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Publication date

2017

Document Version

Final published version

Published in

Proceedings of Coastal Dynamics 2017

Citation (APA)

Hoonhout, B., Luijendijk, A., Velhorst, R., de Vries, S., & Roelvink, D. (2017). How tides and waves enhance aeolian sediment transport at the sand motor mega-nourishment. In T. Aagaard, R. Deigaard, & D. Fuhrman (Eds.), *Proceedings of Coastal Dynamics 2017: Helsingør, Denmark* (pp. 513-521). Article Paper No. 156

Important note

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How Tides and Waves Enhance Aeolian Sediment Transport at The Sand Motor Mega-nourishment

Bas Hoonhout^{1,2}, Arjen Luijendijk^{1,2}, Rufus Velhorst¹, Sierd de Vries¹ and Dano Roelvink³

Abstract

Expanding knowledge concerning the close entanglement between subtidal and subaerial processes in coastal environments initiated the development of the open-source Windsurf modeling framework that enables us to simulate multi-fraction sediment transport due to subtidal and subaerial processes simultaneously. The Windsurf framework couples separate model cores for subtidal morphodynamics related to waves and currents and storms and aeolian sediment transport. The Windsurf framework bridges three gaps in our ability to model long-term coastal morphodynamics: differences in time scales, land/water boundary and differences in meshes.

The Windsurf framework is applied to the Sand Motor mega-nourishment. The Sand Motor is virtually permanently exposed to tides, waves and wind and is consequently highly dynamic. In order to understand the complex morphological behavior of the Sand Motor, it is vital to take both subtidal and subaerial processes into account. The ultimate aim of this study is to identify governing processes in aeolian sediment transport estimates in coastal environments and improve the accuracy of long-term coastal morphodynamic modeling.

At the Sand Motor beach armoring occurs on the dry beach. In contrast to the dry beach, no armor layer can be established in the intertidal zone due to periodic flooding. Consequently, during low tide non-armored intertidal beaches are susceptible for wind erosion and, although moist, may provide a larger aeolian sediment supply than the vast dry beach areas. Hence, subtidal processes significantly influence the subaerial morphology and both need to be accounted for to understand the long-term aeolian morphodynamic behavior of the Sand Motor.

Key words: hydrodynamics, sediment transport, morphodynamics, dunes and ecomorphology, numerical modelling, coasts and climate

1. Introduction

In availability-limited coastal systems, the aeolian sediment transport rate is governed by the sediment availability rather than the wind transport capacity. Aeolian sediment transport models typically incorporate the sediment availability through the shear velocity threshold. However, the determination of appropriate threshold values in practice appears to be challenging, as the shear velocity threshold tends to vary both spatially and temporally (Barchyn, 2014). For example, soil moisture in the intertidal beach area fluctuates with the tidal phase and causes a local modulation of the shear velocity threshold. Moreover, a recurrence relation between sediment availability, and thus the shear velocity threshold, and sediment transport exists that complicates the a-priori determination of an appropriate threshold value. Consequently, aeolian sediment transport models tend to perform poorly in availability-limited systems.

Sherman (1998) and Sherman (2012) summarized the performance of eight aeolian sediment transport models compared to field measurements on a sandy beach. Although it is unknown whether this coastal system was availability-limited, all models systematically overpredicted the measured aeolian sediment transport rates. This finding is in correspondence with an abundance of coastal field studies in which

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aeolian sediment transport rates are overestimated by numerical models (e.g., Jackson, 1999, Lynch, 2008, Davidson-Arnott, 2009, Aagaard, 2014).

In an attempt to explain the poor performance of aeolian sediment transport models in coastal environments, many authors emphasized the importance of sediment availability and bed surface properties. Typical bed surface properties that are found along the coast and known to affect sediment availability are high moisture contents (e.g. Wiggs, 2004; Davidson-Arnott, 2008; Darke, 2008; McKenna Neuman, 2008; Udo, 2008; Bauer, 2009; Edwards, 2009; Namikas, 2010; Scheidt, 2010), salt crusts (e.g. Nickling, 1981), vegetation (e.g. Arens, 1996; Lancaster, 1998; Okin, 2008; Li, 2013; Dupont, 2014), shell pavements (e.g. Van der Wal, 1998; McKenna Neuman, 2012) and sorted and armored beach surfaces (e.g. Gillette, 1989; Gillies, 2006; Tan, 2013; Cheng, 2015). The influence of these bed surface properties on aeolian sediment availability and transport has been investigated and typically resulted in relations between bed surface properties and the shear velocity threshold (e.g., Howard, 1977; Dyer, 1986; Belly, 1964; Johnson, 1965; Hotta, 1984; Nickling, 1981; Arens, 1996; King, 2005).

Modeling rather than parameterization of spatiotemporal variations in aeolian sediment availability can improve coastal aeolian sediment transport estimates. As tides only affect the intertidal beach area, lag deposits and salt crusts typically emerge from the dry beach area, and vegetation is often restricted to the dune area, sediment availability varies spatially. In addition, temporal variations in sediment availability are induced by tidal spring/neap cycles, rain showers, storm surges, seasonal variations in vegetation and progressive armoring of the beach. Due to self-grading of the sediment, progressive beach armoring creates a recurrence relation between sediment availability and transport that challenges the a-priori determination of the spatiotemporal variations in sediment availability. Process-based modeling of the instantaneous shear velocity threshold field can address these challenges and improve coastal aeolian sediment transport estimates.

Expanding knowledge concerning the close entanglement between subtidal and subaerial processes in coastal environments initiated the development of the open-source Windsurf modeling framework that enables us to simulate multi-fraction sediment transport due to subtidal and subaerial processes simultaneously. The Windsurf framework couples separate model cores for subtidal morphodynamics related to waves and currents (Delft3D Flexible Mesh; Lesser *et al.*, 2004) and aeolian sediment transport (AeoLiS; Hoonhout *et al.*, 2016a,b). AeoLiS is a recent process-based model for supply-limited multi-fraction aeolian sediment transport that includes limiting effect of soil moisture, sediment sorting and beach armoring in aeolian sediment transport modeling. The influence of spatiotemporal variations in aeolian sediment availability and the model performance are illustrated by a comparison between model results and a large scale sediment budgets analysis that identifies and quantifies the main sources and sinks for aeolian sediment in the coastal system (Hoonhout, 2017a).

2. Field Site

The Sand Motor (or Sand Engine) is an artificial 21 Mm³ sandy peninsula protruding into the North Sea off the Delfland coast in The Netherlands (Figure 1, Stive, 2013). The Sand Motor was constructed in 2011 and its bulged shoreline initially extended about 1 km seaward and stretched over approximately 2 km along the original coastline. The original coast was characterized by an alongshore uniform profile with a vegetated dune with an average height of 13 m and a linear beach with a 1:40 slope. The dune foot is located at a height of approximately 5 m+MSL.

Due to natural sediment dynamics the Sand Motor distributes about 1 of sand per year to the adjacent coasts (Figure 1). The majority of this sand volume is transported by tides and waves. However, the Sand Motor is constructed up to 5 m+MSL and locally up to 7 m+MSL, which is in either case well above the maximum surge level of 3 m+MSL (Figure 2c). Therefore, the majority of the Sand Motor area is uniquely shaped by wind.

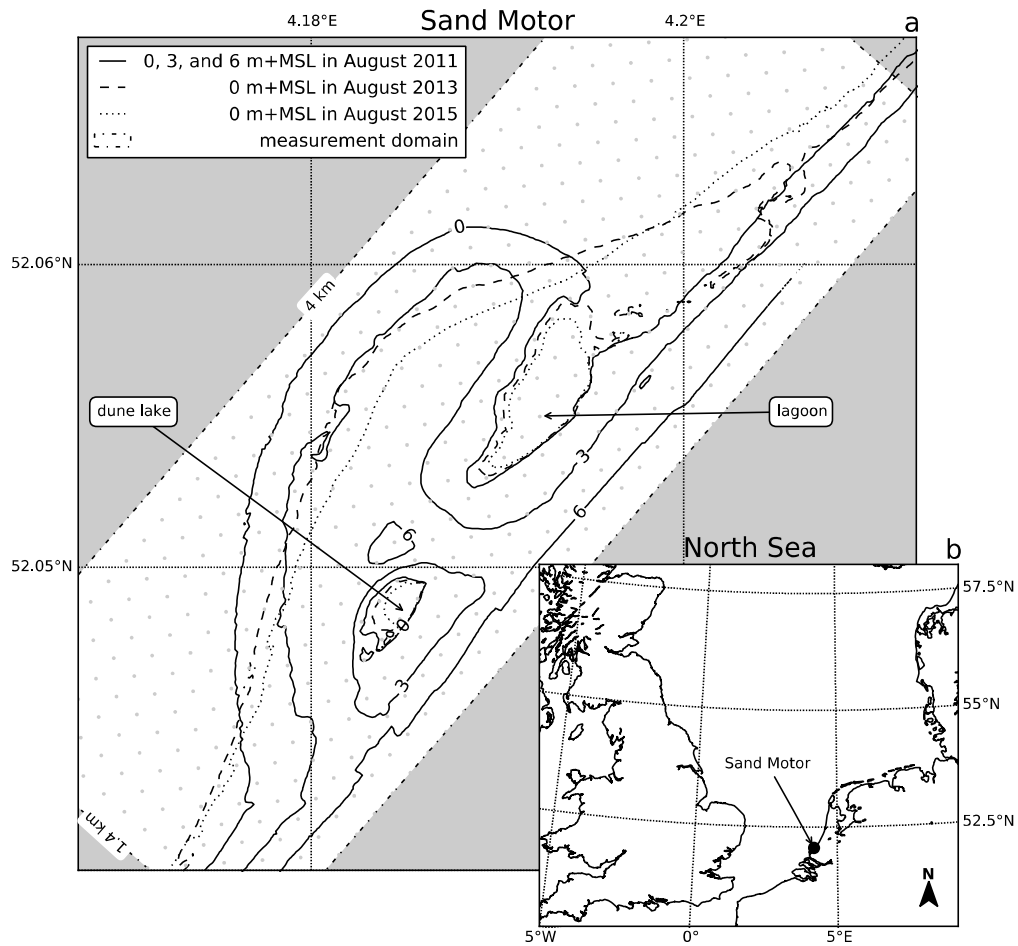


Figure 1. Location, orientation, appearance and evolution of the Sand Motor between construction in 2011 and 2015. The box indicates the measurement domain used in the remainder of this paper. A 100 x 100 m grid aligned with the measurement domain is plotted in gray as reference.

The Sand Motor comprises both a dune lake and a lagoon that act as large traps for aeolian sediment (Figure 1). The lagoon is affected by tidal forcing, although the tidal amplitude quickly diminished over time as the entry channel elongated. The tidal range of about 2 m that is present at the Sand Motor periphery (Figure 2c), is nowadays damped to less than 20 cm inside the lagoon (De Vries, 2015). Consequently, the tidal currents at the closed end of the lagoon, where most aeolian sediment is trapped, are negligible.

The dominant wind direction at the Sand Motor is south to southwest (Figure 2a). However, during storm conditions the wind direction tends to be southwest to northwest. During extreme storm conditions the wind direction tends to be northwest. Northwesterly storms are typically accompanied by significant surges as the fetch is virtually unbounded to the northwest, while surges from the southwest are limited due to the presence of the narrowing of the North Sea at the Strait of Dover (Figure 1, inset).

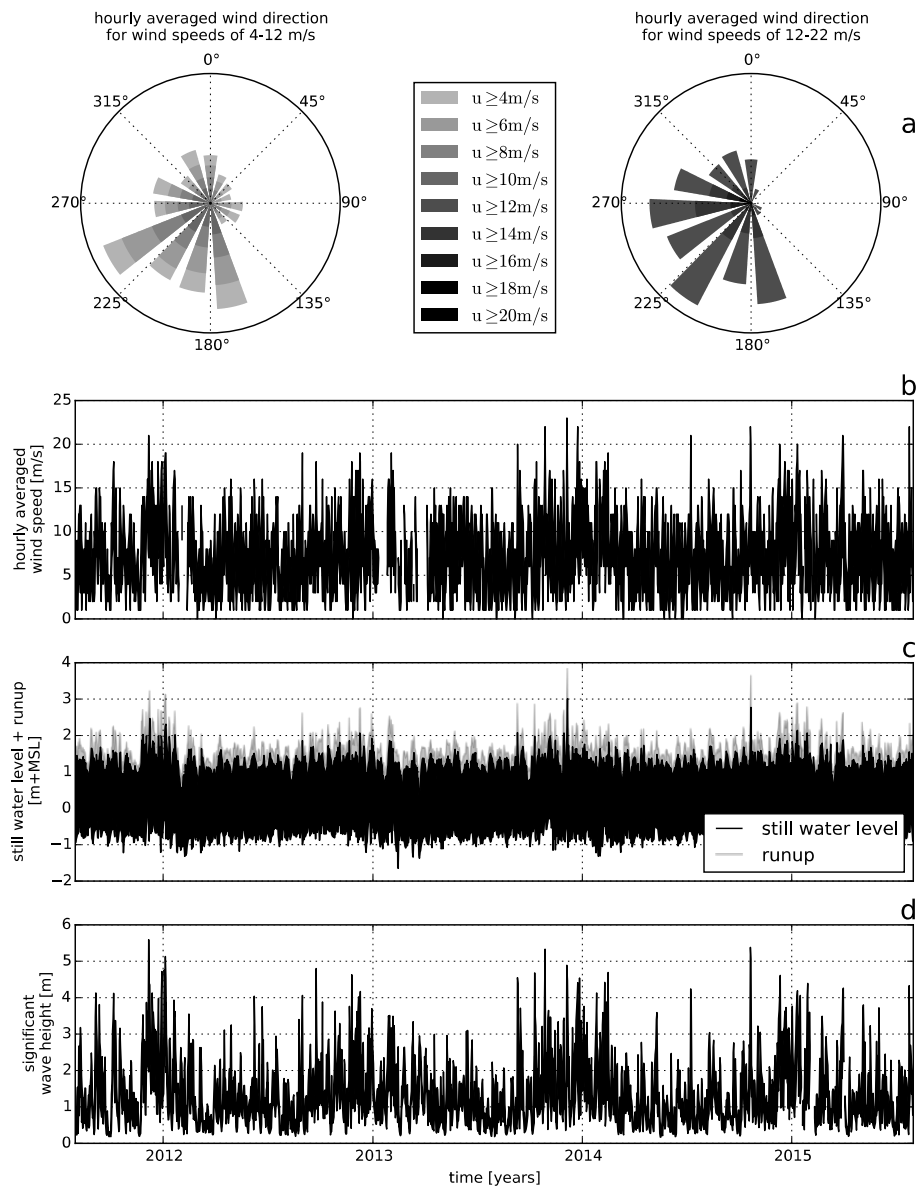


Figure 2 Wind and hydrodynamic time series from 2011 to 2015. Hourly averaged wind speeds and directions are obtained from the KNMI meteorological station in Hoek van Holland (upper panels). Offshore still water levels, wave heights and wave periods are obtained from the Europlatform (lower panels). Runup levels are estimated following Stockdon (2006).

3. Model Approach

The Windsurf framework is applied to the Sand Motor mega-nourishment. The Sand Motor is virtually permanently exposed to tides, waves and wind and is consequently highly dynamic. Hoonhout (2017a) showed that the Sand Motor is an availability-limited coastal system that provides only 25% of the

sediment transport capacity to the dunes. The ultimate aim of this study is to identify governing processes in aeolian sediment transport estimates in coastal environments and improve the accuracy of long-term coastal morphodynamic modeling in availability-limited coastal systems.

The Windsurf framework bridges three gaps in our ability to model long-term coastal morphodynamics:

1. Differences in time scales. Delft3D-FM has implemented a surfbeat model that typically acts on a time scale of a storm, while aeolian processes simulated by AeoliS typically act on a time scale of seasons to years. The difference in time scales is a major problem for numerical models, as it tends to result in infeasible computational times. By creating an online coupling between models, cores can be optimized (e.g. numerical schemes and time steps) to their specific simulated processes. In the Windsurf framework, for example, we use alternately Delft3D-FM with a stationary solver during calm conditions and with an instationary solver during storm conditions.
2. Land/water boundary. Typically models either act on the subtidal domain (e.g. Delft3D-FM) or the subaerial domain (e.g. AeoliS). In both types of models the waterline is the effective model border. By creating an online coupling between models, the artificial divide in numerical modeling between land and water is abandoned. In the Windsurf framework we detail the interaction between subtidal and subaerial processes using the AeoliS model.
3. Differences in meshes. Windsurf accommodates the nesting of state-of-the-art flexible meshes as used in Delft3D-FM with traditional structured meshes as used in AeoliS. Seamless interpolation enables virtually unlimited combination of model cores and knowledge.

4. Schematization

A two-dimensional (2DH) Windsurf model for the Sand Motor mega nourishment is constructed for the four years between September 1, 2011 and September 1, 2015, which is shortly after the nourishment was placed. The model's topography and grid are based on the measured topographies of August 3, 2011 and later. The different model components use different grids: the wave grid is unstructured and is spanning about 40 km alongshore and over 10 km cross-shore, the flow model uses an unstructured grid spanning about 10 km alongshore and 4 km cross-shore, while the aeolian sediment transport model uses a 50 x 50 m rectilinear grid spanning 4 km alongshore and 1.5 km cross-shore with respect to the original coastline, not including the dunes (Figure 4).

Four years of hourly wind speed and direction data measured at 10 m above the bed is obtained from the KNMI meteorological station at Hoek van Holland (Figure 2a,b). Hourly offshore water levels and wave heights are obtained from the Europlatform for the same period (Figure 2c,d).

An average lognormal grain size distribution with a median diameter is used as measured at the Sand Motor field site. The sand fractions cover a range from 0.1 to 2 mm. The amount of shells and other roughness elements in the originally nourished sand is estimated to be 5. The estimate is based on three sediment samples obtained from the field site 0.5 m below the bed surface. Additional fractions ranging from 2 to 32 mm are added according to a lognormal distribution to account for the presence of roughness elements in the bed. The grain size distribution is used to populate the initial bed that consists of 10 bed composition layers with a thickness of 1 cm each.

5. Results

The Windsurf model results are first compared with stand-alone AeoliS results (Figure 5). The former includes both hydrodynamic and aeolian sediment transport, whereas the latter only includes aeolian sediment transport. However, the stand-alone AeoliS model predicts a negligible dune growth over the four year simulation period.

Initially, uniform erosion of the dry beach occurs in the stand-alone AeoliS model, resulting in a significant sediment supply to the dunes, dune lake, lagoon and offshore (Figure 6, lower panel). But sediment supply from the dry beach quickly diminishes to negligible amounts as a beach armor layer develops. The fact that the stand-alone AeoliS model does not include the significant hydrodynamic reshaping of the Sand Motor, and therefore overestimates the dry beach surface area, does not prevent that no alternative source areas become available and sediment supply eventually ceases.

In contrast to the stand-alone AeoliS model, the Windsurf framework includes the reshaping of the Sand Motor due to hydrodynamics. More importantly, the Windsurf framework includes processes of drying, flooding and mixing of the intertidal beach where consequently no armor layer can be established. Therefore, during low tide non-armored intertidal beaches are susceptible for wind erosion and, although moist, may provide a larger aeolian sediment supply than the vast dry beach areas, which is visible by the pronounced erosion band in the low-lying areas.

The predicted importance of the intertidal beach as supplier of aeolian sediment and the low, but still significant aeolian sediment supply in the Sand Motor region, are well in accordance with the analysis presented in Hoonhout (2017a). Hence, subtidal processes significantly influence the subaerial morphology and both need to be accounted for to understand the long-term aeolian morphodynamic behavior of the Sand Motor.

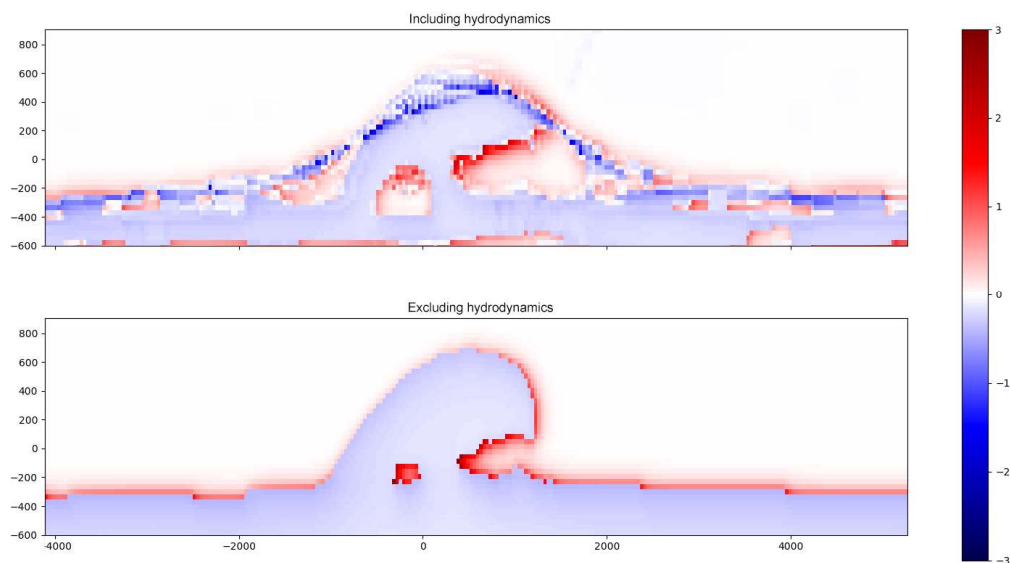


Figure 5 Aeolian erosion/deposition at the Sand Motor as predicted by the Windsurf framework in case hydrodynamics are included (upper panel) and in case hydrodynamics are excluded (lower panel).

6. Conclusions

The Sand Motor hindcast shows that the reduction of aeolian sediment availability due to soil moisture and beach armoring can largely explain the low accumulation volumes in the Sand Motor domain presented by Hoonhout (2017a). At the same time, periodic flooding and mixing of the intertidal beaches ensure a continuous supply of aeolian sediment. Without hydrodynamic forcing, aeolian sediment supply eventually ceases. The accumulation volumes in the dunes, dune lake and lagoon therefore largely depend on the close interaction between aeolian and hydrodynamic sediment transport in the intertidal area. The Windsurf model framework has shown to be able represent the importance of tides and waves for coastal dune growth.

The Windsurf project made significant steps in connecting what have traditionally been different disciplines in coastal sciences. It provides an innovative solution to bridge differences in time scales and meshes as well as the traditional land/water boundary. Preliminary model/data comparisons indicate that the Windsurf framework provides better skill with respect to reproducing morphological measurements than stand-alone models, especially with respect to spatiotemporal variations in aeolian sediment supply and dune growth.

Acknowledgements

The work discussed in this paper is supported by the ERC-Advanced Grant 291206 - Nearshore Monitoring and Modeling (NEMO) and Deltares.

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