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Phase-related patterns of tidal sand waves and benthic organisms: field observations and idealised modelling

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ABSTRACT: Observations from the field show that the spatial distribution of benthic organisms is strongly correlated to the morphological structure of tidal sand waves. In particular the troughs of sand waves are typified by a large benthic community, in contrast to the crest. In this paper, we present an idealised process-based model to study these patterns of biota and sand waves. Our model results agree with the observations that these phase-related patterns can arise on the seabed. Moreover, we show that local topography disturbances may lead to spatial patterns of both sand waves and biomass.

1. INTRODUCTION

Tidal sand waves are common features which occur on the bottom of sandy coastal shelve seas, such as the North Sea. They can grow up to 25% of the local water depth, and migrate at a speed of several meters per year (van Dijk & Kleinhans, 2005). Due to these dynamic properties, they endanger offshore engineering structures, shipping lines and cables.

Moreover, coastal areas are covered by large communities of benthic organisms, living op top and within the seabed (Rabaut et al., 2007). Field observations often show a strong temporal and spatial relationship between marine bed patterns and these organisms (Baptist et al., 2006), while on the other hand, benthic organisms are able to influence hydro- and sediment dynamics. In addition, a wide range of activities in coastal seas (e.g., the ones mentioned above) put an increasing pressure on the long-term stability of the marine ecosystem.

For the planning and execution of offshore engineering projects, knowledge of the distribution of these organisms over sand waves is of great importance. Predictions about the spatial response of benthic habitats to interventions can have considerable consequences regarding the time needed to process new licences for these offshore projects.

The combination of morphodynamic modelling and field surveys can increase our understanding of the governing processes responsible for the spatiotemporal patterns of benthos over sand waves. In this paper we first present an overview of field studies which analysed spatial patterns of biotic as well as abiotic parameters in the marine environment. Second, we use an idealised two-way coupled biogeomorphological model to study the observed phase-related patterns by means of a linear stability analysis.

2. FIELD OBSERVATIONS

The seabed of coastal areas harbours a rich ecosystem, and the benthic organisms living here show a great variety in both space and time (Widdows & Binsley, 2002). These patterns are usually related to the presence of marine bed forms of various dimensions.

For large-scale tidal ridges, van Dijk et al. (2012) reported that the benthic community structure in the troughs was much richer and much denser than on the crests. Small-scale

Figure 1. Typical seabed structure within a sand wave area, displaying the crest (top) and trough (bottom). The green dots represent a horizontal distance of 30 cm. Pictures from Damveld et al. (2018b)

bedforms, such as megaripples, are shown to drive the distribution of benthos as well (van der Wal et al., 2017).

Also for sand waves (meso-scale bedforms) a clear relation has been established between the occurrence of benthic organisms and the morphological structure of the bedforms. Baptist et al. (2006) looked into seasonal spatial variations and found evidence that endobenthic organisms occur in higher densities in sand wave troughs. Moreover, using a video system, Damveld et al. (2018a) found that the number of both epi- and endobenthic organisms are significantly higher in sand wave troughs, compared to the crests (see Figure 1).

Apart from directly monitoring the distribution of benthic organisms, it is also possible to look into other parameters. It is widely known that various abiotic parameters (e.g. sediment type and size, silt content and permeability) are strongly related to the habitat structure of benthos (Reis et al., 2010). Several studies analysed the distribution of grain sizes over sand waves and both a coarsening and a fining of the crests were reported (van Oyen et al., 2013, and references therein). In addition to these abiotic variations in crest/trough, also abiotic patterns have been found on a smaller spatial scale. Cheng et al. (2018) reported that silt content is higher in both the troughs and on the lee side slope of (strongly asymmetrical) sand waves, compared to the crests and stoss slope. Due to the expected spatial correlation between these abiotic variables and the benthos, it follows that benthic habitats are also related to the spatial structure of sand waves.

3. METHODOLOGY

a. Stability methods

To study the evolution of bed and benthic organisms we follow a linear stability approach, which is often used to study morphodynamic rhythmic patterns (Dodd et al., 2003). This method assesses the response of small-amplitude perturbations to a so-called basic state (i.e. a flat bed in morphodynamics). The typical result is a range of modes which show either exponential growth or decay. The mode with the largest positive growth rate is considered the fastest growing mode. The corresponding wavelength, orientation, migration and growth rate are assumed to be the properties occurring in the field.

Using this method, Hulscher (1996) explained the process leading to the formation of sand waves. The interaction of the oscillatory tidal flow with small disturbances on the seabed gives rise to steady recirculation cells in the water column. The direction of these cells near the bed is directed towards the crests of the perturbations, resulting in a net sediment displacement in the same direction. In contrast, gravity favours a downward sediment transport, such that the balance between these two forces eventually leads to either growth or decay of the perturbation.

Various model studies have extended this approach in order to determine the effect of a wide range of physical processes on the initial formation of sand waves. These processes are, for instance, migration due to tidal asymmetry (Besio et al., 2004), sediment sorting (van Oyen & Blondeaux, 2009) and biological activity (Borsje et al., 2009).

Also the formation of biological spatial patterns can be explained using stability analysis. For a fluvial environment, Bärenbold et al. (2016) showed that the interaction between riverbed vegetation and hydrodynamics leads to the emergence of riverine bar patterns.

b. The biogeomorphological model

Building upon the methodology described above, we present an idealised, process-based model, in which hydro- and sediment dynamics are described by the 2DV Navier-Stokes equations, flow and sediment continuity equations and are supplemented with appropriate boundary conditions. The evolution of the bed h is governed by the Exner equation, which reads

$$\frac{\partial h}{\partial t} = -\frac{1}{(1-p)}\frac{\partial q(\phi)}{\partial x}. \qquad (1)$$

Here, p is the bed porosity and q is the sediment transport rate.

Next, the evolution of benthic organisms (represented by the biomass ϕ) is described by logistic growth, according to

$$\frac{\partial \phi}{\partial t} = \alpha_g \phi(\phi_{eq}(\tau) - \phi), \qquad (2)$$

with α_g as the logistic growth rate and ϕ_{eq} as the biological carrying capacity (equilibrium biomass) which depends on the local shear stress τ.

Moreover, the sediment transport depends, amongst other parameters, on the biomass ($q(\phi)$, see eq. 1). It turns out that both evolutionary equations are two-way coupled. As a consequence, the problem can be written as the following linear eigenvalue problem

$$\frac{\partial}{\partial t}\begin{bmatrix}\breve{h}\\ \breve{\phi}\end{bmatrix} = \Gamma(\mathrm{t})\begin{bmatrix}\breve{h}\\ \breve{\phi}\end{bmatrix}, \qquad (3)$$

where the breve ˘ denotes the perturbation amplitude. The complex growth rate of the perturbations $\Gamma(t) = \Gamma_r(t) + i\Gamma_i(t)$ is a function of flow, sediment and biological parameters. The real part Γ_r describes the exponential growth of the perturbations, whereas the imaginary part Γ_i is related to the migration.

An important property of this methodology is that this problem leads to two distinct eigenvalues (Γ_1 & Γ_2). The actual perturbation amplitudes are thus a superposition of two eigenmodes, each displaying its own growth and migration. For further details, we refer the reader to Damveld et al. (submitted).

In next section, we study the evolution of bed and biomass by imposing random perturbations to the flat bed, while keeping the biomass spatially uniform. Furthermore, the system is asymmetrically forced by a combination of the M2 tide and an M0 residual current (0.05 m / s).

4. RESULTS

We present our results in Figure 2, where each panel describes the temporal evolution of the topography and biomass profile. In (a) we define the initial state, where the bed profile displays a random pattern. The biomass has a spatially uniform value of $\phi = 0.1$ kg / m. Other than the basic bed, the basic biomass evolves autonomously due to logistic growth. This is best visible in (a, b and c), where ϕ uniformly increases over time, independent of the perturbations.

When looking at the bed development, it can be seen that, initially, the perturbations with shorter wavelengths decay. After this, the modes that display growth evolve into a bed pattern with wavelengths in the range of hundreds of meters, corresponding to sand wave wavelengths in the field.

It stands out that, independent of the autonomous benthic growth, spatial patterns for the biomass develop as well. Moreover, the phase of these patterns is the opposite of that of the bed. More specific, the biomass crests are concentrated on the lee side slope of the sand wave troughs. Other results, which are not shown here, show that the residual current strength is responsible for this phase shift. In case of a symmetrical tidal forcing, the phase difference is exactly 180°, whereas for an increasing residual current strength, this phase difference decreases towards 90°. However, as residual currents in the field are often on the order of the presented values here, it is to be expected that the phase differences are somewhere in between.

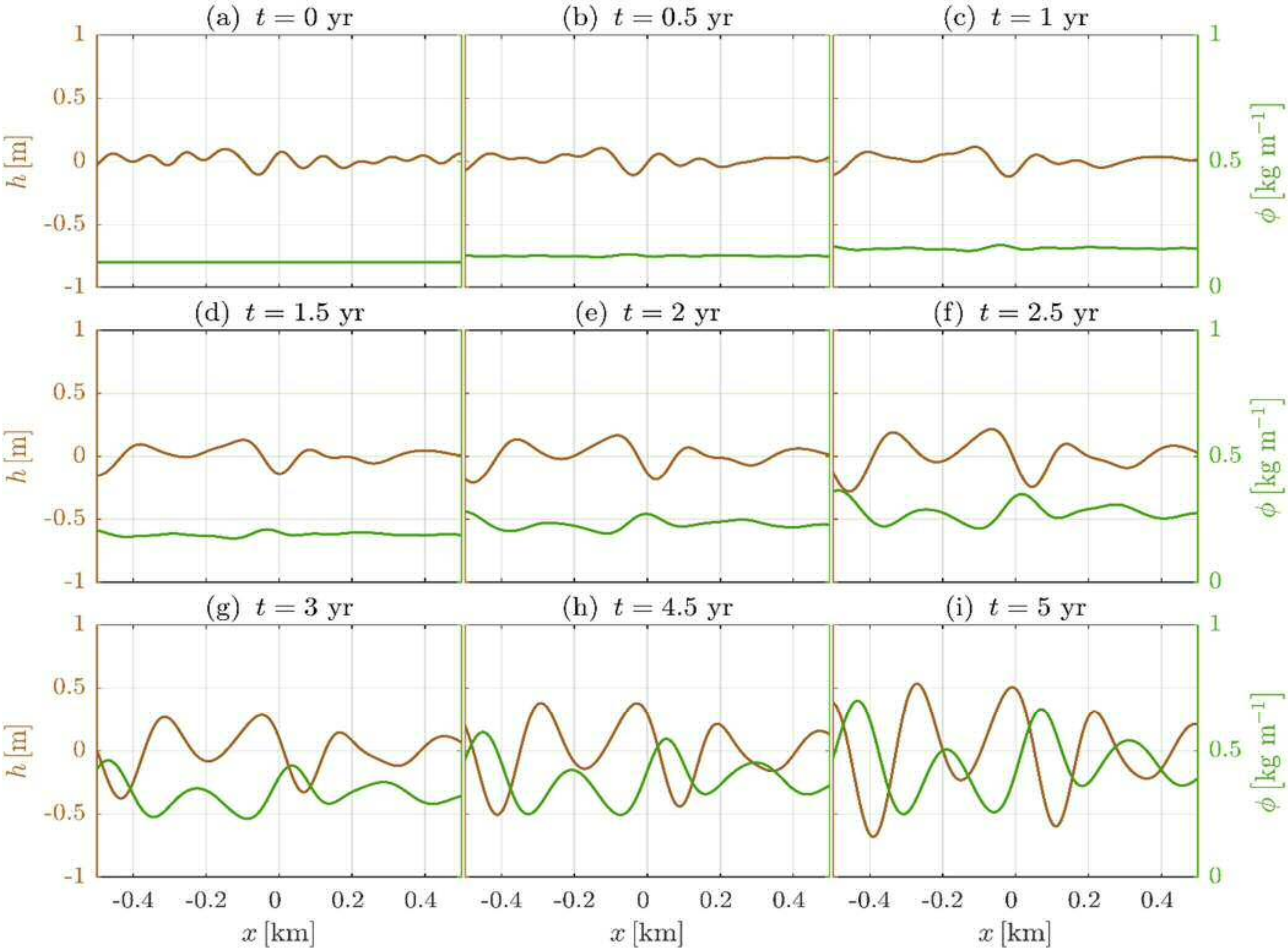

Figure 2. Topography (brown line) and biomass (green line) evolution, where each panel indicates a time step of 0.5 yr. The initial bed (a) is perturbed with an random signal, whereas the initial biomass has a spatially uniform value of $\phi = 0.1$ kg / m.

5. CONCLUSIONS

In this paper we summarise observed spatial patterns of both benthic organisms and other abiotic parameters over marine bed forms, in particular over sand waves. These field surveys show a clear distinction in habitat characteristics between troughs and crests of sandwaves, while even variations on an even smaller spatial scale (slopes) have been observed.

With the biogeomorphological model presented here we are able to simulate these observed patterns. Based on the results from the model we expect overall higher biomass in the troughs of the sand waves. In addition, the lee side of the sand waves is likely to harbour a higher biomass compared to the stoss side.

Although we can successfully model the two-way interactions between sand waves and benthic organisms, more detailed information is needed on the exact species distribution over sand waves. Current knowledge is still scare, and mainly focusses on top/trough differences. Moreover, the implemented biological parameterisations are still strongly idealised. Nevertheless, this methodology allows us to predict the spatial distribution of benthic organisms over sand waves, valuable information from both an engineering and ecological perspective.

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