Modelling the impact of a time-varying wave angle on the nonlinear evolution of sand bars

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ABSTRACT: Sandy beaches are often characterized by the presence of sand bars, whose characteristics (growth, migration, etc.) strongly depend on the wave conditions (wave height, angle of wave incidence, etc.). This study addresses the impact of a periodically time-varying wave angle of incidence with different time-means on the long-term evolution (order days to months) of sand bars. Model results show that heights of sand bars that form in the case of a time-varying angle around a zero-mean are on average larger than those in the cases of time-varying angles around an oblique mean, particularly for large variations in the angle of wave incidence.

1 INTRODUCTION

The surf zone of many sandy uninterrupted beaches often features the presence of several sand bars that are aligned perpendicularly or obliquely to the coast (Fig. 1). These bars display a rhythmic pattern along the shore, with alongshore spacings (distance between successive bar crests) in the order of tens to hundreds of meters. Their migration rates, which depend on the strength of the alongshore current, might reach tens of meters per day along the shore, and their lifetimes range between days to months (e.g., Wright & Short 1985). The presence of sand bars has a direct impact on the shoreline by, among other things, creating areas of erosion and deposition (Komar, 1998). Therefore, increasing our knowledge of the dynamics of these bedforms is important to enhance our insight into coastal processes and, thereby, our capacity to accurately simulate the evolution of coastal systems.

Fair weather conditions favour the growth of sand bars, of which the characteristics (e.g. growth and migration rates) strongly depend on the wave conditions (e.g., Wright & Short, 1985). During severe storms, or during moderate-energy waves with highly oblique wave angle of incidence (with respect to the shore-normal), the bars are wiped away or they are reshaped into linear features without longshore variability (Lippman & Holman 1990,Van Enckevort et al., 2004; Price & Ruessink, 2011).

Various models have been developed to study the initial formation and long-term evolution of sand bars (see review by Ribas et al., 2015). These models simulate waves, currents, sand transport and bed evolution in the surf zone, with incoming waves being the main driver. In most of these studies, wave conditions (wave height, angle of wave incidence, etc.) have been assumed to be time-invariant (constant in time), whereas in reality, these conditions change continuously with time. Exceptions are the studies by Smit et al. (2005) and Castelle & Ruessink (2011), which addressed the impact of time-varying wave conditions on the dynamics of sand bars. The latter study (Castelle & Ruessink, 2011, hereafter referred to as CR2011) presents a systematic analysis of the impact of a time-varying wave forcing on the evolution of finite-amplitude sand bars. It was demonstrated that especially periodic variations in the wave angle of incidence were crucial in the development of bars in terms of their finite amplitude behaviour, migration and their alongshore spacing. A drawback in the study by CR2011 was that the angle of wave incidence was limited to variations around a zero mean (normal incidence). Obviously, in real physical situations, the mean angle is not necessarily 0 degrees. In fact, the nonlinear modelling study by Garnier et al. (2008) demonstrated that beyond a critical wave angle of incidence ($\theta = 7^0$), sand bars do not grow, revealing the importance of this angle for sand bar dynamics.

This study will build on the work of CR2011, with the main extension that also oblique mean angles of wave incidence are considered. Specifically, the following question is addressed: What is the impact of a periodically time-varying wave angle of incidence with a non-zero mean on the growth of sand bars? To this end, simulations will be performed with an available numerical model (morfo55), developed by Caballeria et al. (2002) and Garnier et al. (2006), who simulated the evolution of finite-amplitude sand bars in the nearshore zone in the case of time-invariant wave forcing. Morfo55 uses depth-averaged shallow water equations, including sediment transport and bed updating. Moreover, it includes fully detailed wave-topography feedbacks, wave shoaling and refraction, wave breaking and wave radiation stresses. Further details are given in Garnier et al. (2006). This model will be extended such that it includes a time-varying wave angle of incidence.

Section 2 describes the methodology applied in this study, followed by a presentation and discussion of model results (section 3). In Section 4, the conclusions are given.

2 METHODOLOGY

Following Garnier et al. (2006), the study area is schematized as a rectangular domain with dimensions $L_x \times L_y$ (= 250 m × 2000 m), which is bounded by a straight coast at $x = 0$ (Fig. 2). Periodic boundary conditions are applied at the lateral boundaries ($y = 0$ and $y = L_y$) for each variable in the model (e.g. water level, velocity, bed level, etc), as well as for their y-derivative (e.g., $z_b(x,0,t) = (x, L_y, t)$ and $\partial z_b / \partial y\,(x,0,t) = \partial z_b / \partial y\,(x, L_y, t)$). At the shore boundary ($x = 0$), a vanishing cross-shore flow is assumed. At the offshore boundary ($x = L_x$), a constant significant wave height (H_{rms}), wave period (T_p) and a time-varying angle of wave incidence θ are imposed. The latter varies with time according to:

$$\theta(t) = \theta_0 + \hat{\theta}\sin\left(\frac{2\pi}{T}t\right) \quad (1)$$

with θ_0 the time-mean angle, $\hat{\theta}$ is the amplitude of the variation in the angle and T is the period of this variation. Different values for the mean angle θ_0, amplitude $\hat{\theta}$ and period T are considered, in the ranges $0 \le \theta_0 \le 4^o$, $0 < \hat{\theta} \le 8^o$ and $7 < T \le 224$ days. For the sake of comparison, additional simulations are conducted without time variation in θ, i.e., $\theta = \theta_0$.

Non-cohesive sediment is assumed with a single size d_{50} = 250 µm. The equations are solved on a computational grid with spacing $\Delta x \times \Delta y = 10$ m × 5 m. The hydrodynamic time step $\Delta t = 0.05$ s, while the morphodynamic time step is increased by a morphological amplification factor (Moac) of 90. Test simulations with lower Moacs do not yield different results.

Model simulations start from the Yu & Slinn (2003) single barred beach bottom profile with superimposed random bottom perturbations h (with amplitude 2 cm). This profile, which is uniform in the longshore direction (y), is given by the following equation:

$$z_b^0(x) = -a_0 - a_1\left(1 - \frac{\beta_2}{\beta_1}\right)\tanh\left(\frac{\beta_1 x}{a_1}\right) - \beta_2 x + a_2 \exp\left[-5\left(\frac{(x - x_c)}{x_c}\right)^2\right], \quad (2)$$

with x_c the bar location (= 80 m), a_2 is the bar amplitude (= 1.5 m), a_0 is the water depth at the coast (= 0.25 m). Other coefficients are

$a_1 = 2.97$ m, $\beta_1 = 0.075$ and $\beta_2 = 0.064$.

The simulation time is approximately 300 days. An overview of the important model parameters is presented in Table 1. Futher details are given in Garnier et al. (2006).

Finally, analysis of model results focuses on growth of sand bars, which is expressed by their root-mean-square height as follows:

$$|h| = \left[\frac{1}{L_x L_y}\iint h^2 dx\, dy\right]^{1/2}. \quad (3)$$

3 RESULTS AND DISCUSSION

Figure 3 shows the root-mean-square height |h| of the sand bars versus time in the cases of imposing a time-varying angle of wave incidence θ with different periods T and different time-mean angles θ_0 (panels a-b). Amplitude of the variation in the angle $\hat{\theta} = 2^0$. After a period of about 20 days of a rapid bar growth, saturation of this growth appears in the subsequent period. Note the oscillating behaviour in the height of the bars, reflecting the time variation in the angle of wave incidence θ. This figure reveals that in the case of a time-varying angle around a zero-mean ($\theta_0 = 0$), the saturation height of the bars is on average larger than that in the case of a constant θ (see also Fig. 3c, black line), particularly for small periods T. In contrast, in the cases of $\theta_0 = 2^0$ and $\theta_0 = 4^0$ (panels b and c), the saturation height of the bars is generally smaller than their corresponding heights in case of constant angles θ. Figure 3b further shows that in the case of a time-varying angle θ with an oblique mean angle, bar growth is weaker compared with that of the case with constant θ, particularly for large periods T. This difference in bar growth does not occur in the case of variations around a zero mean (Fig. 3a).

Regarding the impact of using different amplitudes $\hat{\theta}$ of angle variation, model results (Fig. 4) demonstrate that with respect to the case of a constant angle θ, the saturation height of sand bars of the cases with oblique mean angles becomes smaller with increasing amplitude $\hat{\theta}$. The larger this mean angle, the stronger is the decrease in height (panels b, c). In contrast, the height of the bar of the case with zero-mean angle initially becomes larger with increasing variation $\hat{\theta}$, after which it decreases for large variations $\hat{\theta}$.

These outcomes contradict the results obtained by CR2011, who found that saturation height of sand bars of the case of a time-varying angle of wave incidence θ (with zero-mean) is always smaller than that in the case of constant θ. Their model results show that the larger the amplitude of angle variation $\hat{\theta}$, the smaller the saturation height. This contrast between the outcomes of the present study and those of the study by CR2011 might be due to differences that exist between model configurations of two studies. These differences are mainly that 1) the initial bathymetry used in morfo55 is deeper than that in CR2011; 2) morfo55 uses a rigid coastline, while CR2011 uses a dynamic coastline (changes in time); 3) morfo55 applies the sediment transport formulation of Soulsby (1997), while CR2011 uses the formulation of Bailard (1981); and finally 4) the wave model implemented in morfo55 is based on linear wave theory (narrow spectrum with one frequency and one direction), while CR2011 uses the spectral wave SWAN, which accounts for a broad spectrum with multiple frequencies and directions. Which differences are causing the contradiction between outcomes from the present study and those of CR2011 remain to be quantified, and are subject of further research.

4 CONCLUSIONS

1. To conclude, the saturation height of sand bars of the case of a time-varying angle around a zero-mean is on average larger than that in the case of a constant θ. In contrast, the saturation height of bars of the cas-

es of time-varying angles around an oblique time-mean are generally smaller than their corresponding heights in the case of a constant angle, particularly for large variations in the angle of wave incidence.

Table 1: Overview model parameters

Parameter	Value
Domain dimensions $L_x \times L_y$	250 m × 2000 m
Significant wave height H_{rms}	1 m
Wave period T_p	6 s
Sediment size d_{50}	250 µm
Grid spacing $\Delta x \times \Delta y$	10 m × 5 m
Time step Δt	0.05 s
Amplification factor Moac	90

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Figure 1. Transverse sand bars at Horn Island, Mississippi, USA. (Source: http://www.coastalwiki.org).

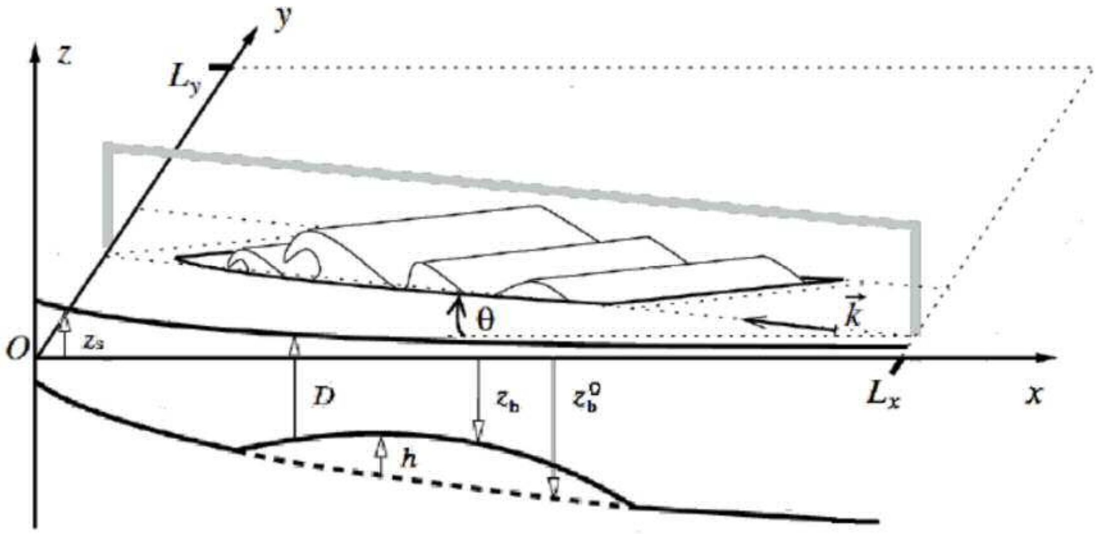

Figure 2. Schematic view of the study area, which is represented as a rectangular domain with dimensions $L_x \times L_y$. The coordinate system, with origin O, is defined such that x indicates a cross-shore, y an alongshore, and z a vertical position. Depth D is the difference between sea level z_s and bed level z_b. Furthermore, bottom perturbation h defined with respect to initial bed level z_b^0, i.e., $h = z_b - z_b^0$. Waves propagate in the direction of wave vector $\vec{k}$, with an angle θ with respect to x-axis. Figure modified after Garnier et al. (2006).

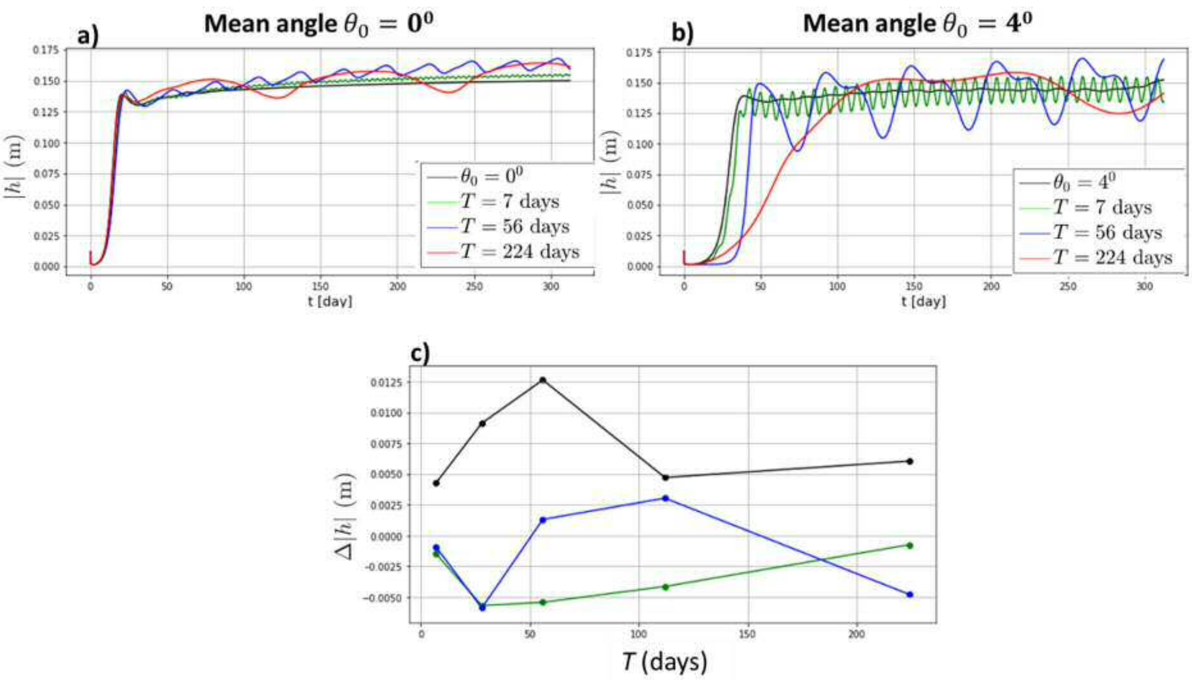

Figure 3. a) Root-mean-square height of the sand bars $|h|$ versus time in the case of a time-varying angle of wave incidence θ with zero-mean ($\theta_0 = 0^0$), and which varies with different periods T. Amplitude of the variation in the angle $\hat{\theta} = 2^0$. The case of a time-invariant angle θ is also shown (black line). b) As in a), but in the case of a time-varying angle θ with a mean $\theta_0 = 4^o$. e): Difference between finite heights $|h|$ of the sand bars of cases with and without a time varying angle θ for different mean angles ($\theta_0 = 0^0$, black; $\theta_0 = 2^0$, green; $\theta_0 = 4^0$, blue)

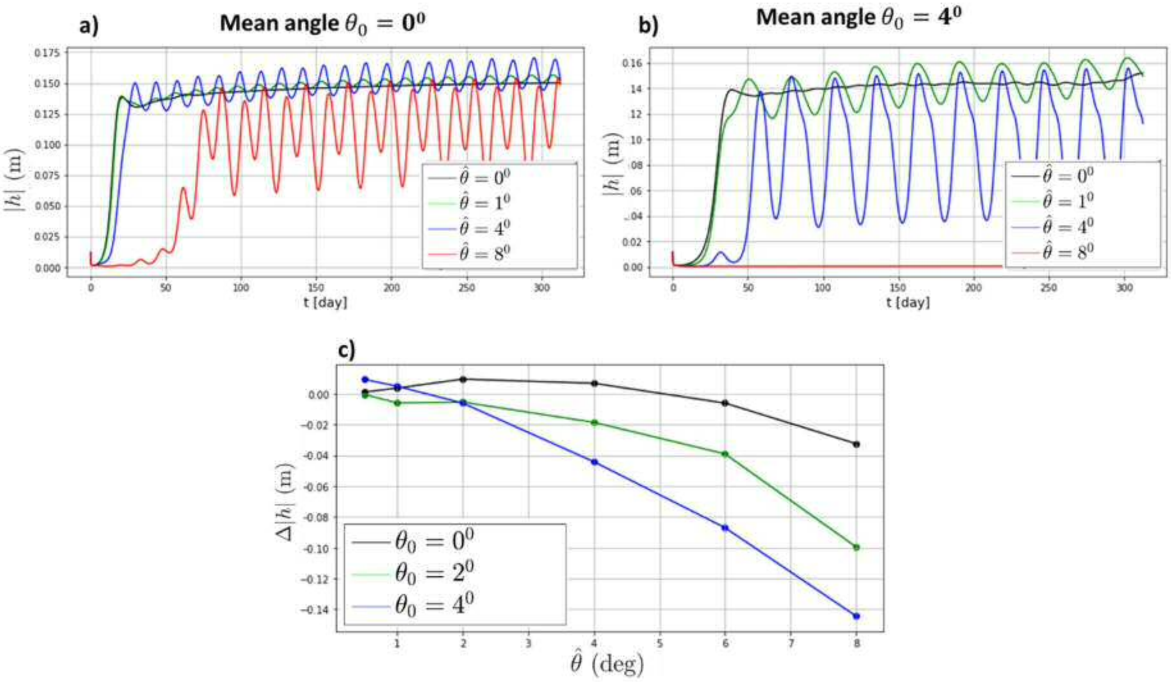

Figure 4. As in Figure 3, but for different amplitudes of angle variation $\hat{\theta}$.