Morphodynamic classification of sandy beaches in low energetic marine environment

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Abstract

Morphodynamic classification of beaches has achieved widespread acceptance in both geological and geomorphological literature. In this sense, the present work classifies twelve Mediterranean low energetic beaches according to the dimensionless fall parameter (Ω) parameter in the Island of Mallorca. Propagation of 44 years of wave data as well as a detailed sediment study allows to provide probabilities for morphodynamical beach state on annual and seasonal basis. Consequently, beaches in Mallorca fall between three major categories which are (a) truly reflective, (b) reflective skewed to intermediate and (c) intermediate beaches. The mallorcan beach position in the morphodynamical scheme is close related to the physiographical and geological framework. Comparison of observed values with those obtained in the analysis leads that for gross beach classification there is agreement between predicted and real state. However on a seasonal classification, mainly during summer, there is no agreement between the predicted state and the real one. As the model does not incorporate the role of summer sea breezes, beach reflective states are highlighted. Real beach configurations correspond to more energetic wave dynamic conditions and to intermediate state scenarios.

Key words: Beach morphology, beach morphodynamics

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Preprint submitted to Elsevier Preprint *16 February 2007*

1 Introduction

The dynamical study of beaches, has adopted the model of a system moving towards a state of dynamic equilibrium under steady forcing conditions (Woodrofe, 2003). According to Wright and Thom (1977), beach morphology relates the mutual adjustment between topography and fluid dynamics. The morphological makeup of beach systems is not accidental because the arrangement and association of forms occur in an organized contextual space and time (Sonu and van Beek, 1971; Sonu and James, 1973; Lipman and Holman, 1990). Since the classification derived by Wright and Short (1983), obtained from the analysis of the evolution during 6 years in a number of Australian study sites, beach systems are comprehended in terms of three-dimensional morphodynamic models that include quantitative parameters (wave breaking height, sediment fall velocity, wave period and beach slope) and boundary conditions for definable form-processes association (e.g. presence or absence of bars as well as its type). This has lead to the classification of beaches into three main categories relating the beach state observations with the physical forcing (Short, 1999): dissipative, intermediate (from the intermediate-dissipative domain to the intermediate-reflective domain) and reflective modes. This classification is quantified by means of a dimensionless fall velocity parameter(abbreviated to DFVP below), , which is defined as :

$$\Omega = \frac{H_b}{w_s T} \tag{1}$$

where H_b is the wave breaking height, T is the wave period and w_s is the sediment fall velocity. The DFVP was first proposed by Gourlay (1968) and rewritten by Dean (1973). Values of Ω less than one are associated with reflective states, values between 1 and 6 to intermediate states and values grater than 6 related to dissipative states (Short, 1999).

The DFVP can be seen as a predictive equation that indicates which beach type will occur under certain ranges of waves and grain size parameters assuming that the beach will fully respond to governing parameters which may take days (e.g. associated with storm periods), or to about a year (e.g. modifications of sediment size and type by nourishment projects) (Benedet et al., 2004). Nevertheless, it is not clear whether the DFVP based solely on wave characteristics and sediment size, should really be termed a morphodynamic parameter or just as a dynamic one.

In this way limitations in applying the Wright and Short approach are recognized particularity for intermediate phases prediction. Wright et al. (1987) found only a

36% of agreement between observed and predicted beach states. DFVP fall velocity parameter is useful in discriminating between extreme beach states, but it does not characterize adequately intermediate situations. Ranashinge et al. (2004), justify this fact because there is a lack of accuracy of beach state models and the degree of subjectivity involved in their identification, but most of the temporal variability in DFVP are related to fluctuations in breaking wave height (Anthony, 1998). Further, restrictions on the applicability of this model relates with the considerations of tidal range effects. Despite the additional parameters that incorporate tide-induced migration of hydrodynamic processes across beach profile (Masselink and Short, 1993), the prediction fails in both the higher extreme of energetic parameters at the megatidal beaches (Levoy et al., 2000; Masselink and Hegge, 1995) and in the lower ones, when it concerns to sheltered microtidal beaches (Masselink and Pattiaratchi, 2001; Goodfellow and Stephenson, 2005). In addition, the effect of sea breezes on beach morphology is not considered and appears as a distortion in the DFVP prediction (Masselink and Pattiaratchi, 1998). Sanderson and Elliot (1999) pointed out that, beach state models are not always practical if complications such as the presence of nearshore reefs exist. Geological factors, as underlying geology (bedrock, accommodation space, inheritance, etc.) and nature and source of beach materials (grain shape, packing, composition, etc.) are factors explaining possible discrepancies between predicted and observed beach states (Jackson et al., 2005; Smith and Cheung, 2002). The Wright and Short model rely largely on dynamic factors, which may be appropriate in wave-dominated linear coast of Australia but further research is necessary for sheltered beaches because is very difficult to include them in the previous classification (Klein and de Menezes, 2001). Anthony (1998), argues that for a full validation of the DFVP it has to be tested against a wide range of natural environments particularly, within lower energy beach systems with a long time response.

The main goals of this paper are (a) to elucidate a beach morphodynamic sequence and classification for microtidal, low energy, carbonate sand beaches with headlands and bay geomorphology; and (b) to address the utility of Wright and Short model in this type of environments.

2 Study Area

The island of Mallorca, the largest of the group called as Balearics, is located in the western Mediterranean Sea. These islands are the eastern emergent part of the Balearic Promontory; a thickened continental crustal unit forming the NE continuation of the Alpine Betic thrust and fold belt build during Middle Miocene (Gelabert et al. , 1992).

Beaches represent 10% of the coasts and are closely related to the basins disposition although they appear sometimes as pocket beaches spread along the cliffs coasts of the island. Mallorca beaches are composed by medium to fine sand with large percentage (more than 70%) of bioclastic sediments most of wich derive from organisms associated with the endemic reef-building seagrass *Posidonia oceanica* (Fornós and Ahr, 1997). *Posidonia oceanica* is the dominant seagrass in the Mediterranean Sea, where it covers about 50,000 km^2 (Bethoux and Chopin-Montegut, 1986) of coastal sandy and occasionally rocky, areas from less than 1 m to about 40 m water depth. The climate is the typical from the Mediterranean Sea with hot dry summers and mild wet winters. The annual mean temperature is approximately 17°C with mean winter and summer temperatures around 10° and 25°C respectively. The mean annual precipitation is about 500 mm and is mostly concentrated in autumn.

Western Mediterranean presents a temperate, oligotrophic, clear sea environment. Waves height rarely exceed 8 m with typical wavelength less than 50 m. These values are considerable reduced nearshore where the maximum height is about 4 m and usually recorded when winds between 6-8 Beaufort scale blow. The prevailing winds during the year are mainly from the north-west and are weak or moderate, sometimes rising to gale force during winter. During autumn-winter, the south-western direction is also important, with variable fetches. Tides are almost negligible in the Mediterranean with a spring tidal range of less than 0.25 m, although changes in atmospheric pressure and wind stress can account for a considerable portion of sea level fluctuations. These physical settings conform coastal areas in the Balearic Islands as low energy systems where significant morphological changes are restricted to severe weather episodes or long moderate events when wave related processes enhance sediment dynamics controlled by wave-storm events(Basterretxea et al., 2004).

3 Data and methods

3.1 Sediment characterization

A total of 122 sand samples were collected at 12 sandy beaches (Figure 1). Samples were taken at several cross-shore elevations in transects perpendicular to the shore at locations with different morphological features (e.g. beach face, surf domain, troughs or bars). Samples were rinsed with fresh water, dried 24 hours in the oven at 95°C and divided into sub-samples for sieving and settling analysis.

Dry sieve analysis was performed using a series of sieves ranging in mesh size from 0.063 mm to 4.76 mm. Grain size distributions were determined using the GRADISTAT© package (Blott and Pye, 2001).

For each fraction a textural analysis was performed. Using a binocular microscope 100 grain counts of loose particles distributed on a microscope slide were made for each settling fraction giving a total of 700 counts per sieved sub-sample. Fourteen components classes were identified (foraminifera, grastropods, bivalves, rock fragments, indeterminate grains, etc.). The percentage weight of components of individual fractions were summed and expressed as a percentage of the total sub-sample (Kench, 1997).

The density of sand samples were measured from the volumetric displacement of 75 g of dry sand in a graduated cylinder containing 50 ml of water at 20^0C (Smith and Cheung, 2003). The mean settling velocity (w_s) of some samples were determined using a settling tower, 2 m long and with internal diameter of 0.11 m with a differential pressure sensor (Giró and Maldonado, 1985). The correlation between sieve size and mean settling velocity was calculated and used to estimate the mean settling velocity for those samples that were not assessed in the settling tower. We have found a good agreement with the sediment velocity values predicted by Gibbs equation (Gibbs et al., 1971) although using D_{50} sieve size and empirical sand density rather than quartz (Figure 2).

3.2 Nearshore wave propagation

To characterize wave climate at the beach, 44 years of hourly data where analyzed. This database is part of the HIPOCAS project (Soares et al. 2002) where a wave hindcast of the Mediterranean Sea was carried out in a high resolution mesh for the period between 1958 and 2001. To cover all beaches, ten grid points located at deep waters where chosen according the orientation and proximity of the study areas (see Figure 1). However, as waves propagate from deep to shallow water they undergo some changes in their spatial energy (i.e. diffraction, refraction, shoaling, etc.) that have to properly be modeled to obtain the wave climate in the near shore region.

Since propagation of the 385,000 HIPOCAS data is unreliable, selected combinations of the long term probability distribution of significant wave height ($0.5 < H_s <$

$5m$) and wave period ($3 < T_p < 12s$) were propagated to the beaches using a mild slope parabolic model (OLUCA). The model solves in a discretized finite difference domain the mild slope equation,

$$\frac{\partial^2 A}{\partial y^2} + \left(2ik_0 + \frac{1}{cc_g}\frac{\partial cc_g}{\partial x}\right)\frac{\partial A}{\partial x} + \frac{1}{cc_g}\frac{\partial cc_g}{\partial y}\frac{\partial A}{\partial y} + \left(\frac{\omega^2}{g} - k_0^2 + \frac{ik_0}{cc_g}\frac{\partial cc_g}{\partial x}\right)A = 0 \quad (2)$$

where A is the wave amplitude (i.e. $\eta = Ae^{ik_0x}$), k_0 is a characteristic wave number, ω the frequency, c_g the group velocity and c the wave celerity. For each beach a mesh of 15x15m resolution was obtained by interpolation from the IHM nautical charts.

To obtain a criteria for the wave height at the breaking point, from the HIPOCAS data-set, we compute the wave height that is not exceeded more than 12 hours per year (H_{s12}) and then propagated to each beach. From this study, we found that the breaking depth at all study sites is around 5 meters. Consequently, the wave height at this depth was chosen as the breaking wave height (H_b)in equation (1).

3.3 Nearshore wave climate

At the beach, a bivariate empirical histogram was built with the wave breaking heights H_b and their corresponding periods T_p. This joint distribution contains information about the annual rate of occurrence of a concrete sea state for a given value of H_b and T_p.

Trends between summer and winter were modeled using a log-normal probability distribution function. This function is characterized by the so-called location parameter μ^* and the scale parameter σ^* as (Castillo, 2005),

$$f(H_b|\mu^*, \sigma^*) = \frac{1}{H_b\sigma^*\sqrt{2\pi}}\exp\left(\frac{-\left(\ln(H_b) - \mu^*\right)^2}{2\sigma^{*2}}\right) \quad (3)$$

From the estimated log-normal parameters μ^* and σ^*, we calculated the mean and the standard deviation as,

$$\mu = \exp\left(\mu^* + \frac{\sigma^{*2}}{2}\right) \quad (4)$$

$$\sigma = \left\{\exp(2\mu^* + \sigma^{*2})(\exp(\sigma^{*2}) - 1)\right\}^{1/2} \quad (5)$$

As shown in Figure 3, the evolution of the estimated mean and standard deviation leads to the conclusion that to analyze correctly beach state, seasonality has to be taken in to account. In this sense, two periods were proposed, the summer covering from April to September and the winter wave climate period from October to March. For each beach the combined (H_b, T_p) empirical bivariate histogram for the summer and winter periods was obtained from the relative wave frequencies.The wave breaking criteria chosen has been Hs12. This criteria allows to propagate 99,86% of the entire wave climate. At the breaking point the density spectra was reconstructed using the entire propagated data and therefore it can be seen as a modal state value if the interval higher probability is considered.

4 Results

4.1 Sediment characteristics

The analyzed beaches consist of medium to fine sands moderately to poorly sorted. Binocular microscopic examination shows that the sediments are composed by a mixture of siliciclastic and biogenic materials mainly composed of foraminifera and shell fragments of gastropods, bivalves which sums around the 94.50% of the bulk sediment. The rest, a 5.5%, relates to quartz grains and cliff face detached fragments (Table 1).

Sand density values range from 2.68 to 2.88 g/cm^3 which are in agreement with carbonates and dolomite mineral densities. Beaches as Ma1 or Ma11 have the biggest density values because they receive a considerable input of carbonate rock fragments from cliffs. The lower density values corresponds to Ma5 with a very important foraminifera bulk component, and also to Ma10 which falls in the pre-Miocene basement domain although is quite rich in quartz and non-carbonates grains being its density lower.

Settling velocities range from 20.47 cm/s to 6.53 cm/s (Table 2). Higher velocities correspond with beach sands rich in non-biogenic and coarse grains, and the lower velocities with the biogenic components. Despite being the sand density similar between the different samples, there are differences between them according to the settling velocity. This fact can be explained by the shape and the settling pattern of biogenic grains (Paphitis et al., 2002; Smith and Cheung, 2003).

Sediment size variation for DFVP calculations are poorly understood because beach mean sediment size and mean size distribution is known to be a conservative property (Figure 4). Mean grain size and settling velocities may also vary little over time on beaches with mature sediment suites, e.g. constant water temperature and salinity, lack of fluvial sediment contributions, etc. (Anthony, 1998). Historical surveys carried in Ma 3 (Cala Millor), highlighted that if different samples are mixed there is not a significant variation between seasonal sampling in terms of mean size (Table. 3). Nevertheless beach sediment size distribution from summer is slightly coarser and less classified than winter size distribution (Fig. 4).

4.2 Nearshore waves

A seasonal energetic displacement is observed for both, propagated wave heights and peak period, due to the existence of different behaviors throughout a climatic year. The winter energetic displacement is represented by an increment in the rate of occurrence of higher crest periods and higher significant wave heights. This effect is accentuated at north oriented beaches, which are more affected by the energetic north swells. A propitious period for this situation is during fall and winter, when severe storm affect the western balearic basin. Results for the different beaches are shown in Table 2, where wave heights and wave periods correspond to the intervals with the maximum frequency in the bivariate histogram for each beach.

4.3 Morphodynamic classification

The morphodynamic state for the studied beaches has been predicted according to the model by Wright and Short (1983) where beach grain size and wave statistics were combined to calculate the Ω parameter in annual and seasonal basis. According to wave energy and sediment properties, beaches in Mallorca tend to fall in an intermediate state. Roughly, three groups of beaches can be separated according to their modal conditions. The first one corresponds to truly reflective beaches which are enclosed beaches or sheltered beaches. Ma4, Ma6, Ma10 and Ma11 which have a 75% of probability to fail below an Ω value of 1 (Figure 5). The second group of beaches present modal conditions in the intermediate states although skewed to reflective positions. Beaches as Ma1, Ma2, Ma3 and Ma8 are good examples of this behavior. Probabilities to be in a Ω value of 2 and lower than 1, are between 60 and 80% of modal states (Figure 6). This type of configuration relates with ridge-runnel and incipient transverse bars beach configuration. The rest of the beaches belong to intermediate states. Probabilities for each predictive state are sparse although

Ω values between 3 and 4 achieve near the 30% of probability, nearest Ω intervals have probabilities larger than 10% (Figure 7). This kind of beaches corresponds with semi-enclosed beaches, usually backed by a field of coastal dunes (Ma5, Ma7, Ma9 and Ma12). During fieldwork longshore, crescentic and transverse bars have been observed, and some of them were just emerged as a berm in the subaerial beach (Figure 8). Distribution probabilities allow to asses the dynamic behavior of each beach according wave climate seasonality. Thus, from figures 5, 6 and 7 we can check that as in winter the probability for a morphodynamic state are higher than in summer. For instance, in the in Ma5, Ma7 and Ma12 during winter the probability and distribution for morphodynamic state is skewed towards reflective stages. Conversely, the same beaches are towards a dissipative positions of the spectrum during summer. Another group of beaches do not present significant differences between winter and summer distributions, although the weight of the more dissipative stages is higher in winter than in summer. This can be clearly observed for enclosed beaches as Ma1, Ma2, Ma3 and Ma4, and even for very sheltered beaches as Ma6, Ma11 o Ma11 (Figures 5 and 6).

5 Discussion

The environmental setting of nearshore and foreshore in the study sites differs from many parameters described for low energy beaches according to Jackson et al. (2002). Significant wave heights are greater than 0.21 m and the mild winds, corresponding to the sea breezes regime during summer, reach values of 5 m/s and occasionally can increase up to 10 m/s (Ramis et al., 1990). From late summer to early winter, storm episodes are frequent with more intensive winds blowing with a SE or NE component, and waves can achieve significant heights of 2.5 m. Nevertheless environmental setting also differs from high energy and open ocean beaches despite appearing the diagnostic morphodynamic characteristics as nearshore bar-rip morphology, cusps and steps(Lipman and Holman, 1990; Masselink and Hegge, 1995).

Recent studies maintain the poor application of high-energy models in predicting two-dimensional morphology in low-energy environments (Eliot et al., 2006; Jackson et al., 2005; Masselink and Pattiaratchi, 2001). However, in the case of Ma3, Ma8, Ma11 and Ma12 empirical studies involving beach profile monitoring bathymetries and sedimentological analysis have found an optimal agreement between Short and Wright model prediction and beach configuration. Thus, Ma3 is a beach with a set of crescentic bars which during summer evolve to a transverse bar until the bar join the beachface (Figure 9). The Short and Wright prediction for Ma3 is a combination of ridge-runnel and reflective states, although with considerable presence of transverse bar to the subaerial beach. Ma8 is a beach characterized by a small variability according to the protection that exerts the *Posidonia oceanica* meadows, but reflective and ridge-runnel stages are quite common and cusps on the emerged beach are a conspicuous form. This configuration ties with the prediction where reflective and ridge-runnel morphodynamical states have similar maximum probabilities of occurrence. All of that, points out that, in the absence of empirical profile and bathymetry-based studies, Wright and Short's model, is a useful parameter for a gross classifications of Mediterranean beaches. However, when predictions are assessed from a seasonal point of view according to wave seasonality, Ω predictions tend to fail, mainly, in semi-enclosed beaches.

Predictions give a reflective configuration for summer season, nevertheless field observations in Ma3, Ma5, Ma7 and Ma12, points up that beach profile slope is smoother (slopes between 0.018 and 0.027). Diagnostic features, as transverse and rhythmic bar corresponding to more dynamic states, are also present (Figure 8). The reason for this situation is that the Wright and Short model does not incorporate sea breeze effects on beach morphodynamics which seems to drive beach dynamics during the relative mild summer wave conditions. The sea breezes induces changes in the incidents wave field that may affect beach morphology and the associated processes, inducing longshore transport and overlaying series of daily mini-storm cycles characterized by erosion in the afternoon and beach accretion acurring the rest of the day (Masselink, 1996; Masselink and Pattiaratchi, 1998).

To check this hypothesis in 2004 during the summer sea breeze and winter conditions, a field survey was carried out in Cala Millor (Ma3). In this study, a wave gage measured wave height at 5 m depth simultaneously with the data provided at deep water by the WAM model at the same HIPOCAS point used for the analysis. This data, once propagated to the beach, were in 83% of cases a 44% smaller than the wave height measured by the wave gage. Conversely, during winter, differences between wave heights propagated from the numerical model and the measured ones are only up to a 20%. This lead to the conclusion that local sea breeze which is not included in the deep water wave model has to be taken into account to proper characterize morphodynamically Mallorcan beaches.

Major differences between beaches seem to be related to geological factors. The geological and physiographic framework controls the spectrum and the angle of incident waves; in fact enclosed beaches present less dynamic states than semi-enclosed beaches.

6 Conclusions

The morphodynamic model of Wright and Short has been used to classify beach morphology on Mediterranean low-energy beaches using 44 years of wave data propagated to the wave breaking depth as well as detailed sediment analysis for each beach. Results relate to the probabilities for modal morphological state in annual and seasonal basis. The Ω parameter leads to separate Mallorcan beaches in three major groups according to the geological framework configuration. Thus modal reflective beaches relates to enclosed and sheltered beaches (a), reflective beaches lightly skewed to intermediate states are common in enclosed beaches exposed to main wave energetic directions (b), and intermediate beaches are hosted in semi-enclosed localities. Other works pointed out the discrepancies between predicted and observed beach states under various conditions. The analysis presented are in agreement for a gross annual classification as well as for winter predictions, when waves have large peak periods and bigger significant wave height. However, Ω fails in summer predictions because it does not incorporate the effect of summer sea breezes which exert an important influence in beach behavior when the action of sea waves is negligible. For this reason reflective stages are over represented respect to the more dynamic features observed on the beaches, including transverse bars, cusps and rips. The Wright and Short model rely largely on dynamic factors, but it just introduces averaged wave statistics and sediment size. Our observations show that, for Mediterranean beaches, further research is required in order to associate the summer sea breezes and associated hydrodynamics to elucidate the controls on beach morphology classification (Figures 5 and 6).

7 Acknowledgments

Financial support from the Balearic Island Government is greatly acknowledged (UGIZ project). Support in experimental sediment characterization from J. Guillén from CMIMA (CSIC) and J.J. Fornós from UIB is greatly appreciated. Field support from B. Casas and P. Balaguer is also acknowledged. Critical comments from Dr. E. Anthony an two anonymous referees more have improved substantially the first manuscript.

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Code	♯ samples	Mean (μm)	Sorting	Skewness	Kurtosis	Type of sediment	Lithoclasts(%)	Bioclasts(%)	Physiography frame
Ma1	7	574.740	1.568	-0.107	0. 976	coarse sand	10.29	89.71	Enclosed
Ma2	10	355.950	1.584	0.083	1.133	medium sands	0.88	99.13	Enclosed
Ma3	15	241.484	0.744	-0.116	1.018	medium/fine sands	1.53	98.47	Semienclosed
Ma4	4	454.025	1.557	0.029	0.948	medium sands	0.76	99.24	Enclosed & Sheltered
Ma5	15	215.780	1.619	0.118	1.197	fine sands	1.64	98.35	Semienclosed
Ma6	4	374.375	1.814	0.040	0.966	medium/fine sands	1.31	98.69	Enclosed & Sheltered
Ma7	20	196.984	1.614	0.090	1.029	fine-very fine sands	4.32	95.68	Semienclosed
Ma8	12	242.592	1.648	0.193	0.965	fine sands	4.47	95.53	Enclosed
Ma9	8	207.225	1.677	0.118	1.228	fine sands	11.76	88.24	Semienclosed
Ma10	8	298.225	1.803	0.196	1.073	medium -fine sands	28.06	71.94	Enclosed & Sheltered
Ma11	4	481.650	1.546	0.112	0.748	medium sands	3.57	96.43	Enclosed
Ma12	15	247.50	1.66	0.15	0.88	fine sands	1.70	98.30	Semienclosed

Table 1

Physiography frame and sediment textural and compositional properties for each study sites

		Summer *(April-September)*		**Winter** *(October-March)*				
Code	Study Site	$H_b(m)$	$T_p(s)$	$H_b(m)$	$T_p(s)$	$D_{50}(\mu\text{m})$	$w_s(\text{cm/s})$	$\rho(\text{g/cm}^3)$
Ma1	Cala Mesquida	0.93	4.73	0.81	4.36	600.590	20.47	2.87
Ma2	Cala Agulla	0.27	4.48	0.54	4.84	346.000	11.80	2.78
Ma3	Cala Millor	0.21	4.72	0.42	7.03	272.307	8.75	2.79
Ma4	Estany d'en Mas	0.60	4.84	1.00	5.33	450.425	15.60	2.78
Ma5	Es Trenc	0.18	4.00	0.75	4.12	207.840	6.78	2.67
Ma6	Cala Pi	0.24	4.36	0.48	5.93	352.925	12.21	2.87
Ma7	S'Arenal	0.27	3.75	0.90	4.12	199.737	6.18	2.78
Ma8	Magalluf	0.33	3.75	0.39	3.75	231.858	7.74	2.81
Ma9	Sant Elm	1.00	4.12	1.09	4.36	200.813	6.53	2.81
Ma10	Platja d'en Repic	0.15	4.36	0.18	4.48	271.888	9.11	2.68
Ma11	Cala Molins	0.54	4.00	0.57	4.24	465.125	16.14	2.88
Ma12	Es Comú de Muro	0.12	4.48	0.57	5.69	239.475	8.06	2.74

Table 2

Waves and sediment parameters for the Wright and Short Ω calculations

8 Figure captions

Figure 1. Geographic location of the study area (a). Position of the HIPOCAS wave data (squares) and beaches studied (circles) (b).

Figure 2. Agreement between sediment fall velocity computed by empirical methods and predictive Gibb's equation incorporating empirical sand density.

Figure 3. Standard deviation(circles) and mean (squares) from the log-normal distribution of H_b at the beach (only shown one point).

Figure 4. Seasonal sediment size distribution at Cala Millor (Ma3).

Figure 5.Probabilities of occurrence of beach states for enclosed and sheltered beaches of Estany d'en Mas (Ma4), Cala Pi (Ma6), Platja d'en Repic (Ma10) and Cala Molins (Ma11). Stars indicate the modal state.

Figure 6.Probabilities of occurrence of beach states for enclosed beaches of Cala Mesquinda (Ma1), Cala Agulla (Ma2), Cala Millor (Ma3) and Magalluf (Ma8). Stars indicate the modal state.

Figure 7.Probabilities of occurrence of beach states for enclosed beaches of Es Trenc (Ma5), s'Arenal (Ma7), Sant Elm (Ma9) and Es Comú de Muro (Ma12). Stars indicate the modal state.

Figure 8.Fieldwork observations of diagnostic beach features during summer season when Wrigth and Short's model predict reflective states. At left, a bar joined to the subaerial beach during night at Es Trenc (Ma5). Children are playing just on top. At right cusp at horns at s'Arenal (Ma7).

Figure 9.Cala Millor (Ma3) aerial photography. Note the configuration of transverse bars along the coastline as well as rips and cusps. Dark areas correspond to *Posidonia oceanica* meadows.

9 Table captions

Table 1.Physiography frame and sediment textural and compositional properties.

Table 2.Waves and sediment parameters for the Wright and Short Ω calculations

Table 3. ANOVA test evaluating Cala Millor (Ma3) seasonal sediment size distributions variability. The statistics conclude that there is not a significant difference between mean beach size seasonal distributions.