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Modelling of a medium-term dynamics in a shallow tidal sea, based on combined physical and neural network methods

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Abstract

The paper presents an approach towards a medium-term (∼decades) modelling of water levels and currents in a shallow tidal sea by means of combined hydrodynamic and neural network models. The two-dimensional version of the hydrodynamic model Delft3D, forced with realistic water level and wind fields, is used to produce a two-year-database of water levels and currents in the study area. The linear principal component analysis (PCA) of the results is performed to reveal dominating spatial patterns in the analyzed dataset and to significantly reduce the dimensionality of the data. It is shown that only a few principal components (PCs) are necessary to reconstruct the data with high accuracy (over 95% of the original variance). Feed-forward neural networks are set up and trained to effectively simulate the leading PCs based on water level and wind speed and direction time series in a single, arbitrarily chosen point in the study area. Assuming that the spatial modes resulting from the PCA are 'universally' applicable to the data from time periods not modelled with Delft3D, the trained neural networks can be used to very effectively and reliably simulate temporal and spatial variability of water levels and currents in the study area. The approach is shown to be able to accurately reproduce statistical distribution of water levels and currents in various locations inside the study area and thus can be viewed as a reliable complementary tool e.g., for computationally expensive hydrodynamic modelling. Finally, a detailed analysis of the leading PCs is performed to estimate the role of tidal forcing and wind (including its seasonal and annual variability) in shaping the water level and current climate in the study area.

Keywords: Tidal inlets; Hydrodynamic modelling; Principal component analysis; Neural networks; North Sea; Wadden Sea; East Frisian Islands

1. Introduction

The investigation of many important aspects of the coastal zone processes – e.g., the analysis of sediment transport or studies concerning the safety of various coastal protection structures and the coast itself – is

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possible only if data concerning medium-term (∼decades) variability of waves and currents in the study area are available. Because of enormous costs and technical difficulties of long-term measuring campaigns on the one hand, and typical shortage of input data required by (usually extremely computationally expensive) numerical models on the other hand, the knowledge of temporal and spatial variability of waves and currents in the coastal zone is usually very limited.

The work presented in this study is part of a research project MOSES ("Modelling of the medium-term wave climatology at the German North Sea coast"), one of the purposes of which is to produce a medium-term database of water levels, currents and mean wave parameters for a coastal area in the German Wadden Sea. Although the state-of-the-art hydrodynamic and wave models are able to reproduce the wave and current processes in shallow tidal seas with high accuracy, their application to medium-term modelling is limited because of enormous computer resources that are required to reach spatial and temporal resolution sufficient to resolve all details of the complicated geometry of the coastal zone. The methods typically used to address these problems, e.g., nesting or grids with varying spatial resolution, only in some cases provide a satisfactory solution. Moreover, the amount of data produced by the models makes their direct usage in further applications (e.g., as input for morphodynamic modelling) practically impossible. Therefore, even if one is able to conduct sufficiently long simulations, additional data analysis tools are necessary, enabling the reduction of the amount of data without loss of information crucial for the understanding of the processes analyzed and for further application of the modelling results.

In the present study the results of high-resolution hydrodynamic simulations of water levels and currents (wave modelling in the study area will be treated in detail elsewhere) are used as a starting point for the development of a neural network-based modelling system, which enables fast and sufficiently accurate hindcasting of temporal and spatial patterns of water levels and currents in the study area. The main idea behind the approach developed is to decompose the dataset into a (small) number of fixed modes, assumed 'universal' over the four decades studied, and to model the time variations of those modes only, thus reducing the dimensionality of the problem by more than three orders of magnitude. The results presented in this paper show that the assumption of the medium-term 'universality' of the modes is justified. Contrary to the earlier works concerning neural network modelling of tides, e.g., by Lee and Jeng (2002), Huang et al. (2003) (see also the review of neural network applications given in this work) or Lee (2004), the approach used here enables to reproduce water levels and currents *in the whole study area*, not only at single stations as in the cited papers. The results presented indicate that the principal component analysis of the results of hydrodynamic modelling is a promising input-reduction tool e.g., for morphodynamic and other studies (as suggested by de Vriend et al., 1993), for which the knowledge of the temporal and spatial variation of water levels and currents is a prerequisite. The idea behind the PCA/NN technique used here is in many aspects similar to the one of Álvarez et al. (2000), who applied PCA combined with genetic algorithms to forecast the space-time variability of the satellite-derived monthly sea surface temperature fields in the western Mediterranean Sea. Similarly, Álvarez (2007) used the combination of the complex PCA (CPCA) and genetic algorithms to the analysis of propagating thermal fronts.

The structure of the paper is as follows: in the next section a description of the study area is given, followed in Section 3 by a description of the hydrodynamic model Delft3D used in the simulations. The verification of the results is presented as well. Section 4 discusses the results of the linear principal component analysis (PCA) of water levels and currents, with emphasis given to aspects crucial for the further stages of the project realization. The results of PCA, together with time series of water level and wind velocity components in a chosen location, are then used to set up and train a feed-forward neural network (NN), as described in detail in Section 5. The trained NN is shown to accurately reproduce the test data and hence to be applicable as a tool for producing the data in periods that could not be modelled with Delft3D because of time constraints. In Section 6 the influence of wind and its seasonal and annual variability on the water level and current climate in the study area is investigated. Finally, Section 7 summarizes and discusses the results.

2. Area description

The main object of the study are the catchment areas of the tidal inlets between the islands of Borkum, Juist and Norderney, belonging to the chain of the East Frisian Islands separating the German Wadden Sea from