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Modelling the influence of storm-related processes on sand wave dynamics: a linear stability approach

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ABSTRACT: Literature shows that storms play a significant role in sand wave dynamics. We present a 3D idealized sand wave model, capable of systematically investigating the influence of storm-related processes, i.e. wind-driven flow and wind waves, on the formation stage of sand waves. Model results show that wind-driven flow affects sand wave migration, and wind-waves affect the wavelength and growth rate of the fastest growing mode.

1. INTRODUCTION

Tidal sand waves are large-scale rhythmic bed forms observed in many tide-dominated shallow seas with a sandy seabed. The behaviour of sand waves is of practical interest because they tend to interfere with navigation, dredging, and pipelines. Process-based morphodynamic models have been developed to increase our understanding of sand wave dynamics (Besio et al. 2008; Van den Berg et al., 2012). In particular, sand waves have been explained as free instabilities of the system (Hulscher, 1996).

Limitations of existing sand wave models (overestimating sand wave heights and inaccurately predicting sand wave migration) suggest that some processes are either poorly represented or still missing. Observations show that storms, not included in the above models, play a significant role in sand wave dynamics (Terwindt, 1971; Harris, 1989; Houthuys et al., 1994). Németh et al. (2002) found that wind-driven flow affects sand wave migration. The effect of wind waves on sand wave growth dynamics has not yet been investigated.

In this study, we present an idealized sand wave model to systematically investigate the influence of storm-related processes on sand wave dynamics, in the stage of formation. Moreover, we aim to identify potentially important storm-related processes, and restrict ourselves to linear stability analysis (e.g. Dodd et al., 2003). Our model adopts the linear stability analysis approach to investigate the fastest growing mode when including storm-related processes. This mode is assumed to be the dominant bed form. Sand wave properties obtained from this analysis are: growth rate, migration rate, wavelength and orientation.

2. METHODS

We present a 3D idealized sand wave model to investigate the influence of storm-related processes (see fig. 1). These processes are included in a schematised way in order to obtain a fast and relatively simple model that is capable of investigating the influence of storm-related processes on sand wave dynamics, and is also capable to identify the most important physical mechanisms.

2.1. Processes included

During fair weather, sand waves are subject to tidal flow; and bed load is the dominant sediment transport mode.

During storms, both wind-driven flow and wind-waves are generated. Larger flow velocities due to wind-driven flow and stirring due to wind-waves can initiate suspended load sediment transport.

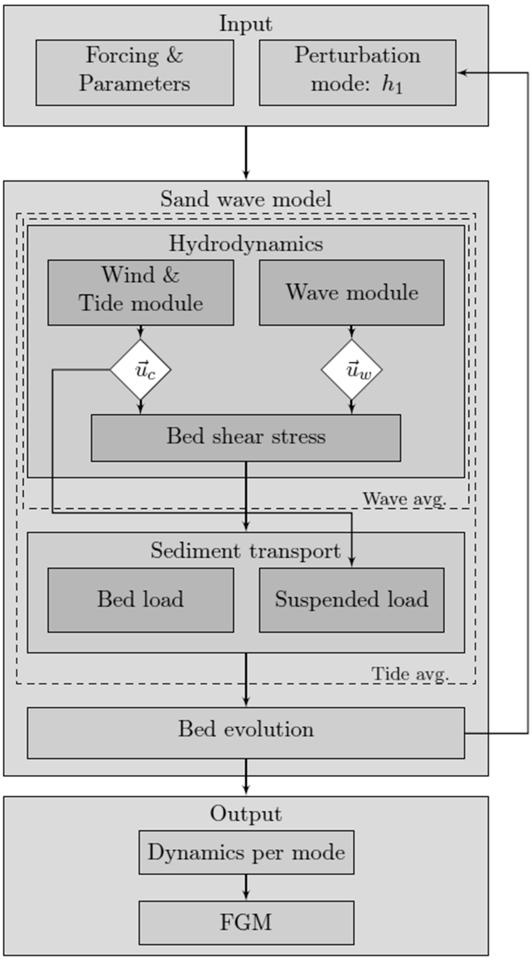

Figure 1. Schematic model overview.

2.2. Model formulation

Both wind-driven currents and tidal flow are described by the 3D nonlinear shallow water equations, including the Coriolis effect. These consist of two horizontal momentum equations and a continuity equation. Wind-driven flow is forced by a shear stress at the water surface. Tidal flow is forced by a horizontal oscillatory pressure gradient, which – in the case of a flat bed – produces a prescribed residual current, M0, and tidal ellipses of the M2, M4 and higher-order harmonic components. Turbulence is described by a constant eddy viscosity, combined with a partial-slip condition near the bed.

Wind-waves are included via a separate wave module based on linear wave theory.

Both the currents module and the wave module generate near-bed velocities, which are translated to a combined bed shear stress.

Sediment transport consists of both bedload and suspended load. Bed load transport is assumed to respond instantaneously with changing bed shear stress, and is modelled as a power law including the bed slope effect. Suspended sediment transport is modelled via the advection diffusion equation. Near the bed, a reference concentration is prescribed as a power law function of the bed shear stress.

Finally, the bed evolution follows from (tidally averaged) sediment conservation.

2.3. Linear stability analysis

Using linear stability analysis, we investigate the stability of the flat bed subject to a spatially uniform tidal motion, called the basic state.

This is done by analysing the response of the system to small-amplitude sinusoidal perturbations:

$$\frac{h}{H} = \varepsilon h_1 = \varepsilon \cos\left(k_x x + k_y y\right). \quad (1)$$

Here, h is the bed level, H the mean water depth, $\varepsilon \ll 1$ a small expansion parameter, h_1 the perturbed bed level and k_x and k_y are the topographic wave numbers in x- and y-direction, respectively.

The unknowns of the system, symbolically represented as φ, are expanded in powers of ε:

$$\varphi = \varphi_0 + \varepsilon\varphi_1 + \mathcal{O}(\varepsilon^2). \quad (2)$$

Here, φ_0 is the basic state of the system, φ_1 is the perturbed state system response, and higher-order terms are neglected since ε is small. The solution of the bed evolution is written as follows:

$$h_1 = \cos\left(k_x x + k_y y - c_{mig}\sqrt{k_x^2 + k_y^2}t\right) \mathrm{e}^{\omega t} \quad (3)$$

Here, c_{mig} is the migration speed in the direction perpendicular to the crest, ω is the growth rate, which results in exponential growth (or decay if it is negative). The system is linearly stable, when

$\omega < 0$ for all k_x and k_y. If $\omega > 0$ for at least one mode, the basic state is unstable. The mode with the maximum growth rate is termed to be the fastest growing mode (FGM). The properties of the FGM are: wavelength, orientation, growth rate and migration rate.

2.4. Solution method

Since the bed perturbations are described as Fourier modes, the horizontal structure of the response of the system according to this linear model also consists of Fourier modes. Additionally, the tidal current is assumed to be harmonic in time. Only in the vertical direction, numerical integration is required to solve the hydrodynamic perturbed state. The basic state can be solved analytically, because a constant eddy viscosity is chosen. As the numerical integration problem is just 1D, the model is fast.

3. RESULTS & DISCUSSION

For typical North Sea conditions, the flat seabed turns out to be unstable, so that some perturbation modes tend to grow. On an initially flat bed containing equally small perturbations of all modes, the FGM will soon dominate all other modes. The FGM is therefore assumed to be the most likely surviving bed form during the stage of formation.

Different storm processes, i.e. wind-driven flow and wind waves, yield different sand wave dynamics (see fig. 2). Wind-driven flow primarily affects sand wave migration, and wave action tends to increase wavelength and reduce the growth rate.

Processes are represented in a schematized way, hence the model results should be interpreted as qualitative indications of the influence of storm-related processes on sand wave dynamics. Note that the model is valid for small amplitudes only; higher-order amplitude effects are likely to yield different properties of fully grown sand waves.

4. CONCLUSIONS

The new idealized sand wave model is capable of qualitatively analysing the physical mechanisms that cause sand wave formation. Additionally, the model is well suited to perform a sensitivity analysis for a large set of model parameters. Preliminary results show that wind-driven flow affects the migration rate of sand waves and wave action affects their wavelength and growth rate.

5. ACKNOWLEDGMENT

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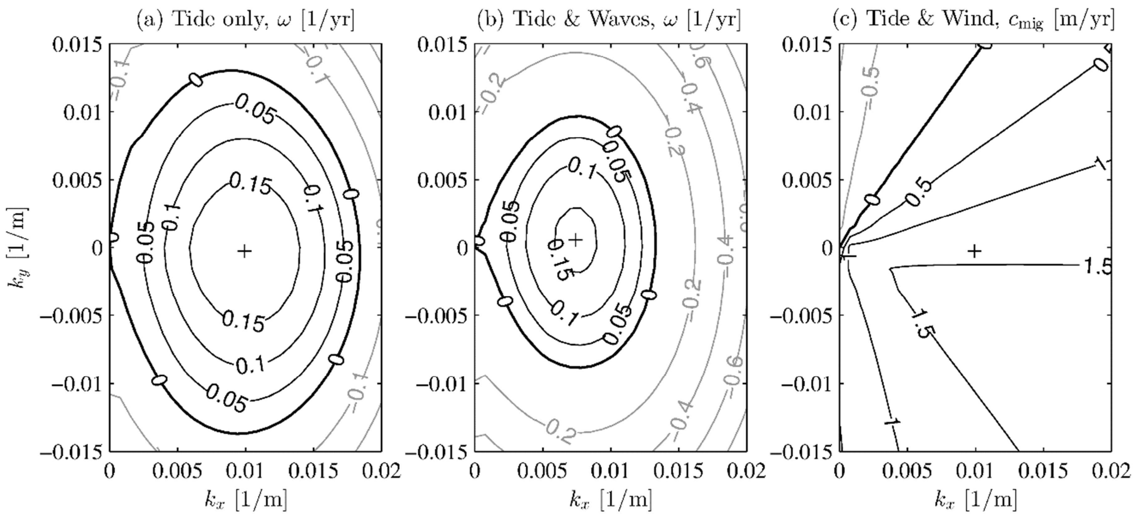

Figure 2. Model output as a function of topographic wave numbers k_x and k_y: (a) growth rates, ω for tide only, (b) growth rates, ω for tide and wind waves, (c) migration rate, c_{mig} for tide and wind forcing. In this example, the tide is symmetric (such that $c_{mig} = 0$ in cases a and b), the wind is parallel to the tidal flow direction and wind waves propagate orthogonal to the tidal flow direction. The growth rates for tide and wind forcing are nearly identical to the tide only case. The fastest growing mode is denoted with a $+$.