between the initial perturbation and the sediment balance. **Weakly nonlinear analyses** are based on the assumption that nonlinear effects are of limited importance to the morphodynamic system; for example, that bedforms of some amplitude are still small in some sense and their development can be explained by means of a perturbation approach (Blondeaux, 2001). Such analyses have also been used to investigate coastal morphodynamics. However, they are not applicable when nonlinear effects are strong, in which case only numerical approaches can simulate the dynamics of the system (Besio et al., 2008).

Complex morphodynamic models

If the relevant physical processes are known, formulated (written as mathematical equations), discretised (translated to a form that can be calculated numerically), and implemented (coded and compiled) into computational modules, complex process-oriented modelling systems can be developed by coupling the modules that describe sub-processes of the full system. In the case of coastal morphodynamics, hydrodynamic (wave and currents), sediment transport (bedload and suspended load) and bed evolution models are coupled to simulate the physical system as shown in Figure 1. Depending on the complexity of formulation and spatial dimension and on typical model application scales, different complex modelling systems can be classified (Figure 8): **Coastal profile models** describe the evolution of beach profiles over time by calculating the cross-shore sediment transport in response to changing boundary conditions. These cover timescales of storms to seasons (Van Rijn et al., 2003). Coastal **shoreline models** describe the evolution of one or several coastlines (isobathymetric contours) under variable forcing. One-line models describe the evolution of a constant shore profile. Such models can be based on behaviour oriented rules, analytical expressions, or numerical approaches. Typical ranges of application are shorelines of some kilometres and their development over years to decades (Hanson et al., 2003a). These concepts have been extended by multi-line (or n-line) models, in which the cross-shore profile can be discretised by several layers. These models have been applied to larger domains (1–100 km) with time scales ranging from seasons to centuries (Steetzel et al., 1998; Sutherland, 2007).

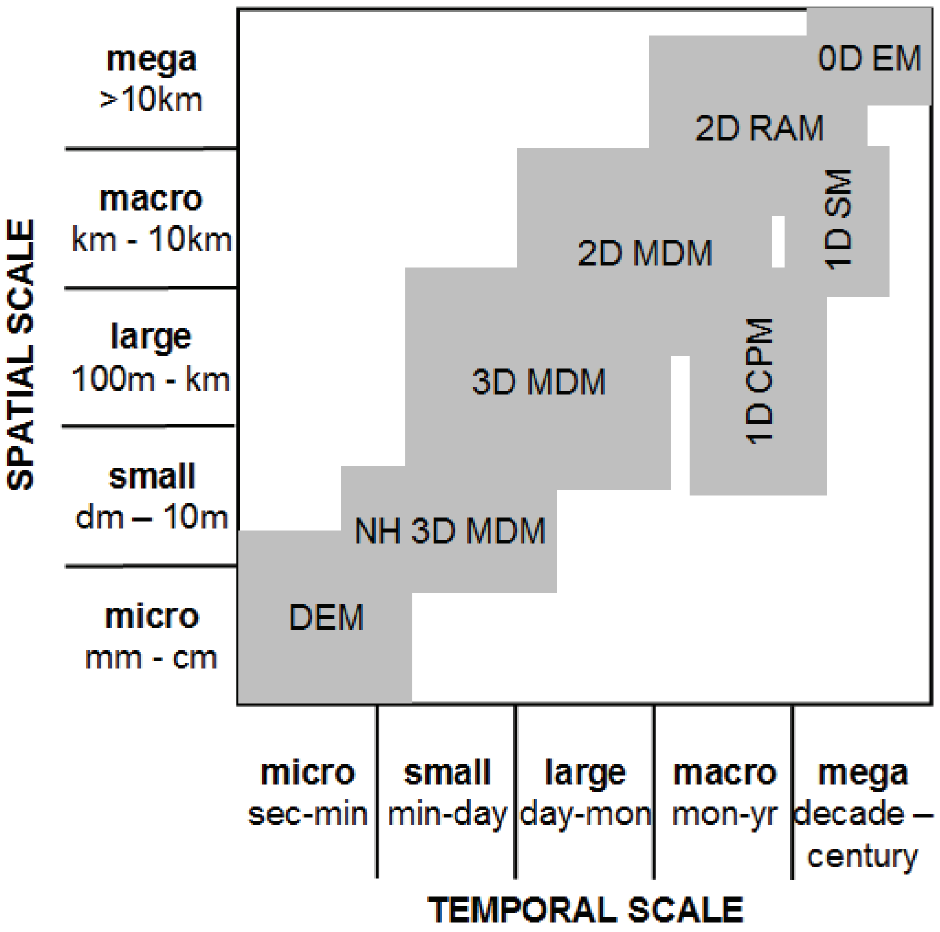

Figure 8: Spatial and temporal scales and applicable morphodynamic modelling systems. Shown are typical ranges of Discrete Element Models (DEM), non-hydrostatic 3D morphodynamic models (NH 3D MDM), 3D coastal area morphodynamic models (3D MDM), 2DH coastal area morphodynamic models (2DH MDM), rapid assessment of morphodynamics models (2D RAM), 1D coastal profile models (1D CPM), 1D shoreline models (1D SM), 0D empirical models (0D EM).

Coastal area models simulate the relevant processes on discrete computational grids covering the entire domain under investigation in 2DH (two-dimensional, vertically integrated) or 3D. Numerous morphodynamic model studies with scientific or applied aims cover schematic or idealised settings (Nicholson et al., 1997; van der Molen et al., 2004), and natural environments like estuaries (Hibma et al., 2003; Winter, 2006a), embayments (Mason and Garg, 2001b), tidal channels and flats (Albers and von Lieberman, 2010; Dissanayake et al., 2009), inlets (Cayocca, 2001; Ranasinghe and Pattiaratchi, 1999; Wang et al., 1995), beaches (Daly and Winter, 2011), or other coastlines (Lesser et al., 2004; Tonnon et al., 2007). Time scales typically cover engineering time and length scales from the meso- to macro-scale. Recent developments allow the simulation of flow and sediment dynamics in full 3D - without the common hydrostatic pressure assumption, which does not incorporate vertical velocity gradients (Figure 9). Fully 3D non-hydrostatic micro-scale morphodynamics are still limited to very small domains due to the very high computational demand (Giri and Shimizu, 2006; Kheiashy et al., 2010).

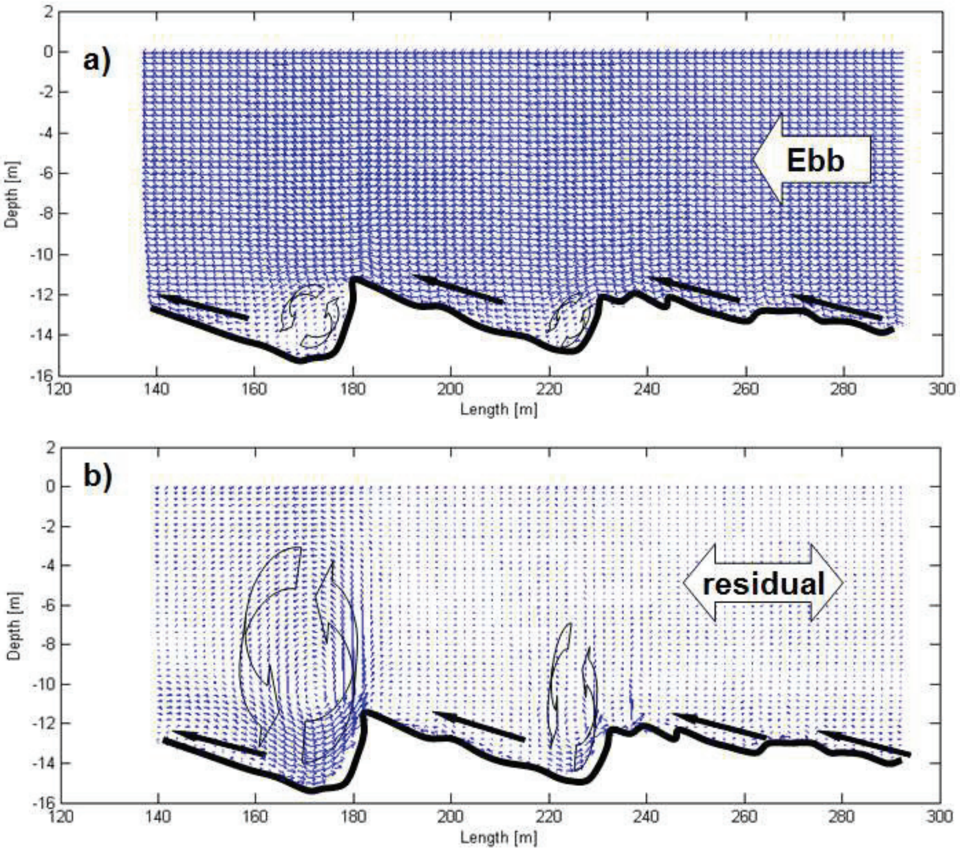

Figure 9: 2DV high-resolution simulation (non-hydrostatic Delft3D-Flow modelling system) of the flow structure induced by large compound bedforms in a tidal channel. The model resolution is 0.2 m in the vertical and 0.5 m in the horizontal, thus enabling (a) a detailed picture of the flow separation on the lee side of the bedforms in the instantaneous currents. The temporal integration of the velocities over one tidal cycle reveals (b) the residual circulation patterns that are assumed to induce and contribute to the development on the large bedforms.

3.2 The modelling process

The process of coastal morphodynamic modelling involves all steps of model development and model application. Commonly modelling is understood as a continuous process of conception and formulation, coding and compiling, verification, calibration, validation and application, often performed by the same person – the “modeller”. However, the complexity of modern numerical modelling systems, the availability of flexible user-friendly and stable software products, and the vast range of applications coupled with the growing acceptance of model simulations in science and decision support have led to a separation of the model development stage and the model application. Today open source or commercial products are often developed and maintained by some (expert) developers and applied by a much larger number of (expert) users for dedicated modelling projects. The process of **model verification** in model development is understood as the technical confirmation whether a mathematical equation is correctly implemented in a computer program. Model verification from a user point of view is the choice of the right modelling system based on well defined criteria. However, morphodynamic modelling system inter-comparisons or –census are rarely published (Van Riesen and Much, 2009).

Numerical models are today standard operational tools in academics, administration, and consultancy. A wide range of modelling systems is easily available and increasingly applied in decision support issues of different kinds. Growing initiatives like the Community Surface Dynamics Modelling System (CSDMS) or OpenEarth.nl not only provide access to free (public domain and open source) modelling systems but also the required pre- and postprocessing software, input data, and even computational resources. At the same time there is a growing public acceptance of the often colourful and spectacular three-dimensional animated simulation results. Availability, the ease of applicability, exaggerated expectations of stakeholders, and economic interests thus makes inexpert use of models an issue of growing concern (Thieler et al., 2000). Not only shortcomings of model formulations or faulty code implementations may lead to unreliable results, but also avoidable issues like missing model verification (the test of the suitability of the model approach to the problem), careless treatment of input data (incorrect “default” model parameters and boundary conditions), insufficient calibration (the tuning of the model to fit measured data), and missing or incomplete validation (the quantification of model skill based on independent data that was not used for the calibration). The large number of different modelling systems and model versions, and the vast variability of model applications also impede an objective inter-comparison or evaluation of models. Considerable effort has been spent to develop objective and generally accepted **guidelines and standards** for reliable, reproducible, and transferable modelling (Gerritsen et al., 2007; Scholten et al., 2001; Van Waveren et al., 1999; Winter, 2007). Some model standard datasets (e.g. Mayerle and Winter, 2010) and procedures (e.g. BAW Standard Validation Document) have been proposed, which could offer the opportunity for objective model inter-comparison. Realistically seen, however, economic interests and time limitations, and maybe even plain ignorance, will continue to obstruct objective modelling system census and model application validity evaluation.

Model reduction

Complex morphodynamic modelling involves the numerical solution of the mathematical equations describing waves, currents, transport and bed evolution considering an initial state of all system variables and the dynamic conditions at the open system boundaries which drive the system dynamics. The full-scale direct computation of all involved processes is not feasible in meso- to mega-temporal scales because of limited computational resources. To overcome this, different model and data reduction schemes are commonly applied: The distinction of the inherent time scales of hydrodynamic and morphodynamic processes leads to model reduction options. Assuming that the morphological evolution takes place on much larger time scales than the underlying hydrodynamic processes, the bed level can be considered invariant (quasi-steady) throughout a typical hydrodynamic cycle (wave, tide). On this basis the hydrodynamics, sediment transport and bottom evolution can be calculated successively in separate computational modules. The repeated feed-back of the new bottom topography into the hydrodynamic module (full morphodynamic loop) results in a dynamic simulation of the bed evolution. Alternatively, after only small changes in the bathymetry the flow field can be adjusted without the time-consuming re-computation of the full hydrodynamics (**continuity correction**) by assuming a constant local flow rate. This allows the calculation of the new flow field by simple consideration of a new flow depth.

Based on the idea that for small bed-level changes the overall flow and wave patterns do not change, tide-averaged transport rates can be considered as a function of flow and wave patterns which do not vary on the morphological time scale, while the local depth does vary on this time scale (de Vriend et al., 1993a; Jones et al., 2007b). Thus, if a certain set of currents and waves is known, the transport at a given location can be assumed to be a function of the water depth only. This approach called RAM (rapid assessment of morphology) allows a very fast computation of bed elevation change (Roelvink, 2006). Further model reduction can be achieved by increasing the morphological time step (lengthening of the tide) by an extrapolation of the computed bottom evolution (**morphological factor**). This factor (n) increases the rate of depth changes, so that after a model simulation over one tidal cycle the morphological changes correspond to n cycles. This is comparable to the concept of the elongated tide proposed by Latteux (1995) who applied it in combination with the continuity correction concept.

Model Set-Up

Some common issues in the modelling process are mentioned here because they form apparently trivial but nevertheless important steps in the modelling process. Model application and (own and third party model) evaluation should be based on a detailed description on the modelling system and the input data. This involves reporting on meta-data of the model bathymetry, sediment and roughness distribution, and surface and lateral open boundary conditions.

The set-up of a numerical model application starts with the definition of the model domain which is to be covered by a **computational grid**. At (or between) the grid nodes the model bathymetry is defined and the hydrodynamic properties and transport rates are computed. Depending on the modelling system, different computational grids are used. Numerical algorithms are optimised for different grid geometries; e.g. structured rectilinear grids, curvi-linear grids, or unstructured (e.g. triangular shaped) elements. For the model initialisation the bathymetry and all state variables (water level, velocity, and transport properties) must be known. For 2DH (two dimensional, depth-integrated) simulations under tidal forcing, simplified initial state variables are usually used (e.g. all zero), and some model spin-up time is to be considered to reach a dynamic equilibrium. The (hydrodynamic) spin-up may require periods of a few tides for coastal models. Three-dimensional simulations taking vertical stratification and mixing into account, e.g. in estuarine processes, require significantly larger spin-up times and should therefore be started with a more realistic realisation of initial conditions. If the model bathymetry is not in equilibrium with the model hydrodynamics and forcing, it will adjust in the initial phase of a morphodynamic simulation. Thus, the bed evolution spin-up time of coastal morphodynamic simulations is dependent on the accuracy of the initial bathymetry discretisation.

The **model bathymetry** may be schematised or extremely simplified (Wang et al., 2011), or based on empirical equilibrium shapes (Daly and Winter, 2011). Recent schematic simulations show the capability of process based models to generate morphological patterns which are similar to natural shapes (Dissanayake et al., 2009; Wang et al., 2011). Realistic model applications, however, require a representation of the real natural morphology. The already mentioned issues of missing synoptic field data acquisition also apply here: Consistent and synoptic bathymetric data covering larger model areas are rarely available. For coastal applications the relevant governmental or military authorities are usually sources of bathymetric information. Other bathymetric data are digitised nautical charts, which commonly lack morphological detail and must be understood as morphological states of mostly unknown origin, time and accuracy. Global compilation datasets like NOAA NDGC ETOPO2 (2 minute horizontal resolution), GEBCO_08 (0.5 minute grid), amongst others, are freely available but have limited validity in shallow waters. The interpolation of bathymetric data to the computational grid involves decision on suitable algorithms for a best representation of data (e.g. triangulation, kriging, nearest neighbour, averaging) and a thorough (manual) control and correction of the derived digital elevation model (DGM). Inconsistencies like faulty model bathymetry due to data or interpolation issues, or the application of non-consistent boundary conditions, may lead to drastic morphological change in the first phase of morphodynamic simulations. The “morphological spin-up” must therefore be taken into account when analysing and interpreting morphodynamic model results.

Common sediment transport equations calculate transport rates dependent on the driving hydrodynamic conditions and properties of the sediment material. However, realistic transport rates (and thus morphological evolution) can only be expected if the lateral (and vertical)

distribution of sediments is realistically discretised in the model. The necessary field data for this purpose are commonly difficult to obtain and often virtual sediment properties are taken. The choice of sediment distribution may range from uniform and constant values throughout the whole domain to a high-resolution detailed schematisation also in the vertical. Synoptic datasets of sediment distributions are scarce, although some compilations do exist, including that of Figge (1981) for the German Bight and of Flemming and Ziegler (1995) for a tidal basin of the East Frisian Wadden Sea. Due to the lack of consistent high-resolution field data, model-based predictions of the lateral distribution of representative grain sizes have been suggested (Hirschhäuser et al., 1998; Wang et al., 2011). The prediction of grain-size frequency distributions by application of a multi-fractional morphodynamic model was shown by van der Wegen et al. (2010a) for San Pablo Bay in California, and – with a different approach – by Kwoll and Winter (2011) for a tidal inlet in New Zealand.

The correct parameterisation of the **bed roughness** in numerical models is of similar importance because this parameter directly influences the hydrodynamic result, and indirectly (and directly) also the sediment transport computation. The hydraulic roughness of the bed is difficult to estimate in coastal environments because particle effects are overlain by the form roughness of ripples and large bedforms that are of substantial spatial variability and also change in time. Due to its high uncertainty and considerable effect on the model results, the bed roughness is commonly used as the main calibration factor in hydrodynamic numerical modelling. Considering the substantial sensitivity of numerical models to the bottom roughness, the approximation of bed roughness by a constant and uniform value is an unjustified over-simplification (e.g. Malcherek and Putzar, 2004; Wilbers and ten Brinke, 2003). Instead, the spatial (and temporal) diversity of bed roughness should be taken into account (Flemming and Ziegler, 1995; Tonnon et al., 2007; van Rijn, 2007a).

Numerical model simulations are driven by hydrodynamic conditions at the lateral open boundaries (see below) and **surface boundary conditions** such as wind- and pressure fields. The quality of the simulation is highly dependent on the quality and characteristics of the meteorological conditions prescribed. Direct measurements of the required wind and pressure at sufficient temporal and spatial resolution are not feasible for large computational domains, and the data have thus to be obtained by local or global estimates, model simulations, data re-analysis products, or remote sensing analysis. Such synoptic meteorological data are typically obtained as gridded wind velocities and atmospheric surface pressures given at different time intervals. The numerical simulation of wind and pressure driven waves and currents requires the specification of correct wind and surface atmospheric pressure fields at all computational grid nodes and for all time steps. Methods for downscaling of meteorological data cover a broad range from simple (linear, blockwise or higher order) interpolation schemes in space and time to statistical methods and regional high-resolution climate models nested into global models (Feser et al., 2001; Flemming and Bartholomä, 1997). If extreme events such as storm surges are to be taken into account, special requirements apply to the downscaling of meteorological data. Under the assumption that relevant meteorological features such as the cyclone geometry are sufficiently resolved by the grid, a direct spatial interpolation between grid nodes may be feasible. However, a direct interpolation between different fields in time cannot account for a realistic dynamic migration of storms. Instead, a fast moving cyclone, which is captured by the meteorological data only at some positions along its pathway, would appear as a chain of appearing and vanishing events if interpolated linearly over time. Winter et al. (2009) propose an algebraic method for the temporal interpolation of climate fields which takes the pathway and evolution of storms into account.

Lateral open boundary conditions: At the open sea boundaries, hydrodynamic, sediment-dynamic and morphological data must be prescribed to drive the simulation. The data can be schematic (e.g. constant values, or harmonics of different amplitude, frequency and phase), derived from direct measurements (e.g. a tidal gauge at a river mouth) or the downscaling of other data sources like large scale to global models. Commonly, model boundaries are defined as far as possible from the domain of interest. It is then assumed that boundary effects (possible inconsistencies in the data) do not influence the results computed some distance from the boundary. The nesting procedure of generating boundary conditions by larger scale models can be performed one-way (from the larger to the smaller model), two-way (also termed domain decomposition), or may be totally avoided if unstructured grids allow for a highly variable computational grid. For large-scale and long-term simulations, the direct ("online") simulation might not be feasible and data reduction techniques are taken into account. The concept of defining 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 tides, 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 a similar morphological effect as the reference simulation has been defined as representative (Cayocca, 2001; Mason and Garg, 2001a). In this context, Winter (2004) suggests that the choice of representative tides should be based on observed rather than on simulated reference morphodynamics. The former authors then find single or double 'representative' tides – typically ranging in the order of 2 to 10% higher than the mean tidal range - which reproduce the morphodynamic effect of the reference data to the best possible extent. Winter (2006b) however, states that single representative tides cannot reproduce realistic morphodynamics because the missing variability of external forcing will lead to unrealistic morphological equilibrium. Instead the natural variability of forcing e.g. by a parameterisation of input scenarios must be taken into account (Roelvink, 2006).

3.3 Model evaluation

Model evaluation as the analysis of model quality is part of the modelling process during preliminary tests, sensitivity analysis and calibration, and the final validation of a model application. It covers the full range from subjective 'eyeballing' to evaluate the plausibility of a model set-up to the calculation of objective automated model skill scores to assess and inter-compare simulations based on dedicated field measurements. **Sensitivity analysis** is the process of evaluating the effect of certain model parameters on the non-linear morphodynamic model results without explicitly addressing the quality of the model. Model **calibration** aims at the reduction of differences between reference data and corresponding simulations by systematically adjusting model parameters. Reference data can be derived from analytical solutions, physical experiments, or field data for which initial, boundary and end conditions exist, or reference model simulations. The availability of reliable field data determines the set of variables that can be inter-compared and evaluated in terms of their goodness of fit. Calibration is transformed to an optimization problem (multi-criteria analysis) if several model parameters are tuned and different variables are involved. **Validation** involves the assessment and quantification of model performance. This step must be performed on the basis of independent data, i.e. data not previously used for calibration.

General guidelines and standards for reliable, reproducible, and transferable numerical modelling have been proposed which also involve suggestions for model evaluation schemes (Dee, 1995; Scholten et al., 2001; Van Waveren et al., 1999; Winter, 2007). Instead of subjective statements on the model quality ("*… results are reasonably good*!"), objective statistical measures such as mean model errors or regressions based on measured data should be applied. Also, the quality of the measurements should be taken into account, as in the definition of a dimensionless adjusted relative mean absolute error (ARMAE) proposed by Van Rijn et al. (2002). In the same publication a rating of models is suggested in which error ranges are associated with qualitative expressions of the kind "excellent", "good", "reasonable", "poor" or "bad". In this scheme a model is considered "excellent" if the ARMAE of current velocity is smaller than 0.1, or it is rated "bad" if the ARMAE exceeds 0.7. However, such qualitative rating has not yet been defined for sediment transport model evaluation.

Standardised skill scores and model evaluation procedures have been in general use in meteorological modelling for many years (Murphy and Winkler, 1987). The application of these objective evaluation methods developed for meteorological forecasts has been proposed for the evaluation of morphodynamic models (Sutherland et al., 2004a; Sutherland et al., 2004b). Winter (2007) reflects on the significance of commonly applied sediment transport evaluation schemes as mean squared errors or discrepancy ratios.

3.4 A short biography of process based morphodynamic modelling

Important contributions to coastal area morphodynamic modelling research over the past two decades include the seminal work of de Vriend (1987) and de Vriend et al. (1993b) on the coupling of hydrodynamic, sediment transport and bed evolution modules to medium-term morphodynamic modelling systems. These papers sum up mainly schematic model results of the G6 Coastal Morphodynamics Group of the EC-sponsored Marine Science and Technology programme (MAST). Aiming at long-term modelling, de Vriend et al. (1993a) introduce reduction techniques for input data, process descriptions and output data, as well as different model concepts. Latteux (1995) then extends these process-based model reduction techniques for long-term simulations by methods such as effective morphological time stepping and the continuity correction. Capobianco et al. (1999) place these long term modelling strategies in the context of coastal zone management. The state of the art in coastal morphodynamic modelling at the end of the 1990s has been compiled in a collection of review papers by Seminara and Blondeaux (2001). Another summary on the state of different models is summarised by Hanson et al. (2003b). Also a special issue of the Journal of Coastal Engineering constitutes a relevant overview on the state-of-the-art of coastal morphodynamic modelling: Lakhan (2004) introduces a collection of papers on various modelling approaches, applications and model validation. In that issue Lesser et al. (2004), for example, present one of the currently most advanced process-based morphodynamic modelling systems (Delft3D). Also in that issue, Sutherland et al. (2004a) suggest the use of different morphodynamic model validation strategies. It also includes the application of process-based morphodynamic models to complex channel–shoal patterns which are shown by Hibma et al. (2004) to be applicable up to basin-scale morphodynamics of an idealised, tidal shelf system (van der Molen et al., 2004). Later, different schemes for morphological updating aiming at more reliable longer-term simulations have been inter-compared and further developed by Roelvink (2006). The application of data-assimilation techniques, i.e. the inclusion of measured data into the simulation is well known from meteorological and hydrodynamic modelling, but has been introduced to coastal morphodynamics only recently by Scott and Mason (2007) and others (Smith et al., 2009; 2011)

The focus of the above-mentioned modelling studies over the past decades had been set to the development of computational modules and their coupling based on schematic, realistic, or real environments (Bertin et al., 2009; Ferrarin et al., 2008; Lesser et al., 2004; Roelvink et al., 2009). These modelling approaches had mainly been developed with the intention of serving as coastal management tools. Typical applications comprise scenario analyses such as the model-based prediction of the morphological impact of coastal engineering (Grasso et al., 2011; Grunnet et al., 2004; Lu et al., 2009; Roos et al., 2008). In the recent past, however, the geo-sciences have also recognised the advantage of numerical modelling: Amongst many local studies, which address site specific topics and characteristics (Dan et al., 2011; Deleu et al., 2004; Di Silvio et al., 2010; Ruggiero et al., 2009; Sutherland et al., 2004b; Winter, 2006a; Xie et al., 2009), others address more fundamental questions on the formation and dynamics of coastal environments. Examples include the evolution of artificial and realistic tidal sand waves which have been modelled by coastal area morphodynamic models (Tonnon et al., 2007) and other approaches (Besio et al., 2008). Others deal with channel formation of tidal inlets (Dissanayake et al., 2009), meandering of rivers (Dulal et al., 2010), shoal pattern formation (Hibma et al., 2003), or controls of delta formation (Geleynse et al., 2011). The very long-term morphodynamic evolution of tidal embayments over millennia by process-based numerical modelling has recently been inter-compared with empirical relationships by van der Wegen et al. (2010b).

4 Synthesis: Combining field data and models

It has been shown that state-of-the-art field observation technology has significantly advanced in recent times. Coastal topography and bathymetry can be measured in great detail by remote sensing and ship based surveys. Successive data reveal bathymetric changes, which are the residual effect of the local morphodynamics. Several involved instantaneous hydrodynamic and transport processes can be resolved by direct measurements, but they are only feasible in small time and length scales. A comprehensive analysis of the coupled coastal morphodynamics system in large to macro scales requires a spatiotemporal extrapolation of field data and a bridging of scales. Various mathematical models of different complexity have been introduced, in which complex process based morphodynamic modelling is a very advanced approach. Many studies have shown the applicability of these models to schematic scenarios and real world environments. The latter are capable of simulating realistic morphodynamics in terms of depositional and erosional budgets. However, models are still limited in the reproduction of morphodynamic patterns in terms of a correct estimation of the migration of bars, banks and channels, and the reaction of morphological elements to variations in forcing (e.g. extreme events).

Various reasons for these limitations may be identified, including issues of model formulation and model application. By definition a model does not duplicate nature, but forms a simplified representation of a natural system, particularly if not all entities are known. Model formulation problems thus include the lack of fundamental understanding of underlying processes and their interactions – especially in the field of sediment transport, and the need for model reduction because of limited computational resources. Thus dedicated field surveys are needed to provide insight in specific processes and process-interactions. Model application problems include the knowledge on and thus the correct specification of initial- and boundary conditions, but also a significant lack of reliable and consistent field data for model evaluation. Here 13 **selected contributions by the author** on coastal morphodynamics are introduced which address the combination of observations and analysis of small- to mega-scale dynamics and different aspects of numerical modelling. These span the topics of large scale observations and dedicated field campaigns for the quantification of relevant processes in tidal domains, to the formulation of simple schematic models, to the development and application of complex morphodynamic models.

In order to introduce typical time- and length scales of coastal morphodynamics in engineering time and length scales, a geo-morphological overview about the morphodynamics of the German Bight coast is given in paper 1.

Paper 1: Winter, C., 2011. Macro scale morphodynamics of the Southern German Bight, North Sea. Journal Coastal Research SI 64: 706-710.

In that paper an overview on the morphologic activity of the German North Sea coast is given, based on all digitally available bathymetric data collected by the relevant authorities for the period 1984-2007. Instead of using traditional methods for the evaluation of coastal morphodynamics (difference maps or isobath comparisons), a new parameter was introduced to integrate all data into one map: The bed elevation range (BER) varies between low values in the foreshore to high values in the tidal inlets and estuaries of the German Bight.

These observed morphodynamics are understood as being product of the interaction of hydrodynamics, sediment transport and bed evolution with forcing conditions (Figure 1). For a sub-region of the German Bight numerical model simulations have been performed and assessed. Paper 2 is on a morphodynamic analysis and simulation of a tidal dominated estuary:

Paper 2: Winter, C., 2006. Meso-Scale Morphodynamics of the Eider Estuary: Analysis and Numerical Modelling. Journal of Coastal Research, SI 39: 498 - 503.

Data and model reduction techniques have been discussed and a method for the definition of a representative boundary condition was proposed. Model simulations of two year and eleven year evolutions showed the models capability in simulating vertical accumulation and erosion rates at some locations. However the rapid horizontal displacement of a tidal channel was not reflected by the simulation. Possible reasons for morphodynamic model shortcomings are insufficient process representations in the hydrodynamic and sediment transport models (model reduction) and erroneous parameterisations of the lateral open sea boundary conditions and surface forcing (data reduction).

4.1 Papers on sediment transport processes and model reduction

It was stated earlier that **model reduction** is necessary as the full-scale direct computation of all involved processes is not feasible because of a lack of knowledge on various processes and limited computational resources. Sediment transport is a major uncertainty in morphodynamic modelling, as the complex processes of mobilisation, entrainment, advection, deposition are commonly poorly represented in numerical models. Paper 3 reports on a sensitivity analysis, calibration and validation of a sediment transport model for the Meldorf Bight (German North Sea coast).

Paper 3: Winter, C., Poerbandono, Hoyme, H. and Mayerle, R., 2006. Numerical Modelling of Suspended Sediment Dynamics in Tidal Channels of the South Eastern German Bight. Die Küste: 253-276.

Extended field data was used to evaluate model performance not only at discrete locations, but also at full tidal channel cross-sections. A prominent dependency of different input parameters to the simulation results was shown. It was shown that a single grain size fraction for **suspended sediments** cannot reflect natural suspended sediment dynamics. Also the bed roughness was identified as a crucial parameter for a correct simulation of sediment transport. Common parameterisations of a uniform and constant **bed roughness** obviously do not hold in the case of asymmetric, dynamic and spatially and temporally variable bedforms.

Detailed process studies require the in-situ measurement and analysis of sub-processes: An important aspect in suspended sediment transport is the formation of flocs and aggregates by fine sediments as there is a fundamental difference in transport characteristics between the aggregates as a whole and the individual particles. A thorough understanding of the relevant flocculation processes under tidal forcing is currently still obstructed by technical limitations. Paper 4 compares two different methods for the in-situ observation and quantification of aggregate sizes and suspended sediment concentration:

Paper 4: Winter, C., Becker, M., Ernstsen, V.B., Hebbeln, D., Port, A., Bartholomä, A., Flemming, B.W., Lunau M., 2007. In-situ observation of aggregate dynamics in a tidal channel using acoustics, laser-diffraction and optics. Journal of Coastal Research SI 50: 1173-1177.

It was shown that - if observed in high temporal resolution - suspended sediment transport temporally occurs in distinct oscillations. A subsequent analysis has shown that the observed "clouds" of suspended sediment are mainly composed of large aggregates. Paper 5 explains the formation of by turbidity clouds by a grouping of large aggregates in oscillating currents:

Paper 5: Winter, C., Katoshevski, D., Bartholomä, A. and Flemming, B.W., 2007. Grouping dynamics of suspended matter in tidal channels. Journal of Geophysical Research, 112: C08010.

This grouping behaviour has been simulated by a numerical model approach which describes the individual particle motion in space and time. Depending on the forcing conditions and individual particle properties, conditions of stable and weak grouping of aggregates are defined.

As stated above the **bed roughness** plays an important role in shallow water hydrology, sediment transport and morphodynamics. This can be shown and quantified by model sensitivity analyses (e.g. Paper 3). Bed roughness can be understood as a super-imposition of different roughness elements, which comprise single grains, small ripples, larger bedforms, and other features on the seabed. Despite a very large number of studies on the problem, yet the initiation and development of bedforms in sandy sediments lacks a fundamental understanding. The author has contributed to some studies on bedform dynamics (Bartholdy et al., 2010; Bartholdy et al., 2011; Bartholomä et al., 2008; Ernstsen et al., 2011; Ernstsen et al., 2006; Ernstsen et al., 2005) and proposed a spectral analysis and a simple phenomenological model for the development of compound bedforms in paper 6.

Paper 6: Winter, C. and Ernstsen, V.B., 2007. Spectral analysis of compound dunes. River, Coastal and Estuarine Morphodynamics: RCEM 2007: 907-911.

In this publication the dynamics of a compound dune over one tidal cycle is analysed. It is shown that the change in morphology during the ebb currents can be described by the change in amplitude and phase of the spectral components after Fourier transformation of the signal. The classification and re-composition of components depending on their phase difference between high water and low water enables a differentiation of a static large bedform (which does not migrate during a tidal cycle) and kinematic small bedforms that have migration rates comparable to flume experiments. Two more sophisticated numerical modelling approaches for the simulation of bedform dynamics were shown in paper 7.

Paper 7: Winter, C., Vittori, G., Ernstsen, V.B., Bartholdy, J., 2008. On the superimposition of bedforms in a tidal channel. In: D. Parsons, T. Garlan and J. Best (Editors), Marine and River Dune Dynamics, Leeds: 337-344.

In that study a linear stability model was tested to explain the large bedforms as being caused by tidal system instabilities. Results show comparable dimensions and migration rates to observed dimensions. A three-dimensional morphodynamic model is shown to reproduce small scale transport rates but lacks realistic trends of morphodynamic evolution.

In any modelling study an objective evaluation is required at the stage of model calibration, validation and inter-comparison. Commonly the evaluation of numerical models often is based on subjective rating. Yet, no commonly accepted regulations for the evaluation of sediment transport models exist. Paper 8 discusses the significance of statistical parameters for the assessment of sediment transport models.

Paper 8: Winter, C., 2007. Evaluation of sediment transport models in tidal environments. Sedimentary Geology 202: 562–571.

The study shows that the occasionally used discrepancy ratio lacks quantitative and qualitative information on model performance because the time context information on timeseries characteristics is lost. To account for time-lag errors in suspended transport models, a separate cross-correlation analysis for the flood and ebb tidal phase is proposed. For a comparison with other model applications, a concluding rating of model performance can be expressed by a dimensionless error definition which takes the quality of field data into account.

4.2 Papers on data reduction and model applications

Morphodynamic model simulations in the meso- to macro-scale involve data reduction techniques as the concept of representative boundary conditions. It is based on the assumption that the long-term effect of natural forcing can be approximated by a reduced set of conditions. In paper 9 the concept of representative tides in morphodynamic simulations is discussed.

Paper 9: Winter, C., Chiou, M., Riethmüller, R., Ernstsen, V.B., Flemming, B.W., 2006. The concept of “representative tides” in morphodynamic numerical modelling. Geo-Marine Letters: 125 - 1328.

It was shown that, on the one hand, the predictive skill of a morphodynamic model was rather insensitive to changes in lateral boundary conditions. On the other hand, the morphodynamic impact of an extreme storm event was significantly influencing coastal morphology. Thus it was concluded that it is the variability in forcing that drives coastal morphodynamics rather than any characteristic scale.

Having stressed out the importance of storm events to coastal morphodynamics, it becomes obvious that a correct specification of meteorological data to numerical model simulations is crucial. Meteorological information is typically provided on coarse grids at large time intervals. The application to small-scale hydrodynamic models of higher spatial and temporal resolution must thus involve dynamic data downscaling. Paper 10 proposes a simple algebraic algorithm which allows the direct interpolation of gridded global meteorological data taking into account storm trajectories.

Paper 10: Winter, C., Chiou, M., Kao, C.C., Lee, B.C. 2009. Dynamic downscaling of meteorological fields for the hydrodynamic simulation of extreme events. Proceedings of Coastal Engineering 2008. 1135-1146. DOI 10.1142/9789814277426_0095

The procedure is tested for a storm surge event in 1999 in the North Sea region where comprehensive datasets are available for the direct validation and the determination of the added value for hydrodynamic modelling.

The lack of knowledge on the spatial distribution of bottom sediment is another restriction in coastal morphodynamic modelling. As often no, or not enough field data is available, simplified distributions of typical grain size are assumed. In paper 11 a process-based morphodynamic numerical model was used to predict the distribution of particle sizes in a coastal setting.

Paper 11: Kwoll, E. and Winter, C., 2011. Determination of the initial grain size distribution in a tidal inlet by means of numerical modelling. Journal Coastal Research (SI).

Results indicate the potential of this approach to predict grain size distributions, provided the governing processes are adequately represented by the model. Also the initiation and development of sedimentary structures can be explained with the help of numerical models, as in the papers 12 and 13:

Paper 12: Diesing, M., Kubicki, A., Winter, C., Schwarzer, K. 2006. Decadal scale stability of sorted bedforms, German Bight, south-eastern North Sea. Continental Shelf Research 26: 902-916.

The paper addresses large bedforms on the continental shelf, termed rippled scour depressions. Their generation and evolution has been explained on the basis of two data-sets from the North Sea (side-scan sonar) and a numerical model simulation of waves and currents. The sorted bedforms have been explained as having been generated by extreme storm events, whereas the quasi-continuous tidal currents form and maintain their final shape

Paper 13: Spiers, K.C., Healy, T.R., Winter, C. 2009. Ebb-jet Dynamics and Transient Eddy Formation at Tauranga Harbour: Implications for Entrance Channel Shoaling. Journal of Coastal Research 25(1), 234-247.

In this article, a large hydrodynamic eddy system at Tauranga Harbour (New Zealand) has been simulated with a two-dimensional hydrodynamic model to explain the trajectory of the eddy and to evaluate its influence on the observed sedimentation patterns. It was shown that the eddy system exerts a directional control over transport of sediments entrained by waves over the ebb-tidal delta.

5 Outlook

Societal concerns and scientific interests drive the need for an in-depth understanding of coastal socio-economics, ecosystems, and biogeochemical and physical process inter-action. Morphodynamic processes can be understood as the physical background and drivers of these systems. System understanding covers the observation and assessment of drivers, processes, interconnections and the need for model development for scenario analyses and prediction of future states. Various modelling approaches are capable of reproducing coastal dynamic characteristics as the hydrodynamics and sediment dynamics across spatio-temporal scales.

Morphodynamic models partly show realistic results in terms of depositional and erosional budgets. However, models are still limited in the reproduction of morphodynamic patterns in terms of a correct estimation of the migration of bars, banks and channels, and the reaction of morphological elements to extreme forcing. Reasons for these limitations were identified in the fields of model and data reduction issues and considerable effort is undertaken to overcome the lack of understanding of processes, to implement state-of-knowledge into numerical modelling systems and to publish model quality.

Future research should assess state-of-the-art model potential and should lead towards bridging the gap between current model qualuty and societal and scientific requirements. The need for model evaluation requires high level concerted field surveys and monitoring, a standardisation of measured data, data analysis, and model assessment measures, and the dissemination of data to the scientific community. This should lead to an identification of model shortcomings, the enhancement of models, and increased model quality. Amongst the manifold possibilities of insufficient model parameterisations, which should be tested and replaced by more reliable routines, the following topics, in particular, should be addressed in future studies on coastal morphodynamics:

- **The effect of the spatio-temporal variability of system characteristics**, which are often taken as constant (e.g. the bed roughness and bed sediment), should be assessed. The interaction of waves and currents with a deformable bed results in a large variety of bedforms which, in turn, influence the hydrodynamics. Future research should aim towards replacing common over-simplifications of bed roughness parameterisations.

- Long-term morphodynamics involve the effect of tidal harmonics and short, extreme storm events. **The role of single extreme events and the chronology of storm series** on the morphodynamics are of significant importance to coastal evolution. However, based on dedicated field surveys and numerical modelling, the model quality for the case of extreme events must be evaluated first.

- Common state of the art numerical modelling systems should be tested on standard cases, and the **model quality should be reported in objective measures** and skill scores. The proposed rules for "Good Modelling Practise" should be followed and their application demanded by stakeholders.

- **The role of small- to large-scale morphodynamics in coastal ecosystems**. Significant morphodynamic drivers and boundary conditions to various ecosystem parameters should be tested and evaluated in coined field and modelling studies. Vice-versa the role of ecosystems to the local morphodynamics should be evaluated; considering for example the stabilising effect of algae to the sediment, the role of biogenic processes to flocculation, etc.

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7 Appendix