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INTEGRATED MODELLING OF COASTAL LANDFORMS

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Abstract: Traditionally, independent tools have been used to simulate wave- or wind-driven processes to simulate coastal morphology change. Coupled models that cross the land-sea division and integrate these collective processes can increase our knowledge on complex morphodynamic interactions and improve predictions of the foreshore, beach, and dune evolution. In this paper we present the initial development of a coupled modelling framework capable of numerically predicting the integrated development of coastal landforms, including both marine and aeolian processes, by using a generic model coupling approach that leverages the Basic Model Interface. The aim of this tool is to support the interdisciplinary design of Nature-based Solutions on varying spatiotemporal scales. As shown for the Marker Wadden case, the implemented model functionalities allow for the numerical description of the coast in an integrated manner and thus create opportunities for modeling coastal landform of the nearshore, beach, and dune that would not be possible with a discrete model approach. Specifically, by coupling two discrete numerical models, AeoLiS and XBeach, the aeolian and marine interaction resulted in a more realistic behavior of processes in the intertidal area. After coupling, bed levels compared better to the observations compared to the superpositioned results of both separate model components, which showed the added value and potential of coupled modelling. These findings have implications on the ability to predict spatio-temporal integrated coastal development – including these interacting aerodynamic, hydrodynamic, and ecological processes, which are essential in the interdisciplinary design of NbS.

Introduction

Increasingly, nature-based solutions (NbS) are used to provide ecosystem and protective services to coastal landscapes. Given the eco-geomorphological nature of these features, they often have an influence on subaqueous, subaerial, and subterranean processes. Comprehensive understanding of and the ability to predict spatio-temporal integrated coastal development – including these interacting aerodynamic, hydrodynamic, and ecological processes - are essential in the interdisciplinary design of NbS.

Numerous process-based numerical models have been previously developed which aim to provide quantitative tools for simulating relevant coastal processes that drive geomorphic change along sandy coasts. However, most of these standalone tools are restricted to a single coastal domain e.g., subaqueous or subaerial processes only (e.g. Lesser et al., 2004; Roelvink et al., 2009; Hoonhout and de Vries, 2016) and thus have limitations for use in effectively simulating the geomorphic evolution of NbS across engineering time-scales (days to decades). This lack of tools that are capable of describing integrated subaerial, subaqueous, and ecological coastal development has resulted in unexpected, or even unwanted, outcomes in performance of some NbS, and thus negatively affected the multifunctional potential of these solutions in terms of ecosystem services.

Several recent efforts have been undertaken to integrate these processes in cross shore profile modelling through the coupling of existing, disparate numerical models (Cohn et al., 2019; Luijendijk et al., 2019; Roelvink & Costas, 2019). Although these modelling frameworks have demonstrated the potential of coupled modelling, the approaches these were built upon were not generic and thus not portable to 2D domains and based on the combination of specific models together. As a result, the application range of these modelling frameworks is limited. Additionally, these approaches generally are based on offline approaches in which separate model components frequently write model data to the disk and communicate using these files. Such an offline approach results in high computational costs. Online coupling techniques, on the other hand, do not require continuous writing and reading from the disk but exchange model data through a common protocol without writing state variables to files. This allows for faster coupling and applying smaller coupling intervals. Component modelling using online coupling techniques is relatively new to the coastal community (Hutton et al., 2020).

In this paper we present the initial development of a coupled online modelling framework for coastal landforms in a generic fashion. The aim of this tool is to facilitate the interdisciplinary design of coastal solutions, or NbS specifically, on varying temporal and spatial scales. A case study is used to demonstrate the benefits of a coupled modelling approach and to highlight new process capabilities that are possible with ongoing 1D (Windsurf) and 2D (CoCoNuT) model coupling developments.

Methodology

In this section, the intended functionalities and technical details of the coupling framework are described, followed by some examples of interactive processes that are now included due to the coupling of model components.

Model Coupler Description

The aim of this work is to develop a generic coupling framework that executes numerical model components in series and regulates the exchange of information between these components at user-defined intervals. To be applicable for long-term morphodynamic simulations in varying environments, the exchange of parameters should be comprehensible, the outcomes should be mass-conservative, and the coupling time for coupled simulations being comparable to those of independent model simulations.

The framework utilized in this work leverages the *Basic Model Interface* (BMI) protocol, which provides a set of functions that enables the coupling of numerical models (Hutton et al., 2020). The first iteration of this BMI-enabled coupled framework for coastal applications is Windsurf (https://github.com/openearth/windsurf), for which there was capability to call numerous 1D coastal profile models that share a common grid (Fig. 1).

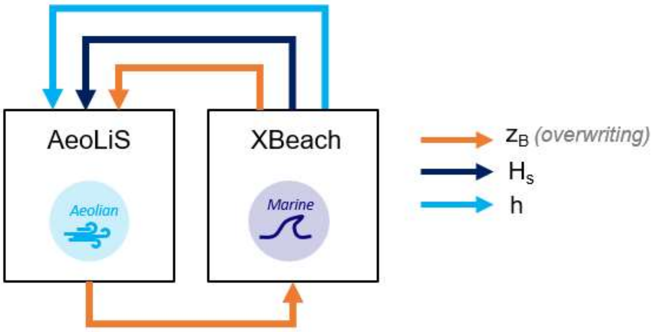

Fig. 1. Schematization of a possible parameter exchange settings within the Windsurf framework, such as is used for the Marker Wadden case study.

A next step in this development is a more modular approach which allows for independent BMI-models to be coupled together independent of their input grid resolution or type (structured or unstructured). The in-development Coastal Coupling Numerical Tool (CoCoNuT) is a wrapper that utilizes the BMI, providing coastal engineers with a relatively simple tool for the coupling of existing numerical models. The CoCoNuT tool utilizes the same methodology as the python-implementation of Windsurf, although when fully implemented it will enable full 2D simulations, as opposed to focusing on 1D coastal profile applications. The information exchange between the model components runs through a central grid which serves as the main component for storing and exchanging model input and output (Fig. 2). This setup is chosen to keep the information exchange between models generic, orderly, and manageable. In order to limit computational costs, an interpolation matrix is generated at the initialization phase of CoCoNuT for use throughout the simulations. During each parameter exchange step, the parameter is multiplied with this interpolation matrix. Additionally, to make sure the approach is mass-conservative a correction-matrix is computed and applied every parameter exchange (Velhorst, 2017).

Currently, CoCoNuT supports the AeoLiS (Hoonhout and de Vries, 2016), Delft3D Flexible Mesh (Lesser et al., 2004; Kernkamp et al., 2011), SWAN (Booij et al., 1999) and XBeach (Roelvink et al., 2009) stand-alone model components, which are all BMI-compatible. The selection of exchangeable parameters is completely flexible and can be defined in two directions: from the main component to the model components and vice versa. Moreover, two types of parameter exchange can be chosen: 1) a cumulative exchange where a parameter change is added to existing values (e.g. bed level change) and 2) overwriting existing values (e.g. wave heights). This range of possibilities allows the model coupling to be set up as desired.

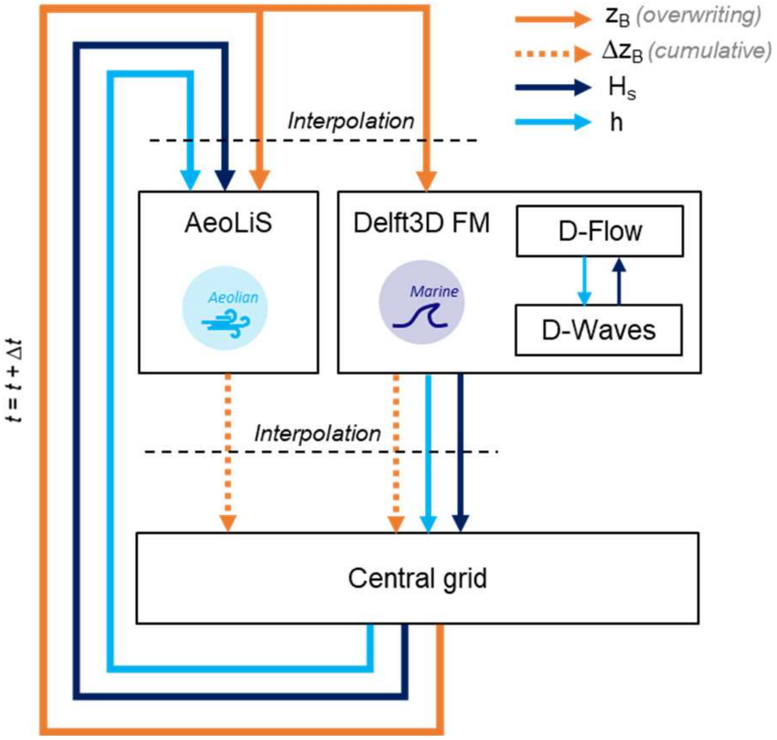

Fig. 2. Schematization of a possible parameter exchange settings between several model components using the CoCoNuT model coupling framework. Note that this exchange setup is different from the one used for the Marker Wadden case study.

For this particular demonstration case, here we specifically leverage the Windsurf codes to demonstrate model coupling capabilities for a 1D case.

Future work will highlight the full 2D potential of the expanded CoCoNuT framework, which is further described in the Outlook section.

Process Interactions Using Coupled Modeling

The model functionalities described above allow for the numerical description of the coast in an integrated manner and thus create opportunities for modeling coastal developments that would not be possible with a discrete (e.g., single model) approaches. For example, the natural development of coastal foredunes represents contributions from both aeolian and marine processes over engineering timescales – requiring integrated modeling to effectively characterize relevant sediment transport and morphologic interactions.

Although it is geographically de-coupled from the dunes, the intertidal zone is an area governed by elaborate process interactions, such as wetting, drying, sorting, and mixing, that has an important control on aeolian transport dynamics that contribute to dune growth in coastal settings. During wave run-up events, the soil moisture content in the subaerial domain is increased which limits the availability of sediment for aeolian transport. Despite the important role of moisture from precipitation, groundwater, and swash influencing threshold velocities for the initiation of wind-blown sand transport, the intertidal zone has been found to be a significant contributor for aeolian sediment flux towards dunes (de Vries et al., 2014). Thus, this intermittently wet zone is critical to include within aeolian transport models in order to effectively define the source area (deflation zone) for aeolian transport that contributes to dune growth. It is thought that the importance of this zone is in part due to hydraulic mixing – thus requiring a definition of marine processes to effectively model. Conversely, aeolian processes preferentially winnow sediments from the intertidal zone and are therefore important for characterizing armouring processes and resulting changes in the local grain size distribution within the intertidal zone. Although the individual contributions from marine or aeolian processes, both within the intertidal zone or elsewhere, are small at the ~second timescale, the influence of these separate processes aggregate with time.

Demonstration case

The morphological development of a man-made sandy beach and dune at the Marker Wadden Islands (the Netherlands) is used to examine the benefits of a coupled modelling approach. The Marker Wadden is a group of artificial islands, located in Lake Markermeer, making them subject to unique conditions in comparison with other sandy shores. Specifically, the region is characterized by a lack of tidal action, mild storm conditions and poorly sorted nourished sediment. The combination of lack of tidal action, nourished sediment, fresh water, and limited storm conditions has resulted in anomalous biological and morphological developments compared to the regular Dutch coast.

Field Observations

During field trips, a beach scarp and a lack of vegetation on the artificial dune were observed (Fig. 3). In part due to this scarp, aeolian supply from the intertidal zone was noted to be limited. Since there was no vegetation to capture the sand that does move by wind, the aeolian domain is governed by structural erosion and relatively limited local deposition. Furthermore, the mild wave regime contributes to limited hydraulic mixing within the intertidal zone. This lack of marine sediment sorting results in a strongly developed desert pavement limited further aeolian erosion, stabilizing the bed.

We measured the armouring process by taking various sediment samples during our fieldtrips at multiple cross-shore locations and weighing the percentage of coarse material, defined as particles larger than 2.8 millimeters. In the subaerial domain (i.e. elevations above the maximum runup level) the percentage of coarse particles increased from less than 1 percent in the original sediment to over 40 percent in the desert pavement.

Fig. 3. Field trip to the Marker Wadden. Top left: Beach scarp formation along the sandy ridge. Top right: Desert pavement development on top of the artificial dune. Bottom left: Sediment sampling from the subaerial domain. Bottom right: Remaining sediment fraction after sieving a sediment sample from the desert pavement (photographs by B. van der Valk).

Bathymetric and topographic measurements obtained from Ton et al. (2019) confirmed the structural aeolian erosion from the subaerial domain and the later stabilization of the bed (Fig. 5). Additionally, as a result of the low energy conditions that the sandy edge is prone to, a horizontal platform developed approximately one meter below the water line (Fig. 4). These measurement results are used to validate the model outcomes.

Modelling approach

We applied the online coupling approach to simulate a one-dimensional transect of the Marker Wadden. For this demonstration purpose, we used the predecessor of CoCoNuT for coupling of the model components, the Windsurf framework (Cohn et al., 2019). Although the parameter exchange slightly differs between the Windsurf and CoCoNuT frameworks, the main aspects of the coupling approach are unchanged (e.g. exchange of hydrodynamic and morphodynamic parameters, utilizing BMI, executing model components in series). Two model components were included: XBeach and AeoLiS to respectively describe the subaqueous and subaerial domains. AeoLiS and XBeach exchanged bed levels during each time step and additionally, the wave characteristics from XBeach are provided to AeoLiS to compute hydrodynamic mixing of sediments in the top layer.

The simulation period was 2 years and in order to reduce computational time, representative wind, water level and wave series were used. For the hydrodynamic conditions, it was found that the morphodynamics were governed by more extreme events, so the XBeach forcing is made up out of the 76 highest storms, with 12 hours per storm as combined time-series. To align the AeoLiS and XBeach simulation periods, the AeoLiS wind series is constructed out of regular, high energetic, wind conditions that account for a similar potential transport as the bruteforce series. Both simplifications have been verified by comparing the model outcomes with bruteforce simulations.

To be able to capture the structural scarp formation, a cross-shore resolution of 1 meter was chosen. In AeoLiS, eight sediment fractions were implemented, based analysis of the sediment samples collected during the field trip. In order to reproduce the platform development just below the waterline, the XBeach setup was based on an existing model setup, earlier used to simulate the nearby Houtribdijk, which showed similar behavior. Additional standalone simulations of the same scenario using just AeoLiS and XBeach were completed for comparison to the coupled model. It has to be noted that some calibration steps have been taken to improve the morphological results. Because of this, the comparison with measurements do not necessarily say anything about the predictive power of this model setup but focusses on the advantages of coupled modelling over a discrete approach.

Modelling results

Standalone AeoLiS and XBeach models were capable of generally simulating the expected coastal profile development at Marker Wadden. For example, XBeach was able to simulate the shallow horizontal platform in the marine zone ($175 < x < 250$ m) and the cross-shore position of the structural beach scarp that was observed in the data (Fig. 4A, $x = 275$ m).

By computing the erosion from the aeolian zone (Fig. 4A), we could establish that both measurements and stand-alone AeoLiS simulation results indeed show structural erosion from the subaerial beach, resulting in a net deflation of the landscape surface with time (Fig. 5). The armouring process, causing this bed level stabilization, is clearly indicated by the increased share of coarse material in the subaerial domain in the AeoLiS simulation (Fig. 4C).

However, the super-position of these standalone models resulted in an overprediction of erosion around the waterline (Fig. 4B-II). During the entire simulation period, the "intertidal" area is prone to aeolian and hydrodynamic erosion, while in reality hydrodynamic erosion causes to this area to shift landwards with time, reducing the subaerial beach extent. By coupling the models, the aeolian and marine interaction resulted in a more realistic behavior of processes within the intertidal area. After coupling, bed levels compared reasonably well with observations, showing a more realistic erosive pattern around the waterline, demonstrating the added value and potential of coupled modelling. Within the overlapping subaerial-subaqueous zone ($225 < x < 275$ m), the coupled modelling approach resulted in a RMSE value of 0.17 m, compared to 0.45 m for the super-position of both standalone models.

The limited amount of sediment eroded from the intertidal area in the coupled approach, resulted in a lower availability of sediment for transport offshore, resulting in slower growth of the horizontal platform (Fig. 4B-I). This demonstrates that model coupling does not only influence the development directly inside the interactive zone, but also developments elsewhere in the coastal profile.

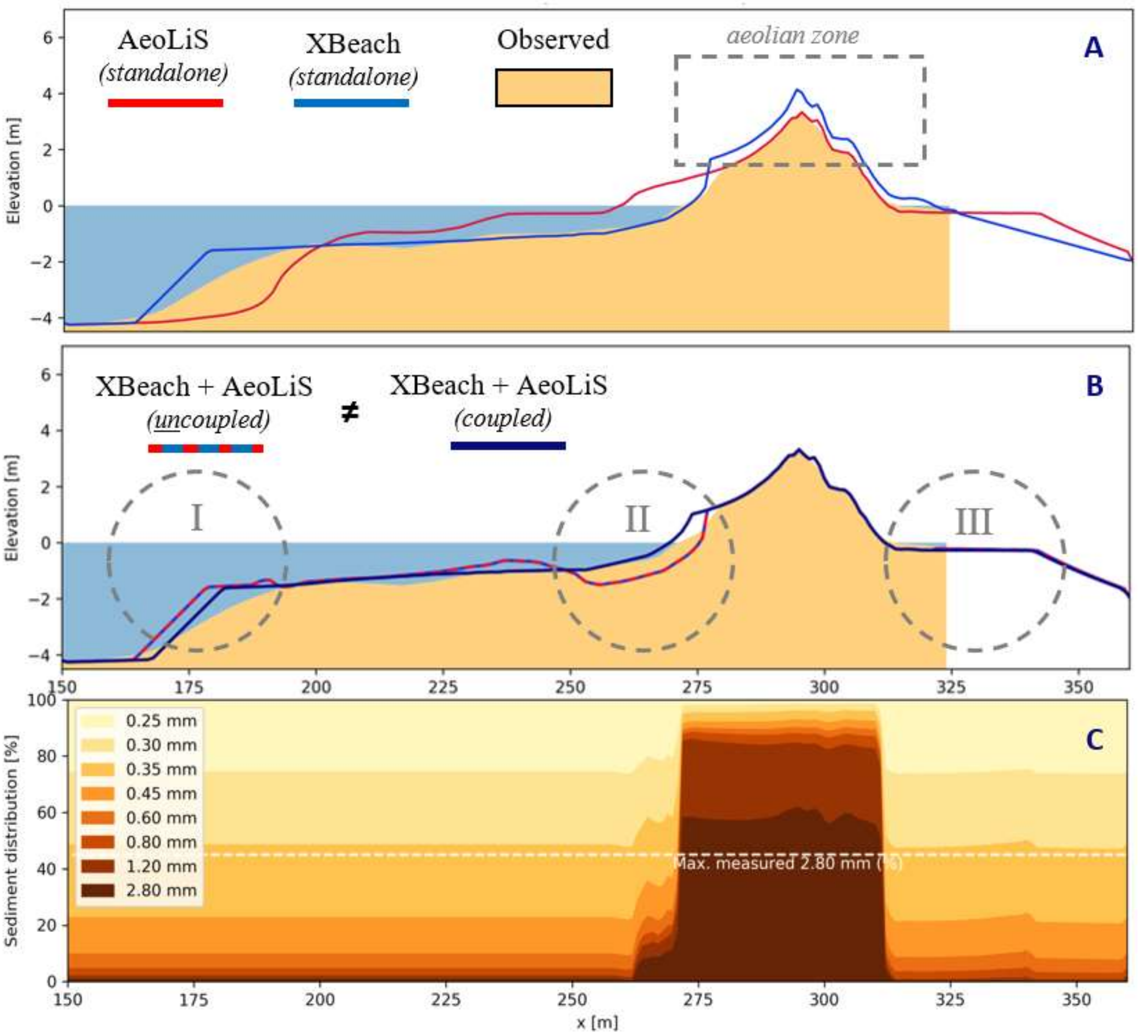

Fig. 4. Morphological development after two year at the Marker Wadden. A) Standalone AeoLiS (red) and XBeach (blue) simulations compared with the observed bed (yellow), B) Superposition of standalone AeoLiS and XBeach simulations (dotted line) compared to the coupled model results (dark blue), C) Spatial varying sediment distribution for eight grain sizes influenced by aeolian armouring.

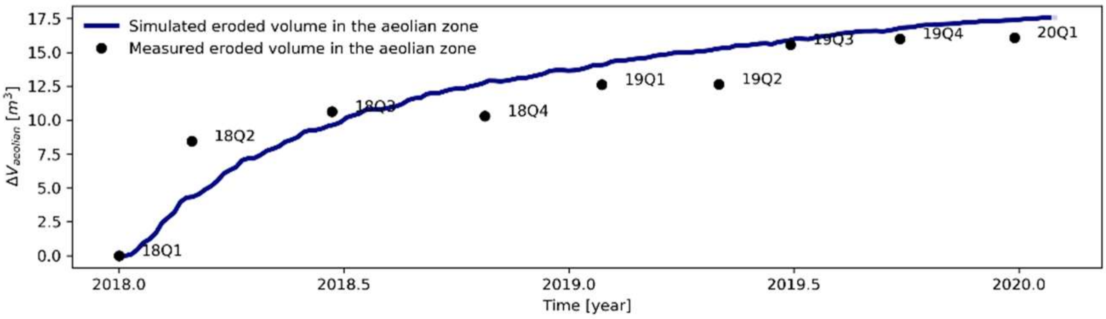

Fig. 5. Comparison between modelled (blue line) and observed (black dots) erosion from the aeolian zone decaying over time due to armouring.

While resolving aeolian processes with AeoLiS and marine processes with XBeach includes the majority of processes relevant for profile change at the site, it is possible that adding more models to the framework through integration into CoCoNuT could further improve predictive skills. For example, the horizontal "beach" at the lee side of the sand ridge is the result of aeolian sand being trapped by the lagoon as wind-blown sands are deposited into the water surface (Fig. 4B-III). However, this region is also characterized by complex spatial gradients in surface moisture in the lagoon-side due to groundwater effects and fluctuations in lagoon water levels. Incorporating more complex or representative approaches for the lagoon-side water level and surface moisture patterns could therefore contribute to a more realistic morphologic predictions in this zone within the model. Our goal is to extend the framework with more models during future development, such as a hydrological model.

Conclusion

In this paper we presented the initial development of a BMI-based model coupling framework relevant on coastal applications that is the basis for the 1D Windsurf and 2D CoCoNuT (Coastal Coupling Numerical Tool) frameworks. These tools include coupled modelling capabilities for numerically predicting the integrated development of coastal landforms. The aim of this tool is to facilitate the interdisciplinary design of coastal solutions, or NbS specifically, on varying temporal and spatial scales. As shown for the Marker Wadden case, the implemented model functionalities allow for the numerical description of the coast in an integrated manner and thus create opportunities for modeling coastal landform of the nearshore, beach, and dune that would not be possible with a discrete model approach. Specifically, by coupling two discrete numerical models, AeoLiS and XBeach, the aeolian and marine interaction resulted in a more realistic behavior of processes in the intertidal area. After coupling, bed levels compared better to the observations compared to the superpositioned results of both separate model components, which showed the added value and potential of coupled modelling.

Outlook

While this 1D application at Marker Wadden demonstrates the value that coupled modeling can have on successful simulation of coastal profile change in a scenario with relatively limited alongshore gradients in processes over short spatial scales, many sites and scenarios have alongshore gradients in processes that must be considered to effectively model spatial landscape evolution. The final objective of this framework development is to facilitate the simulation of coastal landform development at time scales of storms, seasons, and decades through describing interactions of the aeolian, marine, and ecological parts of the coastal system for 2D spatial domains. The next steps in this development trajectory are increasing the temporal (decadal) and spatial (two-dimensional, kms) scale of the model components, add new model components to capture a greater variety of coastal domains (i.e. hydrological, BMI-compatible wave models, ecology and abiotic conditions) and examine more demonstration and validation cases.

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