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MORPHODYNAMICS OF NEARSHORE RHYTHMIC FORMS: AN ENERGY-BASED CLASSIFICATION

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The present paper describes the bar system at Lido di Dante (Ravenna, Italy), a 3 Km beach facing the northern Adriatic Sea. The system shows a twofold behavior. A visual classification of the bar plan shape is presented in order to find a relation between the state of the system and the forcing conditions. If the total energy of storms exceeds a certain threshold, the changes between morphodynamics states are controlled by the forcing parameters (storms). However, under calm conditions the system returns to equilibrium, independently from the forcing signal, following a self-organization behavior. The area is strongly influenced by the room available for the bars. The available space is controlled by the position of the Bevano river mouth that represents the southern boundary of the study site.

INTRODUCTION

The mechanisms related to sand bar formation and motion are still not well understood. The use of video systems, capable of monitoring the dynamics involved with the emerged and submerged beach, has improved the knowledge of the morphodynamic behaviour of the bars but, on the other hand, many more questions have arisen. The previous knowledge on sand bars was only deducted from direct surveys and/or from aerial/satellite photographs. In most of the study sites around the world, the number of datasets available, from direct surveys and from aerial imagery, are not many, with some exceptions. Of course the instantaneous observation of the state of the system for only few times in a year is not enough to understand the causes for variations in shape and position of the submerged forms. The most common idea is that the occurrence of a forcing event leads to a change on the sea floor caused by sand movement. Moreover, the planar and the cross-sectional shapes of the bars are usually separated into categories obtained from direct observations. The most widely used morphodynamic classification is the one published by Wright and Short (1984) that consists of three main classes (plus four sub-classes) The Ω parameter (Dean 1973) is used to identify different morphodynamic states. The Ω parameter includes wave height, period and sediment fall velocity: moving from a "reflective beach" to a "dissipative beach" there is an increase in wave height and a decrease in sediment size and slope.

New studies based on video systems, such as Argus (Lippmann and Holman 1990), have changed the previous knowledge and have produced new models regarding the mechanisms related to the formation of bars (Stive and Reniers

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2003). The possibility to look at bars almost every day has permitted to notice that these features often change even when the dynamic conditions are non-energetic. A new classification based on video observations was done by Lippmann and Holman (1990) that introduced more morphological states, included the residence time of each class and the transitions between classes related to wave characteristics. A more detailed classification of submerged features is that of Wijnberg and Kroon (2002), where the authors reviewed the concept of relaxation time (De Boer 1992). Moreover, new theories on the formation of rhythmic features due to a self organization response to perturbations are under development (Caballeria et al. 2002; Coco et al. 2004).

FIELD SITE

The Lido di Dante beach is a 3 km-long stretch of coast, almost aligned in a N-S direction, divided in two parts: the one in front of the Lido di Dante village (almost 1 km) is protected by a breakwater and three groins, the other one (almost 2 km) is completely natural with dunes backed by a pine forest (Fig. 1). The present study is about the unprotected part of the beach that extends from the southernmost groin of the protected area to the Bevano river mouth (Fig. 1). The bars are attached to the submerged delta of the river. The Bevano outlet is extremely active (Balouin et al. 2004) and, since the Argus system was installed (February 2003), it moved northwards for almost 100-150 m. Most of the migration took place mainly between 2003 and the end of 2004, while in 2005 the mouth remained almost stable, only migrating about 30 m. At the beginning of 2006 engineering works, performed by Regional Authorities, moved the mouth 500 m southwards.

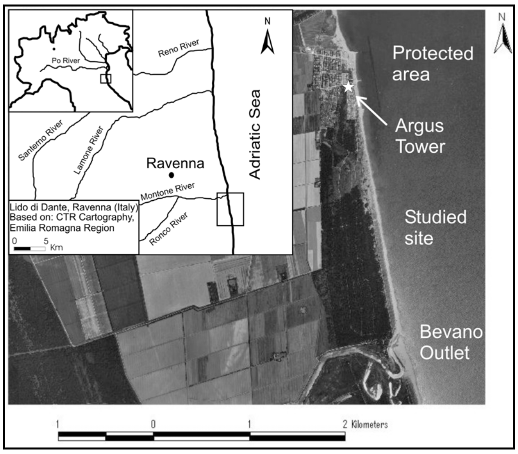

Figure 1 . Study site: Lido di Dante, Ravenna.

The tidal regime is strongly asymmetric, showing both diurnal and semi-diurnal components. The maximum tidal range is about 1.2 m during spring tides. The wave climate is usually of low energy, with H_s lower than 0.5 m, mainly from the East (65% of occurrences) (Gambolati et al. 1998). Two different storm directions prevail in the Adriatic Sea: the Scirocco from SE, and the Bora from NE. The Argus system consists of four cameras, three looking at the protected part of the beach and one looking at the natural one. The present paper will focus on results coming from the video monitoring of the natural area.

METHODS

Wave Data Analysis

Offshore wave data were analyzed in order to find the number and the intensity of storms that occurred during the study period. Significative wave height (H_s) and peak period (T_p) came from the records of a wave-rider buoy deployed in front of Ancona (Fig. 2) that is part of a network of buoys installed around the Italian coastline (RON, National Wave Measurement Network). During the study period the buoy was located at a depth of 70 m. Considering that the site is about 200 km away from the studied beach, it was decided to transfer the wave data using the ratio between the effective fetches (S.P.M. 1984) at the two sites (Fig. 2).

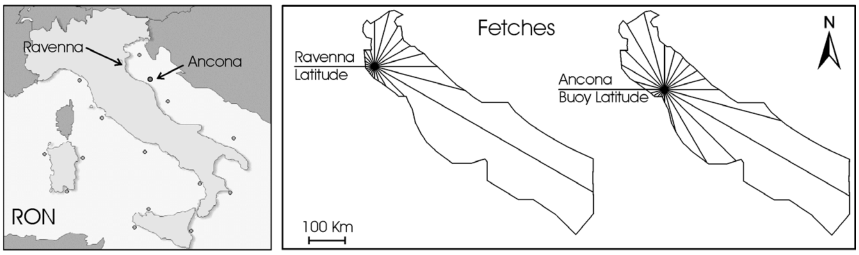

Figure 2 . RON network of buoys (left) and fetch lengths and directions (right).

Each storm was identified defining a significative wave height (H_s) threshold of 1.5 m, a maximum directional spreading of 45° and a minimum duration of six hours, meaning that for this period H_s remained above the threshold. Two events are considered separated if the interval between them is more than 12 hours. Then the total energy of each event can be computed using the wave height (H_s) integrated the storm over the storm duration:

$$E = \int_{t_1}^{t_2} H_s^{\,2}\, dt \qquad \left[m^2 \cdot hr\right] \tag{1}$$

According to the classification proposed by Mendoza and Jimenez (2004) the events were separated into five different classes, defined considering an increasing range of energy values (Table 1).

Table 1 Energy-based storm classification scheme

STORM CLASS	ENERGY RANGE (m^2 hr)
I-weak	E < = 58.4
II-moderate	58.4 < E < = 127.9
III-significant	127.9 < E < = 389.7
IV-severe	389.7 < E < = 706.9
V-extreme	E > 706.9

The offshore wave records were transformed to the breaking point (H_b) using linear wave theory and assuming that breaking was defined by a ratio between wave height and water depth of 0.4. The longshore wave power component (P_l) was also computed.

Image Analysis Method

The three years datasets captured with the Argus system were analyzed developing some new tools within the Argus environment. The aim of the analysis was to study the bar plan shape, to calculate the bar crest wave amplitude and length, to find a possible correlation with the offshore wave forcing. The first step was to manually select the images when the bars were clearly visible. The total number of days useful for the analysis was 114. According to method of Armaroli et al. (2005) the available images were automatically filtered to only use those captured with a tidal elevation between 0 and –0.2 m below mean sea level and with a wave height greater than 1 m. Then the pixel luminosity intensity was sampled along cross-shore arrays, spaced every 50 m, starting from the groin up to 1700 m away. To notice that the image resolution in the cross-shore direction decreases slowly moving southward of the camera: it is better than 0.25 m close to the camera and less than 1 m up to 1700 m. The decision to use an array spacing of 50 m comes from the bar crest analysis already done in Armaroli et al. (2005) where the rhythmic features showed a maximum spacing of that magnitude. The pixel sampling was undertaken on oblique timex images and the arrays were then rectified using photogrammetric techniques.

A routine was developed to automatically identify the maximum luminosity along the cross-shore transects as a proxy of bar location (Lippmann and Holman 1989; Alexander and Holman 2004). Once the bar crest position was found for all the arrays, the results were compared with the rectified images showing an excellent correspondence. An operator control was introduced to correct on the screen for errors induced by the automatic procedure. Sometimes the routine was not able to find the luminosity peak or its position did not correspond to the actual bar crest. This normally happens because images are not always clear (mist, fog, etc..) or there is too much foam in the surf zone, that generates a wide white band and consequently a “no-peak” intensity profile. The operator has the possibility to change the incorrect data by picking the correct location directly on the screen along each sampled array. In the software there is also the possibility to reject an image if it is not suitable for the analysis or to delete an array if it is unclear or the peaks are non existent. The manually sampled bar crests on the oblique interpretation were compared with their actual position on the rectified images, showing again a good correspondence. An average position of the bar crest was finally computed for the successive analysis in order to have one mean location and shape per day. The data were rotated and shifted to compensate for the distortion introduced by the obliquity of the coast (Alexander and Holman 2004). The difference in the longshore position of the bar crest between the raw data and the rotated ones was between 1 and 5 m.

A new Argus tool named L-BAIT (Longshore Bar Amplitude Identifier Tool) was written to analyze the rhythmic features and to calculate bar crest wave amplitude (A) and length (L) according to the scheme in Fig. 3 The analysis was done for each sampled bar crest location. If the difference between the cross-shore position of each location and the adjacent was more than 5 m it was decided to consider that location as a horn or a bay. The selected points were then saved in a separate file and analyzed automatically to compute the amplitude and length of rhythmic features. The 5 m filter was introduced because during the analysis was noted that a lower value was too close to the pixel resolution and caused the sampling of noise rather than real features; a higher value caused instead a loss of information when the rhythmic elements were several (7 to 9). The wave length was computed between both horns and crests. Of course if the bar was linear the matrix containing amplitude and length was found empty and that day(s) was (were) not considered for the successive analysis. The bar wave length was associated with the mean longshore position between horns (or bays) related to it.

The amplitude was calculated as half of the average value of the bar wave height (h) computed as the difference between one horn and the two adjacent bays (and between one bay and the two adjacent horns (Fig. 3). The obtained value was associated with the longshore position of the horn (bay) used to evaluate the bar wave height.

It was decided to analyze only the length computed between horns and consequently the amplitude calculated between one bay and two horns (Fig. 3).

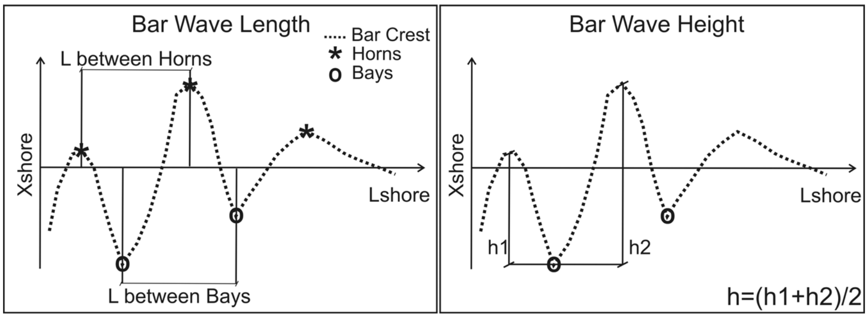

Figure 3 . Bar wave length and bar wave height planar scheme; the mean height (h) is defined as (h1+h2)/2; consequently the amplitude is found as h/2.

Morphodynamic Classification

In order to identify the beach morphodynamic state according to the classification of Wright and Short (1984), a visual classification of the bar crest outline was performed on plan view timex images (Lippmann and Holman 1990; Ranasinghe et al. 2004). Examination of the images revealed that a double system of bars was on average present only starting at distance of 1000-1200 m from the tower and we decided to classify only this sector as the morphodynamics of the beach next to the structures were often not well-defined due to complex breaking patterns. Three of the authors separately interpreted the images to classify the morphological characteristics of submerged features. In Table 2 the three main classes are presented.

Table 2 . morphological classes

Extended name (inner bar+outer bar)	code
Longshore Bar/Terrace + Oblique/Longshore Bar	LB/LT+OB/LB
Transverse/Linear Bar + Rhythmic/Oblique Bar	TB/LB+RB/OB
Transverse Bar/Terrace + Rhythmic Bar	TB/LT+RB

The classification includes the inner bar and its evolution according to the changes observed in the outer one. The first part of the term used to describe each class (left part of the extended and short names, Table 2) refers to the inner bar while the second part (right) refers to the outer one. It is important to underline that the analysis of pixel luminosity presented in this paper was instead only based on the outer bar.

RESULTS AND DISCUSSION

Bar Wave Lenght

Plots with the crescentic bar wave length and its longshore variability were produced to have an overall view of its distribution and magnitude. Each plot in Fig. 4 includes all the wave lengths for a given year. It is possible to notice the similarity between 2003 and 2006, and again between 2004 and 2005. Considering the similarity, the study area can be divided into two parts: a first one stretching between the groin and 1150 m from the tower; the second one extended between 1150 m and 1700 m. In the first part the wave length distribution is almost always below or equal to 350 m. In the second part there are higher values, with a maximum of 750 m. In 2003 it was observed that in the northern part of the beach there were rhythmic features that could be associated with crescentic bars. In the southern area there were "undulated" features that corresponded to the oblique submerged bars previously observed by Armaroli et al. (2005). It is important to underline the persistence of the undulated features in 2003 and the disappearance of them in 2004 and 2005. They appeared again in 2006. Note that the analysis for 2006 only includes the first 6 months of the year.

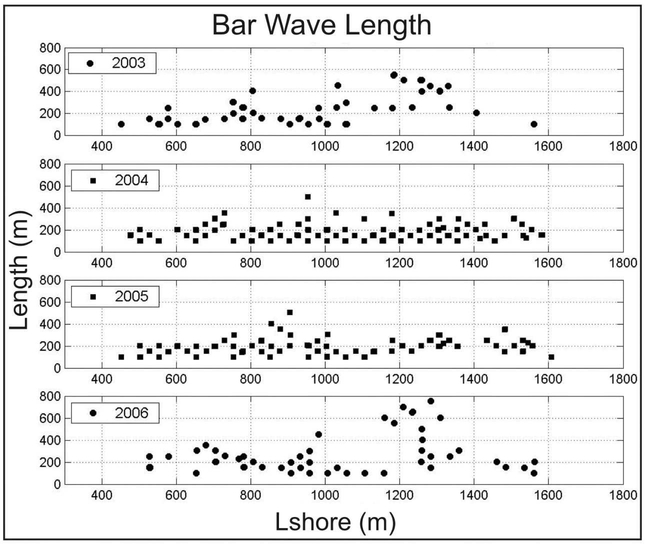

Figure 4 . Bar wave length distribution for every year.

In 2004 and 2005 the whole area is characterized by the presence of crescentic bars, with a wave length shorter than 400 m, showing that the rhythmic configuration was generally stable.

To find an explanation for the wave length distribution and magnitude in the analyzed period, a correlation between the mean wave forcing and the mean wave length was investigated. The wave parameters (e.g. H_s, T_p, H_b, P_l) were averaged between the day of bar analysis and the previous 24 hours. No correlation was found. In Table 3 the maximum, minimum, mean and modal values are presented. To notice that the mean value of bar wave length is 200 m. This rather small value derives from the influence, on the computation of the arithmetic mean, of short wave lengths that persisted in 2004 and 2005. Moreover, considering the whole study period, there is an influence of the stability of crescentic forms in the northern part of the beach, even when the southern sector is characterized by wide oblique bars (2003 and 2006).

Bar Wave Amplitude

Bar wave amplitude was associated with the position of rhythmic features (horns) and plotted for the whole study area, for every year (Fig. 5). The distribution of amplitudes along each transect has a marked variability in the cross-shore direction. There are sections where the values vary within a small range, while at other points the amplitudes change from high values (30 m) to small ones (5 m). Most of the figures are above 5 m (the mode is 7 m, Table 3). The consistent variability of amplitude along several arrays derives from the formation and successive merging of rhythmic forms, that joined into wider cross-shore and longshore forms. But the main factor resulting from the analysis presented here is the role of alongshore feature migration. In this paper this behavior has not been investigated but future works must consider the north-south movement of crescentic forms, driven by both calm and energetic conditions. An analysis of shoreline variability at the site, presented in Kroon et al. (in press), suggests a relationship between shoreline variability and offshore feature location. At Dutch sites, Ruessink et al. (2000) showed that 85% of short term variability (days to weeks) was related to patterns migrating alongshore. These patterns of variability in the beach profile are not evident on longer time scales (Lippmann and Holman 1990).

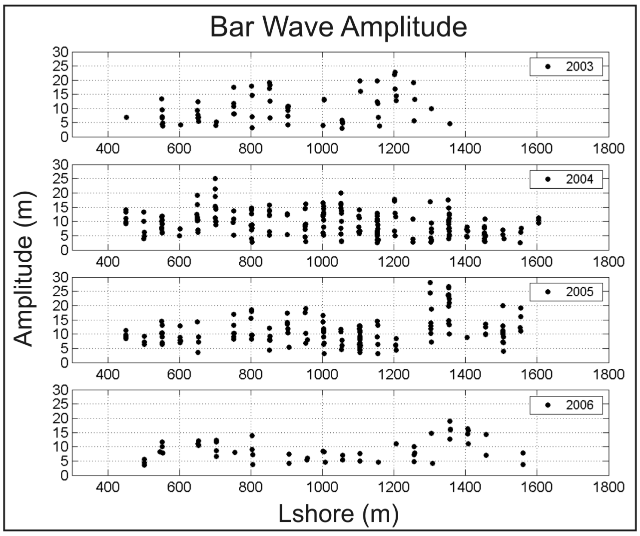

Figure 5 . Bar wave amplitude distribution for every year.

Table 3 . max, min, mean and modal values of bar wave length (L) and amplitude (A)				
	Max (m)	Min (m)	Mean (m)	Mode (m)
L	750	50	200	150
A	30	3	10	7

The same procedure followed for the bar wave length was applied to the amplitude to test a correlation with the wave forcing. In Fig. 6 the relationship with H_s is shown for each year (not considering 2006 because the wave data only covered the first three month of the year). It is immediately visible that there is no correlation in 2003 and 2004, while in 2005 there is an inverse linear correlation with R^2 = 0.4132 (significance = 95%). No other correlation was found, in agreement with the work of Van Enckevort and Ruessink 2003. The reason why in 2005 the increasing wave height generates a decrease in amplitude is not clear. Later in the paper, where the conceptual morphodynamic model is described, a possible explanation will be presented.

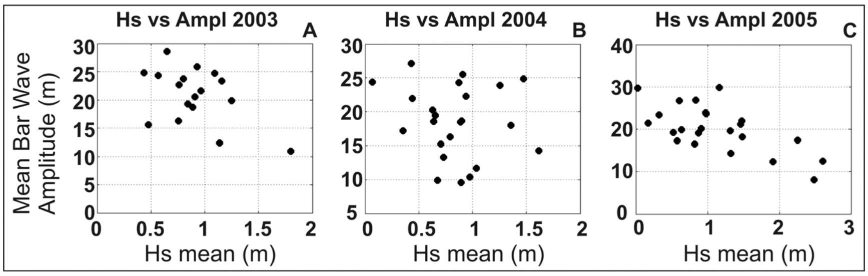

Figure 6 . Correlation between mean bar wave amplitude and mean wave height (Hs) in: A) 2003; B) 2004; C) 2005. In 2005 there is an inverse liner correlation (R^2 = 0.4132, significance = 95%).

Sediment Supply and Accommodation Space: how long is a piece of string?

The idea was that the crest of oblique or linear bars, that are predominant in 2003 and 2006, is equivalent to a shorter length, if considered as a non-extendible piece of string, than that of numerous crescentic features (2004 and 2005). Each horn was connected with the adjacent bay through a segment, in order to obtain a simplified bar crest shape. Then every segment was measured and the total bar crest length was computed as the sum of all the segments connecting horns and bays. The result are shown in Fig. 7 There are some differences between the two configurations and the range of length variability is between 1360 and 1460 (maximum difference is almost 100 m). Of course, images with gaps in the bar crest location were not considered. Even if the length remains almost the same over the entire considered period, the distinction between the two pairs 2003-2006 and 2004-2005 is still present. In fact, the maximum lengths (e.g. larger than 1460 m) are reached in 2005 and in both years there are several days where the bar crest length is greater than 1400 m. During 2004 and 2005 the study area is characterized by the presence of numerous crescentic features. The whole submerged area is 1350 m long (between 350 m and 1700 m from the camera). The maximum crest length variation is 100 m that is only 7.5% of the total length. In 2003 and 2006 the length is below 1400 and in 2006 the variability is very small (only 30 m). However, one must consider that, for the latter year, the analysis was done for only the first half of it.

Mean bar wave length and mean bar wave amplitude were correlated, for each day, to find if the results described above derive from an inverse linear relationship, but this was not found. Therefore ones wanders why the crest length remains almost constant. An explanation could be that the amplitude of the rhythmic features (in a cross-shore direction) is small if compared to the spacing of horns and bays when the bars are crescentic (longshore direction), e.g. when the total length of the crest is expected to be greater. The mean values of the distances between horns and bays (segments) for the entire study period is between 50.7 and 54.2 m.

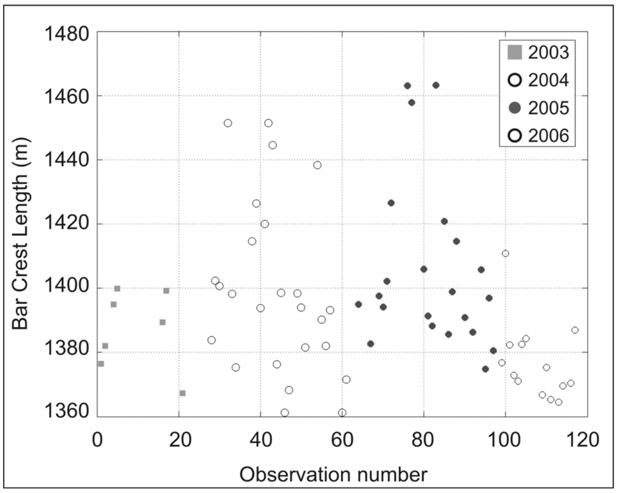

Figure 7 . Bar crest length computed considering the crest as a piece of string.

The bar system at Lido di Dante is mainly exposed to calm wave conditions but it shows dramatic changes related to perturbations. If we consider the different morphological states observed between 2003 and 2006, it is possible to divide the area in two parts. The submerged features are almost always rhythmic in the area close to the groin while they have variable configurations in the central and southern areas. Considering the latter stretch of coast it is possible to divide the study period in four main categories. In 2003 the system is stable with a morphodynamic configuration with two wide oblique bars. After a perturbation due to a strong storm in December 2003, the forms reorganized themselves (Armaroli et al. 2005). In 2004 a new morphodynamic state was reached, with a high degree of rhytmicity on the whole area. The system was not stable and there were some transitions from a configuration with many rhythmic forms to a configuration with few rhythmic forms (from TB/LB + RB to LT(LB) + OB/RB and TB/LB + RB/OB) and vice versa. In 2005 the system was still rhythmic, but there were only two class transitions due to a storm, occurred in January, capable to straighten the bars. However, they became rhythmic again (from LT(LB) + LB to TB/LT + RB) after few days. In fact this is the year when there is a correlation between the forcing sequence and the mean bar wave amplitude, as if the bars were in equilibrium with the forcing signal. At the beginning of 2006 the system was still rhythmic but, after the deviation of the Bevano river mouth (February 2006), the bars returned to the initial configuration with two wide oblique forms (TB/LB + RB/OB). In the last part of the observation period the features close to the groin, that were rhythmic, became almost linear. It is believed that the main factors controlling the variation of the bar shape are sediment input, accommodation space and storms (Fig. 8).

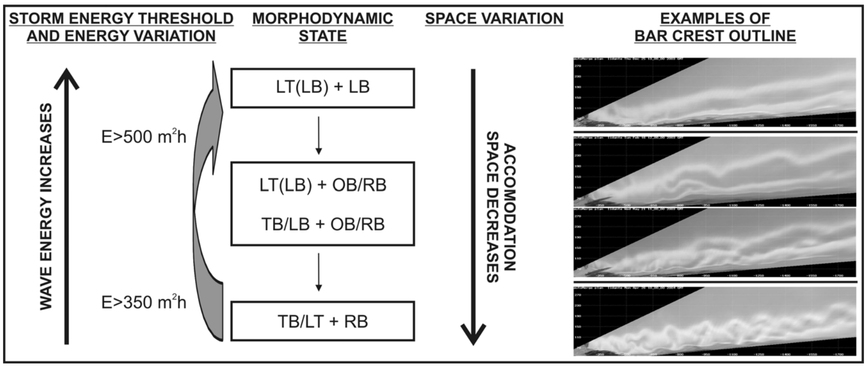

Figure 8 . Conceptual model of bar morphodynamics as a function of wave energy and availability of space for sediment storage.

The impact of storms on submerged features depends on the duration of the storm and consequently on the total energy of the event. In Fig. 8 it is clearly underlined that the class shift from a high to a low rhythmicity corresponds to an event with $E > 350$ m^2h, while the complete rectification of the system occurs only if $E > 500$ m^2h. The clustering of successive events that have E below the defined thresholds, but that occur one after the other one, has the same impact of one large event. Ferreira (2006) also noted the impact of storm clustering on the erosion of dunes and beaches. The conceptual model presented in Fig. 8 must be read as: downward = calm conditions (self organization and accommodation space decreases, 2004 and 2005); upward = E threshold defined inside the figure (all years) and, from the last state (TB/LT+RB) to the middle one (TB/LB+RB/OB), accommodation space increases under calm conditions (2006). The linear bar is not a stable state and its residence time is only of a few days.

CONCLUSIONS

Storm energy has the capability of changing the bar shape only if it reaches a threshold value. Following a period with a low-energy regime the system goes into self-organization by reaching a stable configuration that depends on the available space for sediment storage. The latter theory will be confirmed or not by the behavior of the bars under energetic conditions in winter 2006. We expect that the system will remain stable and that the bars will not become rhythmic even after a perturbation event.

The volumetric sediment input relevance was not investigated and future works should consider the direction of longshore transport and the amount of transported sand available for a given area. Transitions between states do not seem to be simply controlled by the characteristics of incident waves, unless when the system reaches stability from a morphodynamic viewpoint. The concept of energy threshold should be tested on sites exposed to more energetic wave regimes. In this case, a site-specific behavior could be assessed, together with the permanence of non-linear responses under increasing energy levels.

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