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Short and medium-term evolution of a coastal sector in Cadiz, SW Spain

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Abstract

The present paper is a combined study on the medium and short-term evolution of the littoral between Chipiona and Rota (SW Spain). The analysis of coastal evolution over a period of 24 years (i.e. medium-term), was carried out using six, well temporally spaced, photogrammetric flights. Cliff top and dune toe were used as shoreline indicators to solve problems related to the use of watermark in tidal environments. Short-term littoral variations were monitored monthly by means of an electronic theodolite over a period of 2 years. The width variations of the dry beach were surveyed by always using a constant, average value for the mean sea level position derived from the numerous surveys carried out. The obtained data was representative of both seasonal and annual variations.

Over medium-term, most of the littoral recorded erosion, while accretion has been recorded over recent years in the southern part. Coastal erosion was related to the impact of several storms and dune accretion was linked to the action of eastern winds.

Over the short-term time frame, about the same percentage of coastal erosion and accretion was recorded. Most of the important accretion trends were observed at the central and southern parts of the littoral, the largest amount of erosion being recorded in the southern end of the littoral, in a nourished beach. All the studied beaches (except Punta Candor dunes) showed more short-term changes than medium-term ones, because of different factors, essentially the great seasonal variability of the studied beaches.

The partial discrepancy between the medium and the short-term trends was related to the applied methodology, which demonstrates the problem of comparing different coastal features (dunes and cliffs on one hand, and beaches on the other) and to the implications of 2–3 years of lasting fair weather conditions that favoured beach and dune accretion, within an historical retreat tendency related to storm actions.

Keywords: Coastal evolution; Aerial photographs; Beach profiles; Cadiz

1. Introduction

Shoreline position fluctuates in a variety of time scales, and this behaviour introduces many difficulties when reconstructing medium-term coastal trends (Carter, 1988; Crowell et al., 1993; Jiménez et al., 1997; Short, 1999). Variability in coastline position may be the response to a single factor or a combination of them (Bird, 1993; Forbes et al., 2004). Principal causes of coastal erosion or accretion are individual large storm events (Stone et al., 1996, 1997; Donnelly et al., 2001), seasonal variability in wave energy and/or circulation in the nearshore zone (Sonu and James, 1973; Masselink and Pattiaratchi, 2001), multiyear to decadal-scale variations in storminess, wave energy and coastal morphodynamics (Thom and Hall, 1991; Forbes et al., 1997; Zhang et al., 1997; Shand et al., 2001) and long-term variations in the relationship between climate and sediment supply (Orford et al., 2001, 2002).

Coastal changes are surveyed using a wide variety of methods and data sets according to the study time spans (Smith and Zarillo, 1990; Dolan et al., 1991; Crowell et al., 1991, 1993; Jiménez and Sánchez-Arcilla, 1993; Gorman et al., 1998; Jiménez et al., 1997; El-Asmar, 2002). Studies on short-term shoreline dynamics are usually carried out at small spatial scales, during a time span of less than 10 years (Crowell et al., 1993). The most common technique used is

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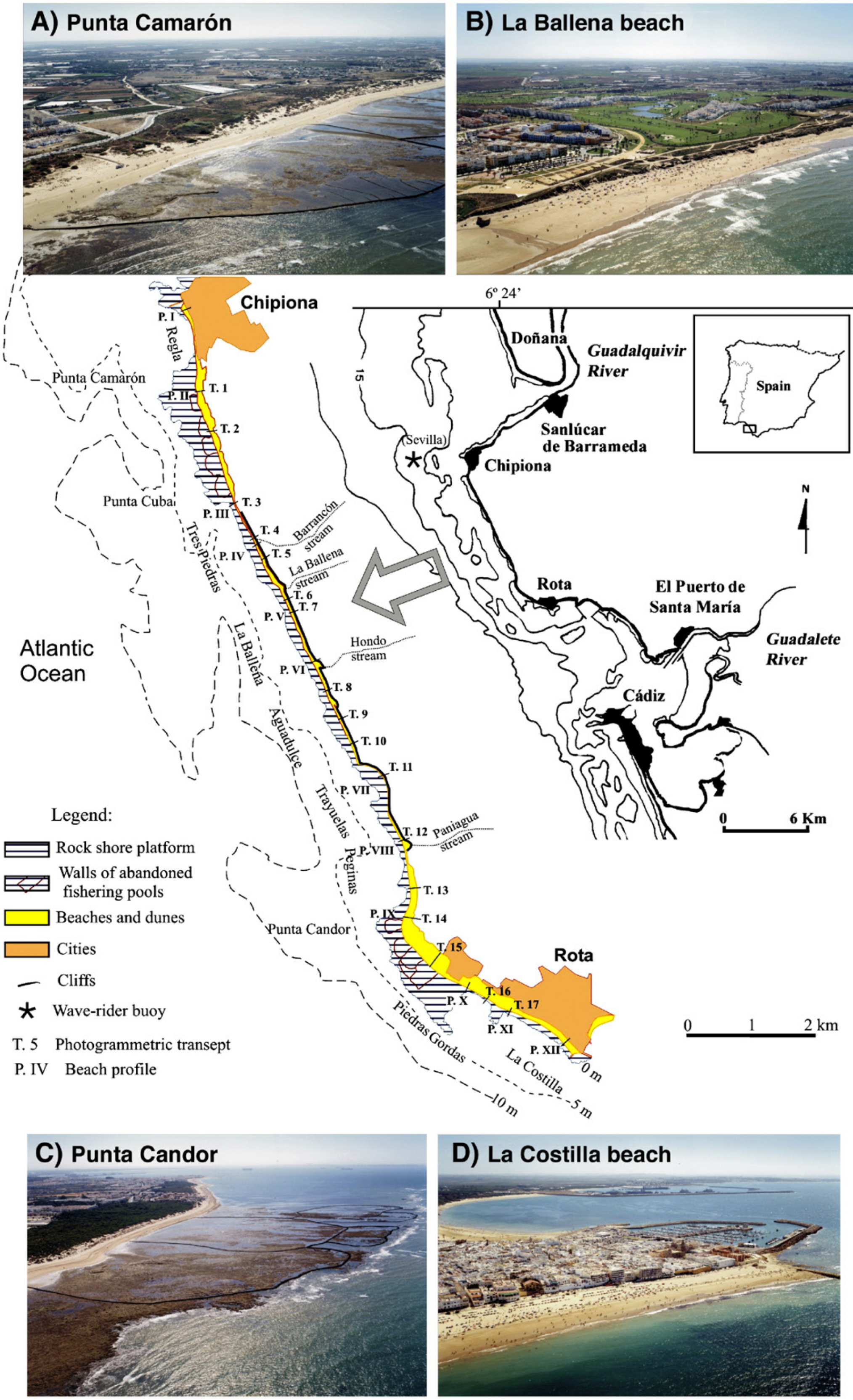
A) Punta Camarón
B) La Ballena beach
Chipiona
P. I
Regla
Punta Camarón
P. II
T. 1
T. 2
Punta Cuba
T. 3
P. III
Tres Piedras
T. 4
Barrancón stream
T. 5
P. IV
La Ballena stream
T. 6
T. 7
P. V
Atlantic Ocean
La Ballena
Hondo stream
P. VI
T. 8
Aguadulce
T. 9
T. 10
T. 11
P. VII
Trayuelas
T. 12
Paniagua stream
P. VIII
Peginas
T. 13
P. IX
T. 14
Punta Candor
T. 15
Rota
P. X
T. 16
T. 17
P. XI
P. XII
Piedras Gordas
La Costilla
0 m
-5 m
-10 m
0 1 2 km
Legend:
Rock shore platform
Walls of abandoned fishering pools
Beaches and dunes
Cities
Cliffs
Wave-rider buoy
T. 5 Photogrammetric transept
P. IV Beach profile
6º 24'
36º 42'
15
Doñana
Guadalquivir River
Spain
Sanlúcar de Barrameda
(Sevilla)
Chipiona
N
Rota
El Puerto de Santa María
Guadalete River
Cádiz
0 6 Km
C) Punta Candor
D) La Costilla beach

beach topographical profiling or 3D survey, repeated at regular intervals, in order to measure daily to annual variations in shoreline position and beach volume (Morton, 1979; Carter, 1988; Komar, 1998; Corbau et al., 1999; Short, 1999).

Vertical aerial photographs, satellite images, maps and charts are very useful tools for the reconstruction of coastline changes at long (>60 years) and medium (between 60 and 10 years) temporal scales and spatial scales (Crowell et al., 1993) and, further, they display coastal type distribution, land uses and dune field evolution (Taney, 1961; Dolan et al., 1980; Leatherman, 1983; McBride et al., 1991; Fisher and Overton, 1994; Jiménez et al., 1997; Forbes et al., 2004). The precision and accuracy of aerial photogrammetric measurements depend on their own characteristics (Dolan et al., 1980; Crowell et al., 1991; Andres and Byrnes, 1991; Moore, 2000) and on the difficulties of locating shoreline position, typically taken as the high water line (especially in microtidal environments, Dolan et al., 1979, 1980; Leatherman, 1983; Pajak and Leatherman, 2002), or identified in mesotidal environments as the seaward vegetation limit, dune foot or cliff top (Crowell et al., 1993; Fisher and Overton, 1994).

The prediction of the future coastline trend at short and medium terms (years–decades) must be based on the study of coastal changes which have occurred in the recent past, taking into account a comparable time scale. However, this approach requires the combination of data obtained from the two main methods cited above. Morton (1979) analysed coastal evolution at geological and recent time scales. The former was related to natural processes and the latter was principally linked to human activities. Smith and Zarillo (1990) studied medium and short-term beach variations, by using two vertical aerial photographs to reconstruct the medium-term coastline trend, and the Emery (1961) methodology of beach profiling to measure short-term shoreline position changes over a period of 13 months. They concluded that short-term changes in shoreline position can be quite important and such coastline variations may be the single largest source of error in quantitative calculations of medium and long-term shoreline position changes.

In Spain, Jiménez and Sánchez-Arcilla (1993) and Jiménez et al. (1997) analysed the Ebro delta evolution. Jiménez and Sánchez-Arcilla (1993) obtained similar trends using shoreline position data from three sets of aerial photographs, covering a period of 32 years, and from beach profiling techniques, carried out with a seasonal periodicity over 4 years. Jiménez et al. (1997) studied the short-term evolution (over 2 years) of the Ebro delta, with seven sets of aerial photos with a time span of four months, and beach profiling techniques. They obtained a perfect agreement from a qualitative point of view, i.e. erosion and accretion zones always coincided, but recorded small differences in measured values, especially in very flat coastal sectors.

The quantitative comparison of data obtained from these different techniques requires: i) the availability of data which is representative enough for the studied coast; ii) to measure variables and parameters that represent similar natural processes acting at different time scales, and iii) the reduction of all the data and parameters to a common, comparative, time scale. The results obtained by this general procedure can then be used for establishing predictions of short and medium-term coastline trends, provided that no human intervention will alter the prevailing natural coastal processes in the near future.

The current work presents the results of a combined study on the short and medium-term evolution of the littoral between Chipiona and Rota (SW Spain). It is an interesting sector showing a variety of coastal environments distributed along a quite homogeneously oriented coast. The littoral is not greatly affected by human structures, which consist only of two small groynes at either end of the studied littoral, some rip-rap revetments and seawalls and a small number of beach nourishment works.

In this study, short-term variations have been monitored with a monthly periodicity during a period of 2 years, the obtained data being representative of both seasonal and annual variations. The analysis of coastal evolution for a period of 24 years (medium-term trend, according to Crowell et al., 1993), was carried out using several, well temporally spaced, photogrammetric flights.

2. Studied zone

The studied coast is located between the villages of Chipiona and Rota, respectively south of the Guadalquivir river mouth and north of Cadiz Bay, in southwest Spain (Fig. 1). This littoral is composed of about 14 km of southwest-facing sandy beaches, composed of fine to medium quartz rich sands, backed by dune ridges and low cliffs. Dunes are well developed in the southern part of the littoral and at Punta Camarón and Punta Candor, while cliffs prevail in the northern and central parts (Fig. 1). Their composition essentially consists of a basal, continuous, resistant layer of clays, overlaid by Quaternary silts, clays and sands (Baena et al., 1987). Cliff retreat has formed a wide and smooth intertidal rock shore platform which is well developed in the nearshore and foreshore zones.

Littoral orientation ranges from NNW–SSE in the coastal sector between Chipiona and Punta Candor, to NW–SE in

Fig. 1. Location map of the studied littoral with aerial views of several studied beaches photographed during low tide conditions, from North to South: A) rock shore platform and dune ridges at Punta Camarón headland; B) smooth and wide foreshore zone and a narrow dry beach backed by a cliff at La Ballena beach, in a long, straight coastal sector. Coastal retreat is evident because of the presence of two undermined bunkers nowadays located in the upper foreshore; C) rock shore platform at Punta Candor promontory, where small walls form little ponds ("corrales"), historically used for fishing; D) La Costilla beach, with a relatively wide dry beach. A groyn limits the beach southward. Photos obtained from "Demarcación de Costa", Spanish Ministry of Environment.

the southern sector, between Punta Candor and Rota. Coastal plan form is apparently straight and homogeneous, without important headlands. Rock platform forms small local promontories in the nearshore and low foreshore zones at Punta Camarón, Punta Candor, Piedras Gordas and La Costilla. Additionally, two groynes limit the studied area at its northern and southern edges, while a gentle embayment can be observed at Trayuelas (Fig. 1).

Tidal regime is mesotidal, with tidal ranges of 3.2 m and 1.1 m in spring and neap tides respectively. Dominant winds blow from ESE (19.6% of annual occurrence) and WNW (12.8%). Significant wave height is usually lower than 1 m and during storms is about 3 m (Reyes et al., 1999). This data classifies the area as a low energy coast (Benavente et al., 2000). Dealing with wave characteristics, wave height presents great seasonal variability, and wave period is quite constant throughout the year.

Due to coastline orientation, the littoral is mainly affected by winds and waves (both sea and swell wave conditions), approaching from western directions, generating a prevailing south-eastward littoral drift. Winds and waves from southern directions give rise to an opposing drift, which achieves particular importance in the southern sector.

3. Methodology

3.1. Wave climate

As was mentioned earlier, wave climate fluctuations have a strong influence on the rate of coastline changes, over both medium and the short-term time scales. Information on wave climate characteristics during the studied period was gathered from different sources and compared with data on coastal evolution at medium and short temporal scales.

The temporal distribution of the most important storms in Cadiz Gulf and related information about maximum recorded wind speed and wave height (Rodríguez et al., 2003), were used for the medium-term study.

Wave climate data for the short-term study was obtained from the offshore, non-directional buoy "Sevilla" (Fig. 1), which belongs to the REMRO (Wave Climate Service of the CEDEX, Spanish Ministry of Environment). Hourly data on wave height and period were used to obtain monthly maximum and average values.

3.2. Medium-term beach evolution

In order to study the medium-term shoreline evolution, six photogrammetric flights were used (Table 1).

Table 1
Photogrammetric flights used in the present study

Year	Scale	Source	Characteristics	Calculated error of distances (%)
1956	1:30,000	USA Army	B & W	4.51
1977	1:18,000	Ministry of Environment	B & W	0.76
1984	1:30,000	Spanish Army	B & W	1.69
1990	1:5,000	Ministry of Environment	Colour	0.96
1992	1:20,000	Regional Administration	Colour	1.00
2001	1:5,000	Ministry of Environment	Colour	0.16

Abbreviations: B & W = black and white.

Coastline evolution was reconstructed by means of measurements made at 17 transects homogeneously spaced along the littoral (Fig. 1). Photogrammetric data was obtained through a Wild APT-2 prism stereoscope, which has a zoom system with a 0.01 mm optical resolution. Transects were drawn along rectilinear lines which are normal to the shoreline and pass through reference points such as road intersections, corners of buildings and other human structures common to all photogrammetric flights. The distances between the reference points and the coastline were surveyed along each transect. Coastline was identified with the cliff top or the toe of vegetated dunes to avoid problems related to high water level position because of tidal variations (Dolan et al., 1980; Crowell et al., 1991; Pajak and Leatherman, 2002) or seasonal variability (Dolan et al., 1980; Smith and Zarillo, 1990).

Results were influenced by the nature of the coastal form considered in each case: dune toe was measured along transects T1–T3 and T13–T17, and cliff top variations were determined from transects T4–T12 (Fig. 1). It must be noted that a dune toe can undergo seaward or landward displacements, i.e. shoreline advance or retreat, while a cliff top can only record erosive trends or stability. Nevertheless, if significant sand accumulation takes place and dunes are formed at the cliff base, it is possible to measure coastal advance, although this process was never observed in the studied littoral.

According to Crowell et al. (1997), different methods exist to calculate coastal erosion rates. The most common is the "end-point-rate", which determines the amount of shoreline movement by selecting two shorelines, usually the earliest and the most recent ones. The main disadvantages of this method are that all the potential information between the two-used shoreline is ignored and the position of one or both shorelines can be aberrant, consequently generating a large error (Dolan et al., 1991; Honeycutt et al., 2001). Fenster et al. (1993) used a statistical modelling technique that determines the straight or curved line (polynomial) that best fits the data set. Another easy method consists of calculating the regression for the whole data set (Crowell et al., 1997). This last method was used in the present paper to obtain erosion and accumulation values.

Finally, in order to solve photo inaccuracy, the measurements taken from the aerial photos were compared with the surveys carried out in the sheet "Cádiz" from the analytic topographic map of Andalusia, edited in 2000 at 1:10,000 scale (Instituto Cartográfico de Andalucía). As a further step, we calculated the inaccuracy of each photogrammetric flight

Table 2
Distribution of storms in Cadiz Gulf during the 1956–2001 period

Date	Maximum wind speed (km/h)	Maximum wave height (m)	Date	Maximum wind speed (km/h)	Maximum wave height (m)
Jan. 1963	>130	No data	Jan. 1982	No data	Up to 5
Feb. 1963	>130	No data	Dec. 1987	65–75	7–8
Jan. 1970	>113	No data	Dec. 1989	>100	Up to 6
Dec. 1972	No data	6–7	Dec. 1995	>85	No data
Jan. 1973	No data	6–7	Jan. 1996	>85	No data
Jan. 1979	No data	Up to 5	Feb. 1996	>85	No data
Feb. 1979	No data	Up to 5	Dec. 1998	>115	Up to 5
Mar. 1979	No data	Up to 5	Jan. 1999	>115	Up to 5
Dec. 1981	No data	Up to 5			

and its arithmetic mean value, giving the relative error of each photogrammetric flight (Domínguez et al., 2005).

3.3. Short-term beach evolution

In order to characterize beach morphology, seasonal changes and the evolution trend at a short temporal scale (i.e. 2 years), a beach monitoring program was developed at monthly intervals from March 1996 to May 1998. An electronic theodolite was used to survey twelve shore-normal transects (Fig. 1), extended from the dry beach to a closure depth equivalent to the mean spring tide low water level. The average positions of mean, low and high water level were calculated considering collected data as a whole. The analysis of the topographic data led to the calculation of beach width, from the profile benchmark to the high and mean water levels, and the estimation of erosion/accretion volumes of sand per unit of beach length (m^3/m). The first survey was considered as a base line, i.e. it was attributed a 0 value.

A least-squares linear regression analysis was used to quantify linear erosion and accretion and beach volumetric evolution, the slope of the fitted line being an estimation of the short-term evolution. Obtained values were confirmed by detailed field observations and studies (Anfuso, 2002; Benavente et al., 2002; Anfuso et al., 2003a,b; Anfuso and Gracia, 2005).

4. Results

4.1. Wave characteristics

According to Stone and Oxford (2004) and Forbes et al. (2004), the understanding of storm nature and climatology is fundamental to the knowledge and the prediction of short and long-term coastal behaviour. In the Atlantic Ocean, the importance and distribution of storms are related to the NAO (North Atlantic Oscillation) index values, which represent the differences of atmospheric pressures at sea level between Azores and Iceland. In southern Europe, positive NAO values are associated with low cyclonic activity and *vice versa* (Rodwell et al., 1999). During the last decade the Atlantic beaches have been affected by fewer but more powerful storms related to the recently recorded positive NAO values, which are expected to increase in the near future due to global warming (Keim et al., 2004).

In this study, wave climate during the medium-term period was characterized by the occurrence of several storms (Table 2, modified from Rodríguez et al., 2003).

High-energy events in the Cadiz Gulf occur mainly in the months of December and January and secondarily, in February and March (Table 2). The most important storms in the zone are those approaching from W and SW directions (Rodríguez et al., 2003).

During the short-term study, wave climate was broadly representative of this coastal region, coinciding with the observations of Sánchez (1988), Muñoz (1996) and Rodríguez et al. (2003). According to the data obtained from the offshore buoy "Sevilla", the 1996–1998 interval was a low energetic one, recording a high percentage of wave heights lower than 0.5 m (Fig. 2). This period, especially 1997, was characterized by the predominance of

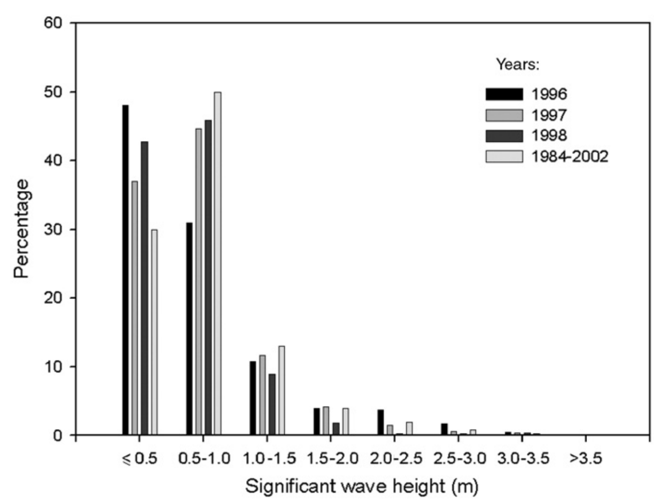

Fig. 2. Significant wave height during the short-term study and the whole data set recorded by the offshore scalar buoy "Sevilla" belonging to the REMRO network (Wave Climate Service of the CEDEX, Spanish Ministry of Environment).

Table 3
Medium and short-term coastal changes at the different studied transects and profiles

Location	Transect [(1)]	Evolution trend (m) (1977–2001)	Rate at medium-term scale (m/year)	Profile	Evolution trend (m) (1996–1998)	Rate at short-term scale (m/year)
Regla		0[(2)]	0	P I	+3.0	+1.3
P. Camarón	*T 1*	−16.2	−0.6	P II	−2.7	−1.2
P. Camarón	*T 2*	−33.0	−1.3			
Tres Piedras	*T 3*	−15.0	−0.6	P III	−3.0	−1.3
Tres Piedras	T 4	−6.0	−0.2	P IV	−3.3	−1.5
La Ballena	T 5	−9.4	−0.4			
La Ballena	T 6	−9.0	−0.4	P V	−3.7	−1.6
La Ballena	T 7	−6.3	−0.3			
Aguadulce	T 8	−10.5	−0.4	P VI	+3.7	+1.6
Aguadulce	T 9	−0.12	0.0			
Aguadulce	T 10	−7.2	−0.3			
Trayuelas	T 11	−20.4	−0.8	P VII	+2.2	+1.0
Peginas	T 12	−3.7	−0.1	PVIII	+1.4	+0.6
Peginas	*T 13*	−8.7	−0.3			
P. Candor	*T 14*	−59	−2.4	P IX	−2.5	−1.1
Piedras Gordas	*T 15*	−21.5	−0.9			
Piedras Gordas	*T 16*	+1.4	+0.1	P X	+2.0	+0.9
La Costilla	*T 17*	+15.0	+0.6	P XI	+12.3	+5.5
La Costilla		0[(2)]	0	P XII	−12.3	−5.5

(1): normal characters correspond to transects surveyed at cliff top, surveys carried out at dune toe being in italics; (2): urban beaches backed by promenades, i.e. artificially stabilized at the medium-term scale.

waves approaching from the SSE and SSW, that did not majorly affect the studied littoral (Anfuso and Gracia, 2005).

4.2. Medium-term evolution

On dealing with the medium-term coastal evolution, studied transects were measured on the photogrammetric flights and errors (Table 1) and erosion/accretion tendencies were obtained (Table 3). The data from the 1956 flight was eliminated due to two main reasons: to solve clustering problems, related to great differences in the studied time spans (Jiménez and Sánchez-Arcilla, 1993) and because of the significant errors associated with this flight (Table 1).

For the period 1977–2001, values of erosion or accretion for the first survey were plotted versus time, and linear fits were calculated, according to the methodology of Dolan et al. (1991). Usually, the data presents high correlation factors and shows clear trends (Fig. 3). Dune toe and cliff top medium-term evolution is presented in Table 3.

According to this information, almost 80% of the data recorded erosion, 10% accretion and the remaining 10% recorded a stable trend because of human structures, i.e.

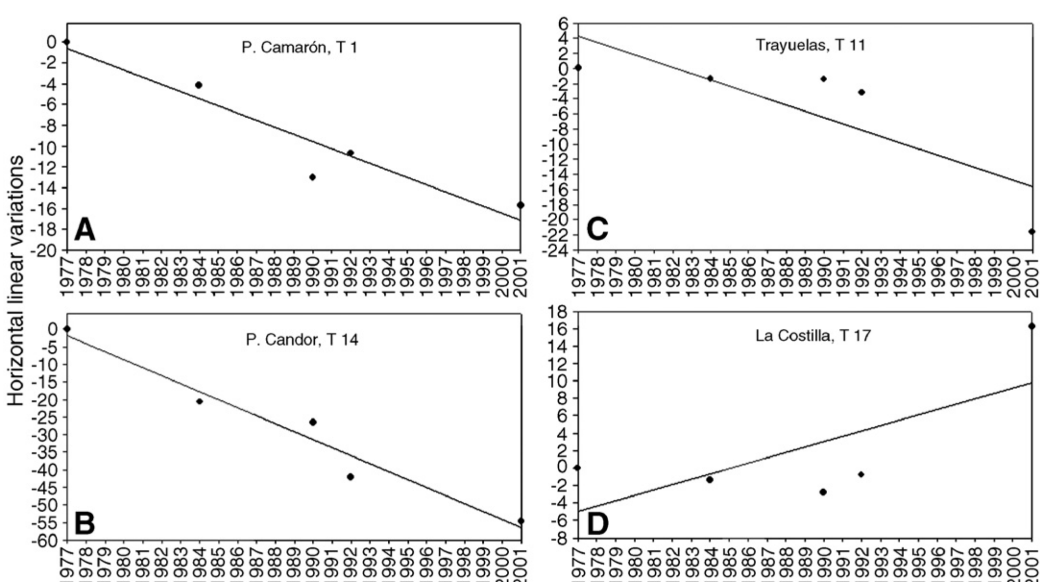

Fig. 3. Examples of coastline evolution during the medium-term period, obtained from photogrammetric measurements.

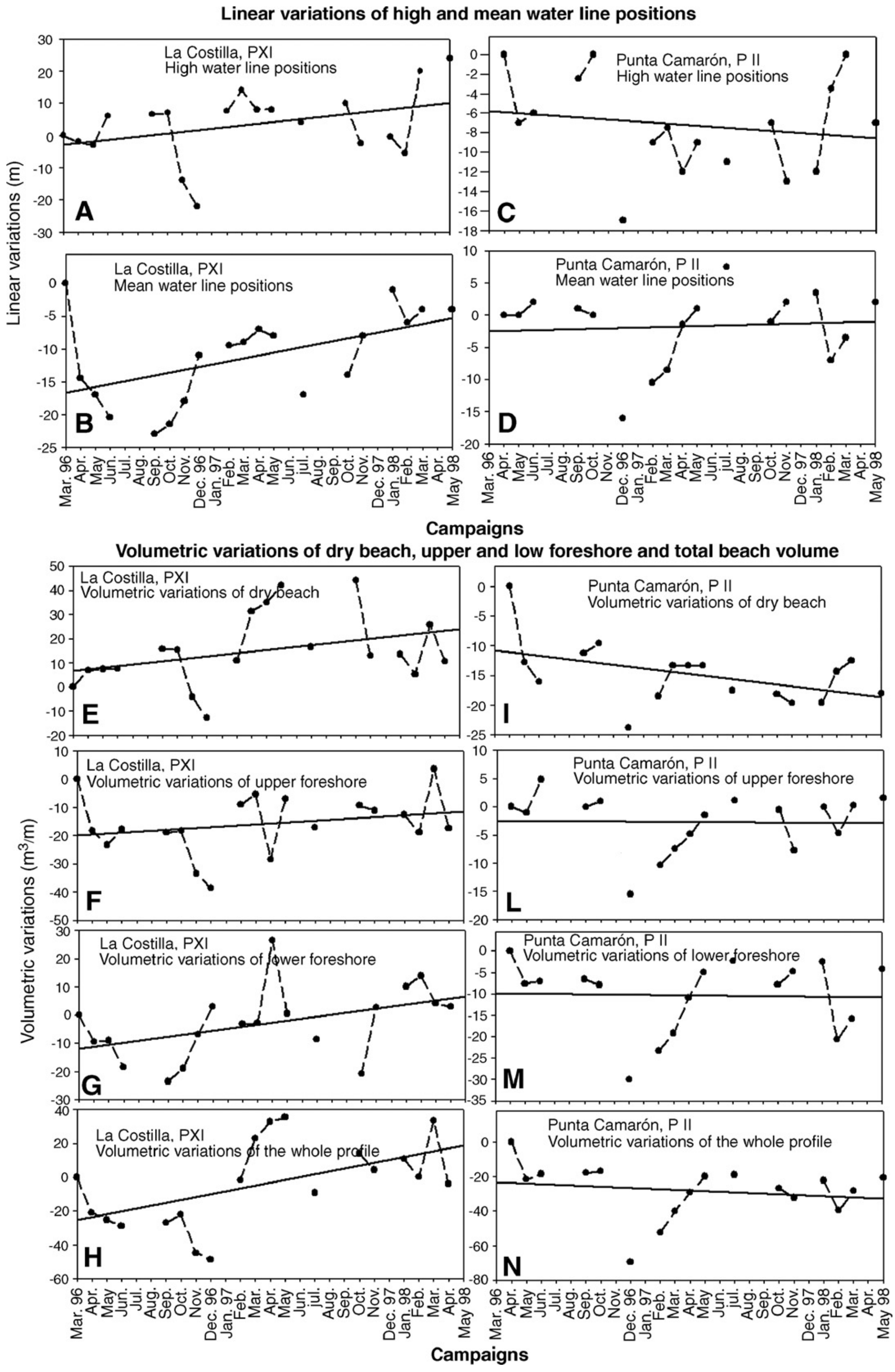

Fig. 4. Short-term evolution: examples of distances (m) surveyed from the profile benchmarks to the high and mean water levels, and volumetric variations (m^3/m) for different parts of beach profiles and for the whole profiles.

seawalls at Regla and La Costilla beaches. Dunes located at Punta Camarón, Punta Cuba and Punta Candor recorded important erosion while recent accretion was recorded in the southern part of the littoral, especially in La Costilla (T17, Table 3 and Fig. 3D).

Cliffs recorded erosion along the whole littoral, especially at Peginas embayment (Fig. 3C) and in Aguadulce beach, with a very small erosive trend recorded in the southern part of Aguadulce beach (T9, Table 3).

4.3. Short-term evolution

Linear variations and volumetric changes were plotted versus time (Fig. 4) and values of erosion or accretion were measured on the corresponding regression lines, considering the points of intersection between the regression lines and axes. Usually, linear regression presented low correlation factors because of the great dispersion of data, linked to seasonal coastal variability, but in most cases indicated a clear erosive or accumulative tendency.

Evolution of high and mean water lines of the same profile usually recorded common tendencies (Fig. 4A and B). An opposing behaviour was only observed at La Ballena and Punta Camarón (Fig. 4C and D).

Volumetric changes generally showed a good correspondence with linear retreat data, especially with high water line variations (Fig. 4A and H, C and N). Some differences were observed between volumetric evolution and mean water line trend at La Ballena and Punta Camarón (Fig. 4D and N). These beaches, within a general negative volumetric trend (Fig. 4N), recorded slightly erosive trends or stability at the mean sea level (Fig. 4L and M), related to the welding of sand bars on the upper foreshore (Anfuso, 2002; Anfuso et al., 2003b).

Taking into account the obtained results, high water line variations were used to quantify coastline evolution at the short-term and to obtain coastline tendencies (Table 3), which can be easily compared with the ones recorded at the medium-term.

To summarize, at the short-term time frame (Table 3), the data recorded about the same percentage of erosion and accretion. Most of the important accretion trends were observed at Aguadulce (P. VI) and La Costilla (P. XI, Table 3 and Fig. 4), the largest erosion being recorded in the southernmost part of this latter beach (P. XII, Table 3).

In order to explain coastal behaviour and compare coastal erosion and accretion rates at medium and short-term time frames, the data presented in Table 3 was plotted in Fig. 5 within which different intervals were depicted. Only beach profiles and transects which were strictly equivalent were plotted, resulting in 12 locations. Measures from dunes, cliffs and artificially stabilized areas were also differentiated.

The figure showed four different areas. Two of them included the beaches which showed a similar behaviour at short and medium time scales. The beaches which showed a change in coastal trend, i.e. erosion at short-term and accretion at medium-term or *vice versa* were included within the two resting areas.

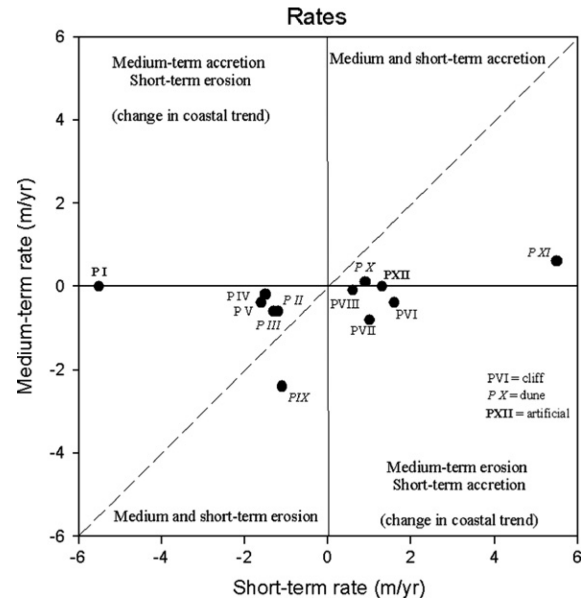

Fig. 5. Short versus medium-term evolution rates at 12 studied transects, measured in dunes, cliffs and urban areas.

Almost all the beaches recorded medium-term erosion, showing the same percentage of accretion and erosion at the short-term time frame.

5. Discussion

5.1. Methodological aspects

The obtained results indicate that aerial photographs and beach profiling are very useful and appropriate tools for the detection of coastal changes at medium, seasonal and short-term time frames. However, the resulting data is, obviously, partially conditioned by these methodologies. According to Fig. 5, the studied beaches show greater short-term changes than medium-term ones, with the exception of Punta Candor dunes (PIX). This was due to different factors, related to the applied methodology and to the nature of the measured features. In fact, dunes may record accretion and erosion, but erosion is always very rapid and time located, whereas accretion is a process which usually takes place with low rates over a long time. Cliffs may experience erosion only, consequently it is not an appropriate tool to record beach accretion trends which may be reflected by cliff stability or low erosive trends, or by the formation of incipient foredunes (which was not the case in the studied littoral).

Over a medium-term scale, cliff top and dune toe were used as shoreline indicators as they are easy to map and prevent problems related with the high water mark, which is subject to important tidal and seasonal variations. According to Crowell et al. (1993) and Fisher and Overton (1994), it is very difficult to determine the exact position of high water marks in tidal systems due to problems in reconstructing astronomical and meteorological tidal conditions at the time of the photo. Moreover, according to Dolan et al. (1980) and Smith and Zarillo (1990), the high water level is often incorrectly used in medium and long-term studies because it is considered to be representative of the "seasonal mean shoreline position", while in reality it is an indicator of very short-term changes in shoreline position. Hence, the use of high water line often generates the single largest source of errors in quantitative calculation of medium and long-term shoreline position changes, i.e. it represents the "noise" (very short-term changes related to storms and/or seasonal variations) with respect to the "signal" (the real long-term trend, Smith and Zarillo, 1990; National Research Council, 1990; Crowell et al., 1993). Furthermore, after analysing shoreline variations at Delaware and New York, Honeycutt et al. (2001) concluded that the inclusion of storm-specific

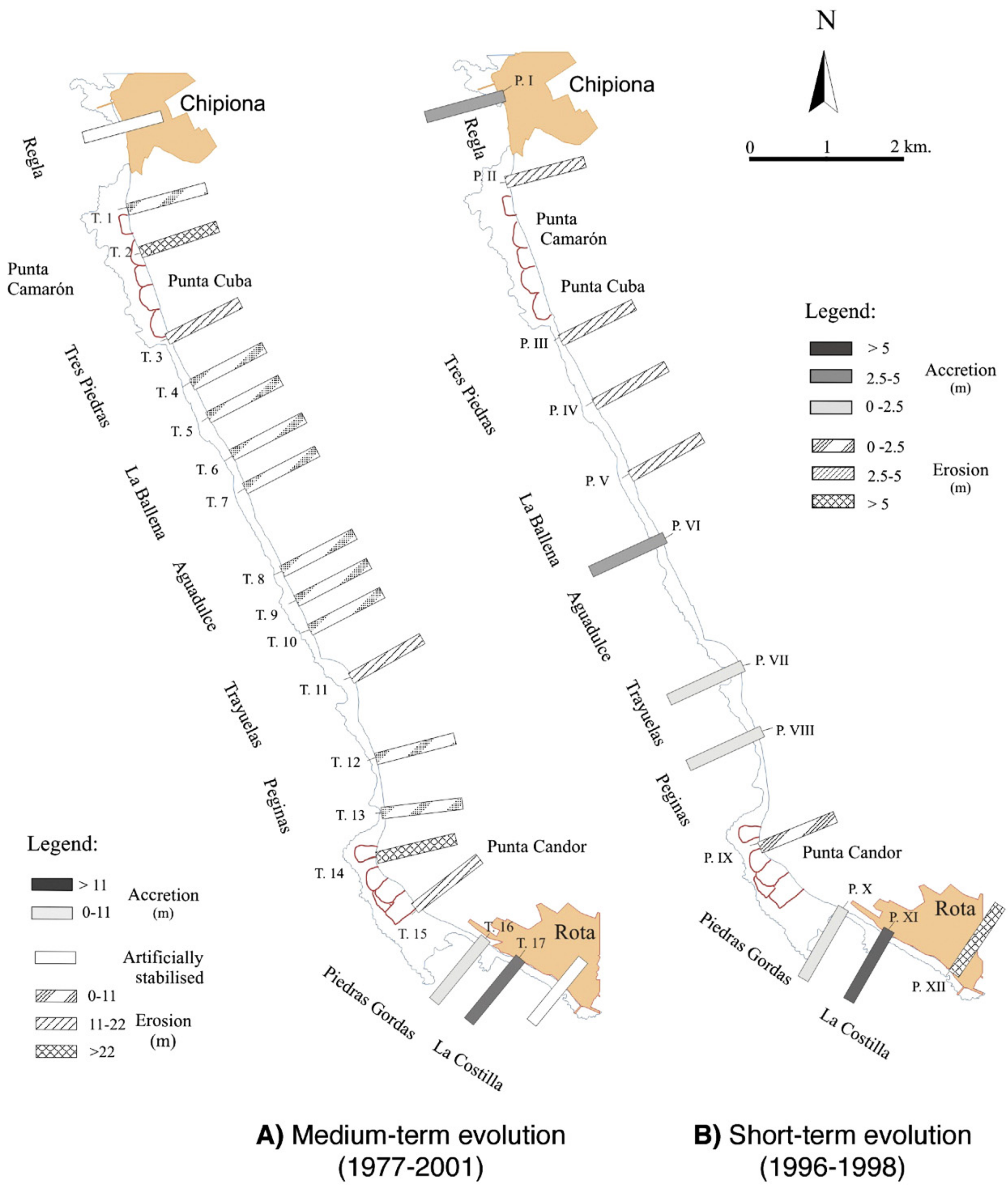

Fig. 6. Distribution of values of littoral evolution measured at short (A) and medium-term (B) scales.

shorelines, related to very important erosive events, drastically increases the errors in the forecasting of future positions.

Within the present study, this problem potentially existed because the variation of the shoreline indicators, e.g. cliffs and dunes, was linked to the action of storm events: the retreat processes were time-located and rapid, while dune recovery was much slower, from several months to years.

However, retreat rates resulting from field surveys were of the same order of magnitude as the medium-term variations (Table 3), thus suggesting that the last data was not overestimated. This may be due to three main reasons. Firstly, the short-term data, which referred to beach behaviour, evidently presented greater variability than the dunes and cliffs. Secondly, storms in the studied littoral do not represent extreme events such as those recorded in the U.S.A., i.e. Hurricanes and North Easters. The third reason is related to the temporal distribution of the flights used in the study. Following suggestions made by Dolan et al. (1991) and Crowell et al. (1993), photogrammetric flights covered long time intervals (Table 1) that often included several storm events (Table 2). Then the obtained results established a significant net change in shoreline position that was not greatly related to the influence of one single storm. The only exception to the previous assumption is probably in the case of Punta Candor, where dune ridges are particularly exposed to storm effects.

Lastly, no data of historical trends exists for urban beaches, i.e. Regla and La Costilla beaches, because they are protected by human structures and hence classified as stable sectors in Fig. 5 — a clear methodological limitation.

On dealing with the short-term study, and following Morton (1991), the great sample density obtained by means of the monthly monitoring program provided a very good measurement of the seasonal variability and a way to distinguish this from the short-term trend. These assumptions were further confirmed by the lack of any clear relationship between changes recorded at the short-term time frame and the observed seasonal variability. The latter presented non-linear changes linked to the great seasonality of the dry beach width, that recorded most important variations in the beaches with intermediate slopes (i.e. P. XI, Fig. 4A, and also PVI and PVIII, in Fig. 5).

5.2. Medium-term evolution

Broadly speaking, cliffs and dunes recorded a general erosive trend with high values in dune ridges (Table 3 and Fig. 6). According to Dolan et al. (1991) and Forbes et al. (2004), the medium and long-term phenomena that determine coastal evolution are rising sea level, shift of sediment supplies and storm action. In the studied littoral, data from recent sea level trends (historical to decadal) shows stability or even a slight fall (Lario et al., 2002; Araujo, 2002). Two other factors play an important role in this coast: the reduction of fluvial sediment, which has greatly decreased since the 1960s and 1970s because of dam construction in the Guadalquivir River catchment area (Aberg, 2005), and above all, storm wave action (Rodríguez et al., 2003).

The effects of storm attack on cliffs and dunes is, in the studied littoral, essentially controlled by local constrains such as coastal orientation, cliff lithology, dimensions and morphodynamic state of the beaches at the time of storm impact, and especially the presence of rock shore platforms in the nearshore and foreshore zones.

Regarding coastal orientation, the studied coastline shows two small headlands at Punta Camarón and Punta Candor and a slightly different orientation in the southern part, which is more exposed to winds and waves approaching from southern directions.

Cliff lithology is more or less constant along the zone. Small lateral differences are responsible for the formation of decametrical coastal entrances and horns (Fig. 7A and B), as well as for the large embayment observed at Trayuelas. In this case, the resistant basal level, with a thickness ranging from 1 to 1.5 m (Fig. 7A), is exposed only in the very bottom of the cliff and is easily over-passed by wave processes that produce the retreat of the more friable overlaying levels.

Fig. 7. Small cliff entrances in the northern (A) and southern (B) parts of Aguadulce. Cliff is composed of clay levels; the basal, resistant one presents a pale colour and is about 1 m thick at Aguadulce; (A) sand accumulation is visible at the base of the cliff.

Here, cliff retreat formed a rock shoal, which is not visible in the presented maps because of its rather small extension. During high tide, waves concentrate their impact on the cliff bottom because of the shoal, according to a well documented mechanism observed in several beaches by Morton and Sallenger (2003).

Beach width and morphodynamic state varied considerably along the littoral, often presenting significant seasonal behaviour (Anfuso et al., 2003a). Wider beaches, with a well developed berm during fair weather conditions, were observed at Regla, Aguadulce and La Costilla (Anfuso et al., 2003a; Anfuso and Gracia, 2005). It is probable that these aforementioned beaches worked as a bluff to wave erosion, protecting the backing dunes and cliffs during the first storm phases. In fact, these beaches recorded small erosion and/or accretion at the medium-term frame and accretion at the short-term (Fig. 6).

The rock shore platform partially protects the coast from small storms but strongly controls wave refraction and diffraction processes during important storms, emphasizing their erosive effects on the littoral. During strong storms, currents transport sediments offshore, behind the rock shore platform edge, and the eroded sediment is definitively lost from the local sedimentary budget (Muñoz and Enríquez, 1998). This process was confirmed in the areas with extended rock shore platforms (Punta Camarón, Punta Cuba and Punta Candor, Fig. 6), where large coastal retreat rates were observed.

It is also interesting to notice that many coastlines record "erosion–accretion" cycles. Douglas and Crowell (2000) and Fenster et al. (2001) observed in storm-influenced coasts how the shoreline moved systematically landward under the influence of storm-related processes, but rarely had the opportunity to observe the full recovery to pre-storm conditions. According to these authors, post-storm accretion can continue for a decade and the return to pre-storm conditions depends on the duration and intensity of any individual storm and the frequency of successive storms.

In the studied case, medium-term recovery took place in the dune ridges located at the southern part of the studied littoral, due to the sedimentary supplies coming from the neighbouring beaches, which are exposed to prevalent winds blowing from the SSE. According to the obtained results, a period of 2–3 years of fair weather conditions represented the minimum time span to produce dune growth.

Erosive trends generally prevailed along the whole littoral in the 1977–1984 and 1984–1990 periods (Fig. 3). Following Ferreira (2005), the coastal retreat recorded after the first interval could be related to the arrival in 1979 of storm groups to the Gulf of Cadiz, i.e. the effects of several important storms that struck the coast in a few months (Table 2).

The significant erosion recorded in the 1990 photogrammetric flights was linked to the recent effects of the December 1989 storm (Table 2). In the following period (1990–1992), no storms took place and some growth was observed at the dunes of Punta Camarón and La Costilla (Fig. 3A and D). The accretion recorded in the former beach was also associated with the nourishment works carried out in 1992 at Regla beach, where 500,000 m^3 of sand were injected along a 4 km coastal sector (Muñoz et al., 2001). Finally, some erosion was also observed during the following period (1992–2001), while accretion was only recorded at La Costilla and Punta Candor (T13 and T17, Fig. 3D), mainly because of the 300,000 m^3 and 20,000 m^3 of sand respectively injected into these areas during the considered interval.

5.3. Short-term evolution

In accordance to observations made in different coastal areas by Larson and Kraus (1991) and Crowell et al. (1993), the recorded short-term accretion (Fig. 6), especially in the southern part of the studied littoral, was related to the periodical transfer of sediments from offshore relict deposits to the beaches, essentially sand ribbons, which are quite abundant in front of Rota (Parrado et al., 1996, 1999). Nevertheless, further studies are necessary to quantify and characterise the sedimentary interchange between the beach and the nearshore zone.

Sand transfer was attributed to the predominance of "fair-weather conditions", i.e. the period, lasting years to decades, between extreme storm events (Lee et al., 1995). A similar behaviour, i.e. accretion at short-term and erosion at medium, decadal term, was also observed by Lee et al. (1995), as a result of a beach profiling monitoring program carried out over 10 years in northern Carolina (USA), and by Corbau et al. (1999), who studied a littoral sector located in northern France, comparing the results of a 2 year monitoring program with the long-term littoral trend.

Taking into account the data presented in Table 2 and following Muñoz and Enríquez (1998), storms in the Gulf of Cadiz have two main recurrence periods; 2–3 and 6–7 years. According to data recorded in the offshore buoy, no important storms struck the coast during the short-term study period — the last important ones occurred in December 1995 and January–February 1996, just before the monitoring program presented in this paper. Fair weather conditions recorded during the short-term study were associated with the prevalence of wind and low intensity waves approaching from the S, SE and SW (Anfuso and Gracia, 2005). The resulting north-westward transport interacted with the natural and artificial structures, giving rise to updrift accretion and downdrift erosion.

Accretion was recorded at Regla, Aguadulce and La Costilla beaches. In the first case, accretion occurred updrift (i.e. southward) of the groyn that limits the studied area to the North (Fig. 6). At Aguadulce beach, the cliff is slightly set back and hence aeolian sand accumulation is favoured at the cliff toe (Fig. 7A), forming small foredunes at some places. At La Costilla beach, accretion was linked to the sedimentary inputs coming from the nourishment works carried out in 1996 and 1997 in the southernmost part of the beach, where 197,000 and 94,000 m^3 of sand were respectively injected

(Muñoz et al., 2001). Nourished sand was moved from PXII to PXI, where a wide rock shore platform blocked sediment transport approaching from the SE.

These accreting beaches recorded a great seasonal variability of the dry beach width because of beach pivoting (around mean sea level), related to the prevalence of cross-shore transport upon the longshore one (Anfuso et al., 2003a,b). This seasonal behaviour was especially observed in autumn, when beaches passed from a constructive, intermediate state related to fair weather conditions, to an erosive, dissipative state due to the increased storminess. Beach recovery usually took place over several months by means of the subtidal bars that arrived at the littoral and welded onto the berm (Anfuso et al., 2003b).

Finally, erosion processes prevailed in exposed, straight coastal sectors, where the rock shore platform is well developed. According to Nordstrom and Jackson (1992) and Jackson et al. (2002), under normal wave conditions, beaches located in such coastal areas are preferentially affected by longshore transport that gives rise to smooth and intermediate beach slopes. In the studied zone these types of beaches showed small morphological changes associated with a parallel retreat (Anfuso et al., 2003a) and, consequently, presented few variations in the dimensions of the dry beach (Fig. 3C).

6. Conclusions

Considering the increasing demand of recreational beach use, the knowledge of coastal response to environmental changes has become important: there is a need for understanding and predicting shoreline changes at a variety of time scales. The fundamental steps for the adequate prediction of coastal response should be based on the understanding of storm climatology and the nature of impacts on different coastal sectors. In the present study, aerial photographs from different years were used to reconstruct the medium-term coastal evolution, while a morphological monitoring program was carried out for 2 years to obtain short-term littoral trends.

Historical shoreline evolution was obtained by monitoring cliff top and dune toe positions, which recorded a clear tendency with no or small cyclic variations due to their own characteristics. In fact, monitored figures mainly recorded coastal erosion or stability, dune and cliff erosion being generally rapid, time located and smaller than the high water line variations, while dune accretion was less significant and slow. The dune and cliff monitoring program solved problems related to the determination of the high water level position, which is quite difficult in tidal environments.

Beach profiling was a very useful method for obtaining short-temporal changing trends. The methodology adopted allowed measurement of dry beach width variations by always using a constant, average value of the mean sea level position derived from the numerous surveys carried out. This method solved problems related to the varying sea level position, and linear erosion/retreat data presented a good correlation with the volumetric variations calculated for the studied beaches. Results showed how the studied beaches presented both significant and minimal seasonal variations that were not related with their short-term trend.

In conclusion, this littoral recorded a balance between erosion and accretion at short-term scale and coastal retreat at medium-term. The partial discrepancy was related to the applied methodology and to the incidence of 2–3 years of fair weather conditions which favoured beach and dune accretion, within an historical retreat tendency related to storm action. Medium-term accretion/erosion rates were smaller than the short-temporal ones, partially because of the applied methodology. This further demonstrates the problem of comparing different coastal features, i.e. dunes and cliffs on one hand, and beaches on the other. A beach monitoring program, carried out over several years, could give rise to more accurate results which are useful to characterize beach morphodynamic behaviour and predict future shoreline position.

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