OBSERVATION AND MODELING OF CRESCENTIC BARS IN BARCELONA EMBAYED BEACHES

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Abstract: Two events of crescentic bar formation in La Barceloneta beach are analyzed (Mediterranean coast of Spain). They occurred on October 2003 and on December 2005, during Eastern storms with offshore root-mean-square heights between 1.5 m and 2 m, peak periods of about 9 s and angles of incidence relative to shore-normal between 15^o and 30^o. The final alongshore spacings are about 300 m in the first event and about 100-200 m in the second. A nonlinear morphodynamic model is then applied to La Barceloneta conditions to reproduce these two events. The model is able to simulate the final shape of the crescentic bars, reproducing the observed spacings.

INTRODUCTION

Field observations of crescentic bars

Shore-parallel sand bars can display a number of different shapes, the most simple being rectilinear (linear shore-parallel bars). Under certain wave conditions, these bars can develop alongshore inhomogeneities that consist of shallower and deeper areas alternating along the bar (Wright and Short, 1984). When this occurs, a prominent circulation pattern characterized by the presence of rip currents is also established. These strong and narrow offshore-flowing currents are part of a larger circulation cell, which includes an onshore-flowing component as well as feeder currents taking the water alongshore into the rip. The rip currents flow offshore in the channels that breach the bar and the onshore flow takes place over the shoals.

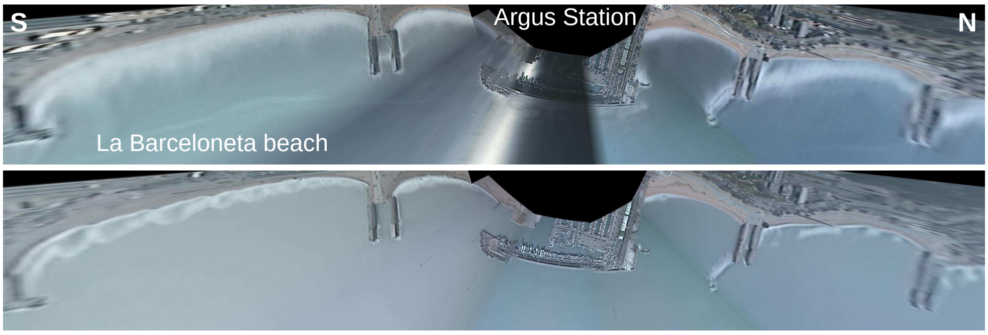

Fig. 1. Planview images of Barcelona city beaches. Upper panel: Linear shore-parallel bar in La Barceloneta on the 10 of December of 2005 at 9h. Lower panel: Well-developed crescentic bar with shoreline attachments (megacusps) on the 13 of December of 2005 at 8h.

This results in a wavy shape of the bar in planview, thus called crescentic bar (see the lower panel of Fig. 1). These alongshore undulations and the corresponding circulation cells frequently occur at regular or quasi-regular intervals. Crescentic bars have been observed on many beaches (up to 33 references are listed in Table 1 of van Enckevort et al., 2004) but systematic field studies are scarce, especially in the case of embayed beaches.

Most of the knowledge of mid-term dynamics of crescentic bars relates to bar state models (Wright and Short, 1984). During the peak of a storm, a shore-parallel bar is developed or enlarged and migrates offshore (longshore bar and trough state). Under the subsequent lower energetic conditions, the bar becomes crescentic and migrates slowly onshore (rhythmic bar and beach state) until the horns occasionally weld to the shore (transverse bar and rip state). The following stormy period destroys the rhythmicity and rebuilds the shore-parallel bar.

Previous modeling of crescentic bars

Although the formation of crescentic bars has been often attributed to the hydrodynamic forcing by infragravity edge waves, it is nowadays well accepted that the most plausible cause is a positive feedback between breaking waves, currents and the evolving morphology (self-organization processes). Small random perturbations are always present in the bottom of any alongshore-uniform beach. The existence of such bottom perturbations will cause changes in both the currents and the wave properties (such as their height and angle of incidence). Their joint interaction will produce small perturbations in the net sediment transport that in turn will modify the bottom of the beach. If there is a positive feedback between a certain developing perturbation (like a crescentic bar) and the associated sediment transport, the former will grow and dominate the beach bathymetry.

The existing modeling studies based on self-organization describe the generating mechanism and predict the order of magnitude of the wavelength and the migration rate (Deigaard et al., 1999; Falqués et al., 2000; Caballeria et al., 2002;

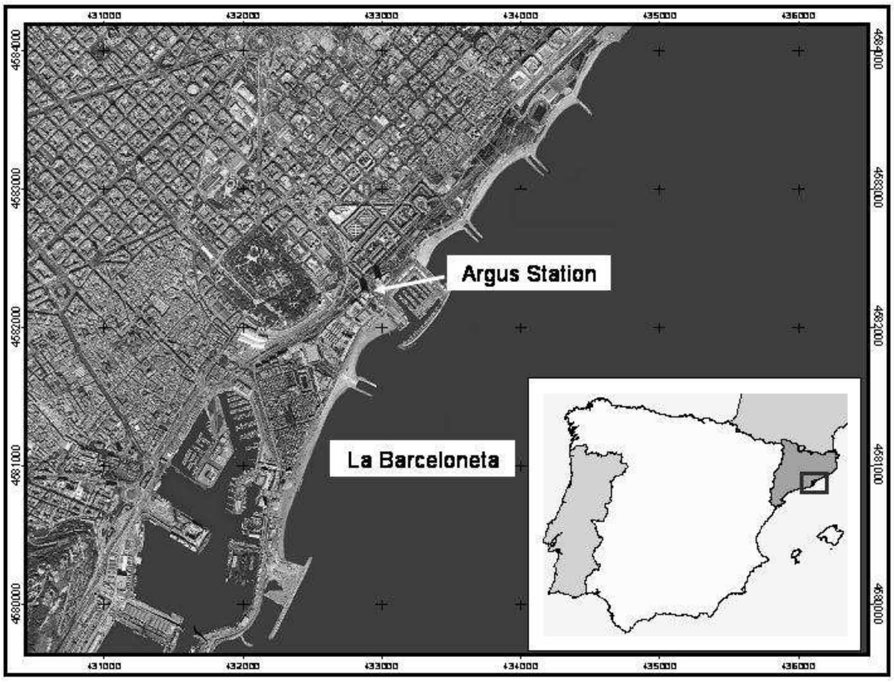

Fig. 2. Study region including the location of the Argus video station.

Damgaard et al., 2002; Reniers et al., 2004; Calvete et al., 2005). However, a serious limitation of our present knowledge on crescentic bars is the lack of quantitative comparisons between field observations and model results. A pioneer study is that of van Enckevort et al. (2004), where observations of crescentic bars in four open beaches were qualitatively compared with existing model results.

Present study

The embayed beaches on the waterfront of Barcelona have been monitored with an Argus video system since November 2001 (Ojeda and Guillén, 2006). In one of these beaches, La Barceloneta, a single shore-parallel bar is usually present, which often exhibits a crescentic shape (see Fig. 1). This system is therefore an ideal lab to test models for crescentic bar formation. The aim of the present research is to investigate the formation and evolution of crescentic bars in La Barceloneta, comparing field observations with the predictions of the nonlinear morphodynamic model proposed by Garnier et al. (2006).

The field site is presented in the next section and two events of crescentic bar formation observed in La Barceloneta are reported in the third section. The model, presented in the fourth section, is then applied to La Barceloneta conditions and the corresponding results are described in the subsequent section. The sixth section contains a discussion of the model results and a comparison with the observations.

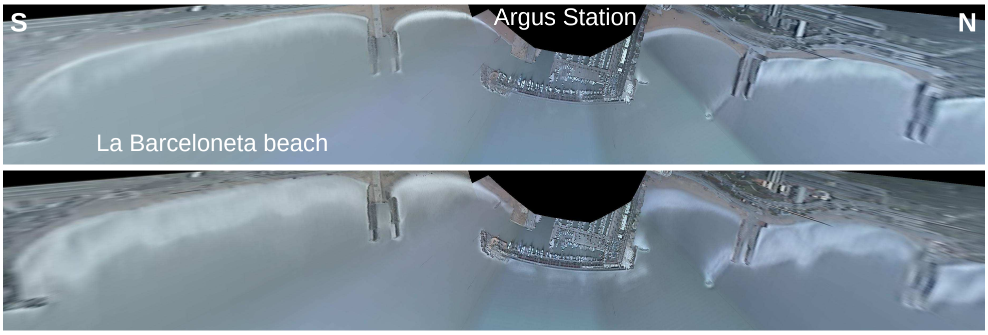

Fig. 3. Planviews of Barcelona city beaches. Upper panel: Linear bar in La Barceloneta on the 15 of October of 2003 at 8h. Lower panel: Crescentic bar on the 18 of October of 2003 at 16h.

FIELD SITE

The field site is located in La Barceloneta beach, at the seafront of Barcelona city (Spain). This artificial beach has an orientation N18^{o}E, a length of 1100 m and it is confined between two groins, the southern one showing an L-shape (see Fig. 2). In the nearshore domain (water depth <5 m), the sediment has a mean grain size of 0.40 mm and the mean slope is 0.033.

Being a microtidal region (water level fluctuations <0.20 m), the winter storms are the major hydrodynamic forcing in Barcelona city beaches. Due to the shoreline orientation, the most important ones are those coming from the East, which are frequently associated to the cyclonic activity in the Western Mediterranean Sea. Their typical duration is of a few days and their main occurrence is from October to April. The significant wave height, H_s, can increase up to 6 m during winter storms but the mean annual H_s is lower than 1 m. Before 2004, only one virtual buoy was providing directional wave information every three hours (WANA2066051 point). These data are computed by the Spanish National Institute of Meteorology using the numerical models HIRLAM and WAM. Since 2004, direct hourly measurements of a directional buoy located at 69 m depth are also available (COST-BARCELONA buoy). Bathymetries of La Barceloneta beach collected on the 6 of October of 2003, the 5 of November of 2003 and the 26 of October of 2005 revealed the existence of two types of profiles: constant sloping beaches during summer (before the arrival of winter storms) and profiles with one bar after the occurrence of significant storms.

An Argus video system (Holman and Stanley, 2006), composed of five full color cameras, was located on November 2001 atop a building close to the Olympic Marina, at 142 m high (see Fig. 2). They span a 180^o view and allow full coverage of the four beaches surrounding the marina (Ojeda and Guillén, 2006). Nearshore bars are seen as white stripes (high intensity values) in the time exposure images (averaged over 10 minutes). These images from the five cameras are rectified and merged to a single planview image (see Fig. 1).

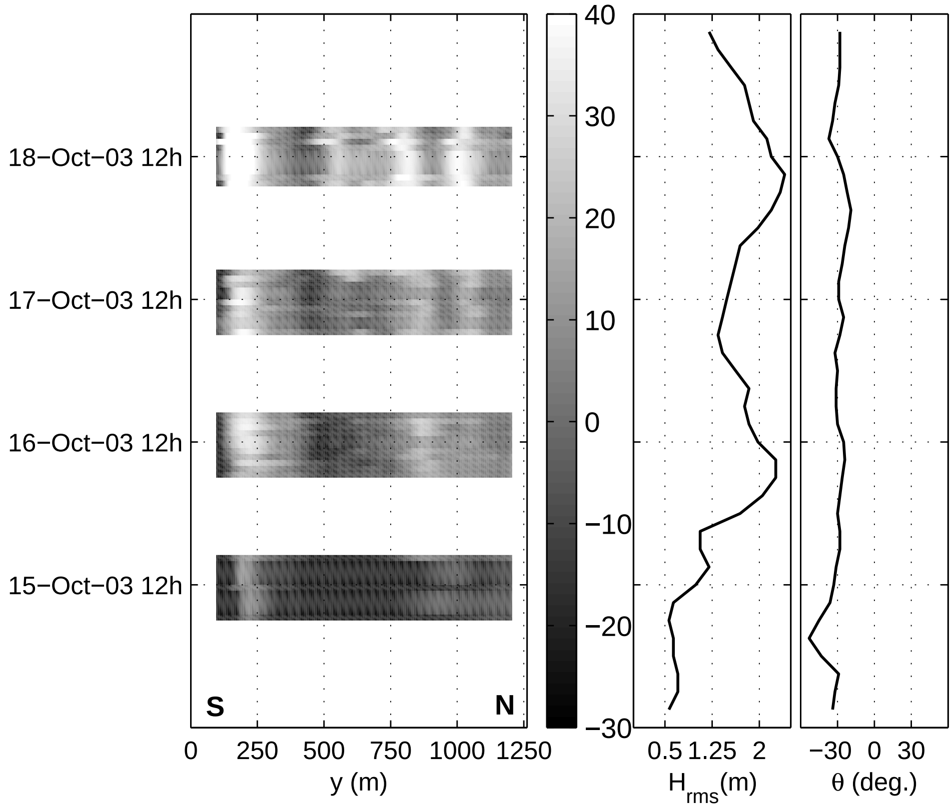

Fig. 4. Crescentic bar event in La Barceloneta during October 2003. Time series of (from left to right) the bar crest lines, $\hat{x}(t, y)$, the root-mean-square wave height, H_{rms}, and the angle of wave incidence, θ, relative to shore-normal. In the first panel, $y\!=\!0$ corresponds to the southern edge of the beach. Wave conditions were obtained from the WANA2066051 point.

FIELD OBSERVATIONS

Methodology

The characteristics and dynamics of the nearshore bar in La Barceloneta beach have been studied using the planview images obtained from the Argus station. A detailed description of the methodology can be found in van Enckevort et al. (2004) and Ojeda et al. (2007). Bar detection capability of this system is restricted to a range of wave conditions ($0.9 < H_s < 3.5$ m), when wave breaking patterns can be identified. The lines of maximum intensity are extracted from the images using the BLIM program developed by the University of Utrecht. Three preprocessing steps are then applied in order to remove (1) the pixel induced noise, (2) the large-scale shoreline curvature and (3) the bar crest obliquity. The obtained quantity, $\hat{x}(t, y)$, is assumed to be representative of the perturbations of the bar crests with respect to an averaged position. The overall behavior of the bar crest lines from November 2001 to December 2004 was described in Ojeda et al. (2007), including their response to storms and the coupling with the shoreline dynamics. The present contribution focuses on the two most clear events of crescentic bars formation found from November 2001 to December 2005.

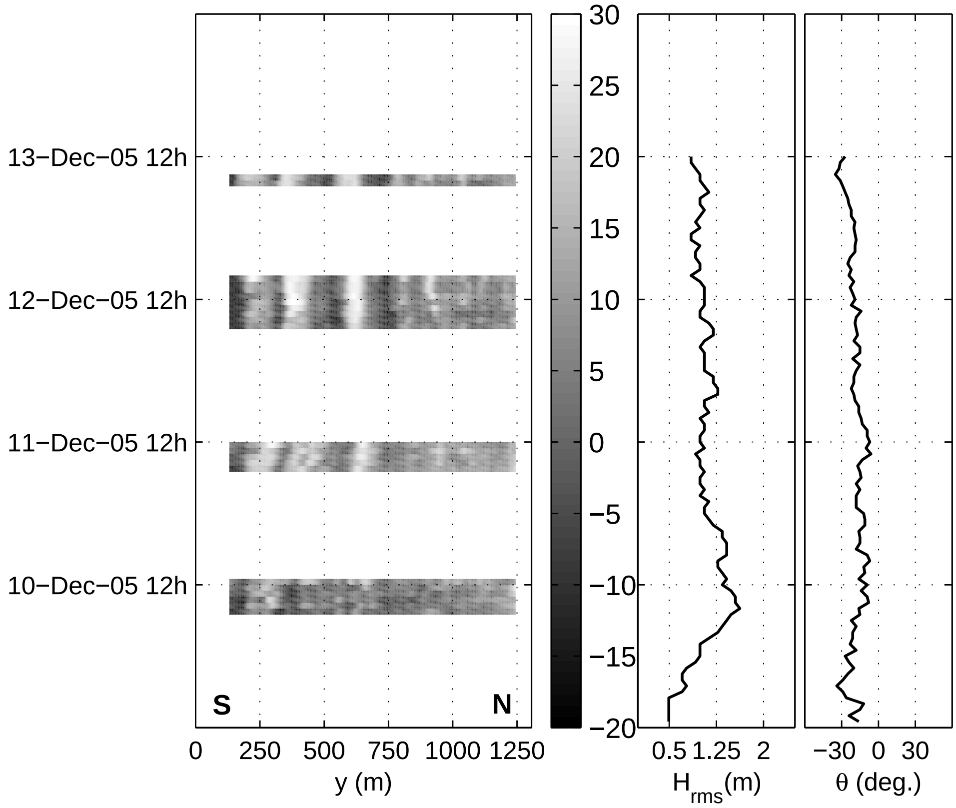

Fig. 5. Crescentic bar event in La Barceloneta during December 2005. Graph description can be found in the caption of Fig. 4. Wave conditions were obtained from the COST-BARCELONA buoy at 69 m depth.

Detected crescentic bar events

The first event of crescentic bar formation of the studied period occurred during a major Eastern storm in October 2003. A crescentic bar emerged (see the lower panel of Fig. 3) and prevailed during the entire 2004 (Ojeda et al., 2007). A space-time diagram (timestack) of the bar line perturbations $\hat{x}(t, y)$ corresponding to this event is shown in Fig. 4, together with the wave conditions. In the first panel, $y = 0$ m corresponds to the southern edge of the beach. Only one seaward perturbation around $y = 250$ m was present on October 15th. As described in Ojeda et al. (2007), this seaward perturbation was present near the southern tip of La Barceloneta from November 2001 to December 2004, probably formed during a period of extreme wave conditions in October 2001. On October 18th, the last day of the storm, four perturbations could be detected along the 1100 m alongshore length, giving an alongshore spacing of about 300 m. The averaged offshore wave conditions during the storm were a root-mean-square height of $H_{rms} = 1.9$ m, a peak period of $T_p = 9.9$ s and an angle of wave incidence of $\theta = 28^o$, relative to shore-normal. The averages were taken from October 16th at 3h to October 19th at 3h ($H_{rms} > 1.25$ m), using the data from the WANA2066051 point.

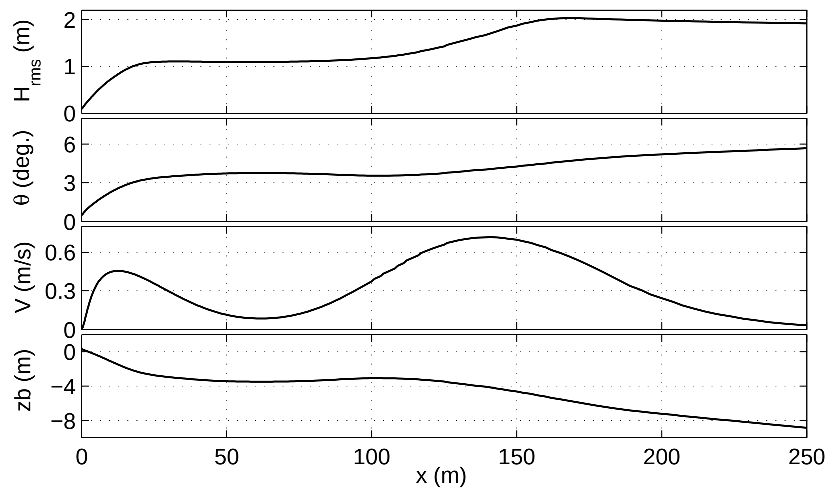

Fig. 6. Initial reference state used in the simulation of the first event of crescentic bar formation in La Barceloneta. The cross-shore distribution of (from top to bottom) wave height, angle of wave incidence, longshore current and beach profile are shown. The x-axis is the cross-shore direction. The profile is taken from a bathymetry measured on the 5 of November of 2003.

The second event of formation of a crescentic bar in La Barceloneta occurred during a less energetic Eastern storm in December 2005. The planviews corresponding to this event have been shown in Fig. 1. A well-developed crescentic bar with at least six undulations is visible on December 13th at 8h, displayed in the lower panel. This can also be seen in the corresponding timestack, shown in Fig. 5. Only the seaward perturbation at $y = 250$ m was detected on December 10th, whereas six seaward perturbations were visible on December 13th. They were spaced every 200 m in the southern half of the beach and every 100 m in the northern half. The storm-averaged offshore wave conditions corresponding to this event were $H_{rms} = 1.1$ m, $T_p = 8.7$ s and $\theta = 17^o$. The averages were taken from December 10th at 4h to December 13th at 12h ($H_{rms} > 0.75$ m), using the data of the COST-BARCELONA buoy.

MODEL FORMULATION

A nonlinear 2DH morphodynamic model (Garnier et al., 2006) is used to describe the initial formation and further evolution of crescentic bars in La Barceloneta. The model describes the feedbacks between depth-averaged mean currents, waves and an erodible bed in a nearshore zone bounded by a straight and infinite coastline (no groin effects are included). The hydrodynamics is modeled with the wave- and depth-averaged shallow water equations for water momentum balance, water mass conservation and wave energy and phase conservation. Waves are assumed to have a narrow spectrum in frequency and wave vector whilst their heights are assumed to be random and to follow the Rayleigh distribution, characterized by H_{rms}. Bed level evolution is described with a sediment mass conservation equation, where the sediment transport is modeled with the Soulsby/van Rijn formula (Soulsby, 1997).

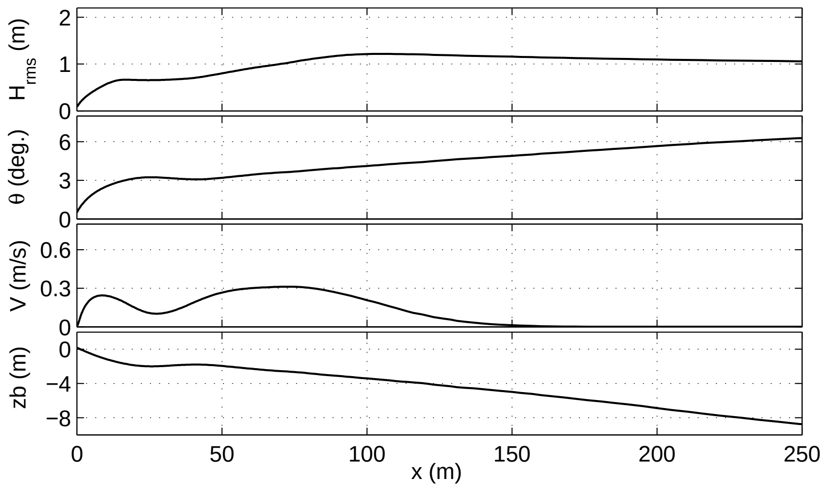

Fig. 7. Initial reference state used in the simulation of the second event of crescentic bar formation in La Barceloneta. Graph description can be found in the caption of Fig. 6. The profile is taken from a bathymetry measured on the 26 of October of 2005.

The model solves the full set of nonlinear equations and provides information about the mid-term behavior of the system O(weeks). The solution procedure starts by selecting an initial alongshore uniform reference state that is in equilibrium (i.e. steady). In this study, the chosen reference profiles $z_b^o(x)$ are obtained from the available bathymetries measured in La Barceloneta (on the 5 of November of 2003 for the first event and on the 26 of October of 2005 for the second). Then, the offshore wave conditions are imposed at 69 m depth and the cross-shore distribution of the equilibrium hydrodynamic quantities is computed: H_{rms}, θ, the longshore current, V, and the elevation of the mean free surface, z_s. Figures 6 and 7 show the initial reference state used in events 1 and 2, respectively. The lower panels display the reference beach profiles, $z_b^o(x)$. As can be seen, on the bathymetry measured on the 5 of November of 2003, the bar was located at about 100 m from the shoreline, whereas this distance was approximately 40 m in the bathymetry of the 26 of October of 2005. Table 1 summarizes the parameter setting used to simulate the two events, including the wave conditions imposed at 69 m depth. The reason why the angle of wave incidence used is smaller than the measured ones (described in the third section) will be explained in the next section.

Once the reference state has been solved, small random perturbations O(cm) are superimposed to it and direct numerical time-integration of the full set of equations (including bed evolution) is performed. The computational domain is a rectangle of 250 m in the cross-shore direction and 2000 m in the alongshore direction. The solution is assumed to be periodic in the lateral boundaries and constant wave conditions are imposed on the offshore boundary. This latter assumption is in agreement with the measured wave conditions leading to crescentic bar formation in La Barceloneta (see Figs. 4 and 5).

Table 1. Parameter setting used in the model of this study.

Wave conditions event 1			Wave conditions event 2			Other parameters	
$H_{rms}(m)$	T_p (s)	θ	$H_{rms}(m)$	T_p (s)	θ	d_{50} (mm)	z_0 (m)
1.9	9.9	10^o	1.1	8.7	10^o	0.4	0.01

MODEL RESULTS

Model runs were performed to simulate the two events of crescentic bar formation of La Barceloneta in October 2003 and December 2005. The existing literature shows that formation of crescentic bars is favored by shore-normal wave incidence (for instance, see Calvete et al., 2005) and this was also verified in La Barceloneta. When running the model with the angle of wave incidence measured in the offshore buoys (28^o in event 1 and 17^o in event 2), unreasonably large values for the growth times and the wavelengths were obtained. The offshore wave angle had to be reduced to 10^o to obtain more realistic results. The results presented in the rest of this paper are those corresponding to $\theta = 10^o$ and the measured values of H_{rms} and T_p. They are shown in Table 1, together with the values used for the grain size, d_{50}, and the roughness length, z_0).

Figure 8 shows the result of the model for the conditions of the first event. The upper panel is a time series of the bottom perturbation with respect to the initial beach for a longshore transect located at $x = 50$ m. During the first four days the bathymetry developed what would be the final dominant wavelength, with a spacing between channels of about 400 m. This is best shown in the lower panel of Fig. 8, which displays the Fourier transform of the signal shown in the upper panel. During the subsequent two days the crescentic topography evolved without changing the dominant spacing, the pattern growing in amplitude with nearly no migration. During the seventh day of numerical evolution, before growth saturation had been reached, the model blew up.

Figure 9 displays a planview of the topographic and hydrodynamic results obtained on day 7 (just before the model blew up). Three undulations can be detected in the alongshore length of 1200 m that is shown, corresponding to the dominant wavelength of 400 m. Resembling the observed systems of crescentic bars and rip currents in natural beaches, the shape of the undulations is alongshore variable. The flow field has two main components: the initial longshore current flowing from left to right (waves arrive from the bottom left corner of the planview) and a rip-current system with the alternation of offshore and onshore flowing. This results in a meandering of the longshore current with some strong rips (for instance at $y = 1250$ m).

The results obtained when using the conditions corresponding to the second event are shown in Figs. 10 and 11. The planview with the topographic and hydrody-

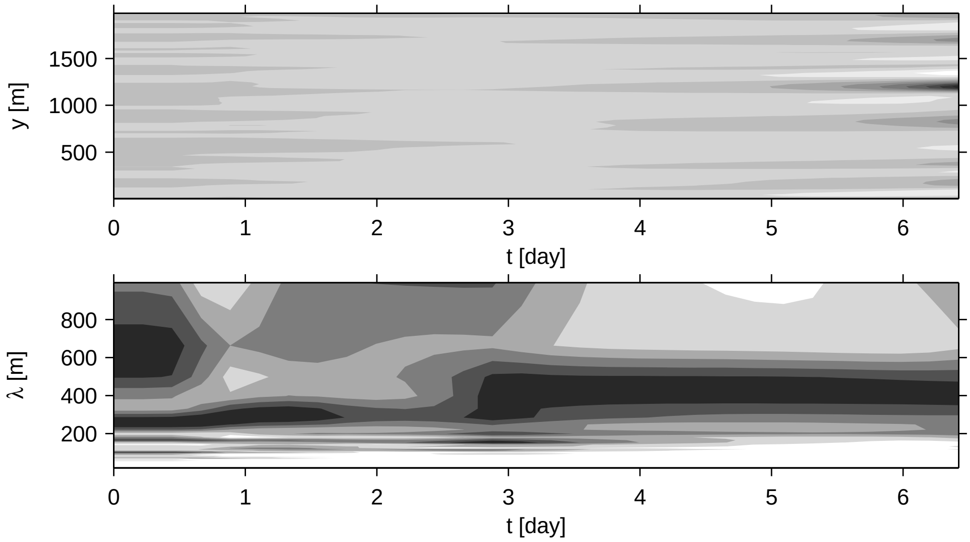

Fig. 8. Model simulation of the first event of crescentic bar formation in La Barceloneta beach. Time series of the bottom perturbation with respect to the initial beach for the longshore transect located at $x = 50$ m (upper panel) and the corresponding Fourier transform (lower panel), which is indicative of the dominant wavelengths. In the upper panel, light (dark) gray corresponds to shallow (deeper) sections. In the lower panel, dark gray indicates larger spectral density.

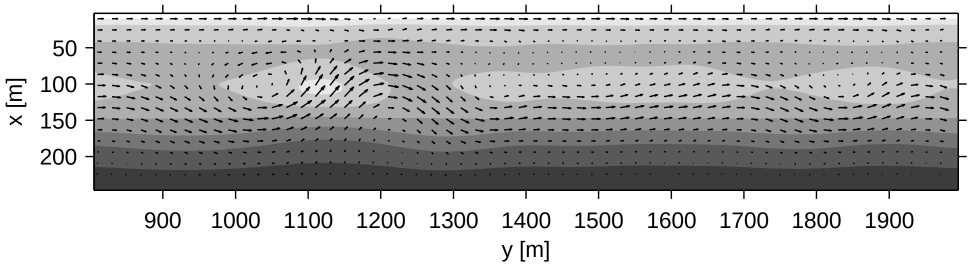

Fig. 9. Planview of the final state obtained for the first event. Colors represent the bottom level (deeper sections are darker) and the small arrows correspond to the 2DH flow field coupled with the emerging morphology. The x-axis is the cross-shore direction ($x = 0$ being the shoreline) and the y-axis stands for the longshore direction (an alongshore length of 1200 m is shown).

namic results obtained by the model before it blew up shows similarities with that of event 1. It consists of a crescentic bar with alongshore variable undulations and the longshore current is meandering due to the presence of rip currents. The most significant difference is a reduction of the length scales by a factor of 2, the dominant wavelength being now 200 m (three undulations in an alongshore length of 600 m). The time series of Fig. 11 shows that the model needed about four days to reach the final dominant wavelength of 200 m. However, in this case there was another detectable (but weaker) wavelength of 100 m. During the subsequent five days the crescentic feature grew in amplitude with nearly no migration, until the model blew up at the end of the eighth day, before saturation had been reached.

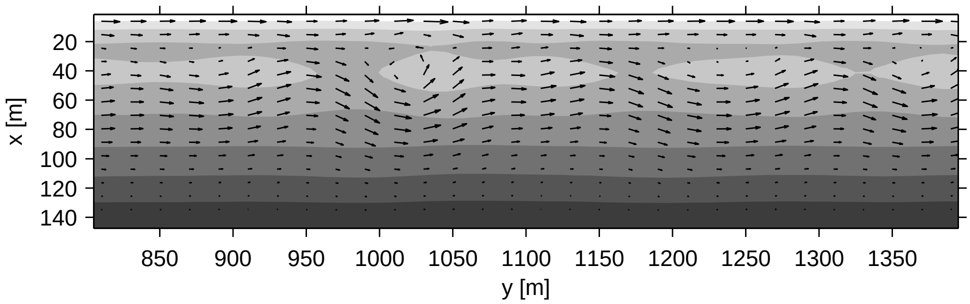

Fig. 10. Planview of the final state obtained for the second event. Graph description can be found in the caption of Fig. 9, but the scaling of the axis is different in the present figure (an alongshore length of 600 m is shown).

DISCUSSION AND MODEL-DATA COMPARISON

The crescentic bars observed in La Barceloneta beach showed a wavelength of about 300 m in October 2003 and of 100-200 m in December 2005. Previous models have predicted that the wavelength of crescentic bars increases roughly linearly with the distance from the shoreline to the crest of the initial bar (Deigaard et al., 1999; Damgaard et al., 2002; Calvete et al., 2005). This is consistent with our observations, the bar being further offshore in the first event, as can be seen in the corresponding planviews (lower panels of Figs. 1 and 3). This is also confirmed by the available bathymetries, the 5 of November of 2003 the bar was located at 100 m from the shore whilst the 26 of October of 2005 the distance was 40 m (see Figs. 6 and 7). In qualitative agreement with what was observed in La Barceloneta, the model used in the present contribution predicted a wavelength of 400 m in the first event and a combination of 200 m and 100 m in the second event. Therefore, the physical processes responsible for crescentic bar formation that are included in the model by Garnier et al. (2006) could explain some of the properties of the bars detected in La Barceloneta.

However, the model was not able to describe appropriately some other characteristics of the detected crescentic bar events. In particular the angles of wave incidence used in the simulations were smaller than those that were measured in the field. It should be pointed out that the existing models (including the one by Garnier et al., 2006) have some properties that limit the comparison of their results with the field observations in La Barceloneta. Firstly, the geometry used in the models is highly idealized: a rectilinear shoreline with periodic boundary conditions (rather than groin simulation) and initial alongshore uniform conditions in the bathymetry. The geometry of La Barceloneta beach is significantly different, since it is limited by groins, it has a curvilinear shoreline and it displays significant alongshore inhomogeneities in all the available bathymetries.

Future work should include the development of the model, prioritizing the description of groin effects. Moreover, events of crescentic bar formation in other

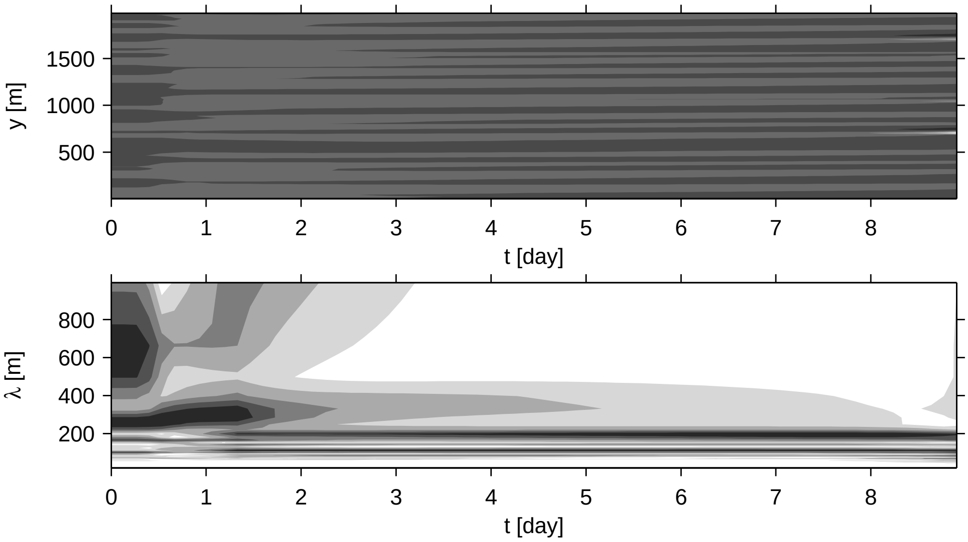

Fig. 11. Model simulation of the second event of crescentic bar formation in La Barceloneta beach. Graph description can be found in the caption of Fig. 8.

beaches should be analyzed to better fit with model results in case of θ larger that 15^o. Finally, the model blew up before saturation of the growth of crescentic bars was reached. This is the case in all the nonlinear models for crescentic bar formation that are available (e.g., Caballeria et al., 2002; Damgaard et al., 2002; Reniers et al., 2004). However, the model used in the present study was able to reproduce the growth and saturation of transverse/oblique shore-attached bars in initially plane beaches (Garnier et al., 2006). More research is needed to obtain growth saturation of crescentic bars in initially barred beaches.

CONCLUSIONS

The characteristic wave conditions leading to formation of crescentic bars in La Barceloneta beach, on the Spanish Mediterranean coast, have been determined. Crescentic bars emerge during Eastern storms with offshore root-mean-square heights between 1.5 and 2 m, peak periods of 9 s and angles of incidence between 15^o and 30^o, relative to shore-normal. The observations are coherent with the theoretical prediction that the wavelength of crescentic features increases when the distance from the bar crest to the shoreline is larger.

Two events of crescentic bar formation detected in La Barceloneta have been reasonably reproduced with a nonlinear morphodynamic model, the predicted and the detected wavelengths being in qualitative agreement (from 100 m to 400 m). Future improvements of the model should be to include groin effects and to consider larger angles of wave incidence for crescentic bar formation.

ACKNOWLEDGMENTS

This research is part of the PUDEM project which is funded by the Spanish government under contract REN2003-06637-C02-01/MAR. The work of F. Ribas, E. Ojeda and D. Calvete is supported by the Spanish government through the programs 'Juan de la Cierva', 'Becas FPU' and 'Ramon y Cajal', respectively. R. Garnier is funded by the Catalan government through the program 'Beques IQUC'. Wave conditions nearby Barcelona are provided by the Spanish institution 'Puertos del Estado'. Thanks to Dr. G.Ruessink for providing the program BLIM.

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