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A multi-scale hybrid long-term morphodynamic model for wave-dominated coasts

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ABSTRACT

Process-based modules based on conservative equations to solve the transport of waves, currents and sub-aqueous sediment, and behavior-oriented modules based on empirical descriptions of cliff erosion, bed-load and terrestrial aeolian sand transport are coupled with up-scaling measures and stability-maintaining approaches in a parallel code to simulate decadal-to millennial-scale morphological evolution of wave-dominated coasts. An application to the southern Baltic Sea for a hindcast of Holocene morphogenesis of the Darss–Zingst peninsula demonstrates the robustness of the model. The model is then used to investigate the morphogenesis and evolution of spits in an idealized fetch-limited sandy coastal environment. Evolution of the spit system can be categorized into three periods according to the simulation results. In the early period all initial coastline perturbations are amplified due to the high-angle wave effects. Size competition between adjacent spits starts afterwards. Interaction between adjacent spits dominates the middle period. Smaller spits tend to retrogress due to unbalanced sediment budget and this sediment loss feeds further growth of their larger neighbors. The retrograded spits are either smoothed or evolve into barrier-lagoons, and relatively stable large-scale spits originating from larger spits are developed in the late period. Low-frequency storms impinging from a regular high angle onto the coastline facilitate the development of spits in the early period, but become a hindering factor afterwards. Terrestrial aeolian transport not only plays a key role in stabilizing the spits, but is also revealed as an important factor for long-term coastline erosion.

1. Introduction

In order to understand physical processes that drive decadal up to millennial scale (referred to as long-term hereafter) coastal morphological evolution numerical models of coastal morphogenesis including different climate scenarios provide a feasible method. Existing coastal morphodynamic models can be classified into three types: 1. process-based; 2. behavior-oriented and 3. hybrid of the former two types. The advantages as well as shortcomings of the first two model types have been widely revealed and discussed (e.g. de Vriend, 2001; Hanson et al., 2003; Fagherazzi and Overeem, 2007). Although high-resolution process-based models are reliable in modeling short-term (from hourly to daily scale) morphodynamics of coastal and shelf areas, direct application of these models to longer-term studies (from annual to millennial scale) is severely restricted and they can hardly perform better than behavior-oriented models. The reason for this originates not only from the numerical errors induced by the solutions for the partial differential equations, but also from insufficient knowledge of the complexity of the natural system. Great efforts have been made by coastal researchers in recent decades to improve the reliability of morphodynamic models. To reduce the errors of process-based models due to the large amount of iterations needed for a long-term computation, 'reduction' concepts, originally introduced by de Vriend et al. (1993a,b) and Latteux (1995), combined with techniques of morphological update acceleration (Roelvink, 2006) have been implemented in modeling studies (Cayocca, 2001; Wu et al., 2007; Dastgheib et al., 2008). For complex coastal systems hybrid modeling, which combines advantages both of process-based (for physical processes well described by differential equations) and behavior-oriented models (for less-known intrinsic self-organizing systems), has shown its promising perspectives for long-term modeling (Jiménez and Arcilla, 2004; Dissanayake and Roelvink, 2007; Karunarathna et al., 2008).

Among different types of coasts, wave-dominated barrier spits and barrier islands (collectively referred to as barriers hereafter) have the most variable morphology. They are constantly shaped by winds, tides and waves and, on a longer timescale, they can shift landward or seaward due to the oscillations of sea level and variations in the sediment supply (Masetti et al., 2008). Although the general processes for formation and evolution of barriers are described by behavior-oriented conceptual models based on equilibrium concepts and simplified process-based cross-shore models, there are very few morphodynamic models that can be used for 2DH area (based on depth-averaged formulations for hydrodynamics and sediment transport) simulation of long-term morphological evolution of wave-dominated barriers. The construction of a long-term 2DH area morphodynamic model for wave-dominated barriers is a challenging work for coastal researchers as it requires not

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only resolving all the different processes acting over different scales for morphological evolution but also maintaining the computational stability especially on the water–land interaction area, which is the most variable part of a wave-dominated barrier. This includes the shallow subaqueous area which is permanently under the influence of wave action and the low-altitude terrestrial area which is affected by aeolian transport during calm weather periods and strong waves during storm surges. For the former problem, a multi-scale concept has to be integrated into the model for coupling the different modules which calculate the processes at their corresponding temporal and spatial scales. Approaches for maintaining the computational stability of a process-based model in a long-term simulation need to be investigated and integrated into the model to solve the latter problem.

Recently Zhang et al. (2010, 2011a,b) presented a modeling methodology for long-term morphological evolution of wave-dominated coasts based on a multi-scale morphodynamic model. The model consists of 8 modules which calculate the processes of interest at different scales. The 2DH current module, the wave module, the bottom boundary module, the sub-aqueous sediment transport module and the cliff erosion module are real-time calculation modules which solve the short-term processes. A bathymetry update module and a long-term control module, in which the 'reduction' concepts and techniques of morphological update acceleration are implemented, are integrated to extend the effects of short-term processes over longer time periods. Promising results were obtained in the model application to a hindcast of 300 years' morphological evolution of the Darss–Zingst peninsula in the southern Baltic Sea. Long-term residual effects of waves as well as short-term effects of storms are revealed as the dominant factors driving the morphological evolution of the research area during the last several centuries (Zhang et al., 2010). Although good agreement between simulation results and measured data is shown for the major part of the coast, some key areas such as the spit and the newly-formed barrier are not satisfactorily reproduced. Analysis of the results indicates that inclusion of terrestrial aeolian sand transport, which is responsible for dune formation and migration, is necessary in a long-term model for wave-dominated barriers for describing better the water-land transition process. The aim of this paper is to introduce further improvements of the existing long-term morphodynamic model by including terrestrial aeolian sand transport effects. This model is then used for a study of the natural morphogenesis of wave-dominated sandy coasts. In Section 2 a brief description of the original model and further model improvements is introduced. Approaches for guaranteeing the computational stability of the model are also described. An application of the model to a real coast is presented in Section 3, and a study of an idealized coast is given in Section 4. Simulation results are critically discussed in Section 5, before the conclusions are drawn in Section 6.

2. The model

2.1. Brief description of the original model

The original multi-scale morphodynamic model for long-term evolution of wave-dominated coasts consists of 8 main modules to describe different physical processes that drive the morphological evolution of the coastal environment. The modules are:

(1) a 2DH (two-dimensional vertically integrated) circulation module based on shallow-water equations,
(2) a wind-induced wave module based on momentum conservation equations,
(3) a bottom boundary layer (BBL) module based on the Grant–Madsen formulation (Grant and Madsen, 1979),
(4) a sub-aqueous sediment transport module based on a process-based formulation of suspended transport of cohesive and non-cohesive sediment and a behavior-oriented formulation of bed-load sediment transport,
(5) a cliff erosion module based on a behavior-oriented formulation (Zhang et al., 2010),
(6) a nearshore storm module based on the XBeach model (Roelvink et al., 2009),
(7) a bathymetry update module based on the technique of morphological update acceleration (Roelvink, 2006) and approaches for maintaining the computational stability, and
(8) a control function set for up-scaling of the short-term effects.

For details of the modules the reader is referred to Zhang et al. (2010, 2011b).

2.2. The terrestrial aeolian sand transport module

The terrestrial aeolian sand transport module follows an empirically modified Bagnold-type formulation (Lettau and Lettau, 1978). Aeolian transport is only activated when the bed shear velocity exceeds a critical shear velocity. The total volumetric transport rate Q ($m^2\,s^{-1}$) accounting for the bed-slope effect is given by:

$$Q = f_2(d)\frac{\rho}{\rho_s g}\left(1-\frac{u_{*cr}}{u_{*wind}}\right)^{0.25} u_{*wind}^3(1-\tan\beta/\tan\varphi), \tag{1}$$

where ρ is the air density ($=1.25$ kg m^{-3}), $\rho_s=2650$ kg m^{-3} is the sand density, g is gravitational acceleration, u_{*cr} is the critical shear velocity for initiation of motion of sands, u_{*wind} is the bed shear velocity of winds, $\tan\beta$ represents the local bed slope, $\tan\varphi=0.62$ ($\varphi=32°$) is the internal friction angle of the grains in the bed, $f_2(d)$ is a function of mean grain size (d_{50}) expressed by:

$$f_2(d) = 1.49 + 5e^{-0.5\left(\ln\left(d/1.53D_{ref}\right)/0.56\right)^2}, \tag{2}$$

where $D_{ref}=0.25$ mm is defined as the reference grain size.

The critical shear velocity for the initiation of sand motion u_{*cr} is calculated by

$$u_{*cr} = A[gd(\rho_s-\rho)/\rho]^{0.5}, \tag{3}$$

where A is a proportionality coefficient. A is a constant (0.1 at the fluid threshold, 0.085 during saltation) according to Bagnold's suggestion. $A=0.09$ is adopted in the model according to the study of Dong et al. (2003). A uniform mean grain size of sand $d_{50}=0.33$ mm is used for the experiments in Section 4.

The wind shear velocity at the land–air interface u_{*wind} is given by:

$$u_{*wind} = \frac{\kappa U_z}{\ln(z/z_0)}, \tag{4}$$

where U_z is the wind speed at z meter above the local cell. A uniform hourly-updated wind speed U 10 m above mean sea level for the whole domain is used in our simulation. z for a local terrestrial cell is determined by the difference between the height of the cell and 10 m above mean sea level. $z=0.5$ is specified for the cells higher than 9.5 m above mean sea level. $\kappa=0.41$ is von Karman's constant, z_0 is the aerodynamic roughness height which is typically between 10^{-4} and 10^{-2} m. We used in our simulation $z_0=0.125$ mm.

In the model the total volumetric transport rate Q is represented by two components (Q_x and Q_y) along the x coordinate and y coordinate, respectively. With the value of Q_x and Q_y the bed elevation update is given by:

$$(1-p)\frac{\partial z_b}{\partial t} + \frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y} = 0, \tag{5}$$

where p is the porosity of sands and z_b is the bed elevation relative to mean sea level.