Testing numerical hydrodynamic and morphodynamic models against BARDEX II Experiment data sets

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ABSTRACT

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The hydrodynamics on barred beaches and mechanics of sediment transport related to sandbar migration, berm formation/destruction, barrier crest dynamics and washover deposition are extremely complex. At this time, process-based models encompassing all these processes are non-existent. Among other shortcomings, the lack of existing intensive high-frequency full-scale data limits the range improvement and validation of nearshore process-based models. In June 2012, the large-scale Barrier Dynamics Experiment (*BARDEX II*) was performed in the Delta Flume, providing new datasets for rigorous testing of existing hydrodynamic, groundwater and morphodynamic models and further assisting their development. Three types of models are expected to be applied and further improved: (1) the short-wave averaged surfzone beach profile evolution models 1DBeach and UNIBEST-TC, (2) the short-wave averaged and infragravity-wave resolving XBeach model that addresses morphological changes of the nearshore area, beaches, dunes and backbarrier during storms including cross-barrier groundwater fluxes and (3) the short-wave resolving hydrodynamic models SURF-GN and SWASH. In this contribution, we present the application of three of the five models. 1DBeach is applied to a morphological sequence characterised by onshore and subsequent rapid offshore sandbar migration for time-invariant wave forcing and falling tide. XBeach model is applied to a rising tide sequence characterized by a rapid shoreline retreated and overtopping and overwash processes. SURF-GN is applied to a high tide run with occasional overtoppings. All these model applications are described and model skills are qualitatively assessed. Guidelines for future model improvements and validation on *BARDEX II* dataset are further discussed.

ADDITIONAL INDEX WORDS: *Numerical model, proto-type experiment, sandbar migration, breaking waves, swash, berm, overwash.*

INTRODUCTION

The hydrodynamics on barred beaches and mechanics of sediment transport related to sandbar migration, berm formation/destruction, barrier crest dynamics and washover deposition are extremely complex. At this time, process-based models encompassing all these processes are non-existent. This is because (1) from a theoretical point of view, numerical models still face a number of shortcomings depending on the range of spatial and temporal scale they address and (2) there is a lack of intensive high-frequency full-scale data to improve and validate the models. In June-July 2012, the large-scale Barrier Dynamics Experiment (*BARDEX II*, Masselink *et al*., 2013) was performed in the Delta Flume providing new datasets for rigorous testing of existing hydrodynamic, groundwater and morphodynamic models and further assisting their development

Process-based phase-averaged models that simulate the underlying physical processes and the flow – sediment transport – bottom evolution feedback, have recently succeeded in simulating surfzone sandbar evolution on timescales of weeks (Ruessink *et al*., 2007) to years (Walstra *et al*., 2011; Kuriyama, 2012) on gently sloping sandy beaches with reasonable skill. Yet, the ability of such numerical models to simulate the migration of surfzone sandbars on steep (say, 1:15) beaches, with its predominant plunging wave conditions, has not been tested. In addition, the bottom evolution in the swash zone, and hence the beach face, is usually handled the same way as in the surf zone, or more commonly ignored resulting in large errors in the intertidal and subaerial domains. *BARDEX II* experiment provides extensive beach profile dataset to challenge and further improve these models.

The open source XBeach model (Roelvink *et al*., 2009) has been used by a rapidly increasing user group worldwide to address the natural coastal response during time-varying storm and hurricane conditions, including dune erosion, overwash and barrier breaching. In contrast to the beach profile evolution models described above, it includes a non-stationary wave driver to account for wave-group generated surf and swash infragravity motions that are a critical component to beach erosion during storms. The model has been recently successfully applied to a number of natural sandy beaches (see Roelvink *et al*., 2009) and a gravel barrier beach in the laboratory in the framework of the *BARDEX I* project (Williams *et al*., 2012). A number of limitations, including storm berm formation and surfzone sandbar

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behaviour, have been pointed out. In addition, the role of the beach groundwater table on sandy beach stability is still poorly understood (McCall *et al*., 2012).

Phase-resolving numerical models based on depth-averaged equations are commonly used to simulate nonlinear wave transformations in shallow water including wave breaking, wave run-up and overtopping. If Nonlinear Shallow Water equations reproduce quite well overtopping processes, the hydrostatic assumption does not allow simulating incoming wave propagation in the shoaling zone. To overcome this limitation two different approaches can be considered: models based on fully nonlinear Boussinesq equations, also named Serre – Green Naghdi equations (Bonneton *et al*., 2011), or based on the nonlinear shallow water equations including non-hydrostatic pressure (Zijlema *et al*., 2011). *BARDEX II* provides extensive data on overtopping across a steep sandy barrier to challenge these phase-resolving wave modelling approaches.

These three distinct types of models, detailed in the next section, will be applied and further improved in the framework of *BARDEX II*. Preliminary results are presented for (1) a sequence of cross-shore sandbar migration with the process-based, phase-averaged, beach profile model 1DBeach; (2) an overwash sequence using XBeach model; (3) an overtopping sequence using the wave by wave model SURF_GN without morphological change. Guidelines for future model improvements and validation on *BARDEX II* dataset are further discussed.

NUMERICAL MODEL

Short-wave averaged surfzone beach profile evolution models

1DBeach

1DBeach (Castelle *et al*., 2010; Dubarbier *et al*., 2013) is a simple coupled, phase-averaged, waves-current-beach profile evolution model coupled to a data-assimilation module (Birrien *et al*., 2011). In this effort, the latter is not used. The bar evolution is driven by the respective contributions of wave nonlinearities that transports the sediment onshore versus the undertow current that distributes the sediment offshore. In the new version of 1DBeach (Dubarbier *et al*., 2013), we use the recent parametrization proposed by Ruessink *et al.* (2012) to estimate the free-stream non-linear wave motion that in turn drives the energetics-type sediment transport formulation (Hsu *et al*., 2006). The model is capable of reproducing both onshore and offshore sandbar migration on timescales of weeks to months (Dubarbier *et al*., 2012) but does not address beach face evolution.

UNIBEST-TC

Similar to 1DBeach, UNIBEST-TC (Ruessink *et al*., 2007) is a coupled, phase-averaged, waves-current-beach profile evolution model. Significant differences with 1DBeach involve, for instance, the suspended transport computed through the integration over the water column of a 1D vertical advection diffusion equation; adaptative morphological time steps; computation of bound-infragravity waves; disregard of wave asymmetry. This model has been recently validated on a number of natural sandy beaches for sandbar migration on the timescales of months to years (Ruessink *et al*., 2007; Walstra *et al*., 2012)

XBeach model

XBeach (Roelvink *et al*., 2009) is a model for wave propagation, long waves and mean flow, sediment transport and morphological changes of the nearshore area, beaches, dunes and backbarrier during storms but does not successfully reproduce cross-shore sandbar migrations. *BARDEX II* will provide more insight on cross-shore sediment transport processes, run-up and overwash to improve the models. In turn, XBeach will provide diagnostics on the mechanisms related to barrier evolution/destruction events. It is the intention to better parameterize the short-wave motion, swash hydrodynamics and storm berm formation.

Phase-resolving wave models

SURF-GN

SURF_GN (Bonneton *et al*., 2011; Tissier *et al*., 2012) is a Boussinesq-like, fully nonlinear and weakly dispersive Green-Naghdi phase-resolving model for shallow water waves. It uses an innovative time-splitting approach with hybrid schemes that allows the description of wave propagation from outside of the breaking region to the swash zone (Tissier *et al*., 2012). This model is particularly suitable to address overtopping and overwash issues that are a critical component to barrier evolution during BARDEX II. It is the intention to further develop this model by including sediment transport.

SWASH

SWASH (Zijlema *et al*., 2011) is an open source NSW model including non-hydrostatic pressure that can simulate wave transformation in both surf and swash zones due to nonlinear wave-wave interactions, wave-current interactions, wave breaking as well as wave run-up at the shoreline. Given that SWASH is a relatively new model and that it is presumably limited when applied to complex shoreline evolution over rapidly varying topographic features, *BARDEX II* will provide a challenging benchmark to for the first time in-depth test the model against overtopping situations.

LABORATORY DATA

BARDEX II (Masselink *et al*., 2013), funded under the Hydralab IV programme, was completed in June-July in the Delta Flume to investigate overwash processes, surfzone sandbar evolution, cross-barrier groundwater fluxes and the role of the beach groundwater table on sandy beach stability. A 4.5-m high sandy barrier was constructed, with the crest of the barrier located at x = 110 m from the wave paddle (Figure 1). Medium-sized sand with a median diameter D_{50} of 0.42 mm was used balancing the desire to provide sufficient hydraulic conductivity and to promote sediment re-

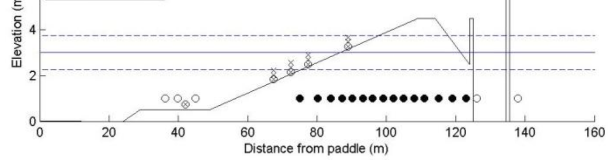

Figure 1. Delta Flume cross-section with barrier profile at the start of the experiment and location of Deltares instrumentation. PT = pressure transducer; EMCM = electromagnetic current meter. Horizontal lines show water levels used.

suspension and nearshore sandbar formation. The near prototype-scale gravel barrier (height 4.5 m; width 30 m) located in the middle of the flume was exposed to a range of wave, tide and water level conditions that are detailed in Masselink *et al*. (2013). In addition, the presence of a lagoon behind the barrier provided a convenient means to experimentally manipulate the groundwater hydrology within the barrier. Below we describe the chosen sequences that will be further used to test the numerical models.

Surfzone sandbar evolution sequence

We use test series C2 to test the beach profile evolution model 1DBeach as both onshore and offshore sandbar migrations were observed. During this falling tide sequence, with a high lagoon level (4.2 m), the sea level was varied over a 1.3-m range, from 3.55 m to 2.25 m, over 4 hours with the beach subjected to accretionary wave conditions with a significant wave height *Hs* = 0 .8 m and a peak wave period *Tp* = 8 s. The sequence was divided into 30-min segments, each with a constant water depth. The maximum difference in water level between two consecutive 30-min segments was 0.2 m during this sequence.

During this sequence (Figure 2), the sandbar initially located at *x* ≈ 70 m slowly migrates onshore as spilling waves occasionally break across the sandbar, with a clear dominance of non-breaking waves, as a result of the high sea level. The sandbar further migrates offshore when sea level dropped resulting in more intense depth-induced wave breaking across the sandbar. This sequence is described in more detail in Dubarbier *et al*. (2013).

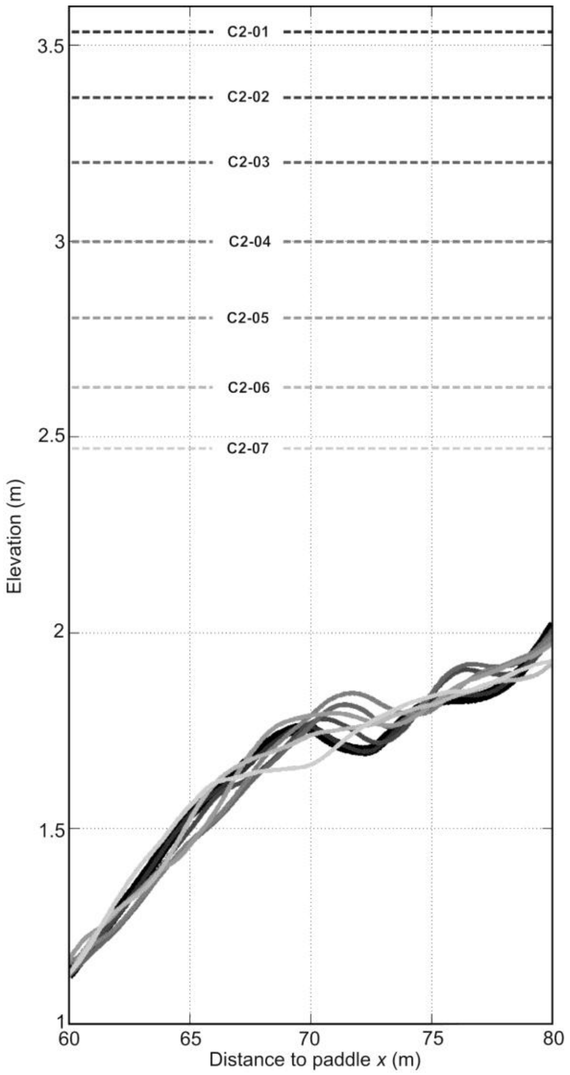

Figure 2. Test series C2 with time-varying sea level (dashed lines) and zoom of the measured beach profiles (ripples are filtered) at 60 m < *x* < 80 m. Time evolution is shown from black to light grey. From C2-01 to C2-04 the sandbar initially located at *x* ≈ 70 m slowly migrates onshore and further rapidly migrates offshore from C2-05 to C2-07 as the sea level drops.

Overwash sequence

We use a part of test series D1 to test the ability of XBeach to simulate a sequence of swash – overtopping – overwash. During this rising tide sequence, with a low lagoon level (1.75 m), the sea level was varied over a 1.05-m range, from 3.15 m to 4.2 m, over 160 minutes with the beach exposed to waves with *Hs* = 0 .8 m and *Tp* = 4 s to achieve a sequence of swash – overtopping – overwash. The sequence was divided into 20-min segments, each with a constant water depth. The difference in water level between two consecutive 20-min segments was systematically about 0.15 m.

During this sequence (Figure 3), the shoreline retreated by markedly with a significant amount of sand transferred from the beachface to the back of the barrier by overtopping and overwash processes. A large amount of sand was also transferred from the beachface to the inner surf zone throughout this test series. During this sequence, the barrier crest progressively steepened (Figures 4a-b) with the subsequent formation of an erosion scarp (Figure 4b) that was progressively flattened (Figures 4c-d) through overtopping and overwash processes. This sequence provides a challenging benchmark for XBeach model.

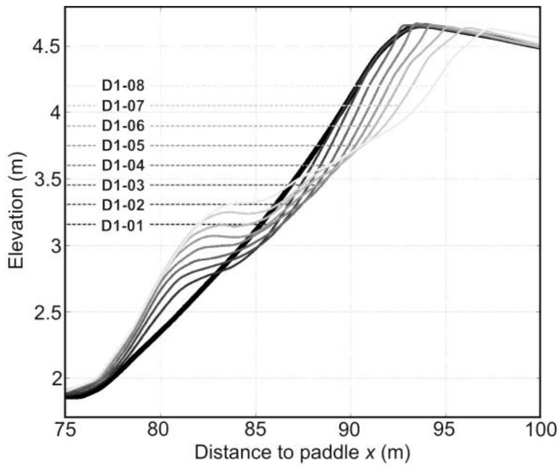

Figure 3. Test series D1 with time-varying sea level (dashed lines) and zoom of the measured beach profiles (ripples are filtered) at 75 < *x* < 100. Time evolution is shown from black to light grey. From D1-01 to D1-07 the barrier progressively erodes at a slightly increasing rate as the sea level rises. Throughout this sequence, a large amount of sand is transferred from the beachface to the inner surf zone (at about 77 m < *x* < 87 m). From D1-05, a significant amount is then transferred from the beachface to the back of the barrier by overtopping and overwash processes.

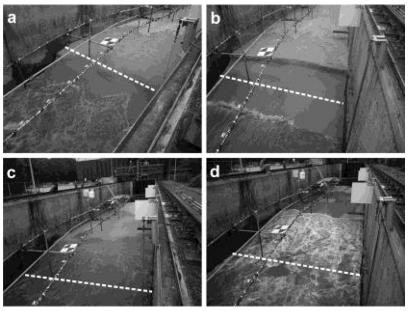

Figure 4. Photo sequence showing drastic beachface shape changes during test series D1 with rising sea level. (a) Gently sloping beach face turning into (b) an erosion scarp of about 20 cm high that is subsequently (c) flattened through increasing overtopping and (d) lowering of the crest through overwash processes. Note that in panel (d) the barrier becomes saturated. In all panels, the dashed white line indicates the initial barrier crest position.

Overtopping sequence

In this contribution, we chose the overtopping sequence D1-07 (Figure 3), *i.e*. for waves with *Hs* = 0.8 m and *Tp* = 4 s and a sea water level of 4.05 m. To address overtopping we used the Argus video system mounted above the barrier crest. Figure 5 shows an example of overtopping events from a timestack across the barrier. Results show that, throughout D1-07, occasional overtoppings occur. Overtoppings were obvious from the video images because of the steep beachface making a clear distinction between the inner surf zone and the barrier (black dotted line in Figure 5). Note that the sharp line in the runup time series in Figure 5 is due to beach shadowing by the scarp, meaning that most of the swash events actually did not make it to the scarp even if it is what it looks like from the timestack. For the same reason, the scarp located at $x \approx 92.5$ m as seen in the rectified video images (Figure 5) was in reality located at $x \approx 95.5$ m (see D1-07 profile in Figure 3).

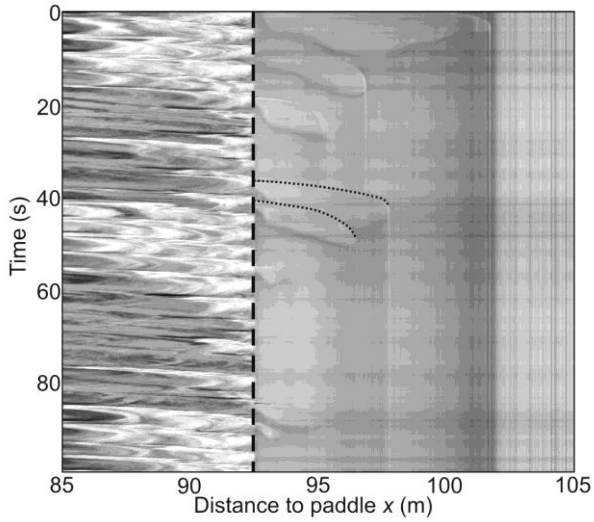

Figure 5. 100-s timestack during D1-07 showing occasional overtopping (two examples are highlighted with the thin dotted black lines at $t \approx 40$ s). The vertical black dashed line indicates the barrier crest location, as seen by the camera (the actual position is $x \approx 95.5$ m), that shadows the beach.

RESULTS

1DBeach

1DBeach was applied to the onshore/offshore sandbar migration sequence described in Figure 2. Details on the model set-up, calibration and validation are given in Dubarbier *et al*. (2013). The best fit model free parameters were found through a simulating annealing algorithm. Using these optimum parameters, the model is capable of reproducing the combined on/offshore events observed during test series C2 (zoom on the evolution in Figure 6). Errors in sandbar elevation and position at the end of the slow onshore migration sequence are about 0.02 m and 1 m, respectively, with a very good agreement of the sandbar shape. For the subsequent rapid offshore migration, 1DBeach fairly predicts the cross-shore location of the bar crest with an overestimation of the offshore sandbar migration of about 0.5 m. In addition, it underestimates the water depth of the bar crest of about 0.04 m. Yet, this sequence is a challenging one as it was characterized by an offshore migration of the bar of about 8 m in only 120 min, *i.e.* a migration rate of about 100 m/day which is much larger than any cross-shore migration rate measured in the field.

While acceleration skewness in 1DBeach was not systematically important to accurately simulate cross-shore sandbar behaviour on timescales of weeks to months on natural sandy beaches with prevailing spilling breaker, here acceleration skewness was crucial to accurately reproduce the onshore sandbar migration for weakly to nonbreaking wave conditions across the sandbar.

XBeach

XBeach was applied to the barrier erosion sequence shown in Figure 3. In this contribution we used the Easter 2012 version of XBeach. Using this version with default settings resulted in a

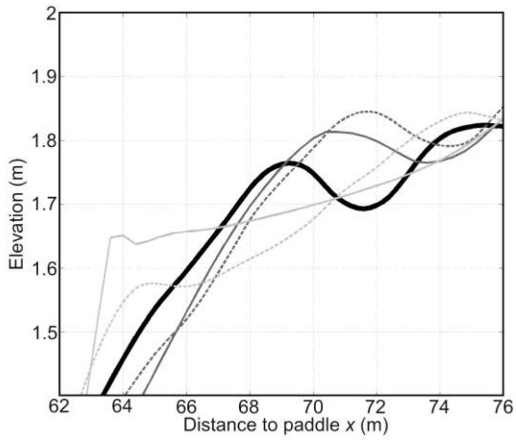

Figure 6. Simulation of beach profile evolution with 1DBeach during test series C2. Zoom at 62 m < x < 76 m. Initial beach profile (thick black line, ripples are filtered), measured (thin dotted line) and simulated (thin solid line) beach profile at the end of the slow onshore migration (dark gray) and at the end of the rapid offshore migration (light gray).

substantial overestimation of the barrier erosion. In this contribution the aim was not to present an in-depth calibration and sensitivity analysis of the model. Instead, here we simply increased the critical avalanching slope under water from 0.3 to 0.4 to reduce the rate at which the beach erodes. Figure 7 shows the model results for test series D1 using the latter parameter setting. Results show that XBeach can simulate the barrier erosion from both avalanching and infragravity motions with reasonable accuracy. In particular, the simulated barrier crest retreat fits very well with the measured retreat. A number of shortcomings can be depicted: (1) the shape the sand deposition (at about 77 m < x < 87 m) resulting from the transfer of sand from the beachface to the inner surf zone is not well reproduced, but the volumes are roughly similar; (2) simulations do not show any significant washover deposition as seen in the measurements (x > 95 m in Figure 3). The underestimation of overwash deposition with XBeach was already pointed out in Roevink *et al*. (2009).

The main morphological response characteristics, *i.e*. a decrease of the, beach face slope, outer shoreline retreat and narrowing of the barrier, are well reproduced. Overall, XBeach model behaves very well particularly because of the challenging sequence involving scarp, truncated swashes and wave reflection.

SURF_GN

Figure 8 shows an example of overtopping simulation with SURF_GN at the beginning of test series D1-07 assuming that the initial beach profile did not change significantly. The model behaves very well in simulating overtopping. Note that in the model we considered a rigid seabed, that is, there was no infiltration. Accordingly, all the overtopping pellicles of water reached the shallow trough in the back of the barrier and further accumulated (at $x \approx 104$ m, see the white area in Figure 8). Results show a large number of overtopping events with about 30 overtopping in 300-s time, meaning that about 40% of the waves overtopped. This is slightly larger than what was computed from the video (about 20%). A comparison of predicted wave height in the shoaling zone suggests that the model actually slightly overestimate wave amplitude, which can explain why the model simulated a large number of overtopping events. Note that no calibration was performed here, meaning that we assumed a very weak (default) bottom friction which is presumably a major

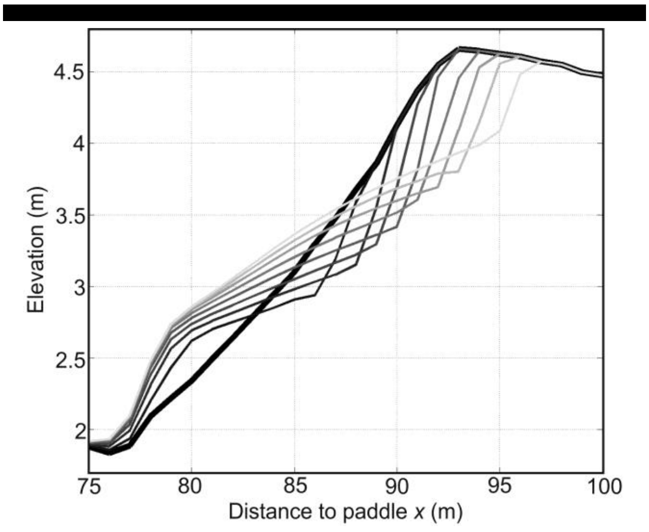

Figure 7. Xbeach model results for test series D1 (measured beach profiles for the same sequence as shown in Figure 3).

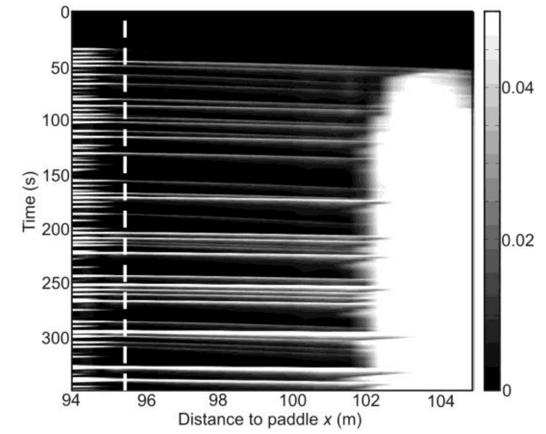

Figure 8. Simulation of overtopping with SURF-GN at the start of test series D1-07. The vertical dotted white line and the colorbar indicates the barrier crest location the height of the water pellicle, respectively.

shortcoming as ripples and megaripples were ubiquitous along the beach profile. This will be explored further.

DISCUSSION AND CONCLUSIONS

Preliminary model results based on a limited range of analysed laboratory data during *BARDEX II* shows that, overall, numerical models can succeed in hindcasting complex beach changes with limited calibration work with fair success. The exception is for models addressing cross-shore sandbar behaviour that systematically needs in-depth calibration before being applied to another field site or laboratory dataset (*e.g*., Ruessink *et al*., 2007).

Despite the prevailing plunging wave conditions during the experiment, 1DBeach fairly simulates the cross-shore sandbar evolution. The limited ability of the model to simulate the shape of the sandbar during the rapid offshore migration can have a number of explanations. For instance, ripples and megaripples that were ubiquitous along the surfzone beach profile were willingly filtered for the simulations. There are also, presumably, a number of misspecifications of the physics in the model. For instance, the sediment transport formulations used herein were mostly developed for spilling breakers. The model does not consider breaking-induced turbulence as a surface boundary condition which, particularly for plunging breakers, results in an underestimation of sand stirring and transport by mean currents (Grasso *et al*., 2012). In addition, the model was not able to reproduce the evolution of the beach face (not shown here), which is a well-known limitation of phase-averaged beach profile process-based models. A detailed analysis of the measured beachface evolutions during *BARDEX II* under changes in wave and tide conditions reveals some recurrent, simple, erosion/accretion patterns motivating the development of simple behaviour-oriented laws of seabed evolution in the swash zone in phase-averaged beach profile models. This, together with the effect of breaking-induced turbulence, will be further explored.

The Eastern 2012 version of XBeach, with limited calibration work, showed a good agreement with the measured barrier evolution. Additional simulations switching on the groundwater module showed very small differences in the morphological evolution, but this will need further investigation. XBeach will be also applied to the final test series E of the experiment, when the sea level was set just beyond the overwash threshold and the barrier was exposed to consecutive 13-min segments of energetic overwash wave conditions, resulting in progressive lowering of the bar crest and sediment transport across the barrier crest into the back-barrier region. It is intended to improve XBeach in predicting washover deposition which was the main model limitations identified in test series D1.

SURF-GN behaved very well in simulating overtopping events. Without calibration work, the number of overtopping events was slightly overestimated. A detailed analysis of the nonlinear wave transformation along the profile suggests that this will be straightforward to fix given that ripples and megaripples will have to be accounted for through an increased bottom friction coefficient. Once calibration done, an in-depth comparison of SURF-GN and SWASH will be performed on a larger number of test series.

The *BARDEX II* experiment took place over a 3-month period from May to July 2012, limiting the range of data and test series analysed and, consequently, the number of model application tests at the time of writing this paper. Note that a more detailed calibration/validation of the hydrodynamics (wave height, undertow, wave nonlinearities) and sand concentration will be necessary before performing an in-depth validation of the morphodynamic models. The results of only 3 of the 5 numerical models used in the "Numerical Modelling" Work Package were shown here. Once in-depth analysed, the data collected in the other Work Packages will be used to further develop and improve all the numerical models as well as extending the range of validation tests. These data are discussed in other papers published in this special issue of JCR (Conley *et al.*, 2013 – swash dynamics; Matias *et al.*, 2013 – barrier overwash; De Winter *et al.*, 2013 – surf zone turbulence; Thompson *et al.*, 2013 – bedform dynamics; Turner *et al.*, 2013 – barrier hydrology).

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