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Coastal storm characterization and morphological impacts on sandy coasts

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ABSTRACT: The present work deals with storm classification, using the Storm Power Index, and beach morphological response to storm events in the Gulf of Cadiz (SW Spain). Over the 1958–2001 period, 377 events divided into five classes ranging from 'weak' to 'extreme' were characterized. Classes I (weak) and II (moderate) accounted for 60% and 23% of events, respectively. Class III (significant), were 9% of the recorded events and Classes IV (severe) and V (extreme) accounted for 5% and 2%, respectively. The probability of storm occurrence per year ranged from 93% for Class I to 15% for Class V. In order to characterize beach response to storm events, 214 beach profiles carried out with a monthly periodicity over the 1996–1998 period along the Chipiona-Rota littoral were analysed, as well as published data. Different beach types were observed: (i) 'Intermediate' beaches underwent important vertical relief changes ranging from 0.3 m to 1.33 m associated with average slope changes from $\tan\beta = 0.06$ to $\tan\beta = 0.03$; (ii) the 'dissipative' beaches were characterized by smaller and homogeneous foreshore vertical changes, from *c.* 0.36 m to 0.65 m, according to the parallel retreat mechanism characterized by small slope variations (from $\tan\beta = 0.025$ to $\tan\beta = 0.035$); and (iii) 'intermediate with rock shore platform' experienced small morphological and foreshore slope variations, related to both beach pivoting and parallel retreat mechanisms. The most important morphological changes were due to the impact of usually 'weak' and 'moderate' events during October and November that produced berm erosion and upper foreshore lowering, and the impact of 'severe', 'significant' and 'extreme' events in December and January which produced dune escarpment, overwash and/or damage to coastal structures. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS: storm; power index; beach erosion; Cadiz; Spain

Introduction

Over past decades, several great storms and hurricanes have caused important economic losses and scores of deaths along the coastlines of the world (Bacon and Carter, 1991; Komar and Allan, 2008). Any environmental impacts on the world's coastal zones may be significant in future years due to ongoing coastal development (Brown and McLachlan, 2002) and predicted climatic change processes (Anfuso and Nachite, 2011; Jones and Phillips, 2011). Classification schemes for distinct meteorological and climatic phenomena (i.e. storms) provide much beneficial information that is useful in evaluating various aspects of these events and in forecasting storm impacts (Dolan and Davis, 1992). In particular, these schemes simplify the event characteristics for the general public; this is especially useful where storms may have, or have had, an impact on the life and property of humans (Zielinski, 2002).

For the past 40 years, coastal scientists and the general public have used the Saffir-Simpson Scale to compare tropical cyclones (Simpson, 1971) and several indices have been used to characterize winter storms. For example, Allen (1981) proposed a storm index based on prevailing onshore wind velocity that reflects storm energy and Halsey (1986) developed a ranking for North-east Atlantic coastal storms (*northeasters* or *nor'easters*) based on a potential damage index. Dolan and Davis (1992) used an intensity scale index based on wave height and storm duration for the northeasters and described morphological changes associated with each one of the five proposed storm classes. Specifically, previous authors associated minor to modest beach erosion with Classes I and II events; significant and severe beach and dune erosion with Classes III and IV events, respectively; and extreme beach erosion, dune flattening and coastal structure damages with Class V events.

More recent work on potential coastal damage associated with energetic events has incorporated more complex natural variables which can be very important during storm events. For example, Orford *et al.* (1992) and Orford and Carter (1995) partially incorporated the role of storm tides in a new storm index and Kriebel and Dalrymple (1995) proposed a risk index by combining the effects of storm surge, wave and duration.

A new storm erosion potential index was proposed by Zhang *et al.* (2001). This index took into account storm tides, wave energy and duration and compared obtained index values with recorded erosion data on the US East Coast. Lastly, Moritz and Moritz (2006) used hourly wave data and period to calculate wave power using the Dolan and Davis (1992) method and a theoretical wave flux formulation and Komar and Allan (2008) compared the decadal variations in measured wave heights to the annual numbers of hurricanes, their intensities and tracks.

Recent studies on wave height extreme values, storm distribution and related beach changes along the Portuguese and Spanish coast of the Cadiz Gulf have been carried out by Rodríguez *et al*. (2003), Menéndez *et al*. (2004) and Almeida *et al*. (2010). The aim of this paper is to examine the relationship between different types of storm event and the morphological response of beaches in the Cadiz area (SW Spain). As described above, storm indexes can be designed around a range of different input data, such as storm surge and wind regime. For this work, the Dolan and Davis (1992) storm index was chosen because the data requirements, significant wave height and storm duration can be derived from the HIPOCAS (Hindcast of Dynamic Processes of the Ocean and Coastal Areas of Europe) network (Sotillo *et al.*, 2006, 2008)

Since the forecasting of storm impacts on sandy littorals may be possible if information is available on past storm event characteristics and associated morphological changes and damages (Morton, 2002), the results from this work are useful for predicting potential storm impact in future decades along the coast studied, which has great tourism value. The methodology used in this study can be easily applied in different coastal areas where cross-shore profiles and wave data, obtained from HIPOCAS network or offshore wave buoys, are available for a monitoring period encompassing an erosion/recovery cycle. Lastly, information obtained within this study constitutes a first step towards the creation of a coastal response model that would incorporate the impacts of previous extreme storms, near-real-time surge and wave run-up predictions.

Study Area

The littoral investigated is located in the Gulf of Cadiz (Figure 1) and faces the Atlantic Ocean on the south-west coast of Spain. The site has undergone in recent decades significant erosion problems with locally recorded values greater than 1 m yr^{-1}, essentially associated with the impact of storm events (Muñoz and Enriquez, 1998; Reyes *et al.*, 1999; Benavente *et al.*, 2002; Anfuso *et al.*, 2007). During the 1990s, in order to balance coastal retreat trends and, especially, to make beaches more attractive by enlarging the dry beach width, *c.* 13 million m^3 of sediments were injected to enlarge the dry beach, with a total cost of US $37 million (Muñoz *et al.*, 2001).

The littoral zone is mesotidal, with mean values for neap and spring tidal ranges of 1 and 3.50 m respectively. Western winds are generally related to Atlantic low-pressure systems and blow from the WNW to the WSW directions (Figure 1). The eastern winds, blowing from the ESE direction, are originally formed in the Mediterranean Sea and greatly increase in velocity due to channelling through the Gibraltar Strait (Figure 1). Due to the coastline orientation, western winds give rise to both sea and swell waves and eastern winds have no important fetch principally giving rise to sea waves. Significant wave height values are usually lower than 1 m and approach from the SW to the WNW directions (Muñoz, 1996; Anfuso and Gracia, 2005).

This paper examines beach morphological response to storm events focusing on the Chipiona-Rota littoral sector (Figure 1); this is partly because the area is affected by winter storms, but also because of the availability of topographic data for the 1996–1998 period. In this sector, beaches are composed of fine–medium sand essentially consisting of quartz (85–95%) and carbonates. Dunes are well developed at Punta Camarón and Punta Candor and a wide, smooth intertidal rock shore

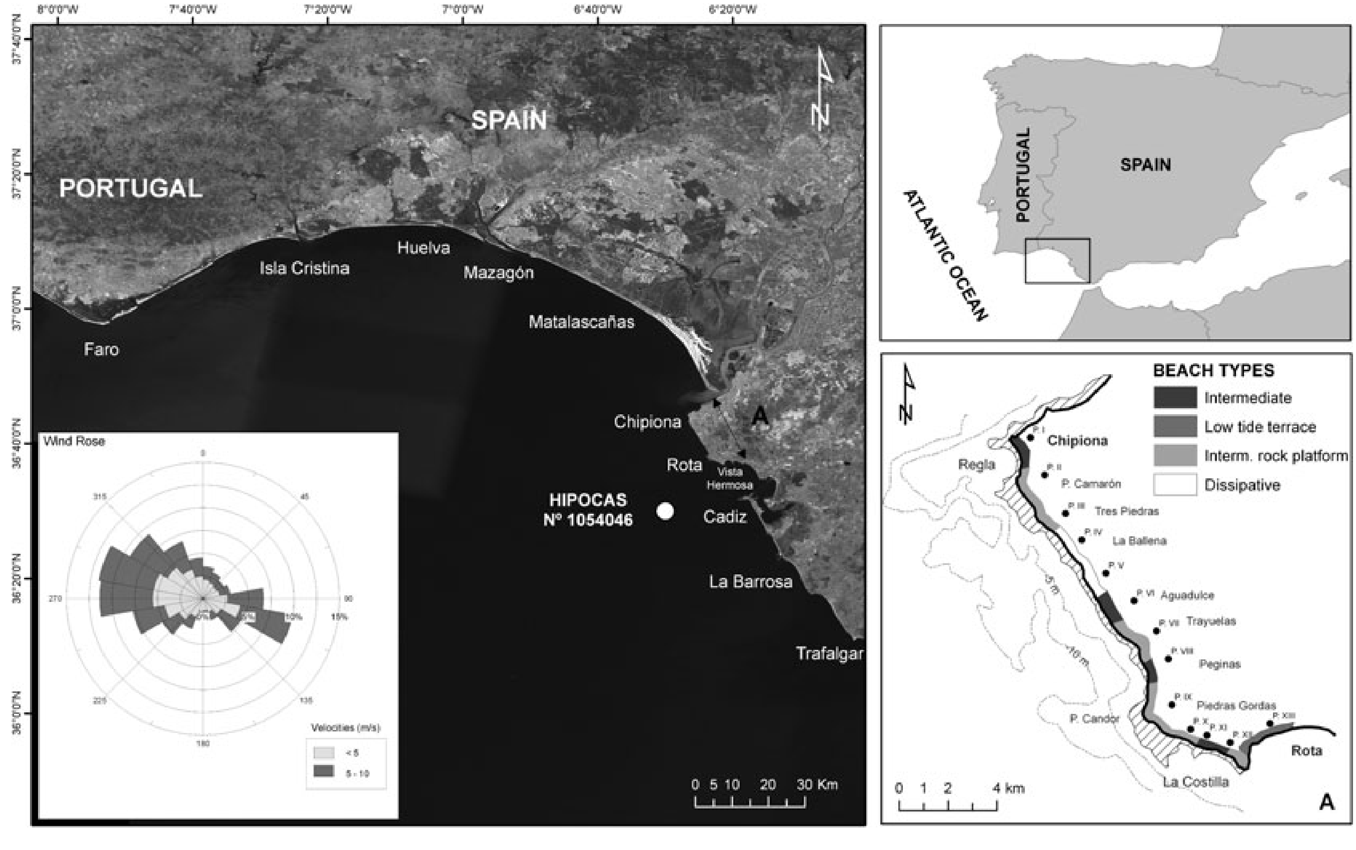

Figure 1. Study area with location of the prediction point nº 1054046 of the HIPOCAS network, distribution of the investigated beach types along the Chipiona-Rota sector and the wind rose for the Cadiz area (wind velocity intervals higher than 10 m/s not presented due to their low occurrence).

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platform, linked to cliff retreat, is observed at places in the nearshore and foreshore zones (Anfuso and Gracia, 2005). Anfuso *et al.* (2003) and Anfuso and Gracia (2005) observed three main beach types: (i) 'intermediate'; (ii) 'intermediate with rock shore platform'; and (iii) 'dissipative' beaches (Figure 1). The 'intermediate' type was observed at Regla (P.I), Aguadulce (P.VI), Peginas (PVIII) and La Costilla (P. XI), was visually close to the 'reflective' state described by Wright and Short (1984) and presented a marked seasonal behaviour. The 'intermediate with rock shore platform' type, observed at P. Camarón (P.II), Tres Piedras (P.III), Trayuelas (P.VII) and Piedras Gordas (P.X), presented a well developed rock shore platform in the low foreshore and intermediate beach slope values. Lastly, the 'dissipative' type, observed at Tres Piedras (P.IV) and La Ballena (P.V), was very close to the 'dissipative' beaches of Wright and Short (1984).

Data and Methods

Present investigations have been carried out within an ongoing Research Project founded by the Spanish Ministry of Science and Technology (no. CGL2008-00458/BTE) on storm characterization and effects in the Cadiz area. Two sets of data have been essentially used: i) HIPOCAS wave data, which allowed the characterization of storm events by the use of the Storm Power Index (Dolan and Davis, 1992) and ii) beach topographic surveys carried out along the Chipiona-Rota sector, which allowed the characterization of beach morphological response to erosive events.

Wave climate and storm characterization

The wave climate data used in this study have been obtained from the prediction point n° 1054046 of the HIPOCAS network (Figure 1), an atmospheric hindcast performed in the Atlantic Ocean and the Mediterranean Sea with a horizontal resolution of about 20 km (Guedes *et al.*, 2002). The 128 518 records used in this investigation covered the 1958–2001 period and were collected with a frequency of 3 h. HIPOCAS data has been extensively validated (Ratsimandresey *et al.*, 2008) and in the Cadiz area, differences of only a few centimetres have been observed between HIPOCAS and buoy wave data (Universidad de Cantabria, 2004).

A storm is defined as a climatic event during which the wave height exceeds a threshold over a minimum, specific time duration. In this work, wave height threshold has been set at 2.5 m because it reflects the deep-water wave height at which erosion affected Cadiz beaches (Plomaritis *et al.*, 2009, 2010) and it represents rare events constituting only 8% of records over the investigated period (Dorsch *et al.*, 2008). The minimum storm duration has been fixed at 12 h – in this way the storm affected the coast at least during a complete tidal cycle. The inter-storm period has been set at one day in order to create de-clustered, independent sets of storm events (Morton *et al.*, 1997; Dorsch *et al.*, 2008).

The Dolan and Davis (1992) *Storm Power Index*, i.e. the energy content for each storm, was calculated. The aforementioned index was preferred because data on storm surge and wind velocity and direction were not always available to apply to other indexes. The Dolan and Davis (1992) Index has been calculated according to the formulation:

$$H_s{}^2 t_d \tag{1}$$

with H_s being the maximum significant wave height (m) and t_d the storm duration (h).

Once the storms were recognized and characterized, the different classes were obtained by means of the natural breaks function (Jenks and Caspall, 1971) that determines the best arrangement of values into classes by iteratively comparing the sum of the squared difference between observed values within each class and the class means.

In a further step, storm trend during the 1958–2001 period has been analysed following Komar and Allan (2008) which stated that records between 25 and 35 years have sufficient lengths to permit analyses of potential trends of increasing wave heights, presence of climate-controlled cycles or annual variations due to climate events.

Frequency analysis has been applied to estimate storm power return periods that were calculated using extreme value distributions (An and Pandy, 2005; Rajabi and Modraes, 2008). The Generalized Extreme Value (GEV) distribution has been calculated from:

$$F(x) = \exp\left\{-\exp[-(x-u)/\alpha]^{1/k}\right\} \tag{2}$$

where x is the random variable and u, α and k are, respectively, location, scale and shape parameters that should be estimated for the sample. The equation reduces to the Type I (or Gumbel, for $k=0$), the Type III (or Weibull, for $k>0$) or the Type II (for $k<0$) distributions. The equation for the Type I (Gumbel) distribution is:

$$F(x) = \exp\{-\exp[-(x-u)/\alpha]\} \tag{3}$$

The method of parameter estimation for each distribution is discussed in detail in Rao and Hamed (2000). The maximum likelihood and the method of moments were used in this work to estimate the parameter distribution.

Morphological changes

In order to qualitatively and quantitatively evaluate the impact on sandy beaches of characterized storm events, an available data set of 214 beach profiles was analysed. Profiles were carried out with a monthly periodicity at 13 locations along the Chipiona-Rota littoral during the time period 1996–1998 (Figure 1). Specifically, an electronic theodolite (with a nominal accuracy of few centimetres) was used to carry out topographic profiles extended from the dry beach to a depth equivalent to the mean spring tide low water level (Anfuso and Gracia, 2005).

In order to quantify the impact of storms on morphological and volumetric changes at investigated beach locations, the profiles were sub-divided into different cross-shore sectors according to their morphological variability (Winant *et al.*, 1975; Lee *et al.*, 1998; Almeida *et al.*, 2010). This entailed a detailed analysis of vertical variation of each profile and standard deviations were used to divide the overall profile into sectors and thereby identify the main active zones (Lee *et al.*, 1998).

In a second step, volumetric and maximum vertical topographic variations of the beach profile were determined by calculating the differences among consecutive profiles for the sector that presented the maximum variability (i.e. the highest standard deviation), fundamentally coinciding with the upper part of the foreshore. Beach profiles and wave data allowed the determination of the upper foreshore slope values and Surf Similarity (Battjes, 1974). Further information on morphological changes and coastal damages associated to storm events in the Cadiz Gulf over the 1958–2001 period was also gathered.

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Results and Discussion

Storm events constitute the most important cause of coastal erosion along the studied littoral since sea level trends during the past 40 years at the Cadiz coast did not show a single clear trend (Marcos and Tsimplis, 2008). Storm generation and tracks across southern Europe are related to the North Atlantic Oscillation Index (NAO), which represents the differences of atmospheric pressures at sea level between the Azores and Iceland (Rodwell *et al.*, 1999). Hurrell (1995), in southern Europe, and Rodríguez et al. (2003), in the Gulf of Cadiz, observed that stormy years prevail during negative values of NAO oscillations while during the NAO positive values, low cyclonic activity is recorded and winters are dryer than normal because of the predominance of eastern winds and the deviation towards higher latitudes of active systems (Rodwell *et al.*, 1999).

The next section describes the wave characteristics and storm events characterization and distribution over the 1958–2001 period. Special attention is devoted to storms recorded during the January 1995–May 1998 period in order to investigate their effects on the sandy beaches and dunes along the Chipiona–Rota sector and at other locations in the Cadiz Gulf.

Wave characteristics and storm distribution

Approaching wave directions clearly reflected the broadly bidirectional wind behaviour (Figures 1 and 2): according to the results obtained in this study, waves approached the beach essentially from western directions; this included 63.4% of wave heights lower than 1 m and 28.6% of wave heights in the range 1–2 m. Significant wave heights > 2 m were observed during the November–March period and heights > 2.5 m were recorded in December and January, while between November and April, the monthly mean significant wave heights ranged between 1.0 and 1.5 m (Figure 2). In the months from December to March, the average and maximum wave periods were 6 and 8 s, respectively.

The distribution of the 377 storm events recorded in this study presented a clear log-normal trend containing five classes obtained using the previously described natural breaks function (Jenks and Caspall, 1971; Table I and Figure 3).

Classes I (weak) and II (moderate) accounted for, respectively, 60% and 23% of records. These values were very close to the ones obtained by Dolan and Davis (1992), Moritz and Moritz (2006) and Mendoza and Jimenez (2008) in their respective studies. Class III (significant), constituted 9% of the events and Classes IV (severe) and V (extreme) accounted for 5% and 2%, respectively.

Average wave height and storm duration values presented important variations (Table I) and mean wave period ranged from 6.7 (Class I) to 8.9 (Class V). Lastly, storm power values were larger than the ones proposed by Dolan and Davis (1992) because of the major threshold of storm wave height selected in this study and the longer duration of the storms investigated.

Dealing with monthly distribution, Class I events were observed during the whole year (except July and August), Classes II and III from October to March-May and Classes IV and V from November to February, with maximum values in December (Figure 4).

In general, storms approached the littoral from the 240° to 280° directions. Specifically, the 260–270° and 240–250° approaching directions characterized Class III events and the

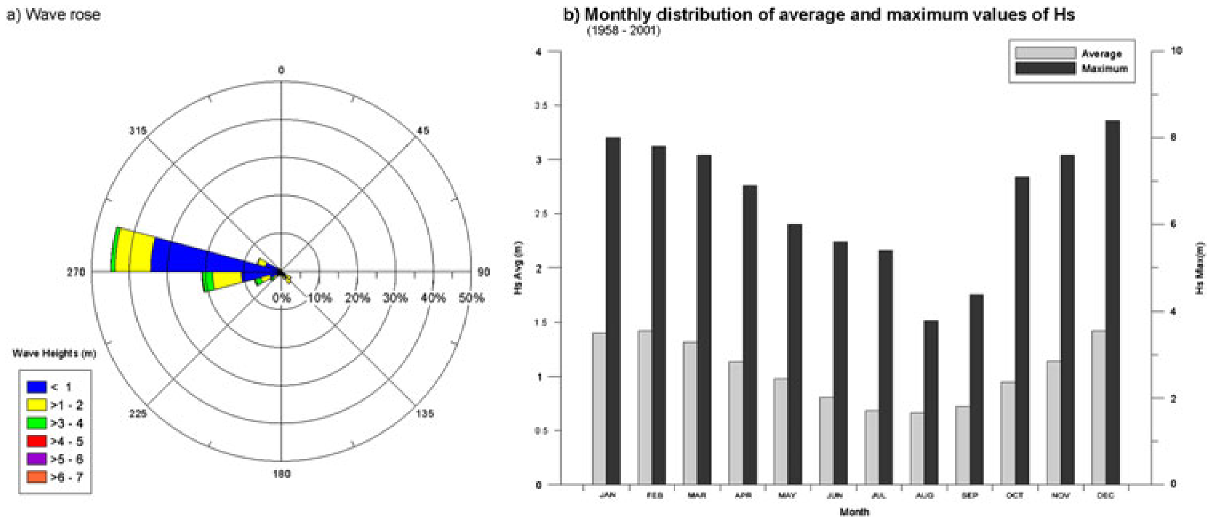

Figure 2. (a) Wave rose obtained from the HIPOCAS wave data; (b) and monthly distribution of average and maximum values of significant wave height. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Table I. Characteristics of the five storm classes: range, frequency (number of cases and percentages), significant wave height, storm duration and storm power index per each class (X = mean values and S = standard deviation)

	Range	Frequency		Wave height		Period	Duration	Storm Power
Class	(m^2 h)	*N*	(%)	*X*(m)	*S*	*X*(s)	*X*(h)	*X*(m^2 h)
I –Weak	<515	227	60	3.29	0.50	6.69	23	256.07
II - Moderate	516–1225	88	23	4.23	0.71	7.13	45	792.28
III -Significant	1226–2537	34	9	5.16	0.60	7.78	65	1693.61
IV- Severe	2538–5167	19	5	5.92	0.70	8.35	101	3374.15
V - Extreme	>5167	9	2	6.75	0.74	8.9	165	7272.60

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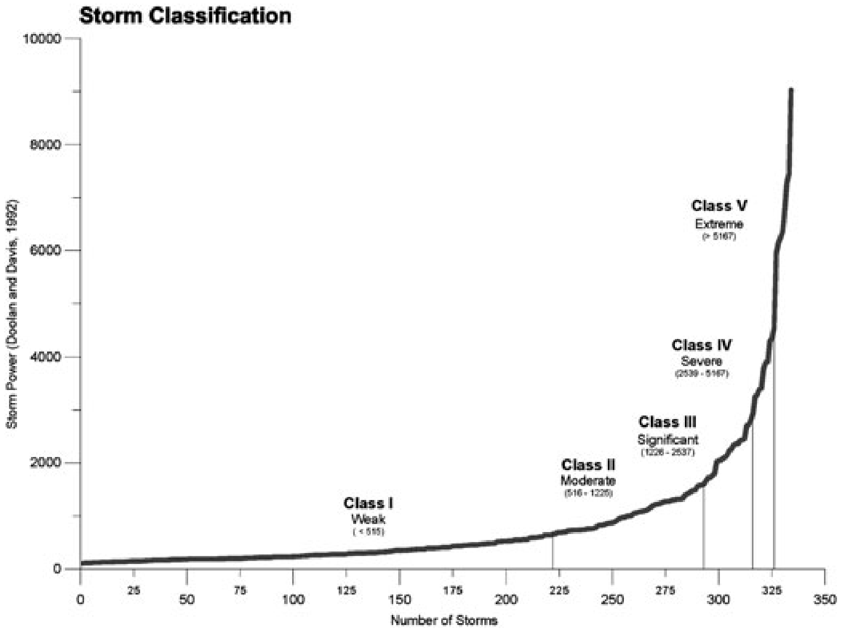

Figure 3. Cumulative curve of storm classes' distribution obtained using the natural breaks function of Jenks and Caspall (1971).

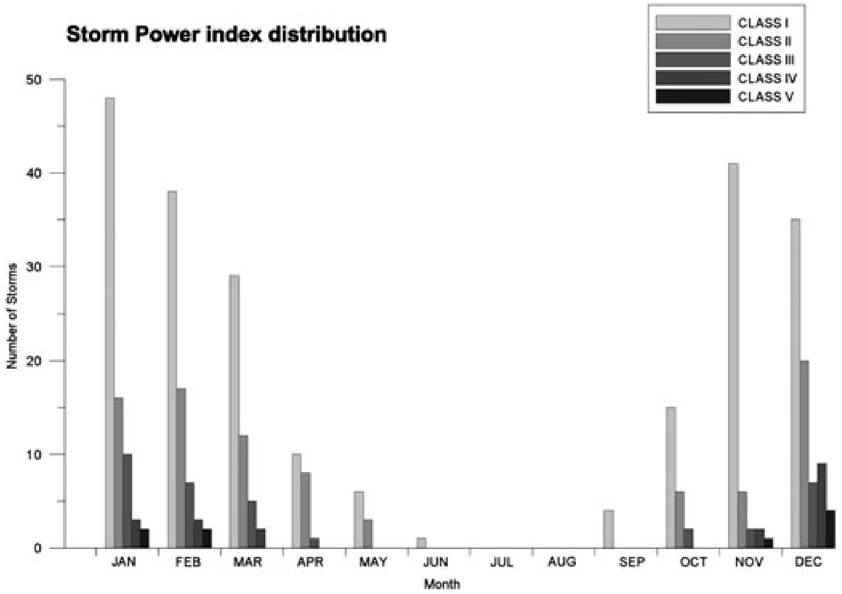

Figure 4. Monthly distribution of Storm Power Index per class.

250–260° and 240–260° directions characterized Classes IV and V, respectively.

Distribution over the period investigated of the number of storms and extreme events (i.e. maximum values of wave height and storm power) per year are presented in Figure 5. An elevated number of storms ($\geq$12) were recorded in 1959, 1960, 1963, 1966, 1978, 1987 and 1996 (Figure 5(a)), wave height values greater than 6.83 m (Class V) were recorded in 1966, 1973, 1981, 1982, 1989 and 2000 (Figure 5(b)) and storm power values greater than 5167 m^2 h (Class V, extreme) were recorded in 1958, 1966, 1970, 1979, 1981, 1989, 1996 and 2000 (Figure 5(c)). Lastly, storm duration, maximum values ($\geq$150 h, Class V) were recorded in 1958, 1970, 1978, 1979 and 1996.

At a regional scale, a strong correspondence was observed between data obtained in this study and results obtained by Rodríguez *et al*. (2003) for the Huelva area along a coastal sector that is broadly similar to the Cadiz area as far as its orientation and exposure to storms (Figure 1). Previous authors identified eight main stormy periods during the 1956–1996 interval. Seven of them coincided with years of high storm power values ($\geq$3000 m^2 h, Class IV), five with years characterized by a great number of storms ($\geq$10) and the six calm periods recorded by Rodríguez *et al*. (2003) coincided with years of low storm power values.

Concerning storm distribution in northern Europe, a certain correspondence was observed between data obtained in this study and observations reported by O'Connor *et al*. (2011) who analysed the gale-day frequency at the Malin Head meteorological station in Northern Ireland. They determined that gale frequency was at a low during the 1950s, increased through the 1960s and reached a peak in the early 1990s, before decreasing until 2009.

The energetic conditions recorded in the Cadiz Gulf area during the 1995–1996 period also corresponded with weather conditions recorded over the same period in Wales (UK) by Phillips (2008) and Phillips and Crisp (2010) who reported

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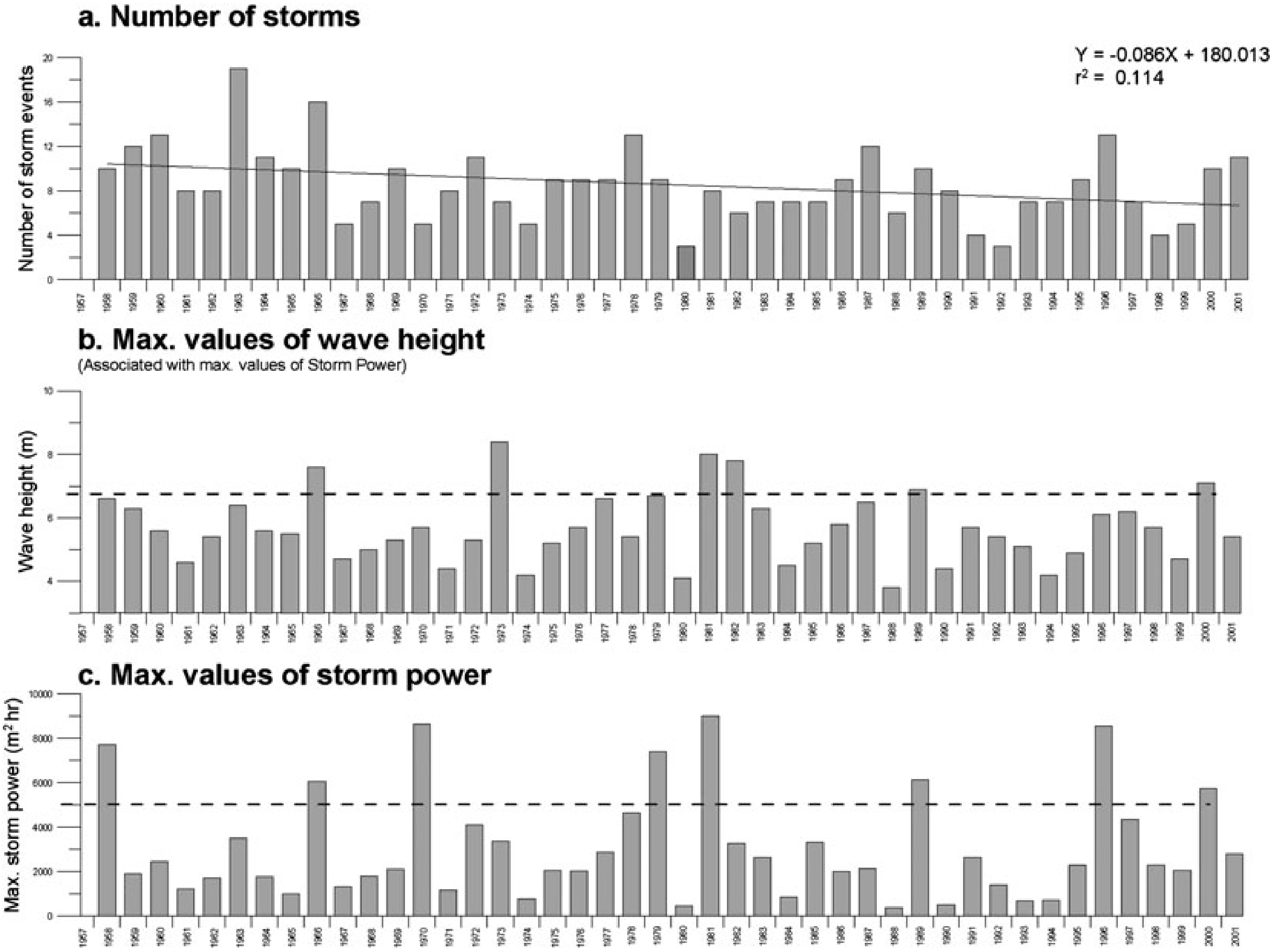

Figure 5. (a) Distribution of the number of storms per year and trend, linear regression equation and r^2 values also presented; (b) maximum values of significant wave height associated with maximum values of Storm Power, (c) maximum values of Storm Power per year during the 1958–2001 period. Thresholds of wave height and Storm Power for Class V events also indicated in (b) and (c).

significant changes in wind direction, high wind speeds and an increase in damage to coastal structures. Specifically, damage was due to the action of severe easterly storms resulting from low atmospheric pressure values linked to the two largest negative NAO Index values recorded over the 1993–2007 period. In the same way, Dailidiene *et al.* (2011) and Kelpšaité *et al.* (2011) in Lithuania observed that 1996 was an exceptional year, characterized by the mildest temperatures on record, low winds and a high frequency of small waves from the east. Similar conditions were observed in Estonia and in the southern Gulf of Finland by Suursaar (2010). In addition, fair weather conditions recorded in the Cadiz Gulf area during 1997 and 1998 were similar to the observations carried out in England reported in Environmental Scientist (2000), which stated that 1997 was the third warmest year and the 1990s the warmest decade on record in the UK, with wetter winters and drier summers. Therefore, there is supporting and diffuse evidence for variations in normal meteorological conditions during the 1995–1996 period as observed in this study.

Storm frequency

The return periods were estimated using the method of the maximum likelihood based on the Gumbel distribution of the annual maximum storm power values. The probability plot for each storm power was represented in Figure 6(a) and (b) and derived using the Gringoten (1963) plotting position formula suggested by Cook (2004) and Goel *et al.* (2004):

$$TR = N + 0.12/m - 0.44 \tag{4}$$

where N is the number of annual maximum observations (i.e. 44 years) and m is the rank of storm power from the lowest to the highest observation. According to the Gumbel distribution, the expected significant storm power for a selected return period can be estimated as follows (reduced value):

$$Rp = -\ln[-\ln(1 - 1/TR)] \tag{5}$$

Specifically, the return period for Class V events was 6 years (Figure 6a), which is in accordance with the 6–7 year recurrence period for most important storms proposed for the Huelva and Cadiz regions by Rodríguez *et al.* (2003) and Muñoz and Enriquez (1998) respectively. Classes I to IV showed a period of recurrence ranging from 1 to 3 years and storm occurrence probability was 93% for Class I (i.e. almost 1 event per year) to 15% for Class V (Figure 6b). Stormy years characterized by numerous Class III to V events (Figure 7) had more than 200 h of storm conditions per year.

The relationship between storm events and damage to structures varies according to storm characteristics and coastal behaviour, and impact can be cumulative. For example a series of storms or a series of stormy years may cause damage that is not immediately visible until a major failure occurs. Coastal damage recorded by Reyes *et al.* (1996), Ballesta *et al.* (1998)

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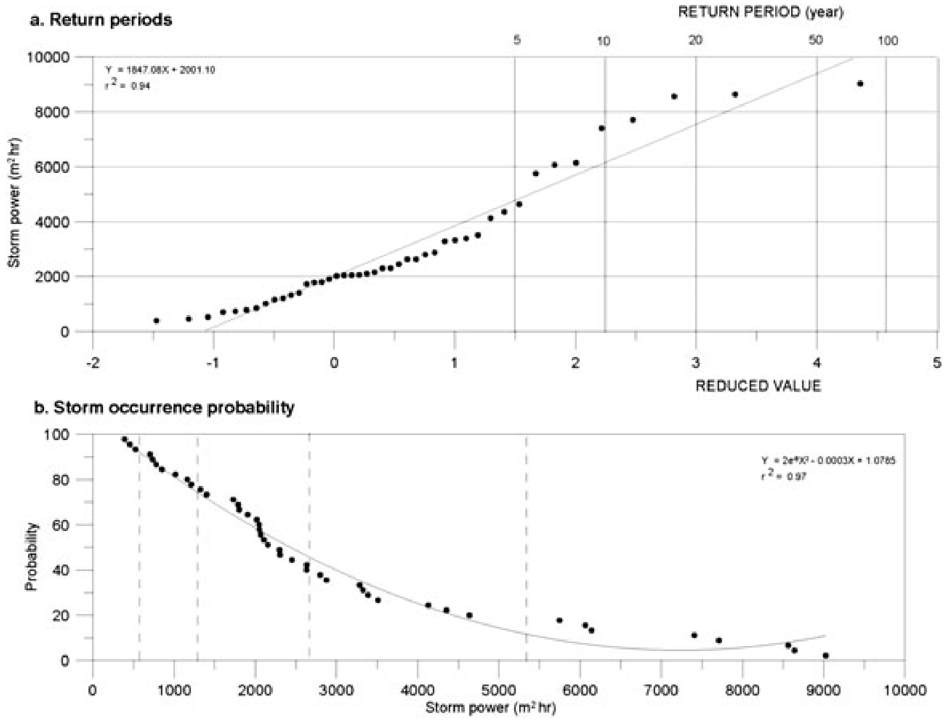

Figure 6. Storm recurrence and probability for the different storm classes in Cadiz. (a) Annual maximum Storm Power plotted versus the reduced value from the Gumbel distribution using the Gringoten plotting position. (b) Storm occurrence probability plotted versus the annual maximum Storm Power.

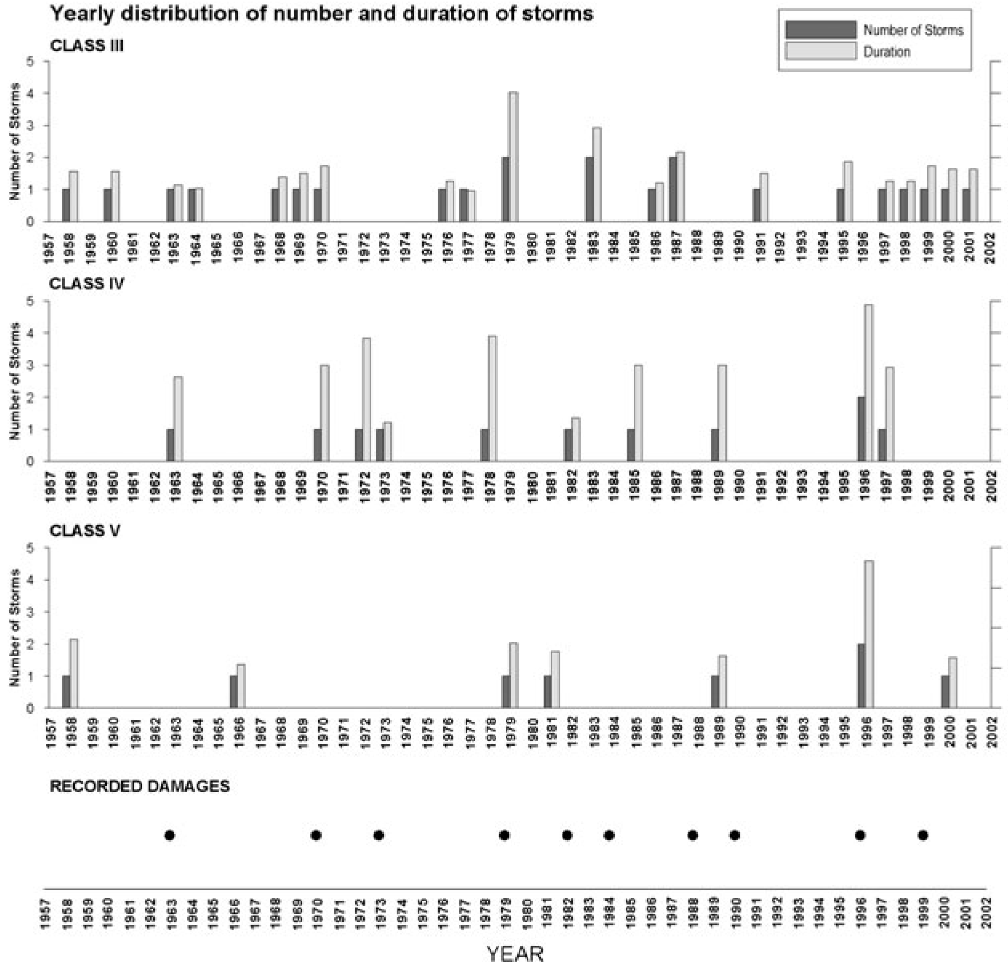

Figure 7. Yearly distribution of number and average duration of storms during the 1958–2001 period for Classes III, IV and V. A cyclic and not always regular behavior is evident. Temporal distribution of damages to human-made structures reported by Reyes *et al.* (1996, 1999), Ballesta *et al.* (1998) and Rodríguez *et al.* (2003) at Isla Cristina, Huelva, Mazagón, Mataslascañas and Cadiz areas are also reported.

and Rodríguez *et al*. (2003) along the Huelva and Cadiz littoral has been plotted in Figure 7, in order to compare their distribution with storm events belonging to Classes III, IV and V. In this case, it is evident that damage recorded over the past decades were related to stormy years characterized by Classes IV and V events. The impacts included damage to summer houses, coastal roads, beach facilities and harbours and, sometimes, produced human losses (Figure 8).

The 1995–1998 period: storm events and associated morphological changes

During the three winter seasons recorded over 1995–1998, the littoral investigated experienced 28 storm events (Figure 9, Table II) that caused severe morphological change and damage along the Cadiz Gulf. In order to evaluate beach morphological response, both published reports and data from surveyed beach profiles (Anfuso and Gracia, 2005) were used. Specifically, in the Chipiona-Rota sector, the magnitude of morphological and volumetric variations related to the impact of such events was investigated using the available data set of 214 beach profiles carried out in the 1996–1998 period. Beach profiles were analysed using the distribution of nodal and anti-nodal points (using standard deviation between successive profiles), which greatly depended on beach type. Antinodes in the 'intermediate' beach were located at mean sea level and nodal points coincided with the berm location. The 'intermediate rock shore platform' and the 'dissipative' beaches possessed antinodes located below high water level or at mean sea level, depending on the beach slope and intensity of erosive processes.

The storm distribution during the 1995–1996 winter season was compared with morphological changes at several locations along the Cadiz Gulf. The 1995–1996 period was one of the most energetic on record, with several powerful storms: the T6 and T7 events, that were 'moderate' and 'severe,' respectively, in December, and T8 ('extreme'), T9 ('severe') and T10 ('moderate') events in January, which often coincided with spring tide conditions (Figure 9).

The morphological response at the different beaches investigated was analysed according to data availability and storm chronology. Morphological change at Vistahermosa, which is located south of Rota, and La Barrosa beaches (Figure 1) was described by Reyes *et al*. (1996) who stated that both beaches were affected by a storm in the second half of December 1995 (corresponding to the T6 'moderate' event in this study). This event caused partial berm erosion according to the beach pivoting mechanism at mean sea level (Jackson and Nordstrom, 1992); subsequent storm events at the end of December 1995 and in January 1996 (the T7 'severe', T8 'extreme' and T9 'severe' events in this study) induced further erosion, especially in the upper foreshore, and affected the dunes, creating 1 m escarpments (at La Barrosa).

Figure 8. Examples of dune and cliff erosion (left side) and beach damages (right side) along the Peginas and Punta Candor areas associated with the impacts of storms over the 1995–1996 winter period (storm events T6–T12 in Figure 9).

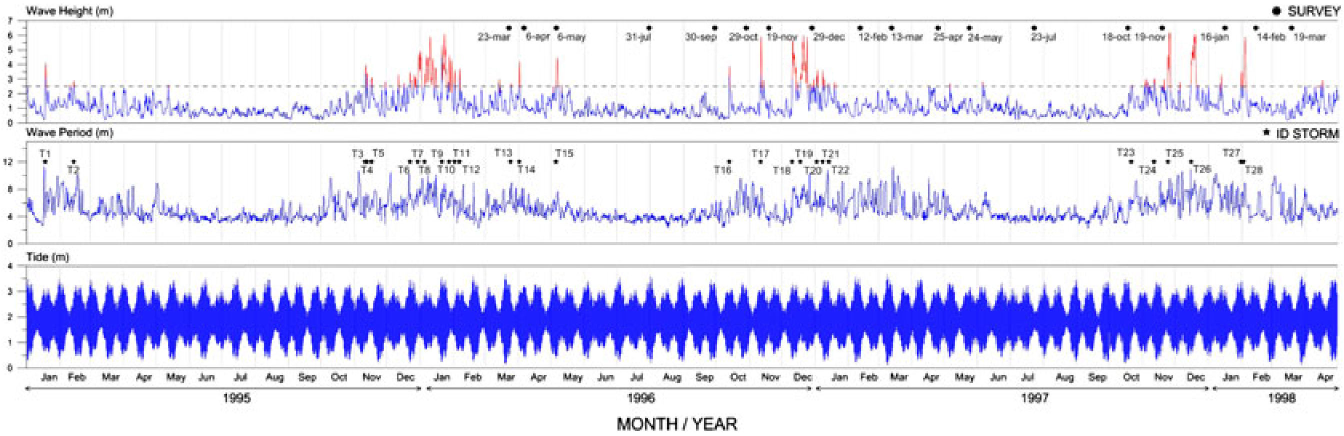

Figure 9. Significant wave height, period and tide conditions over the January 1995–April 1998 period. Temporal distribution of field surveys carried out at Chipiona–Rota sector (C1 to C18.) and storms (T1 to T28) are also indicated. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Table II. Characteristics of storm events

Year	Month	Day	Duration (h)	*Hs* (m)	*T* (s)	*PW* (m^2 h)	Direction (°)	Class	N°
1995	JAN	18	21	4.1	6.9	353.01	250	weak	T1
	FEB	13	18	2.9	6	151.38	258	weak	T2
	NOV	10	21	4	6.9	336.00	225	weak	T3
	NOV	12	15	3.4	6.4	173.40	262	weak	T4
	NOV	16	24	3.1	6.2	230.64	242	weak	T5
	DEC	22	90	3.5	6.8	1102.50	256	moderate	T6
	DEC	29	96	4.9	7.5	3097.29	253	severe	T7
1996	JAN	4	246	5.9	8.7	8563.26	259	extreme	T8
	JAN	20	108	6.1	8.8	4018.68	249	severe	T9
	JAN	27	33	4.6	6.9	698.28	226	moderate	T10
	FEB	1	24	3.6	6.7	311.04	256	weak	T11
	FEB	6	18	3.7	6.5	246.42	273	weak	T12
	MAR	24	21	2.7	7.2	153.09	245	weak	T13
	APR	1	24	4.2	6.8	423.36	270	weak	T14
	MAY	5	54	4.5	7.3	1093.50	239	moderate	T15
	OCT	13	21	3.9	6.4	319.41	247	weak	T16
	NOV	11	33	5.9	7.8	1148.73	256	moderate	T17
	DEC	10	90	5.7	7.9	2924.10	239	severe	T18
	DEC	18	171	6	8.2	6156.00	247	extreme	T19
1997	JAN	2	36	3.6	6.4	466.56	264	weak	T20
	JAN	7	24	3.6	6.6	311.04	251	weak	T21
	JAN	13	15	2.7	5.4	109.35	211	weak	T22
	OCT	21	15	2.6	6.1	101.40	248	weak	T23
	NOV	11	24	3	6	216.00	276	weak	T24
	NOV	24	66	6.2	9.6	2537.04	261	significant	T25
	DEC	15	117	6.1	8.5	4353.57	251	severe	T26
1998	JAN	31	30	3.5	7.3	367.50	242	weak	T27
	FEB	2	66	5.9	8.7	2297.46	246	significant	T28

Reyes *et al.* (1999) analysed the effects of the 23–24 January 1996 storm (the T9 'severe' storm event in this study) at two mesotidal localities within the Gulf of Cadiz, i.e., La Barrosa beach (Cadiz) and Faro beach (in Algarve, Portugal – Figure 1). Faro beach is composed of medium-coarse sand and has a steep foreshore slope with tan $\beta = 0.11$. La Barrosa beach is composed of fine-medium sand and shows an intermediate morphodynamic state with average beach slope values tan $\beta = 0.03$. Faro beach experienced important and rapid changes with average and maximum erosion in the upper foreshore of 13.2 m^3/m and 41.4 m^3/m, respectively, and beach recovery took place in just 12 h with mean values of 13.4 m^3/m. La Barrosa beach experienced beach flattening and dune escarpment with average and maximum sediment loss of 34.43 m^3/m and 60.1 m^3/m, respectively. In this case, the recovery was much longer and took place on a seasonal scale; in fact, full recovery was achieved in July 1996.

Ballesta *et al.* (1998) analysed morphological changes at Marzagón beach (Figure 1) over the November 1995–July 1996 period. Authors reported erosion after storm events that took place at the end of December (the T7 'severe' and T8 'extreme' events in this study) with beach erosion and dune retreat between 3 and 14 m. Further erosion was due to subsequent storm events (the T9 and T10) that produced dune retreat between 7 and 20 m and damage to recreational structures. Complete beach recovery took place on a seasonal scale, in July 2006.

Concerning the morphological changes observed along the Chipiona-Rota sector, a Class II 'moderate' event (T15), with maximum wave height of 4.5 m and duration of 54 hours, affected the coast on 5 May 1996 (Figure 9). It produced partial

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berm erosion accompanied by small foreshore slope changes and maximum vertical erosion (MVE) at Regla and P. Camarón beaches of 0.26 m and 0.76 m, respectively. Beach recovery took place in the following months and almost all beach profiles showed a well-developed berm at the end of October 1996 because of fair weather conditions observed during the summer time (from June to October, Figures 9 and 10, survey C6). As a consequence of the impact of 'weak' (T16) and 'moderate' (T17) storm events characterized by maximum wave heights of 3.9 m and 5.9 m, respectively, significant berm erosion was recorded at several beaches (i.e. profiles P.VII, P.VIII, P.X and P.XI, survey C5–C6, Figures 9 and 10). Specifically, MVE ranged from 0.33 m (e.g., –32.8 m^3/m) at Peginas to 1.22 m (−55.1 m^3/m) at La Costilla, and accumulation took place at low foreshore with an associated foreshore slope decrease from 0.089 to 0.032 and from 0.071 to 0.033 at Peginas and La Costilla, respectively (Figure 10 and Table III).

The topographic survey (C7) was carried out at the end of December 1996 after the impact of two storms of Classes IV ('severe', T18) and V ('extreme', T19), characterized by similar wave height values (5.7 m and 6.0 m, respectively) but different durations (90 h and 171 h respectively, Table II). As a consequence of the impact of aforementioned events, severe erosion was observed with MVE of 0.80 m at La Ballena, 0.42 m at Peginas and 0.71 m at La Costilla (Fig. 10, Table III). It is important to highlight that, despite the impact of a 'severe' and an 'extreme' event before the C7, topographic changes recorded at C6 and C7 were similar because the above-mentioned powerful storms (T18 and T19) impacted already dissipative, flat profiles.

Due to the prevalence of fair weather conditions and despite the impact of three Class I storms ('weak', T20 to T22), the campaign (C8, February 1997) showed accumulation along the investigated littoral – especially at berm location – with maximum vertical accretion (MVA) of 0.53 m at P. Camarón, 0.61 m at Regla and 1.36 at Aguadulce (Figure 10, Table III) and associated foreshore slope increase (i.e. at Aguadulce). No storm conditions were observed in the following months (Figure 9) and beach recovery took place along the investigated littoral with beaches showing an accretionary stage on 17 October, with well developed berm at several localities (survey C13, Figure 10). Field surveys carried out one month later, on 18 November 1997 (C14, Figure 10), found evidence of

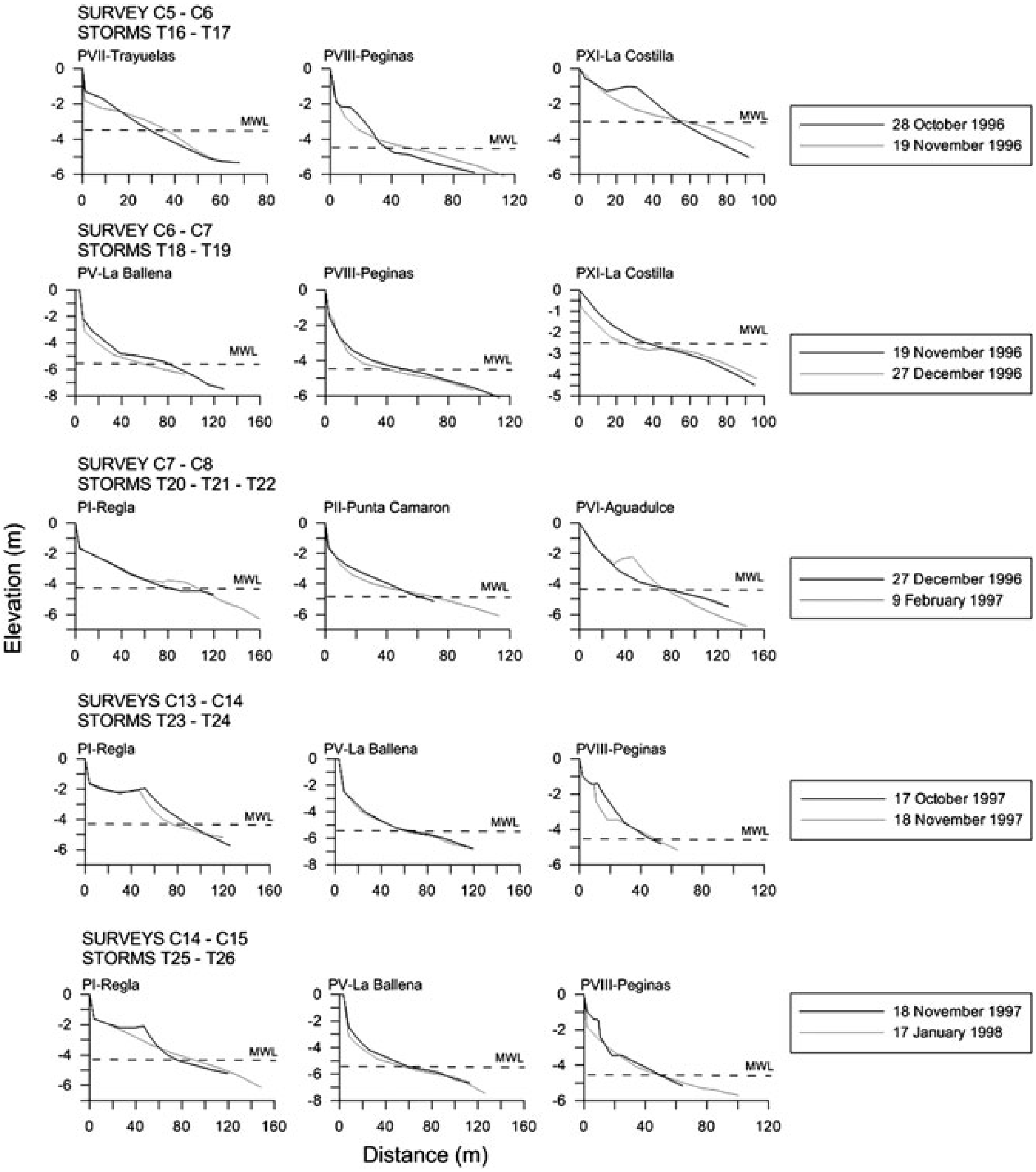

Figure 10. Beach profiles at different beaches along the Chipiona-Rota sector, see Figure 1 for specific location of each beach.

Table III. Beach profile variations at locations presented in Figure 10

Survey (C) Storm (T)	Site	Date	Slope (tan β)	ΔY (m)	Δ Vol (m^3/m)
C5	PVII-Trayuelas	28/10/1996	0.084	−0.57	−6.9
C6		19/11/1996	0.047		
T16	PVIII-Peginas	28/10/1996	0.089	−0.87	−32.8
T17		19/11/1996	0.032		
	PXI-La Costilla	28/10/1996	0.071	−1.22	−55.1
		19/11/1996	0.033		
C6	PV - La Ballena	19/11/1996	0.026	−0.8	−23.3
C7		27/12/1996	0.037		
T18	PVIII - Peginas	19/11/1996	0.03	−0.42	−0.4
T19		27/12/1996	0.036		
	PXI - La Costilla	19/11/1996	0.033	−0.71	−31.9
		27/12/1996	0.025		
C7	PI - Regla	27/12/1996	0.03	0.61	3.9
C8		09/02/1997	0.02		
T20	PII - Punta Camaron	27/12/1996	0.44	0.53	3.5
T21		09/02/1997	0.44		
T22	PVI - Aguadulce	27/12/1996	0.027	1.36	41.2
		09/02/1997	0.056		
C13	PI - Regla	17/10/1997	0.048	−0.85	−30
C14		18/11/1997	0.057		
T23	PV - La Ballena	17/10/1997	0.023	−0.21	−3.6
T24		18/11/1997	0.029		
	PVIII-Peginas	17/10/1997	0.058	−1.15	−0.8
		18/11/1997	0.044		
C14	PI - Regla	18/11/1997	0.057	−0.98	−27.5
C15		17/01/1998	0.027		
T25	PV - La Ballena	18/11/1997	0.04	−0.71	−7.7
T26		17/01/1998	0.036		
	PVIII-Peginas	18/11/1997	0.044	−0.98	−16
		17/01/1998	0.058		

erosion due to the impact of two Class I (‘weak’) events characterized by wave heights of 2.6 m and 3 m, respectively, and durations of 15 h and 24 h, respectively. Erosive processes affected the whole foreshore and/or partially eroded the berm, producing small slope changes and quite high MVE, ranging from 0.21 m at La Ballena to 1.15 m at Peginas (Figure 10).

Further erosion was recorded in the field survey C15 that was associated with two events belonging to Classes III (‘significant’, T25) and IV (‘severe’, T26) and characterized by similar wave heights but different durations (66 h and 117 h, respectively, Table II). Specifically, erosion processes affected the whole foreshore (with MVE of 0.71 m at La Ballena, Figure 10 and Table III) and/or completely eroded the berm (e.g. at Regla and Peginas, with MVE at both locations of 0.98 m, Figure 10 and Table III).

Lastly, two storm events were recorded between C15 and C16, on 31 January and on 2 February, belonging, respectively, to Classes I (T27) and III (T28). As a result, little erosion took place at several beaches (i.e. Peginas, P. Candor, etc.) because these beaches already showed a dissipative eroded profile. Once the berm was eroded, the ‘moderate’ (T28) event, which coincided with spring tide conditions, greatly affected dunes that experienced escarpments at P. Candor.

Morphological model of sandy beach response to storm events

The data presented here suggest that beach morphological response to storm events depends on beach morphodynamic type. Valdelagrana and La Barrosa beaches (described by Reyes *et al.*, 1996, 1999), Mazagón beach (described by Ballesta *et al.*, 1998) and the ‘intermediate’ beaches described in this study, presented similar behaviour. They showed a well developed berm at the end of summer (i.e. October) and, because of the impact of earlier storm events, experienced great erosion values linked to partial or complete berm erosion. This favoured accretion at mean and/or low foreshore according to the beach pivoting mechanism described by Jackson and Nordstrom (1992). Specifically, beach pivoting took place at a point located below high water level or at mean sea level, depending on the intensity of erosion processes and pre-storm beach morphology. As a result of erosion processes, the transition from a steep summer profile characterized by plunging breakers (Surf Similarity Index $\xi = 0.40$, limits following Fredsoe and Deigaard, 1992), to a flat, dissipative winter profile characterized by spilling breakers ($\xi = 0.27$) was observed. Successive energetic events in December and January produced further erosion. As a consequence of storm impacts over the period investigated, mean foreshore slope values in the ‘intermediate’ beaches (Figures 1 and 11) ranged approximately from tan $\beta = 0.06$ to tan $\beta = 0.03$ and associated morphological changes were relatively significant, ranging from 0.3 m to 1.33 m. Beaches investigated by Reyes *et al.* (1996, 1999) and Ballesta *et al.* (1998) experienced morphological changes on the same order of magnitude.

As a consequence of storm impacts, the ‘dissipative’ beach types along the Chipiona-Rota sector presented smaller and homogeneous morphological and topographic changes (from c. 0.36 m to 0.65 m, Figure 11), according to the parallel retreat mechanism (Jackson and Nordstrom, 1992). In fact, foreshore slope presented small variations (approximately from tan $\beta = 0.025$ to tan $\beta = 0.035$, Figure 11) and was always characterized by spilling breakers ($\xi = 0.21$). The ‘intermediate with rock shore platform’ beaches experienced smaller morphological and foreshore slope variations, related to both beach pivoting and parallel retreat mechanisms (Figure 10).

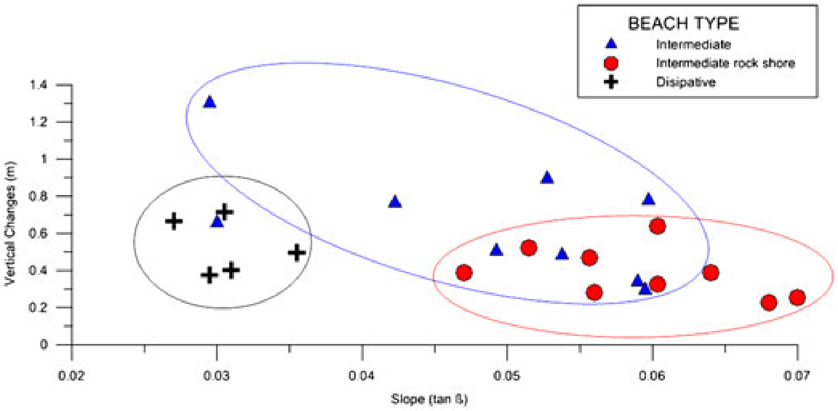

Figure 11. Maximum vertical changes versus average foreshore slope for each beach type. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Considerations of the role of storm succession

In general, the most important morphological changes were recorded: (i) on the beach foreshore because of the impact of earlier storms (usually 'weak' and 'moderate' events) during October and November; and (ii) on the beach foreshore, backshore and dunes because of the impact of 'severe', 'significant' and 'extreme' events in December and January (Figure 10). The role of extreme events versus frequent or persistent lower energy processes on beach and dune erosion has been a matter of long-standing debate in geomorphology. Bryant (1988), Southgate and Capobianco (1997) and Ferreira (2005) suggested that as a cause of beach damage, storm frequency is more important than wave energy. Lee *et al.* (1998) observed that given appropriate sequences, groups of storms can act as large individual events and the cumulative impact of groups of small–average storms is large and inferred to be similar to a low-occurrence single storm event. According to the data analysed in this study, erosion at the end of October 1995 was rapid and important at beaches investigated by Reyes *et al.* (1996, 1999) and Ballesta *et al.* (1998) because it was linked to the impact of very energetic events. Earlier beach changes recorded in the 1996–1997 winter season (i.e. campaign C6) along the Chipiona-Rota sector were rapid when compared with the ones observed in the 1997–1998 winter season (i.e. campaigns C14 and C15). In fact, in November 1996 (C6), the beach responded to a 'weak' and a 'moderate' event that completely eroded the berm producing a smooth winter profile while in November 1997 (C14), the beach responded to two 'weak' events that partially eroded the berm and/or the whole foreshore and successively complete beach flattening took place in January (C15) because of the impact of a 'significant' and a 'severe' event.

Along the littoral investigated, storm sequence (more than groupiness) and pre-storm beach morphology acquired a great importance in the sense that earlier storms produced important morphological changes favouring upper foreshore lowering: successive, more energetic events were able to reach the backshore causing dune escarpments and/or damage to coastal structures, making the littoral susceptible to low energy events and, even, no-storm wave conditions (Figure 10). This is in accordance with Forbes *et al.* (2004) who suggested that dune breaching, development of large overwash channels and barrier crest erosion may render the shore more susceptible to subsequent storm events, even storms of lesser intensity, if the interval between storms is insufficient for rebuilding the pre-storm dune barrier crest morphology. Shoreline vulnerability to erosion and overwash can thereby be significantly increased as a result of individual storms, suggesting the importance of storm groupiness over time scales of weeks to years in driving coastal retreat. This point was also made by Ferreira (2005), who stated that vulnerability to storm action partially depends on the difference between storm frequency and beach recovery period, beach erosion being accentuated when storm frequency exceeds the beach recovery period for individual storms (Morton *et al.*, 1995). The time lag between two storms used to define the existence of a storm group is different from region to region and must be defined after analysis of beach recovery rates and behaviour. In this study, storm sequencing was more important than storm groupiness since beach recovery was very slow. Partial beach recovery was only observed at the 'intermediate' beaches after several weeks of fair weather conditions, but generally full recovery took place on a seasonal scale in the Cadiz and Huelva areas (Reyes *et al.*, 1996, 1999; Ballesta *et al.*, 1998). Opposite behaviour was observed at Faro beach, which generally shows a clear reflective morphodynamic state ($\xi = 1.15$, Reyes *et al.*, 1999; Almeida *et al.*, 2010). This results in rapid erosion but quick recovery, in the order of days, this behaviour enhances the importance of storm groupiness on beach erosion.

Conclusions

The impacts of climate change on coastlines will increase worldwide in future years because of natural processes (i.e. sea level rise and extreme storm surge events) and anthropogenic activity (i.e. increasing construction development and activities related to the constant reclamation of land for recreational, tourism and industrial purposes). The Cadiz littoral will be particularly vulnerable to storm events, especially considering that in many coastal sectors important erosion processes have been recorded and they are heavily urbanized. Special attention must be devoted to beach surface losses which will cause severe economic damage to coastal tourism, which is the main economic activity for the investigated area. Although some European countries have qualitative data on storm processes and related effects and impacts, further investigations must be carried out in the Cadiz littoral to properly understand the potential physical and social consequences of such processes.

In this study, a storm classification into five classes was obtained for the events recorded over the 1958–2001 period. Most powerful storms, i.e. Classes IV and V events, approached, respectively, from the 250–260° and 240–260° directions and took place from November to February, with maximum values in December. The number of storms per year demonstrated a slight decrease during the period investigated while maximum

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storm power values presented a cyclic behaviour more than a defined trend. Return period of Class V events was 6 years and values from 1–3 years were observed for Classes I to IV.

Beach response to storm events greatly varied along the littoral investigated, essentially depending on the sequence of storm events and the beach morphodynamic state. Significant morphological changes were recorded because of (i) the impact of earlier storms (usually ‘weak’ and ‘moderate’ events) during October and November, and (ii) the impact of ‘severe’, ‘significant’ and ‘extreme’ events in December and January. In general, most beaches in the Cadiz and Huelva areas presented a well developed berm at the end of summer (i.e. October) and, because of the impact of earlier, low-energy storm events in November, experienced great erosion values linked to the partial or complete berm erosion that favored accretion at mean and/or low foreshore, depending on the intensity of erosion processes and the pre-storm beach morphology. As a result of erosion processes, the transition from a summer, steep profile (tan $\beta = 0.06$) characterized by plunging breakers (Surf Similarity Index $\xi = 0.40$), to a flat (tan $\beta = 0.03$), dissipative winter profile characterized by spilling breakers ($\xi = 0.27$) was observed. Associated morphological changes were relatively significant, ranging from 0.3 m to 1.33 m.

Other beaches presented a more dissipative flat profile (tan $\beta = 0.025$) characterized by spilling breakers ($\xi = 0.21$). Beaches experienced small and homogeneous morphological and topographic changes along the foreshore. Successive, more energetic events impacted lowered beach profiles and easily reached the backshore producing dune escarpment and/or damage to coastal structures, making the littoral also more susceptible to following events, even if they do not correspond with energetic conditions. Recorded morphological changes at dissipative beaches ranged from c. 0.36 m to 0.65 m.

The morphological and topographic characteristics and changes observed at the beaches investigated, expressed through the use of the Surf Similarity Index, beach slope and volumetric and vertical variations, are easy to extrapolate to other coastal areas around the world. Furthermore, results obtained in this work, improve and enlarge the general database on storm impacts and beach and dune response, this way being very useful for the prediction of potential storm impacts on sandy coastal areas.

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