On the development of large-scale cuspate features on a semi-reflective beach: Carchuna beach, Southern Spain

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Abstract

Carchuna beach, located on the southeast coast of Spain, has a series of natural permanent horns of time-dependent horizontal dimensions, which do not appear to be periodically spaced, and do not propagate alongshore. Until at present, it has been assumed that the permanency of these forms is related to the existence of bed rocks; nevertheless, analysis of the configuration of the depth contours and the bed sediment composition does not justify this hypothesis. This paper explores the formation of cuspate features by the effects of the wind wave dynamics and their development by nearshore circulation and infragravity waves, including edge waves. Three levels of wave energy flux conditions are considered. In all likelihood, wave refraction of severe storms on submerged fluvial valleys is the main cause for longshore variation of breaking wave height, which seems to be one of the initial conditions necessary for the cuspate to initiate. Moderate storms enhance the deepening of the embayments, whereas mild sea states are able to maintain the features by self-organization. The possibility of the occurrence of edge waves due to the non-linear interaction between the components of a gravity wave spectrum approaching the shore under moderate storm conditions is explored. Preliminary analysis of video images taken by an Argus station seems to confirm this hypothesis.

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1. Introduction

Carchuna beach, bounded by Cape Sacratif and Carchuna horn, is ca. 3900 m long with an approximately W–E alignment, showing cuspate features (Figs. 1 and 2). Its plan form commonly shows five cusps with horns spaced 850, 650, 850, 475, and 1710 m respectively (Fig. 2, H-1 to H-6). Cape Sacratif (west boundary of the beach) represents the first horn of the cuspate system. The extent of the other four horns seaward depends on the wave climate. Analysis of aerial photographs since 1956 and images from a video-camera station installed in November 2002 does not reveal a significant change in the position of the horns, although their cross-shore length and width may vary in time.

Rosen (1975) studied the set of cusps at the end of the beach.
that they are both erosional and depositional, and caused by reversals in wave direction that result in the erosion of the embayments and deposition on the horns of the cusps. Other mechanisms that have been mentioned in the literature on the topic are eddies, which form on the lee side of the horns and induce sediment to be transported back to the horns, or seiches (long-period standing waves; Wilson, 1972) that have nodes or antinodes at which the horns can form. Since the first observations by Munk (1949) and Tucker (1950), the existence of these morphological patterns have often been related to infragravity waves, particularly to edge waves, which generate beach cusps with a spacing of half their wavelength (Bowen and Inman, 1971; Guza and Inman, 1975).

A common and still debated question is whether the topography induces the circulatory system, or whether it is the circulatory system that redistributes sediments and builds up the bottom configuration, with the consequent interaction between the morphology and the currents. Based on observations made by Sonu (1972), a theory was derived which argues that an irregular topography always controls the water circulatory system. As a result, the circulatory system would be generated by the existing topography. However, according to Noda (1974), there is no explanation for topography generation if the circulatory system is not assumed to be responsible for it. Moreover, rip currents can also be generated on beaches without initial bottom irregularities, for example, due to the interference of two incident wave fields (Dalrymple, 1975) or as a result of a bed-flow instability (Barcilon and Lau, 1973; Hino, 1975).

Other authors have analyzed the possibility that these rhythmic formations are the result of inherent instabilities of the morphodynamic equilibrium, as studied by Werner and Fink (1993), or due to the coupling between small perturbations on a reference uniform bottom topography and the disturbances thereby produced on the water motions (Deigaard et al., 1999). The previous existence of a rhythmic topography is not necessary for any of these explanations, but rather an initial bed or water surface perturbation.

Another analysis of the problem focuses on the relation between the wave angle approach and
the shoreline orientation (Ashton et al., 2001). It is assumed that alongshore sediment transport smoothes the coastline, but this is only valid when angles between waves and the shoreline are small. However, when these angles are sufficiently large, small perturbations of a straight shoreline will grow.

The objective of this paper is to analyze the generation and permanence of the large-scale cuspatc features existing at Carchuna beach. It seems that alongshore variation of wave refraction induced by submerged fluvial valleys is the main source of their initial formation. Nevertheless, other mechanisms may also be important, not only in their generation but in their maintenance or reinforcement. The first section of this paper is a description of the physical environment and date; next, the methodology is presented: wave propagation and wave breaking are evaluated as a step to a discussion on nearshore circulation patterns induced by different intensities of wave breaking. Subsequently, the influence of wave direction on the evolution of features is considered, and finally the selective mechanisms of the generation of infragravity waves and the enhancement of some edge wave modes by the cuspatc features are discussed.

2. Physical description and data

Carchuna beach is located on the southern slope of the Sierra Nevada, facing the Alborán Sea. The area of study is defined by the hydrological basin, beach, and continental shelf down the $-200$ m isobath.

The geologic setting is formed by two groups of clearly differentiated materials: pre-orogenic ones, with a high degree of metamorphism that constitutes the Alpujarrian nappies (Blumenthal, 1935; Copponex, 1959; Boulin et al., 1970; Aldaya, 1969, 1970, 1981) upon which more modern (Holocene) materials, constituting alluvial deposits, are placed.

The main erosional agents are rain-induced runoff and the resulting sediment yield. Rainfall and the existence of an important surface runoff are the principal agents that can model the surface. Rainfall on the coast of Granada is scarce, averaging 350–400 mm/yr, and corresponds to a semi-arid area (Pulido, 2000). Its temporal distribution is irregular, especially during the dry season (July–September) when torrential rains often occur.

The short streams which discharge in Carchuna beach have their sources in the high mountainous relief of the Alpujarrian complex. The hydrological basins of these rivers are characterized by steep relief; the foothills over Carchuna beach and neighboring areas exceed a 40% slope with non-cohesive material covering the rock substrate. The hillsides show frequent outcrops of rocks as a consequence of the high erosion rate.

The maximum tidal range is $1.1$ m with a mean value of $0.6$ m. South Atlantic and South Mediterranean storms generate wind waves under limited fetch conditions (approximately $300$ km) and average wind speed $u_{10}$ is $18$–$22$ m/s. The most energetic wave climate approaches are E, ESE, SW, WSW, and SW with probabilities of occurrence in a mean year given in Table 1. This table also shows the conditional probability to wave

| Sector | Probability (%) | Pr[$\theta$|Hs < 1] | Pr[$\theta$|Hs < 1–2] | Pr[$\theta$|Hs > 3.5] |
|--------|----------------|-------------|----------------|-------------|
| E      | 21.01          | 34.2        | 43.23          | 0.70        |
| ESE    | 2.22           | 51.6        | 32.17          | 0.19        |
| SW     | 6.01           | 46.43       | 39.11          | 0.75        |
| WSW    | 14.37          | 31.45       | 41.35          | 1.45        |
| W      | 26.72          | 28.02       | 41.39          | 2.45        |
| Calms  | 29.67          |             |                |             |
height, with a mean period in the range 7–9 s, obtained from the annual sea state regime.

Under South Atlantic storm conditions, swell waves generated in the Gulf of Cadiz propagate through the Strait of Gibraltar. These swell waves impinge the coast simultaneously with the local wind waves, but at slightly different angles.

The analysis of the bathymetry is significant for the objectives of this study (Fig. 2). First of all, seaward of Cape Sacratif, the existence of a submerged fluvial valley or submarine canyon, known as Jolucar Canyon, can be identified. From there, the seabed contour offshore Carchuna beach is straight and convergent toward Carchuna horn, following the plan form of the alluvial plain and providing an insight as to a previous emplacement of the main stream mouth. As in other alluvial plains in the surrounding area, this change of location is related to anthropogenic action (mainly due to the recent intensive agricultural activities that need water redistribution). For further applications the following three zones can be distinguished:

**Zone 1.** Foreshore and nearshore extending from the coast to approximately the 25 isobath.

Four beach profiles are shown in Fig. 3; beach slope increases from west to east (from $\tan = 1/30$ to $\tan = 1/8$) and beach alignment is approximately west–east. The grain size in the beach is heterogeneous, varying from fine to coarse or very coarse sand with cobbles (Fig. 4). The sediment is

![Fig. 2. Area of study. Distances between horns are given and three zones can be appreciated in the bathymetry.](image-url)
composed of the clast of metamorphic materials proceeding from the surrounding relief, mainly schists and quartzites. The overall morphodynamics of the beach is reflective with waves breaking in collapsing or plunging.

**Zone 2.** Continental shelf extending from the nearshore down to a water depth of approximately 75 m. A gradual adjustment of contour lines can be seen as water depth increases. In zones 1 and 2 the sediment over the shelf is characterized by massive sands and gravels changing upward to prodeltaic deposits. These deposits form homogenous sequences of heterometric gravels and poorly classified sands (Hernández-Molina et al., 1993).

**Zone 3.** Continental slope extending from 75 m down to (at least) 500 m water depth (deep water for wind waves). The shelf break is between −75 and −100 m water depth. Next to Jolucar Canyon the gradient of the continental slope is more abrupt than in the eastern region. The upper slope is characterized by sediment flows proceeding from the outer shelf region which are channeled through the small submarine canyons such as Jolucar Canyon (Giermann et al., 1968; Alonso and Maldonado, 1992; Pérez-Belzuz, 1999).

The streams flowing into Carchuna beach have concave longitudinal profiles with slopes decreasing toward the mouth. Their main courses extend below the mean sea level approximately down to 75 m depth (Fig. 5).

These profiles show three different regions: (1) the upper region extending from 300 m altitude down to 40 m; (2) the middle region, where the stream slows down and discharges water and solids into the sea, extending to between +40 and −75 m; and (3) the offshore region where the slope is steep again. As can be seen, the upper and offshore regions are quite similar (Fig. 5, regions 1 and 2), with slopes of about 20%.

As a result of the fluvial and marine processes, the offshore bathymetry opposite Carchuna beach is characterized by straight and convergent contours toward Carchuna horn, furrowed transversely by several submerged valleys (Fig. 2), Jolucar Canyon being the most prominent. As previously described, the area studied constitutes a physiographic unit. The presence of Jolucar Canyon and the coarse sediments at Carchuna horn suggests that the sediment exchange through the west and east boundaries of the unit is almost negligible. Moreover, the actual sediment supply from the local streams is also negligible, because of the construction of a large number of greenhouses and the construction of terraces in their beds to divert water for irrigation.
Nowadays, it can be concluded that there is no sediment input to Carchuna beach. Because of the large grain sizes, which armour the foreshore, as well as the mild annual wave energy flux, the beach is eroding slowly, but consistently.

3. Methodology

3.1. Wave propagation and wave breaking in the study area

A parabolic numerical model (Kirby and Dalrymple, 1983) which includes wave breaking was used to analyze wave propagation under different initial wave conditions. It is a weakly non-linear combined refraction and diffraction model, which incorporates shoaling, refraction, energy dissipation, and diffraction effects. It is solved in finite difference and is applied with two nested grids with a resolution of 5 m for the one closest to the shore. The results are shown in Fig. 6, where vector length is proportional to the wave height at the point considered, and its direction indicates the direction of propagation.

Fig. 6 shows the propagation pattern of a sea state with significant wave height of 1 m, and a wave period of 8 s propagating from the west. It can be observed that the presence of the canyon and the submerged fluvial valleys produce local convergences and divergences of the wave energy flux; waves converge toward Cape Sacratif, and energy concentration takes place in the embayments. The propagation coefficient, defined as the ratio between the deep water wave height and a representative wave breaking depth at Cape Sacratif and at the embayments was evaluated.

To analyze the propagation pattern for the most energetic sea states in the study area, the alongshore evolution of the propagation coefficient for waves coming from both the west–south and the south–east was obtained. Two levels of wave energy, 1 and 4 m significant wave height, were considered. The first one is representative of mild and moderate sea states (50% of exceedance). The 4-m wave height in deep water (90% of exceedance) represents storm conditions in the area.

Figs. 7 and 8 show the results of the propagation coefficient (data were averaged alongshore $2 \times 2$ over 50 m) for west–south and south–east, respectively.
Fig. 7a shows the longshore distribution under westerly waves with wave height oscillating and decreasing eastward, getting maximum values at both sides of Cape Sacratif and westward of the horns. For a mild wave climate, and irrespective of the incoming wave direction, the convergences of energy flux take place approximately at the same locations.

Fig. 7b represents the longshore variation of the dimensionless wave height evaluated at a representative wave breaking depth of storm conditions. It can be seen that these results are similar to the previous ones, but the maximum and minimum values are less pronounced. Between H-2 and H-3, the values of the propagation coefficient curves of storm waves are significantly closer on the three wave directions analyzed than under mild conditions because waves break inside the embayments. It can also be observed that between H-4 and H-5 wave energy concentration is higher under storm conditions than for mild ones because H-4 provides less protection. Finally, it should be mentioned that the range of variation of the propagation coefficients between H-1 and H-2 is wider for mild conditions because wave breaking takes place inside the embayments.

The alongshore variation of the propagation coefficients for easterly waves is represented in Fig. 8a,b. It can be observed that the energy flux concentration takes place eastward of the horns, with lower differences between maximum and minimum values than those produced by the westerly waves. Again, those maxima are shorter for storm conditions than for mild ones.

3.2. Nearshore circulation induced by wave breaking

Attending to the mechanism generating cuspate features, swash cusps and surf zone cusps are traditionally considered (Inman and Guza, 1982). While the first ones may be generated by the swash and backwash excursion over the beach face and berm (Guza and Bowen, 1981), the second ones may be formed by the currents of the nearshore circulation cells (Bowen and Inman, 1969), whose typical wavelengths can vary between 1 m on lakes to hundreds of meters on beaches exposed to the ocean (Inman et al., 1971), which are often called giant cusps (Komar, 1971).

However, none of these mechanisms is responsible for the generation of Carchuna. Rather, the mechanisms involved in the development, mainte-
nance, enhancement or attenuation, depending on wave climatic conditions, are related to the surf zone circulation and they are therefore similar to the one for surf zone cusps.

In order to study the development of the cuspate features, it is necessary to know whether these features can last under the continuous temporal variation of the wave climate. Among other factors, cuspate evolution has to be related to the nearshore circulation induced by wave breaking. In this section that circulation is analyzed for three wave energy flux intensities, representative of severe (rare), moderate (frequent) and mild (habitual) conditions.

3.2.1. Severe storm conditions

Bagnold (1940) described the circulatory system in a cuspate shoreline for waves approaching the beach normally, and where wave breaking occurs evenly alongshore in a straight line. In his circulation model, wave surge piling up on the horns is divided into two diverging streams towards the adjoining embayments. In the middle of the cuspate arc, flows coming from both sides converge,
resulting in a stronger return flow through the center of the embayment. Sediment eroded in the arc is deposited outside the bay where the central stream loses strength, causing the bathymetric lines seaward of the breaker line to adopt a cuspate form alongshore symmetric to the shoreline. This new bathymetric configuration prevents wave breaking to be uniform alongshore.

The depth of closure at Carchuna beach can be estimated to be in the range of \( h \sim 6-7 \) m. The bathymetric contours are approximately parallel (Fig. 2). Generic beach profiles, taken at an embayment and at a horn, and identified respectively as B1 and B2 in Fig. 9, are parallel seaward from the crossing location. Intriguingly enough, the crossing point is located approximately at the depth of closure. The constant difference of about 0.5 m in the deeper parts of the profile is partly due to the slightly alongshore convergent bathymetry.

Thus, to have uniform alongshore wave breaking, the most energetic sea states have to occur \((H_s > 3.5 \text{ m}, \ T_s > 7-9 \text{ s})\). Because they generally occur with a large wave period, the incidence angle is strongly corrected by refraction. Under such conditions, Bagnold’s model seems to be applicable. Since wave breaking approximately occurs evenly alongshore (plunging or collapsing break-
ers), the nearshore circulation would then adjust to Bagnold’s scheme: eroding horns and transporting material towards the center of the bay. If the storm lasts long enough, the system seems to arrive at an equilibrium geometry: an alongshore uniform coastline.

It should be underlined that this circulation pattern is almost identical to the swash mechanism for beach cusp initiation and maintenance (Dean and Maurmeyer, 1980) and like Bagnold’s model, only explains the development of the so-called equilibrium geometry. The basic concept of this type of mechanism is that the interaction of the cusp topography and the breaking-induced flow causes circulation cells that tend to construct and then perpetuate the cuspate feature. Moreover, to initiate the beach cusp, a small perturbation of elevation on the beach face and a synchrony between the incoming wave period and the natural swash period are necessary.

3.2.2. Moderate sea state conditions

This section relates the nearshore circulation to moderate sea states, $H_s = 1–2$ m and $T_p = 6–8$ s impinging obliquely. As can be checked by the refraction–diffraction model, westerly waves propagate well inside the embayments (tan = 1/50) before breaking in plunging. Higher breaking waves occur inside the embayments than on the horns, where waves are breaking in collapsing. Thus, due to their obliquity and the set-up gradient inside the embayment, an alongshore current towards the horns is generated, transporting sediments and reinforcing the submerged topography of the horn. The intermediate sea states are able to erode the embayment, increasing the curvature of the arc and supplying sediment to the circulation system.

Similarly, under waves arriving from E–ESE, the alongshore current flows from the center of the embayments towards the western horns. For those directions, the wave height gradients are not so significant, and the currents are probably weaker than those generated by the westerly waves. In other words, easterly waves are not as effective as westerly waves to build up cuspate features.

This circulatory scheme, in contrast to Bagnold’s model, reinforces and enhances the embayment-horn systems. In principle, as long as the sea state characteristics last, this mechanism does not stop since alongshore variation of wave height increases as the horn grows. This could be the reason why after the occurrence of intermediate storms, it can be observed that the horns have advanced toward the sea. Only the variation of the wave energy flux, magnitude or direction can stop this cuspate feature from further development.

3.2.3. Mild sea state conditions

Finally, under mild sea states, ($H_s < 1$ m, $T = 4–6$ s) waves propagate inside the embayment, breaking on the steep shoreface (tan = 1/10), with strong plunging and collapsing breakers (Iribarren number, $I_r > 2$). On the other hand, waves spill and plunge (tan 1/20, and $I_r < 1$) on the horns. At both sides of the horn, an alongshore current towards the bay is generated, smoothing the horns. The sediment transported to the bay produces a seaward movement of the embayment, which provokes a seaward advance of the wave breaking. This changes the breaking obliquity, and has the effect of reducing the Iribarren number, changing the type of breaking, and generating a current towards the horns.

Depending on the temporal sequence of incoming wave energy (height and period), the longshore flow moves the sediment into the embayment or to the horns, causing cuspate features to develop through a combination of positive and negative feedbacks. When incipient changes occur on the embayment, more deposition takes place to form the horns, whereas more fully formed embayments tend to retard deposition and erosion. In other words, there is a self organization that is quite robust and not strongly af-

![Fig. 9. Profiles in points and embayments.](MARGO 3329 20-6-03)
fected by small changes in the incoming wave energy flux, as long as it is mild.

3.3. Cuspate evolution and wave incidence angle

So far, the evolution of the cuspate has been analyzed in terms of the magnitude of the wave energy flux. This section addresses the dependence of cuspate evolution on angle of approach.

On a periodic coastline, depending on the wavelength and the angle of wave incidence, oscillatory behavior can be enhanced or suppressed (Larson et al., 1987). If the initial shoreline is assumed to be:

\[ y(x, 0) = B \cos(\lambda x) \]

where \( B \) is the initial amplitude of the shoreline perturbation, \( \lambda \) is its alongshore wave number, and the mean beach position is located at \( y = 0 \). The solution to the one-line equation is periodic alongshore (the \( x \) direction):

\[ y(x, t) = B \exp(-G \lambda^2 t) \cos(\lambda x) \]

where \( G \) is referred to as the longshore diffusivity, showing that the amplitude of the perturbation approaches zero exponentially with time (\( t \)).

The diffusivity coefficient depends on the \( 5/2 \) power of the wave height, the cosine of the double of the wave incidence angle, \( \theta_b \), and inversely on the total depth (depth of closure plus the berm height). For a small or moderate angle of incidence, the one-line model gives that the cuspate should be smoothed. However, for \( \theta_b > 45 \) the sign of \( G \) changes. This results in an exponential increase of the periodic shoreline features, irrespective of their wavenumber and incoming wave energy flux.

Given the orientation of the beach and wave refraction, it is hard for energetic sea states to impinge on Carchuna beach with such large angles. Only sea states from the west or from the east, generated by winds parallel to the coast (associated with South Atlantic or South Mediterranean storms), can generate the prescribed conditions. Additionally, local waves generated under diurnal sea breeze conditions with small wave periods can satisfy the above requirements. Such conditions generally occur in fair weather.

It can be concluded that although the enhancement of the cuspate features can occur under such conditions, these are frequently insufficient to justify the permanence of the features over several years. The following section explores the permanence mechanisms related to the development of infragravity oscillations.

3.4. Infragravity oscillations at Carchuna beach

Hasselmann (1962) showed that the non-linear interaction between the components of a gravity wave spectrum approaching the shore can force secondary infragravity waves. When wave breaking of the incident swell takes place, these forced oscillations are released as free waves (Longuet-Higgins and Stewart, 1962), propagating towards the shore, and they are reflected back at the shoreline. For certain angles of incidence, these shoreward propagating waves can be radiated to deeper waters as leaky waves are reflected back towards the shore at a given trapping depth. In the latter case, waves are effectively confined at the shore, as is the case of edge waves.

Wave spectra arriving at Carchuna beach during moderate storm conditions usually show two peak harmonic frequencies, \( f_1 \approx 0.14 \) Hz and \( f_2 \approx 0.17 \) Hz, with different directions of propagation in deep water, \( \theta_1 \approx 245-270^\circ \) and \( \theta_2 \approx 200-230^\circ \), corresponding to different generation conditions. The largest peak belongs to westerly waves, which are usually generated in the Gulf of Cádiz, and propagates through the Strait of Gibraltar, whereas the shortest one travels in southwestern

![Wave spectrum at Cape de Gata-Baja (Alborán Sea) (December 23, 2000, 5:00)](MARGO 3329 20-6-03)

Fig. 10. Typical wave spectrum in the Alborán Sea under storm conditions.
direction, and is associated with waves generated in the Alborán Sea.

The non-linear interaction between these two more energetic components, according to Hasselmann’s theory, would excite a secondary oscillation at a frequency, $f_3 = f_2 - f_1 \approx 0.03$ Hz, with a vector wave number, $k = k_2 - k_1$, where $k_1$ and $k_2$ are, respectively, the vector wave numbers of the wave components. For the case in which its modulus approaches the linear theory wave number, the excitation is resonant and the amplification factor grows, theoretically, without limits.

A scalar buoy located at Cabo de Gata, 40 miles east of Carchuna, has been operating since 1997. The recorded data represent the wave climate along the continental shelf of the Alborán Sea. Moreover, the WAM model has a hindcasting point near Carchuna. Fig. 10 shows the wave spectrum of the water surface elevation recorded during a storm that occurred on the 23 December, 2000, at 5:00 a.m. At that time, WAM predicts a peak wave direction of 260° and a wind mean direction of 230°.

For those wave components, Fig. 11 shows the cross-shore depth evolution of the linear and the forced oscillation wave numbers. Both curves approach as water depth decreases, converging at a depth of around 1.5 m.

In order to estimate the depth at which most of the waves propagating as incident swell are expected to break, the two-peaked spectrum was split into two parts, one from $f = 0.1$ Hz to the frequency $f = 0.16$ Hz, and the second one from $f = 0.16$ Hz to $f = 0.23$ Hz. Evaluating at the beach $H_{rms,i}, i = 1.2$ from the zero-order moment of these spectra, propagated with their corresponding peak frequencies, a root mean square wave height $H_{rms} = \sqrt{H_{rms,1}^2 + H_{rms,2}^2} = 1.2$ m is obtained. Considering a breaking index $\gamma = 0.8$, this sea state has a breaking depth, $h_b = 1.5$ m, which coincides with the converging depth of the wave number curves (Fig. 11).

Therefore, a forced oscillation with a period around 33 s would be released at breaking under resonant conditions, with a wavelength of about 125 m. The direction of propagation of the released free wave is $\theta \approx 192°$.

The trapping depth for such a free wave is $h_t = 28.8$ m. Interestingly enough, this depth is approximately the same as that at which the shelf profile sharply changes the slope. This wave en-

![Fig. 11. Evolution of the wave number of the forced oscillation with water depth.](image)

![Fig. 12. Convergent bathymetry used for the analysis of edge wave propagation.](image)
ergy confined to the shore up to depth $h_1$ is expected to propagate in the longshore direction as an edge wave.

It seems that the necessary circumstances for edge waves to occur at Carchuna beach are found under moderate storm conditions.

3.4.1. Propagation of edge waves

The propagation of edge waves at Carchuna beach has been explored. Because of the small radius of curvature of the contour depths, it can be assumed that waves are propagating alongshore on a straight beach, with a convergent bathymetry (Fig. 12) and are partially reflected back and forth at Cape Sacratif and Carchuna horn.

Fig. 13 shows the evolution along the convergent bathymetry of the wave lengths of the modes for the secondary wave forced by the two swell components considered above. While the higher modes grow rapidly alongshore, the variation of the first mode is very slow. This result reinforces the possibility that low mode edge waves, which are indeed the likeliest to occur, can smoothly adapt themselves as they propagate alongshore.

Beach materials at Carchuna beach are made of fine sand and coarse gravels. Partial reflection of edge waves of wave length $L$ at horns would build up rhythmic beach lobes with wave lengths of approximately $L/2$ (see Baquerizo and Losada, 2001; Baquerizo et al., 2002).

On the other hand, the results presented in Section 3.2 provide a solid basis for the hypothesis that at Carchuna beach the convergence of moderate wind wave energy fluxes is a mechanism for the maintenance of the horns. Under such conditions they would act like reflecting structures that select the modes of the edge waves. Moreover, such waves may be important in the development of smaller beach cusps between horns.

Fig. 14a presents the shoreline between H-5 and the middle point (Mp) of the last embayment, obtained from Argus time exposure images taken on January 20 (2003). Smaller beach cusps of lengths around 60, 120 and 200 m show up as is indicated in Fig. 14b, which corresponds to the linearly detrended shoreline of the stretch of the coast starting at H-5. In order to assess the presence of such wavelengths in the shoreline, a fast Fourier transform was performed.

Fig. 14c shows the amplitude of the component oscillations in terms of their inverse wavelengths. It can be seen that oscillations about 200, 135, 115, and 65 m, which are close to the ones observed in the shoreline (Fig. 14b), are present with a higher energetic content than other components. The 65-m length is about half of the 125-m length of the possible free trapped oscillation analyzed in Section 3.4, which is indeed close to the wavelength of the first edge wave mode in Fig. 13. Other wavelengths are also in the order of magnitude of $L/2$, where $L$ is the wavelength (H-5, Mp) of the stretch of the coast, as can be seen in Fig. 13.

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**Fig. 13.** Alongshore evolution of the edge wavelength.

**Fig. 14.** (a) Shoreline between H5 and the middle point (Mp) of the last embayment. (c) Spectral components of the linearly detrended stretch of the coast shown in (b).
4. Future work

In the previous sections several mechanisms related to large-scale cuspate feature generation and permanence have been discussed. In fact, one single process is not sufficient to explain the morphology. Instead, it seems that there are several mechanisms which can help to give a coherent and consistent explanation.

In order to further explore and explain which mechanisms are responsible for large-scale cuspate feature development and permanence, a three-video camera station was installed at Cape Sacratif in November 2002 (based on Argus Technique; e.g. Lippmann and Holman, 1989). The resulting analysis will be focused on shoreline mapping and wave propagation. The analysis is aimed at obtaining: (1) the relationship between weather sea state conditions and wave propagation patterns; (2) wave energy concentration alongshore; and (3) the circulatory system and horn shape response. The importance of this field work is confirmed by the preliminary analysis of some images as shown in the previous section, Fig. 14.

5. Conclusions

Carchuna beach, bounded by Cape Sacratif and the Carchuna horn, is ca. 3900 m long with an approximately west–east alignment, showing cuspate features (Figs. 1 and 2). Its plan form commonly presents five cuspatates with horns spaced 850, 650, 850, 475, and 1710 m, respectively (Fig. 2, H-1 to H-6). In relation to their generation and permanence, the following conclusions may be drawn.

(1) It seems that under severe storms ($H_s > 3$ m, $T = 7–9$ s) the alongshore variation of wave refraction induced by the submerged fluvial valleys is the main source of initial formation of the cuspate features. Moderate sea states ($H_s = 1–2$ m, $T = 6–8$ s) generate a circulatory system that reinforces the horn and the embayment shape. Apparently, the only limit that this mechanism has is the storm duration. Erosion of the embayment supplies the material that causes the horns to protrude seaward. Mild and low energy sea states ($H_s < 1$ m, $T = 4–6$ s) may develop a self organization that is quite robust and not strongly affected by small changes in the incoming wave energy flux, maintaining the cuspate features in a dynamic equilibrium. For cusp features to grow or to disappear, a significant change in the energy flux intensity is needed.

(2) For this specific case, it seems that wave direction is not relevant for the development of the cuspate system.

(3) Other mechanisms may also be important, not only in their generation but in their maintenance or development. Under moderate wind wave energy conditions, non-linear interaction between the components of a gravity wave spectrum approaching the shore can force secondary infragravity waves, which would be released at breaking. There is trapping of free waves at a depth at which the shelf profile sharply changes its slope. This wave energy when confined to the shore is expected to propagate in the alongshore direction as an edge wave. Research results illustrate the possibility that the lower edge wave modes, which are indeed the likeliest to occur, can smoothly adapt themselves as they propagate alongshore.

(4) Partial reflection of edge waves of wave length $L$ at horns would built up rhythmic beach lobes with wave lengths of approximately $L/2$, (Baquerizo and Losada, 2001). These results provide a solid basis for the hypothesis that at Carchuna beach, the convergence of moderate wind wave energy fluxes may be a mechanism for the maintenance of the horns. The spectral analysis of a stretch of coastline confirms the existence of smaller beach cusps whose wavelength $\lambda$ is about $L/2$ of the lower edge wave modes.

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