Storm influences on sand wave dynamics: an idealized modelling approach

Geert Campmans *University of Twente, Enschede, The Netherlands – g.h.p.campmans@utwente.nl*
Pieter Roos *University of Twente, Enschede, The Netherlands – p.c.roos@utwente.nl*
Suzanne Hulscher *University of Twente, Enschede, The Netherlands – s.j.m.h.hulscher@utwente.nl*

ABSTRACT: We investigate the influence of wind waves and wind-driven flow on sand wave dynamics using a two-model approach. Using a linear stability analysis, we find that waves decrease sand wave growth and wind causes sand wave migration. Combining linear stability analysis with a typical North Sea wave and wind climate explains variability in sand wave migration rates. Using a nonlinear sand wave model we show that waves reduce sand wave height and wind causes sand wave asymmetry as well as migration.

1 INTRODUCTION

Sand waves are dynamic bed forms of hundreds of meters wavelength and several meters in height. They are observed in many tidally dominated seas with sandy beds, such as the North Sea. Offshore activities require a detailed knowledge of sand wave dynamics. Various observational studies suggest that storms affect sand wave height and migration rate (Terwindt, 1971; Fenster et al., 1990).

Our aim is to understand how storms influence sand wave dynamics. We do so by applying an idealized modelling approach that is able to isolate two storm effects: wind waves and wind-driven flow effects. The sand waves that we investigate are generated by a symmetrical tidal current.

To investigate the effects of wind waves and wind-driven flow on sand wave dynamics we applied a two-step approach, in which we systematically analyse storm effects on small-amplitude sand wave dynamics using a linear stability analysis (Campmans et al., 2017), followed by an idealized nonlinear sand wave model to analyse storm effects on finite amplitude sand wave dynamics (Campmans et al., 2018b).

The linear stability model allows for a large number of model runs due to its semi-analytical solution method. This enabled us to investigate wind wave and wind-driven current scenarios to investigate a real North Sea wave and wind climate (Campmans et al., 2018a).

2 MODEL FORMULATION

2.1 Tides, wind and waves

The tidal currents in our model are described by shallow-water equations. Hydrostatic pressure balance is assumed in the vertical. Turbulent mixing is modelled by a constant vertical eddy viscosity with a partial slip boundary condition. A uniform pressure gradient is incorporated to force a tidal current. The model domain is spatially periodic. in the horizontal.

Wind effects are modelled by a constant uniform shear stress applied at the water surface, causing a wind-driven flow.

Wind waves are modelled using linear wave theory. Near-bed orbital velocities result in an increase in bed-shear stress, but do not affect the tidally or wind-driven currents.

2.2 Sediment transport

Sediment transport is modelled by a bed load transport formula, given by

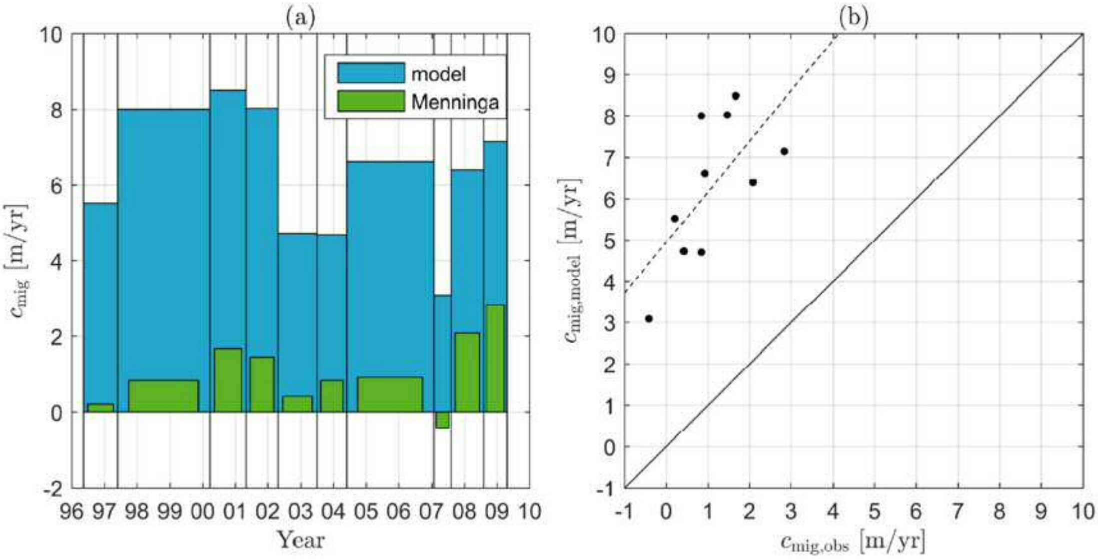

Figure 1. Observed (Menninga, 2012) and modelled sand wave migration c_{mig} in the North Sea, between 1996 and 2010. *Figure after Campmans et al. (2018a)*

$$q_{\mathrm{b}} = \alpha|\tau|^{\beta}\left(\frac{\tau}{|\tau|} - \lambda\nabla h\right), \tag{1}$$

in which α is a bed load coefficient, τ the bed shear stress, β the exponent expressing the nonlinearity of sediment transport, λ the slope correction factor and h the seabed topography. Here, sediment is transported nonlinearly in the direction of the shear stress, corrected for gradients in the bed slope. Sediment transport is computed on an intra-wave time scale, where the tidal current is assumed constant, and is then averaged over a wave period. Similarly, on the intra-tidal time scale sediment transport is averaged.

2.3 Bed evolution

The seabed evolution is determined by sediment conservation using the wave and tidally averaged sediment transport.

3 SOLUTION METHODS

3.1 Linear stability analysis

The first method to gain insight into the solution of small-amplitude sand wave dynamics is linear stability analysis. The output for the linear stability analysis is a growth rate and migration rate for a sinusoidal bed perturbation of a chosen wavelength. The growth rate and migration rate describe the small-amplitude behaviour until finite-amplitude effects become important.

3.2 Nonlinear solution method

To analyze the finite amplitude dynamics of sand waves, a nonlinear solution method is required. In this solution method the shallow-water equations are transformed to a rectangular computational domain, where the finite-difference method is used to solve the hydrodynamics. In the nonlinear model the bed evolution is numerically integrated to investigate the morphodynamic evolution of finite-amplitude sand waves.

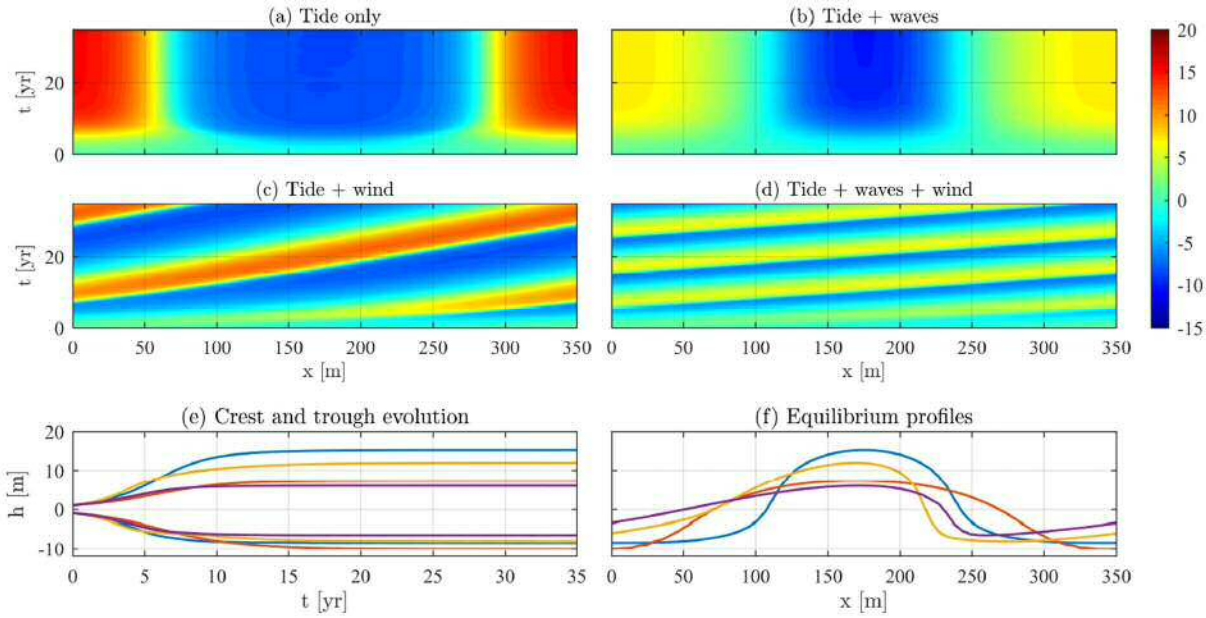

Figure 2. Sand wave evolution h(x,t) for four forcing conditions: (a) Tide only, (b) Tide + waves, (c) Tide + wind and (d) Tide + waves + wind. The colorbar indicates the seabed topography in meters. The bottom panels show (e) the crest and trough evolution in time and (f) the equilibrium profiles. Where in (e) and (f) the line colors correspond to the colored text in this caption. *Figure after Campmans et al. (2018b)*

4 RESULTS

4.1 Linear stability analysis

Using the linear stability model the influence of wind waves and wind-driven flow on the growth- and migration-rate was systematically investigated. Both wind and, in particular, waves decrease the growth rate of sand waves. Wind-driven flow generates a residual current that causes sand wave migration. Although waves do not cause sand wave migration, they do enhance migration caused by other mechanisms such as wind-driven flow.

Combining the linear stability sand wave model with 20 years of wave and wind data the influence of a typical North Sea storm climate has been investigated. Using this approach a hindcast of variable sand wave migration, observed by Menninga (2012), showed a qualitative agreement, see Figure 1.

4.2 Nonlinear sand wave model

The developed nonlinear sand wave model was used to investigate the effects of storms on the finite amplitude dynamics of sand waves. The evolution of small amplitude bed perturbations towards fully grown sand waves has been investigated for four forcing conditions in Figure 2. It is found that sand wave height is mainly reduced by waves, but also by wind. Wind generates a residual flow component that causes sand waves to migrate and results in a horizontally asymmetric sand wave shape.

In the results above, the sand wave wavelength is restricted by the model domain length of 350 m. This allowed to systematically investigate storm effects. However, to allow sand waves to freely adapt their wavelength similar model simulations were carried out on a longer model domain (4 km), shown in Figure 3.

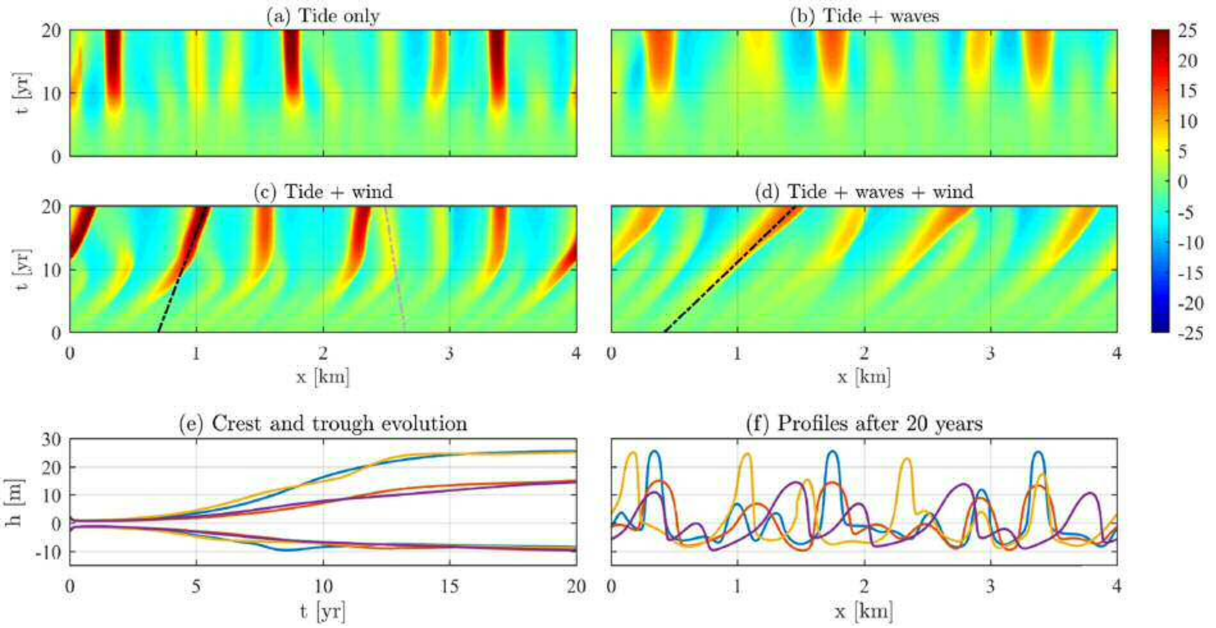

Figure 3. Sand wave evolution h(x,t) for four forcing conditions: (a) Tide only, (b) Tide + waves, (c) Tide + wind and (d) Tide + waves + wind. The colorbar indicates the seabed topography in meters. The bottom panels show (e) the crest and trough evolution in time and (f) the equilibrium profiles. Where in (e) and (f) the line colors correspond to the colored text in this caption. *Figure after Campmans et al. (2018b)*

Finally we investigated the effect of storm duration. In results thus far, modelled wave and wind conditions are constant in time, whereas in reality storms often occur for a short duration, followed by a period of relatively calm weather. To simulate such storm intermittent behaviour, a storm (*tide* + *wave* + *wind*) condition is alternated by a fair-weather (*tide only*) condition for various storm durations. In Figure 4, the crest and trough evolution is shown for six different storm durations: constant fair-weather, 1 week storm, 1 month, 2 months, half a year, and constant storm conditions. For each of the scenarios a single storm is modelled with the remaining part of the year being fair-weather. The model results show that for intermittent storm conditions the sand wave crest and trough height oscillates between the equilibrium crest and trough heights of sand waves in constant fair-weather and constant storm conditions. We interpret this as a storm-dependent *dynamic equilibrium*. Even storms of relatively short duration already have a significant effect on the sand wave height.

5 CONCLUSIONS

By applying the two-model approach in our research we were able to systematically analyse the wave and wind effects on initial sand wave formation as well as for specific wave and wind conditions on finite amplitude sand wave dynamics. We have shown that particularly wind waves reduce the growth rate and the sand wave height in equilibrium conditions. Wind-induced flow causes sand wave migration, which can be

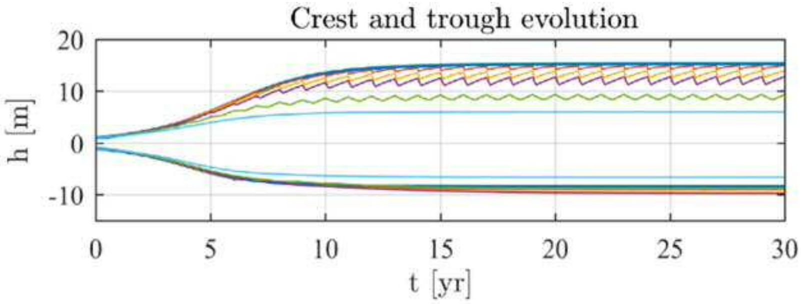

Figure 4. Crest and trough evolution for alternating storm and fair weather conditions. The storm duration for each line is: constant fair-weather, 1 week, 1 month, 2 months, half a year, constant storm. *Figure after Campmans et al. (2018b)*

enhanced by waves. North Sea wave and wind data combined with the linear stability model shows promising results in being able to hindcast sand wave migration. Finally, we show that storms reduce sand wave height, even when they occur for short periods of time.

6 ACKNOWLEDGEMENT

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7 REFERENCES

Campmans, G.H.P., Roos, P.C., De Vriend, H.J., Hulscher, S.J.M.H., 2017. Modeling the influence of storms on sand wave formation: A linear stability approach. Continental Shelf Research 137, 103-116. DOI: 10.1016/j.csr.2017.02.002

Campmans, G.H.P., Roos, P.C., Schrijen, E.P.W.J., Hulscher, S.J.M.H. (2018a). Modeling wave and wind climate effects on tidal sand wave dynamics: A North Sea case study. Estuarine, Coastal and Shelf Science 213, 137-147. DOI:10.1016/j.ecss.2018.08.015

Campmans, G. H. P., Roos, P. C., de Vriend, H. J., & Hulscher, S. J. M. H. (2018b). The influence of storms on sand wave evolution: A nonlinear idealized modeling approach. Journal of Geophysical Research: Earth Surface, 123, 2070-2086. DOI:10.1029/2018JF004616

Fenster, M.S., Fitzgerald, D.M., Bohlen, W.F., Lewis, R.S., Baldwin, C.T., 1990. Stability of giant sand waves in eastern Long Island Sound, USA. Marine Geology 91, 207-225.

Menninga, P.J., 2012. Analysis of variations in characteristics of sand waves observed in the Dutch coastal zone: a field and model study. (Master Thesis), Utrecht University (NL) .

Terwindt, J.H.J., 1971. Sand waves in the Southern Bight of the North Sea. Marine Geology 10, 51-67.