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Improvement of morphodynamic modeling of tidal channel migration by nudging

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ABSTRACT

State-of-the-art process-based models have shown to be applicable to the simulation and prediction of coastal morphodynamics. On annual to decadal temporal scales, these models may show limitations in reproducing complex natural morphological evolution patterns, such as the movement of bars and tidal channels, e.g. the observed decadal migration of the Medem Channel in the Elbe Estuary, German Bight. Here a morphodynamic model is shown to simulate the hydrodynamics and sediment budgets of the domain to some extent, but fails to adequately reproduce the pronounced channel migration, due to the insufficient implementation of bank erosion processes. In order to allow for long-term simulations of the domain, a nudging method has been introduced to update the model-predicted bathymetries with observations. The model-predicted bathymetry is nudged towards true states in annual time steps. Sensitivity analysis of a user-defined correlation length scale, for the definition of the background error covariance matrix during the nudging procedure, suggests that the optimal error correlation length is similar to the grid cell size, here 80–90 m. Additionally, spatially heterogeneous correlation lengths produce more realistic channel depths than do spatially homogeneous correlation lengths. Consecutive application of the nudging method compensates for the (stand-alone) model prediction errors and corrects the channel migration pattern, with a Brier skill score of 0.78. The proposed nudging method in this study serves as an analytical approach to update model predictions towards a predefined 'true' state for the spatiotemporal interpolation of incomplete morphological data in long-term simulations.

1. Introduction

Global climate change and its projected local effects on coastal systems have led to growing attention on studying the physical evolution of coastal morphology (de Vriend et al., 1993a; Plater and Kirby, 2012; Smith et al., 2009; Southgate, 1995). Various approaches have been established to simulate the long-term behavior of coastal environments (Dissanayake et al., 2009). Empirical formulations have been shown to identify equilibrium states and spatiotemporal deviations from these (de Vriend et al., 1993b; Dean, 1990; Friedrichs and Aubrey, 1988; O'Brien, 1931). Also process-based mathematical models have been developed and applied over the past decades. Nowadays morphodynamic modeling systems, which combine computational modules for the simulation of waves, currents, sediment transport and bed evolution, are standard tools for coastal research and decision making in coastal zone management (Lesser et al., 2004; Nicholson et al., 1997). State-of-the-art morphodynamic models have shown to be applicable to the simulation and prediction of different coastal morphologies (Hibma et al., 2003, 2004; Lesser et al., 2004; Wang et al., 1995; Winter, 2006). However, in decadal time scales these models often show limitations in reproducing natural complex morphological evolution patterns like the movement of bars and tidal channels (De Vriend et al., 1993a; Scott and Mason, 2007; Winter, 2006). In practice numerical morphodynamic models are based on various assumptions and simplifications and have uncertainty in their parameterizations (Brown et al., 2007; Hesselink et al., 2003; Pinto et al., 2006; Ruessink, 2005). Still the main challenge is to meld the longer-term morphological changes with shorter-term processes such as the direct effects of waves and tides (Masselink and Hughes, 2003; Roelvink, 2006). The evolution of small scale elements in long term simulations often cannot be reproduced by morphodynamic model simulations (Winter et al., 2006). This holds also for the simulation of bank erosion processes which are still insufficiently understood and formulated in common numerical models. Besides the often coarse discretization of the steep morphological gradients leads to limitations in realistic simulations of gradual or abrupt bank erosion processes (van der Wegen et al., 2008).

Tidal channel migration and meandering are ubiquitous features of meso-scale coastal evolution influenced by sediment transport processes, tides, wind, waves, bank erosion, human intervention, extreme events and their interactions. Many studies address channel migration and meandering in unidirectional (river) flow by means of statistical

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analysis (Nanson and Hickin, 1986; Richard et al., 2005), empirical formulations (Hudson and Kesel, 2011) and numerical model simulations (Darby et al., 2002; Duan and Julien, 2005; Duan et al., 2001; Howard, 1992; Motta et al., 2012). Less effort has been spent on channel meandering in tidal environments. Facing the important role of tidal channel dynamics in coastal systems, and the known limitations of current models in the reproduction of some morphodynamic pattern dynamics, here the applicability of a nudging method based on a data assimilation (DA) concept is tested. Nudging is understood as a first-order application of DA in which the model state is forced towards an updated state without changing the model system. DA essentially combines observation data with model predictions considering their uncertainties (Lahoz et al., 2010). Various DA schemes, such as variational data assimilation, Kalman filters, and optimal interpolation (OI) scheme, have been widely applied in climate, meteorological and hydrodynamic modeling (e.g. Brasseur and Nihoul, 1994; Ghil and Malanotte-Rizzoli, 1991; Park and Xu, 2009; Robinson and Lermusiaux, 2000). For coastal research, DA has been successfully applied in coastal hydrodynamic models (Wilson et al., 2010; Zhang et al., 2011). However, for coastal morphodynamic models, the DA approach is still new, yet some pioneering results seem promising: Van Dongeren et al. (2008) developed a data-model assimilation method ('Beach Wizard') which is capable of estimating nearshore subtidal bathymetry based on remote observations by using an optimal least-squares estimator approach. A variational DA scheme has been shown to improve the capability of a simple one-dimensional (1D) morphodynamic model (Smith et al., 2009). The use of DA in the morphodynamic modeling of Morecambe Bay over a 3-year period has been shown by Scott and Mason (2007). In their study, model performance was found to be improved with data assimilation. However, the use of uniform spatial and temporal observation errors and constant background error correlation length scales in the study needs to be discussed and evaluated further. Smith et al. (2007) described a simplified 1D model of bedform propagation to illustrate the basic theory of data assimilation and examine the effect of the background error covariance matrix on the results. Their study showed that the quality of data assimilation analysis is greatly reduced when the background error correlations are poorly specified. The correct specification of background error correlations is a balancing act between the adoption of the observed information and the spreading/smoothing of it. Thornhill et al. (2012) further evaluated the influence of correlation length scale parameters with a three-dimensional (3D) variational data assimilation scheme on a morphodynamic model of Morecambe Bay. An optimal spatial constant length scale was found for that system but the influence of spatially-variable fields has yet not been investigated.

This study describes the morphological evolution of the Medem tidal Channel in the Elbe Estuary, German Bight, Southern North Sea. Bathymetric data analysis reveals a pronounced channel migration from 1990 to 2007. A stand-alone 2D depth-averaged (2DH) morphodynamic simulation of the hydrodynamics, sediment transport and bed evolution of the channel shows limited skill in reproducing the channel evolution. The application of a nudging method, based on a 3D-variational (3D-Var) DA scheme to compensate for errors in the model predictions, is tested. The popularity of 3D-Var arises from its conceptual simplicity. The data assimilation analysis is reduced to an equivalent minimization problem defined by a cost function. The computation is robust and efficient as long as a reasonable error covariance matrix is specified. The application of 3D-Var requires the definition of a background error covariance. This parameter is approximated by an error correlation length scale in this study. A sensitivity analysis is carried out in which the effect of a user defined correlation length scale on the error correlation for the definition of the background error covariance matrix is quantified. The correlation lengths can be defined as spatially homogeneous (circle) or heterogeneous (ellipsoid).

Results show that the nudging method enhances model predictions in updating the bathymetry. Criteria for the selection of the correlation length scale for the nudging method of morphodynamic models are suggested. The potential for the application of data assimilation schemes on more complex and practical coastal morphodynamic models is discussed. The developed method in this study can be used to provide bathymetric states with high temporal and spatial resolution, as a higher order spatio-temporal interpolation of incomplete bathymetric data.

2. Study area and observation analysis

2.1. The Medem Channel

The Medem tidal Channel, the location of this study, is the northern branch of a tidal channel system in the estuary of the river Elbe in the German Bight, Southern North Sea (Fig. 1). The Elbe Estuary is the largest estuary and a very important waterway connecting the port of Hamburg to the North Sea. The Elbe Estuary is dominated by a semidiurnal tide with a mean tidal range of about 3 m at the inlet (meso-tidal estuary). The tides are asymmetrical with a shorter flood period than the ebb period and a higher flood current speed than the ebb current speed, which leads to a flood-dominant character. The long term mean annual river discharge is 722 m^3/s, the flux of suspended particulate matter (SPM) is about 800,000 tons/year (Kappenberg et al., 1995). The turbidity maximum is located between about 80 km and 100 km downstream the Geesthacht weir (see Fig. 2) (Kappenberg et al., 1995). The morphology of the outer Elbe Estuary is dominated by tidal flats and sandbanks, and the two main braided tidal channels, the primary southern channel serving as the main navigational waterway to the port of Hamburg, and the northern secondary Medem Channel. The central part of the channel is characterized by medium sand with grain sizes of 200–600 μm, while the tidal flats are fine sands with muddy components (grain sizes of 60–150 μm). The Medem Channel has a maximum depth of 16 m and a width of 1.5 km. The bed elevation range (the difference of minimum and maximum bed elevations) of the Medem Channel area over two decades was shown to be more than 20 m, displaying the highest morphological activity in all the German Bight (Winter, 2011). More information on the hydrodynamics and geomorphology of the Elbe Estuary is reported by Boehlich and Strotmann (2008) and the references therein.

2.2. Bathymetry analysis

Twelve datasets of annual bathymetric soundings between 1990 and 2007 were provided by the German Federal Maritime and Hydrographic Agency (BSH). These data have been interpolated to individual digital elevation models of 80–90 m resolution. The morphological evolution of the study area (*ABCD* in Fig. 1) can be shown by a quantification of differences and the relocation of bathymetric contour lines and cross-sections (*A*–*A*′ in Fig. 1). The Medem Channel developed significantly between 1990 and 2007 (Fig. 3). Three main features shall be pointed out: firstly, the flatness of the left bank (south bank); secondly, the vertical steepness of the right bank (north bank); and thirdly, the channel migration was approximately 1.7 km to the north in the period from 1990 to 2007. The migration rates are somewhat constant with a value of 90 m/year from 1990 to 1996, followed by a decrease to about 50 m/year during the period of 1996 to 2000, and then increased again, up to a maximum migration rate of 450 m/year between 2004 and 2005.

3. The morphodynamic model

3.1. Model setup

The pronounced morphodynamics of the Medem Channel serve as a study case for the application of a process-based morphodynamic model. To allow for a long term simulation at sufficient spatial resolution and at acceptable computational cost a 2DH numerical model has been set up using the modeling system Delft3D (Lesser et al., 2004).