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ESTABLISHING STORM THRESHOLDS FOR THE SPANISH GULF OF CÁDIZ COAST

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Abstract

In this study critical thresholds are defined for storm impacts along the Spanish coast of the Gulf of Cádiz. The thresholds correspond to the minimum wave and tide conditions necessary to produce significant morphological changes on beaches and dunes and/or damage on coastal infrastructure or human occupation.

Threshold definition was performed by computing theoretical sea-level variations during storms and comparing them with the topography of the study area and the location of infrastructure at a local level. Specifically, the elevations of the berm, the dune foot and the entrance of existing washovers were selected as threshold parameters. The total sea-level variation generated by a storm event was estimated as the sum of the tidal level, the wind-induced setup, the barometric setup and the wave-associated sea-level variation (wave setup and runup), assuming a minimum interaction between the different processes. These components were calculated on the basis of parameterisations for significant wave height (Hs) obtained for the oceanographic and environmental conditions of the Gulf of Cadiz. For this purpose real data and reanalysis time-series (HIPOCAS project) were used. Validation of the obtained results was performed for a range of coastal settings over the study area. The obtained thresholds for beach morphological changes in spring tide conditions range between a significant wave height of 1.5 m and 3.7 m depending on beach characteristics, while for dune foot erosion are around 3.3 to 3.7 m and for damage to infrastructure around 7.2 m. In case of neap tide conditions these values are increased on average by 50% over the areas with large tidal range.

Furthermore, records of real damage in coastal infrastructure caused by storms were collected at a regional level from newspapers and other bibliographic sources and compared with the hydrodynamic conditions that caused the damage. These were extracted from the hindcast database of the HIPOCAS project, including parameters such as storm duration, mean and maximum wave height and wave direction. Results show that the duration of the storm is not critical in determining the occurrence of coastal damage in the regional study area. This way, the threshold would be defined as a duration ≥30 hours, with moderate average wave height (≥3.3 m) and high maximum wave height (≥4.1 m) approaching from the 3rd and 4th quadrants, during mean or spring tide situation.

The calculated thresholds constitute snapshots of risk conditions within a certain time framework. Beach and nearshore zones are extremely dynamic, and also the characteristics of occupation on the coast change over time, so critical storm thresholds will change accordingly and therefore will need to be updated.

Keywords

Storm surge, HIPOCAS, threshold, wave runup, coastal erosion, Gulf of Cadiz

1. Introduction

Storms constitute one of the most significant natural threats to coastal communities, representing the world's foremost coastal natural hazard in terms of property damage and lives lost (Murty, 1988). Storm events can cause coastal erosion, coastal flooding, damage to infrastructure and other undesirable effects, thus creating the need for scientific tools, such as vulnerability maps, predictive techniques or warning systems, that can help to prevent these negative consequences. The development of such tools requires an adequate understanding of both the hydrodynamic processes acting during a storm, and the coastal response to this hydrodynamic forcing.

In general terms the impact of storms on the coast is determined by the cumulative effect of large-, meso- and local-scale processes. Barotropic forcing is the main large-scale process affecting short-term sea-level variations. The spatial distribution of atmospheric pressure during a storm can lead to sea-level temporal changes on the coastline (inverse barometer effect). Meso-scale processes are governed by the action of the onshore winds piling up water on the coast (wind setup). The magnitude of this setup is largely affected by the bathymetric characteristics of the continental shelf, such as average slope, width and depth. Furthermore, the generation and growth of the waves (large-scale) and wave transformation processes over the inner continental shelf (meso-scale) are also affected by the above parameters. Finally, closer to the shore (local-scale) the action of wave breaking and the swash processes produce an upwards and subsequently landwards displacement of the sea level (Masselink and Hughes, 2003).

The joint action of all the aforementioned processes produce an increase in water levels on the shore, which shift wave attack higher on the beach profile, thus facilitating wave runup to reach areas further inland than fair weather waves (Stockdon et al., 2007). This can result in overtopping of dune ridges and coastal defences, dune breaching, overwashing and other types of coastal damage. The storm surge adds to the astronomical tide to generate the storm tide, so under certain circumstances the combination of storm surge and spring tides (Pye and Blott, 2008) can have devastating consequences on coastal lowlands.

The potential severity of the consequences of storms has led to a considerable effort by coastal scientists in understanding and predicting storm impacts at different temporal and spatial scales. One of the approaches used by several authors is the modelling and calculation of storm surge components and the comparison with coastal topography, in order to determine the effects on the coast of different types of storm events. For instance, Sallenger (2000) established a model defining four storm-impact regimes (swash, collision, overwash and inundation) on barrier islands based on the relative relationships between the elevation of coastal features and that of storm-induced water levels. Benavente et al. (2006) used the computation of storm surge components added upon tidal height for determining flooding regime in a low-lying coastal zone in cases of modal and extreme storms. Storm-induced inundation was also studied by Jiménez et al. (2009) in microtidal coasts, where they defined it by calculating wave runup at the peak of the storm. These procedures allow the construction of vulnerability maps that help determining the coastal zones at risk of experiencing storm-induced damage.

However, none of these authors focused on the possibility of defining the minimum hydrodynamic conditions necessary to produce a certain type of effect on the coast, as well as estimating the possible effects by using only the offshore wave height and tide level. These conditions constitute the critical storm thresholds, which can be defined for storm impacts such as beach erosion, dune recession or damage to infrastructure located on the backbeach. Threshold definition is an important issue regarding prevention of the negative consequences of storms, as it represents the first step in the development of accurate predictions of storm impacts. This facilitates the implementation of both strategic and operational measures for an adequate coastal planning and management aimed at risk prevention, such as risk mapping, development of warning systems and so on.

In this paper an approach is performed on establishing a methodology for the definition of critical thresholds for storm impacts on the Spanish coast of the Gulf of Cádiz. The historical distribution of storms in this area has been studied by Rodríguez-Ramírez et al. (2003), and several authors have worked on storm effects on this coast (e.g. Ballesta et al., 1998; Reyes et al., 1999; Benavente et al., 2002, 2006), but no previous work has been done regarding storm thresholds. In this work two types of storm effects were investigated: the generation of significant morphological changes on beaches and dunes, such as berm erosion, dune foot erosion or washover occurrence, and the generation of damage on coastal infrastructure or human occupation. In both cases the thresholds correspond to the minimum wave and tide conditions necessary to produce the aforementioned effects. For this purpose two complementary approaches were used: the computation of theoretical water levels for different storm conditions, and the collection of newspaper data on the consequences of past storms. The method is developed for the regional coastline of the Gulf of Cádiz (SW Spain) and tested for a variety of local settings along the study area.

2. Study area

2.1. The Gulf of Cádiz

The Gulf of Cádiz is located on the Southwestern coast of the Iberian Peninsula, facing the Atlantic Ocean and surrounded by the Spanish, Portuguese and Moroccan shores. The Spanish part of the Gulf extends along 280 km between the Spain-Portugal border and the

Strait of Gibraltar, and it can be divided into two main sectors: the coast of Huelva province (to the West) and the coast of Cádiz province (to the East) (Fig. 1).

APPROXIMATE LOCATION OF FIGURE 1

Huelva coast shows a regular W-E to WNW-ESE orientation. It is located in the Guadalquivir Neogene Depression, which is formed by postorogenic sub-horizontal sedimentary materials. As a consequence, coastal landscapes are mainly low-lying areas including linear sandy beaches, low sandy cliffs and well-developed sandspits, such as El Rompido and Doñana, enclosing marshland areas. These have been generated by a strong longshore drift directed towards the East. The coast is fed by several important water courses, mainly the Guadiana and Guadalquivir rivers, where dam construction in the last decades has greatly decreased sediment supply to the coast (Rodríguez-Ramírez et al., 2003). Cádiz coastline shows a general NNW-SSE orientation, interrupted by short W-E traits related to recent faults (Fig. 1). From the geomorphological point of view two sectors can be differentiated, located North and South of Cape Trafalgar respectively. The Northern sector belongs to the end of the Guadalquivir Depression and as such is composed of the aforementioned soft, sub-horizontal Neogene materials, giving rise to a generally linear, low-lying coast with several wide embayments. Significant rivers such as Guadalquivir and Guadalete flow into this area, the extensive damming of their basins having also caused an important decrease in sediment supply to the coast (Plomaritis et al., 2009a). The Southern sector belongs to the Betic Ranges, showing higher relief areas on Paleogene and Neogene detritic and calcareous materials that were faulted and folded by the Alpine Orogeny. As a consequence, it is characterized by a young, indented coastline, with alternating cliffs and pocket beaches controlled by numerous neotectonic features.

Regarding the hydrodynamic regime, tides in most part of the Gulf of Cádiz are of mesotidal semi-diurnal type, with tidal range strongly decreasing from Cape Trafalgar eastwards. Mean spring tidal range (MSTR) is 3.06 m in Huelva, 2.96 m in Cádiz, 2.30 m in Barbate and 1.22 m in Tarifa (Fig. 1) (Instituto Hidrográfico de la Marina, 2009), so the area around the Strait of Gibraltar can be considered a microtidal environment according to Davies' (1964) classification. Theoretical maximum tidal range in the Gulf of Cádiz during equinoctial spring tides would reach 3.74 m with a coefficient of 120, but wind and atmospheric pressure during storms may add up to 50 cm to the astronomic high tide in the case of severe storms (Marcos et al., 2009).

Both sea and swell waves generally approach the coast from the W and SW, giving rise to a prevailing longshore current towards the E and SE (Fig. 2). Changes in shoreline orientation along the Gulf of Cádiz make the angle of wave approach progressively diminish towards the Strait of Gibraltar, rendering longshore drift much weaker in this area. Average wave height is less than 1 m, with waves over 1.5 m being considered storm waves by the Ministry of Public Works both in Cádiz and Huelva coasts (Benavente et al., 2000). Therefore, the study area can be classified as a low-energy coast according to Tanner (1960) and Hegge et al. (1996), with Huelva coast generally showing slightly lower wave energy than Cádiz coast (MOPT, 1992). The winter storm period spans between November and March, when storm wave heights commonly exceed 4 m, with the 20-year significant wave height being 7.3 m (Puertos del Estado, 2006).

APPROXIMATE LOCATION OF FIGURE 2

2.2. The test sites

Two test sites (Bota and Cortadura-Camposoto) were chosen, located on the western and central Gulf of Cádiz respectively (Fig. 1). The first test site, Bota beach, is located close to Punta Umbría village in the western part of the Huelva Ria. It is a linear, sandy beach extending along 4 km between the villages of El Portil and Punta Umbría. It is a natural beach backed by a foredune and non-vegetated dunes (Fig. 3A). A shore-parallel road runs along the back of the foredune, producing very high human pressure during the summer season. The road affects only the northern sector of the beach, as in the southern sector it is located further inland. This allows a better development of the foredune in the southern area. The beach is composed of fine to medium quartz-rich sands, and it shows a clearly seasonal behaviour, with a dissipative profile during the winter months and an intermediate morphology during fair weather conditions. Between both states, flat bars occasionally appear on the foreshore.

The second test site, Cortadura-Camposoto, is located around Cádiz city, in the southern part of the Bay of Cádiz (Fig. 1). It includes two different sandy beaches (Cortadura to the North and Camposoto to the South) extending along 10 km, providing the opportunity for studying the effects of storms on two different, nearby types of environments. Bathymetric contours in both sites are broadly parallel to the coastline and the nearshore zone shows a generally gentle slope, interrupted by several shoreline-parallel rocky outcrops. In detail, Cortadura is an urban beach located in Cádiz city, backed by a seafront on its major part and, on its southernmost sector, by foredunes and a low, mostly non-vegetated dune ridge artificially stabilised by fences (Fig. 3B). It shows an intermediate-dissipative profile composed by medium to fine quartz-rich sands, where wide, flat bars are often observed on the foreshore (Plomaritis et al., 2009b). On the other hand, Camposoto is a natural beach backed by low dune ridges and salt marshes, and belonging to the Bay of Cádiz Natural Park. The dunes are vegetated and show several washover fans of different types and forms. A road and several car parks are located between the dunes and the salt marshes, connected to the beach by wooden pathways (Fig. 3C). The beach is composed of medium sand, showing an intermediate-dissipative, highly seasonal profile (Plomaritis et al., 2009b).

APPROXIMATE LOCATION OF FIGURE 3

3. Methods

Human occupation along the Gulf of Cádiz coast can be affected by storm events in two ways. First, by causing direct storm-related damage to human infrastructure, such as seawalls, drainage systems, beach access structures and so on, with the associated economic losses. And second, by producing morphological changes such as long-term reduction in beach width or damage to dune ridges, leading to investments in measures like beach replenishment or dune protection. Therefore, both types of thresholds were considered in this work.

Two complementary approaches were adopted for the definition of the aforementioned thresholds. On one hand, theoretical storm-induced sea-level variations were calculated and compared with the topography of the test sites at a local level (Sallenger, 2000). On the other hand, newspaper records of real damage in coastal infrastructure caused by storms were collected at a regional level and compared with the hydrodynamic conditions that caused the damage.

3.1. Computation of theoretical sea-level variation

The most common effect of storms in the Gulf of Cádiz beaches is the generation of morphological changes such as beach flattening, erosive escarpments on the beachface, formation or reactivation of washover deposits and dune erosion (Benavente et al., 2002). A major issue in the generation of these effects is sea level during the storm reaching coastal features such as the berm or the dune foot. For this reason, the comparison between coastal topography and storm-induced water level was used in order to calculate minimum wave and tide conditions needed to produce morphological changes. The same rationale was applied for calculating the threshold for damage to coastal infrastructure, by using the elevation of the infrastructure on each case.

This way, four different types of threshold were investigated on the test sites according to the characteristics of each location: (a) morphological change in all beaches, mainly berm erosion, (b) dune erosion in all beaches, (c) overwash in Camposoto beach, and (d) damage to infrastructure in Cortadura beach. For each case the elevation of (a) the berm, (b) the dune foot, (c) the entrance of existing washovers and (d) the base of the seawall were respectively selected as threshold parameters. The elevations were average summer values derived from topographic surveys carried out in the test sites by DGPS and total station, that were averaged along 300 m long stretches of coast on each site.

The total sea level variation (TSLV) generated by a storm event was estimated following the procedure by Benavente et al. (2006) as the sum of the forcing agents involved in the storm:

$$\mathrm{TSLV} = \mathrm{TL} + \mathrm{WiS} + \mathrm{BaS} + \mathrm{WaR} \qquad (1)$$

where TL is the tidal level, WiS is the wind-induced setup, BaS is the barometric setup and WaR is the wave-associated sea level variation, which is composed by the wave set up and the vertical swash excursion.

For obtaining the tidal level (TL) values, the mean high water springs (MHWS) and the mean high water neaps (MHWN) levels in Huelva and Cádiz coasts were extracted from tide gauge data-series (Instituto Hidrográfico de la Marina, 2009), being around 3.3 m and 2.5 m above the hydrographic zero, respectively.

The coastal sea-level variation generated by the combination of wind-induced surge (WiS) and barometric setup (BaS) was estimated based on a correlation between this surge and offshore wave properties in the study area. The meteorological setting in the Gulf of Cádiz favours such a correlation, since the predominant atmospheric and oceanographic conditions that result in surge generation and storm wave heights are the same. The aim was to compute an easy-to-use threshold based only on tide conditions and wave height, instead of a complex expression where four variables (tide, wind, waves and atmospheric pressure) had to be combined in a joint-probability approach. For this purpose the sea-level residual extracted from the tide gauge time series in Mazagón harbour (Huelva) was used as a surge indicator, while Gulf of Cádiz offshore wave buoy (Fig. 1) provided the wave parameters time series. Both datasets overlap over a period of 12 years between 1996 and 2008, being the longest time series available in the Gulf of Cádiz.

A peak over threshold (POT) analysis was undertaken over the 12 years in order to extract statistically independent data of wave height and surge level on the coast during storms (Kamphuis, 2000). For the above analysis only the storm season events (October to March) with $H_s \geq 2.5$ m were used (with Hs calculated for offshore conditions). In order to avoid data of momentary storm events that cannot produce a significant surge, a storm duration restriction of at least 12 hours was used. Furthermore, consecutive storm events with calm conditions of less than 24 hours between them were considered as a single storm group event. For the above conditions a total of 204 events were extracted and used to build the correlation. The logarithmic trend was fitted giving the following equation with a value of $r^2 = 0.61$ (Fig. 4).

$$S = 41.45 \ln (H_0) - 36.16 \qquad (2)$$

where S is the surge height, considered to be the combination of WiS and BaS, and H_0 is the offshore significant wave height. To demonstrate the applicability of the above correlation over the Gulf of Cádiz the data of sea-level residual from the tide gauge in Cádiz harbour (years 2008-2010) are also presented on Figure 4. It has to be noted that the majority of the events used for fitting Equation 2 correspond to storm events coming from westerly directions. The secondary wave direction (SE) that is shown in Figure 2 does not involve surge generation in the study area, as easterly winds and waves occur during conditions of high atmospheric pressure (so barometric setup is not generated), easterly winds are roughly parallel to the coastline (so they do not induce any significant wind setup) and the corresponding wave fetch is very short.

APPROXIMATE LOCATION OF FIGURE 4

Finally, the most critical factor in determining storm thresholds in coastal areas is wave-associated sea-level variation (WaR) (Sallenger, 2000). Several formulations were tested for runup calculation in the study area, including those by Holman (1986), Ruessink et al. (1998) and Stockdon et al. (2006). Due to the characteristics of beach slope and wave steepness in the test sites and following the proposal by Benavente et al. (2006), the expression by Komar (1998), modified from an initial equation by Holman (1986), was selected for runup calculation:

$$WaR = 0.36\ g^{0.5}\ H_0^{0.5}\ T\ \tan\beta \qquad (3)$$

where H_0 represents significant deep-water wave height, T is deep-water wave period, tanβ is average beach slope and g is gravity. Wave data were computed on the basis of the extreme regime relationship of H_0 and Tp (spectral peak period) established for the Cádiz wave buoy by the National Ports Authority (Puertos del Estado, 2006):

$$Tp = 4.95\ H_0^{0.49} \qquad (4)$$

Deep-water significant wave height (H_0) was then estimated using reverse shoaling and assuming linear wave theory. Beach slopes were averaged from topographic profiles performed at the test sites by DGPS and total station. Average winter slopes in Bota, Cortadura and Camposoto were 0.029, 0.017 and 0.024 respectively, while average summer slopes were 0.065, 0.025 and 0.044 respectively.

Finally, an important issue regarding the threshold for morphological change is the existence of erosive wave conditions for berm erosion to occur. The height of the berm crest is governed, according to Takeda and Sunamura (1982), by offshore wave periods and wave breaking height (H_b). Hence, beach slope over intermediate and shallow water as well as the distance of the breaker zone and the slope of the surf zone can play a role in the final height of the berm crest. In general terms both berm formation and berm erosion require overtopping of the berm crest by waves (Masselink and Hughes, 2003; Weir et al., 2006). Hence, for the case of the morphological threshold two conditions have to be met, namely the total sea-level variation (TSLV) to reach the height of the berm crest and erosive wave conditions to exist in order to shift from a berm-type to a bar-type profile. The most common erosion predictor is the Dean number (1973) (Ω), also known as the dimensionless fall velocity number:

$$\Omega = H_0/(w_s T) \tag{5}$$

where H_0 is the offshore wave height, w_s is the sediment fall velocity calculated using the Soulsby formula for natural grains (Soulsby, 1997) and T is the wave period. The critical value between accretion and erosion condition proposed by Dean (1973) was 1 and it was based on small scale experiments, while larger scale experiments suggested a value between 2 and 2.5 (Masselink and Hughes, 2003). However, in recent large scale experiments by Roberts et al. (2010), they used an erosive Dean criterion of 5 for their experimental conditions. In the present work the methodology of Kraus et al. (1991) was used to determine the Dean number criterion for erosive conditions. In this approach the Dean number is plotted against the wave steepness H_0/L_0, where L_0 is deep-water wavelength computed by the linear wave theory (Dean and Dalrymple, 1991). The conditions for very likely erosion are estimated as $H_0/L_0=0.00014\Omega^3$.

3.2. <u>Newspaper data collection</u>

Another approach at a wider spatial scale was adopted for the definition of a critical storm threshold for damage to infrastructures or human occupation not only in the test sites, but along the whole Spanish coast of the Gulf of Cádiz. The method consisted in comparing recorded evidence of real damage with the hydrodynamic conditions that caused it. Storminess and damage reconstruction from historical records in the Atlantic region has been attempted before with good results (Andrade et al., 2008).

The damage generated by historical storms having occurred in the study area was derived from an extensive bibliographic search, in which the main source of information were local newspapers from Cádiz and Huelva provinces spanning the period between 1945 and 2005. The events recorded in Huelva province were cross-checked with the information about storm periods in Rodríguez-Ramírez et al. (2003). The hydrodynamic forcing causing the damage was extracted from the SIMAR-44 dataset of the HIPOCAS project (HIndcast of dynamic Processes of the Ocean and Coastal Areas of Europe). These data stem from high-resolution numerical modelling and provide 3-hour wind, sea-level (meteorological residual) and wave data spanning the period between 1958 and 2001 (Guedes-Soares et al., 2002). For this work the database was analysed for the grid points (nodes) located closest to Cádiz and Huelva cities, and the data were filtered in order to consider only storm data, i.e. those corresponding to winter months, with wave approach directions from the 3rd and 4th quadrants, and Hs over 2 m. For each storm event having caused reported damage, storm duration, mean and maximum wave height, wave direction and wind speed were extracted from the HIPOCAS database, and tidal height information was derived from t-tide (Pawlowicz et al., 2002) by using the full tidal constituents of Cádiz port. The differences in tidal characteristics between Cádiz and Mazagón are on average less than 10 cm in range and less than 5 minutes in time. The combined analysis of both elements (damage and hydrodynamic parameters) allowed the identification of a minimum threshold of wave and tide conditions having caused real damage to structures in the past.

It is important to note that the wave heights used in the analysis were obtained from the HIPOCAS nodes, and then they were corrected according to the relationship between a two-year period of real data recorded by wave buoys in the area and HIPOCAS modelled data for the same period (Del Río et al., 2009). The expression used was:

$$H_{co} = -0.12 + (1.554\, H_{hi}^{0.822}) \quad (6)$$

where H_{co} is the corrected wave height and H_{hi} is the wave height extracted from the HIPOCAS database.

Several considerations must be made regarding this method. On one hand, only coastal damage related to Atlantic storms (i.e. wind and waves approaching from the 3rd and 4th quadrants) was taken into consideration, as longer fetch in these directions is responsible for generating high waves and surge (Rodríguez-Ramírez et al., 2003). Therefore, reported damage caused by strong Easterly winds that blow under conditions of high atmospheric pressure was not included, as these events do not generate high waves or storm surge due to the short fetch in this direction and the high-pressure conditions. It must also be pointed out that the methodology implies considering only those events for which there is a written record of their destructive effects on coastal infrastructure due to high waves or storm surge. Therefore, reports of damage by wind or flooding by rainfall caused by winter storms on inland areas of coastal cities were not taken into account, nor have shipwrecks or other incidents not directly involving damage to coastal infrastructure.

4. Results

4.1. Thresholds in the local-scale approach

The elevations above the hydrographic zero of the features related to the aforementioned storm effects (morphological change, overwash, dune erosion and damage to infrastructure) are presented in Table 1 for the corresponding test sites.

APPROXIMATE LOCATION OF TABLE 1

Based on equations (1) to (4) the total storm-induced sea-level variation (TSLV) was calculated for each test site, considering spring high tides in a worst-case approach, and it was compared with the elevations in Table 1. The values of significant wave height needed to reach the corresponding TSLV and therefore the critical threshold for each type of process are shown in Table 2. The exact minimum wave height conditions for each threshold were calculated by linear interpolation based on the results of equations (1) to (5) and the elevations in Table 1.

APPROXIMATE LOCATION OF TABLE 2

The thresholds for beach morphological changes, considered as berm erosion, were found to be 3.75 m, 2 m and 1 m of significant wave height for Cortadura, Bota and Camposoto beaches respectively. The reason for the difference between two points as close to each other as Cortadura and Camposoto is mainly related to the heights of the berm crest, which is 0.5 m higher in Cortadura. This variation can be attributed to different transformation of the waves along the nearshore area, related to the submerged rocky outcrops, which could give rise to slightly different infragravity waves under mild accretionary conditions, resulting in a different berm height. Besides, beach slope is significantly gentler in Cortadura, thus creating very low wave runup values. The test of Dean's erosive conditions according to the method by Kraus et al. (1991) resulted in a slight change in the threshold for Camposoto, which would be 1.5 m of significant wave height.

It has to be noted that the majority of experiments undertaken for the evaluation of beach erosion criteria have used equilibrium beach profiles as initial conditions. Hence, for ultradissipative profiles composed of fine sands the Dean number generally produces high values and consequently overestimates the erosive conditions. The introduction of beach slope in the evaluation of erosion/accretion conditions as in the case of Hattori and Kawamata (1980) significantly improves the estimation for the latter beach case. This way, according to this procedure all wave heights above 2 m correspond to erosive conditions in the test sites.

As for dune erosion, the threshold was found to be at a significant wave height of 3.33 m in Bota beach and 3.75 m in Camposoto beach. This can be related to steeper slopes in the former giving rise to higher runup values, so that wave thresholds are lower even if the elevation of the dune foot is higher than in Camposoto beach. On the other hand, it must be noted that the lowest limit for the occurrence of overwash in Camposoto beach is at a significant wave height of 2.57 m, which was found in the Northern sector of the study site and corresponds to the reactivation of an existing washover. This limit is lower than the threshold for dune foot erosion, due to the local morphology of the beach in the mouth of the existing washover area, which is characterised by a topographic depression. The Dean erosive conditions were also tested here, but due to the increased wave height and surge needed for the TSLV to reach the dune foot this always occurs under erosive conditions.

Finally, the threshold for potential structural damage in Cortadura beach was found to be at a significant wave height of 7.19 m. It is clear that the fact of water level reaching the base of the seawall during a storm does not imply that the structure will collapse, but it certainly involves other types of damage such as the flooding of beach facilities located at the base of the seafront. In any case, it must be noted that these thresholds represent minimum values from which there can be negative consequences.

It must be stressed that all these values correspond to spring tide conditions; in the case of storms arriving on a neap tide the threshold values would be increased on average by a factor of 50%.

4.2. Thresholds in the regional-scale approach

The analysis of the newspapers allowed the identification of a significant number of storm events having caused coastal damage in the regional study area. Table 3 shows the main hydrodynamic characteristics of these storms and the type and extent of the damage they caused. As can be observed, long duration of the storm is important but does not seem critical in determining the occurrence of coastal damage. This way, even if the long-lasting events obviously generated important damages, also several events with relatively short durations have caused reported destruction on coastal infrastructure, as occurred in January 1982 in both Huelva and Cádiz coasts. On the other hand, the simultaneous occurrence of a storm event and mean or spring tides can be regarded as an important factor in the generation of damage.

APPROXIMATE LOCATION OF TABLE 3

The details of which specific locations were affected along Huelva or Cádiz coast are not included in Table 3, but it is important to note that most of the destructive effects were reported along Cádiz coast or in both provinces, while very few were reported only in Huelva coast. The locations having recorded damage in the analysed period are shown in Figure 5, where clear hotspots of damage occurrences are observed around Northern Cádiz coast and Western Huelva coast, which are the most densely populated areas along the Spanish Gulf of Cádiz shore.

APPROXIMATE LOCATION OF FIGURE 5

Regarding the time distribution of the storm events with associated recorded damage, Figure 6 shows that the highest frequency was recorded in the 1980s, apart from the unusually intense storm season that occurred in 1996. These periods correspond to strongly negative NAO (North Atlantic Oscillation) conditions, which generate more frequent storms in the study area (Plomaritis et al., 2009a). A slightly increasing trend can be observed in the data that could be related to the combination of two factors: the strong growth in human occupation experienced along the Gulf of Cádiz coasts in the last couple of decades, and the long-term erosion trend recorded at many locations along the study area (Ballesta et al., 1998; Domínguez et al., 2005; Gracia et al., 2006; Del Río, 2007).

APPROXIMATE LOCATION OF FIGURE 6

In order to extract the critical threshold of wave conditions that caused damage reported in the newspapers, average and maximum wave heights of the storm events in Table 3 are presented in Figure 7.

These results allow the acquisition of a critical threshold for the minimum storm conditions capable of generating damage to infrastructure or human occupation in the regional study area. The threshold would be defined as follows:

- Event with duration of 30 hours or higher.

- Moderate average wave height (≥ 3.3 m) and high maximum wave height (≥ 4 m).
- Mean or spring tide situation.
- Average wind speed above 9 m/s, approaching from the 3rd and 4th quadrants.

APPROXIMATE LOCATION OF FIGURE 7

5. Discussion

The application of two complementary methodologies aimed at defining critical storm thresholds at different scales led to a variety of results, which at some points delivered markedly different thresholds for the same type of effect. This way, minimum significant wave height needed for the generation of damage to infrastructure was found to be Hs > 7.2 m in the local test site and Hs > 3.3-4 m in the regional coastline. It is evident from these results that Cortadura beach is not particularly vulnerable in this sense due to its high elevation above zero level, while other beaches along the Spanish Gulf of Cádiz would suffer this kind of damage much more frequently. That is the case for Huelva coast, where average wave height is generally lower than in most part of Cádiz coast (MOPT, 1992). Several authors highlight that the potential damage caused by a storm is greatly determined by its relative intensity, i.e. the relationship between storm and modal wave height in the area (Reyes et al., 1999; Cooper et al., 2004). This way, storms usually have a greater influence in coastal morphology in areas characterized by low modal wave energy (Roy et al., 1994). If more detailed data on storm impacts were available in order to derive separate structural thresholds for Cádiz and Huelva provinces, the latter would probably be lower. It is also clear that if a regional single value of wave height threshold should be chosen in a worst-case approach, this would be the lowest one, namely Hs > 3.3 m. However, the above methodology shows that local morphological characteristics (natural or anthropogenic) play an important role on the derived thresholds.

Regarding the thresholds for morphological change, it must be noted that in all the test sites the significant wave height needed to cause berm erosion shows a return period of less than one year, as would be expected (Fig. 8). Camposoto beach, with a threshold of 1.5 to 2 m of significant wave height, presents a very dynamic behaviour and is in fact eroded and flattened several times every winter season; on the other hand, Cortadura beach, with a threshold of 3.75 m of significant wave height, is more stable and related to its typically seasonal behaviour it requires higher wave energy to change shape from the steeper summer profile to the more gentle winter profile (Plomaritis et al., 2009b).

APPROXIMATE LOCATION OF FIGURE 8

The differences in TSLV over the study area are generally produced by local-scale wave processes, as large-scale (barometric setup) and meso-scale (storm surges) processes do not show a spatial variability over the study area. The former, because the dimensions of the Gulf of Cádiz are comparable with the typical extent of a low-pressure system in the area (Holton, 2004). The latter, because the general morphology of the continental shelf exhibits similar width and bathymetric characteristics in Huelva and the Western part of Cádiz. The above similarities are exemplified in equation (2), where the combination of barometric setup and storm surge in Cádiz are within the 95% confidence interval of the same parameters in Mazagón (Fig. 4). The above relation is not valid eastwards of Cape Trafalgar, where the continental shelf is much narrower and steeper (Fig. 1).

For the local-scale processes the total vertical runup equation of Holman (1986) modified by Komar (1998) was used, which estimates the combined wave setup and the 2% of the highest vertical runups. In the computation of wave runup a worst-case approach was adopted by selecting the beach profiles with the maximum winter intertidal slope, as steeper slopes involve higher wave runup values (Holman, 1986). In fact, authors such as Cooper et al. (2004) point out the higher susceptibility of intermediate-reflective beaches to changes in wave regime. This can be observed in Figure 9a, where the most dissipative test site (Cortadura) presents a significantly low rate of increase in total sea-level variation (TSLV) with increased wave heights, while the steepest test site (Bota) is much more susceptible to higher waves. Despite of the slope differences all the test sites can be characterised as dissipative type beaches with low Irribaren numbers; under such conditions the swash height is saturated and infragravity waves are dominant (Holman and Sallenger, 1985; Ruessink et al., 1998). Overall, in a mesotidal area such as the Gulf of Cádiz, tidal conditions during a storm are a critical factor on which the thresholds depend, with threshold values increasing by 50% between typical spring and typical neap tide conditions. The percentage of TSLV explained by each parameter is presented in Figure 9b for the three test sites. In the most dissipative case (Cortadura) the importance of tidal level is significant with percentages dropping slowly from 100% under minimum wave heights to 60% in case of an extreme storm event. The contribution of waves to TSLV is higher by a factor of 2 in comparison with the wind and barometric contributions for the most dissipative site (Cortadura). In the case of the steepest beach shoreface (Bota), the relative importance of tidal level is decreased and the variation due to local wave processes is increased up to 50% in extreme cases. As expected no significant variation occurs for the surge and barometric setup, since the foreshore slope is not affecting these processes.

On another note, the methodology adopted in this work assumes that if initial conditions remain the same, coastal response to different events of the same magnitude will be similar. Nevertheless, the fact that threshold computation involves choosing a fixed value for intertidal slope and a fixed height of morphological features considered for each site implies ignoring beach state prior to storm arrival. Hydrodynamic processes during a storm continuously reshape beach morphology, modifying parameters like intertidal slope or berm height; in this way, the initial conditions for successive storms are different, so the threshold for morphological change can also be different.

Beaches that have been eroded and flattened by a storm tend to dissipate incident wave energy, which together with the lower wave runup in gentler slopes could point to a lower vulnerability to the impact of subsequent storms, and so to a higher threshold for subsequent morphological change. On the other hand, flattened beaches allow a given water level to reach areas further inland than it would in steeper profiles, hence increasing the probability of damage by subsequent storms to structures located on the backbeach (e.g. by flooding); this would imply a lower threshold for damage to infrastructure for the following storm.

APPROXIMATE LOCATION OF FIGURE 9

In this sense, possible changes in the initial conditions of the coast for storms to act upon are especially important in case of storm groups (Ferreira, 2005), as beach erosion is increased when storm frequency exceeds the beach recovery period for individual storms (Morton et al., 1995). However, storm groups commonly produce limited effects in the study area, since except for the highly dynamic Camposoto beach, most beaches generally show long recovery periods (Benavente et al., 2000). The recovery usually takes place by onshore migration of nearshore bars that get attached to the berm in the beginning of the summer months (Benavente et al., 2000). As a consequence of this, beach profile morphology is generally not recovered during the calm periods within storm groups. On the contrary, beach profiles are eroded by the first storms, increasing their dissipativeness; this facilitates profile self-protection against successive storms, as the energy of shoaling waves tends to be dissipated across the profile, thus reducing wave erosive capacity. Since beach profile is not recovered between two events within a storm group, the effects of several medium-energy storms are generally not higher than those of a single higher-energy event, opposite to the statements by authors like Lee et al. (1998) or Ferreira (2005).

An interesting example of exceptionally severe effects of storm groups in the study area is presented in Figure 10, which shows the consequences of the successive storms that occurred in Cortadura-Camposoto test site between 21st December and 15th January 2010. Average significant wave height recorded during the storm peaks was around 4.3 m, thus above theoretical thresholds for berm erosion in Cortadura, and berm erosion, washover and dune foot erosion in Camposoto, but below the threshold for damage to infrastructure in Cortadura. However, the long-lasting character of the storm group, with significantly low atmospheric pressures and sustained strong winds blowing onshore for almost three weeks, generated a nearly continuous storm surge over the whole period, which together with the coincidence of some storm peaks with spring tide conditions led to widespread, significant damage along the whole Gulf of Cádiz coast (Del Río et al., 2010). In this case, a sequence of moderate storms resulted in as much morphological change and damage as one that would have resulted from a single higher-magnitude event (Lee et al., 1998), which is not a common behaviour in the study area.

APPROXIMATE LOCATION OF FIGURE 10

In this sense, thresholds in the test sites were specifically derived for spring tide conditions, as many authors have pointed out the relevance of the coincidence between storm events and spring tides in meso- and macrotidal environments (e.g. Cooper et al. 2004, Pye and Blott

2008). In fact, the newspaper record analysed in this work shows the prime importance of tide type in causing damage to coastal infrastructure, as 70% of the events with recorded damage occurred during spring tides (Table 3). It is clear that in some cases the long duration of the storm events or storm groups involved transitions between different tide types, but this very rarely included neap tides.

It is important to note that the processes described above are of utmost importance in an area like the study zone, where tourism is a major source of income. Apart from the obvious economic losses caused by damage to infrastructure, storm-induced morphological changes on beaches can also have important socioeconomic impacts in the area. User's demand for wide and healthy beaches often triggers the need for strong investments in artificial beach replenishments, which have indeed been carried out along many beaches in the Spanish Gulf of Cádiz by the Ministry of Environment (Muñoz et al., 2001). Regarding the test sites, La Bota was nourished in 1995 with 930,000 m^3 of sand; Cortadura and the adjacent La Victoria beach were nourished in 1991 and 2004 with a total amount of sediment over 2 million m^3; finally, Camposoto beach was replenished in 1998 with 740,000 m^3 of sand (Muñoz et al., 2001), and here significant efforts are also being made on recovery and protection of the dune ridges. For these reasons, critical storm thresholds may be very useful tools that help to minimize the need for these kinds of investments, by facilitating the development of vulnerability maps, spatial planning strategies, early warning systems and other instruments of risk prevention.

6. Conclusions

Diverse methodologies were applied in the Gulf of Cádiz coast with the aim of establishing critical storm thresholds, regarding these as the minimum wave conditions necessary to cause a certain type of effect on the coast. On a regional scale, newspapers and historical wave databases were used to define critical storm thresholds for the generation of damage to infrastructure or human occupation along the coastlines of Huelva and Cádiz provinces. The resulting minimum threshold is defined by Atlantic storms with an average wave height ≥ 3.3 m, a maximum wave height ≥ 4 m and a duration of 30 hours or higher in mean or spring tide situation. On a more local scale, theoretical computations of water elevation due to storms were performed and compared to beach topography in three test sites in order to assess the risks of beach morphological change, dune foot erosion and overwash. In this case the minimum thresholds in spring tide conditions range between 1.5 and 3.75 m of significant wave height depending on the test site and the risk assessed. The difficulties found in defining a single regional storm threshold are mainly related to the particular characteristics of the study area, where beach morphology, degree of human occupation and other important aspects show significant spatial variability.

Thresholds proposed in this work provide a guideline of coastal response to storms in the area that can help to prevent the negative impacts of storm events. In this sense, they could also be useful for adequately planning future development in the coastal zones which are still undeveloped along this high-pressure area. In the case of damage to infrastructure it must be noted that a forecast of waves exceeding the critical threshold does not necessarily mean that serious coastal damage will always occur, but there is a strong likelihood of some kind of effect on the structures located in the backbeach. Regarding the threshold for storm-induced morphological change, it is clear that beach erosion, dune retreat or washover occurrence do not depend solely on wave height and tidal level, but also on other factors such as previous beach state, storm duration and time interval between successive storms. Nonetheless, the thresholds proposed are aimed to be at the same time scientifically sound and easy to use, which is the reason why in this first approach only wave and tide conditions have been considered, together with an empirically derived relationship between waves and surge. Further work will include the effects of antecedent beach morphology and other more complex parameters, such as dynamic response of the beach .

Finally, another key issue regarding storm thresholds is the time framework considered. All the thresholds proposed in this work were obtained from data spanning a given period of time, thus constituting snapshots of risk conditions at that time. However, beach and nearshore zones are extremely dynamic due to both natural and human-related factors (such as beach nourishments or coastal defence structures), and also the characteristics of occupation on the coast change over time. As a consequence, critical storm thresholds will change accordingly and therefore will need to be updated. In this sense it is important to state that the proposed methodology can be easily applied over any area by using simple morphological measurements (beach slope, berm height, dune foot, etc.) that can be updated frequently. Future work will be directed towards the use of these thresholds as initial values for the generation of dynamic thresholds by means of numerical modelling. The final aim in the framework of MICORE project will be the integration of these thresholds into an early warning system that could provide an adequate prediction of the effect of future storms, to be used by Civil Protection agencies and coastal authorities.

Acknowledgements

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Figure captions

Figure 1. Location map of the study area and the test sites.

Figure 2. Wave rose of the offshore buoy located at the centre of the Spanish Gulf of Cádiz (1996-2002) (wave height in metres).

Figure 3. Aerial photographs of the test sites. A: Bota beach in Huelva coast (Photo: Google Earth). B: Cortadura beach in Cádiz coast. C: Camposoto beach in Cádiz coast.

Figure 4. Correlation for storm data of sea level residual (storm surge) recorded at Mazagón tide gauge and wave height recorded at Gulf of Cádiz offshore wave buoy between 1996 and 2008 (crosses). Circles show the same correlation for Cádiz tide gauge and Gulf of Cádiz offshore wave buoy between 2008 and 2010.

Figure 5. Spatial distribution of storm events in the Spanish Gulf of Cádiz having caused damage to coastal infrastructure between 1958 and 2001, according to the newspaper records.

Figure 6. Yearly frequency of storm events having been reported to generate damage to coastal infrastructure in the Spanish Gulf of Cádiz.

Figure 7. Average and maximum wave height of the events having caused reported damage to coastal structures in the Spanish Gulf of Cádiz.

Figure 8. Return period of significant wave heights in the coast of Cádiz according to the HIPOCAS database. Wave heights have been corrected by means of the calibration in equation (5). The parameters μ and ψ are the location and scale parameters of the Gumbel distribution (Graphical product of CAROL software, University of Cantabria).

Figure 9. (a) Relationship between significant wave height and the associated total sea level variation (TSLV) according to the equations (1) to (4) in the test sites. (b) Relative

contributions of waves (dotted line), pressure plus winds (dashed line), and tides (dash dotted line) in controlling TSLV on the test sites.

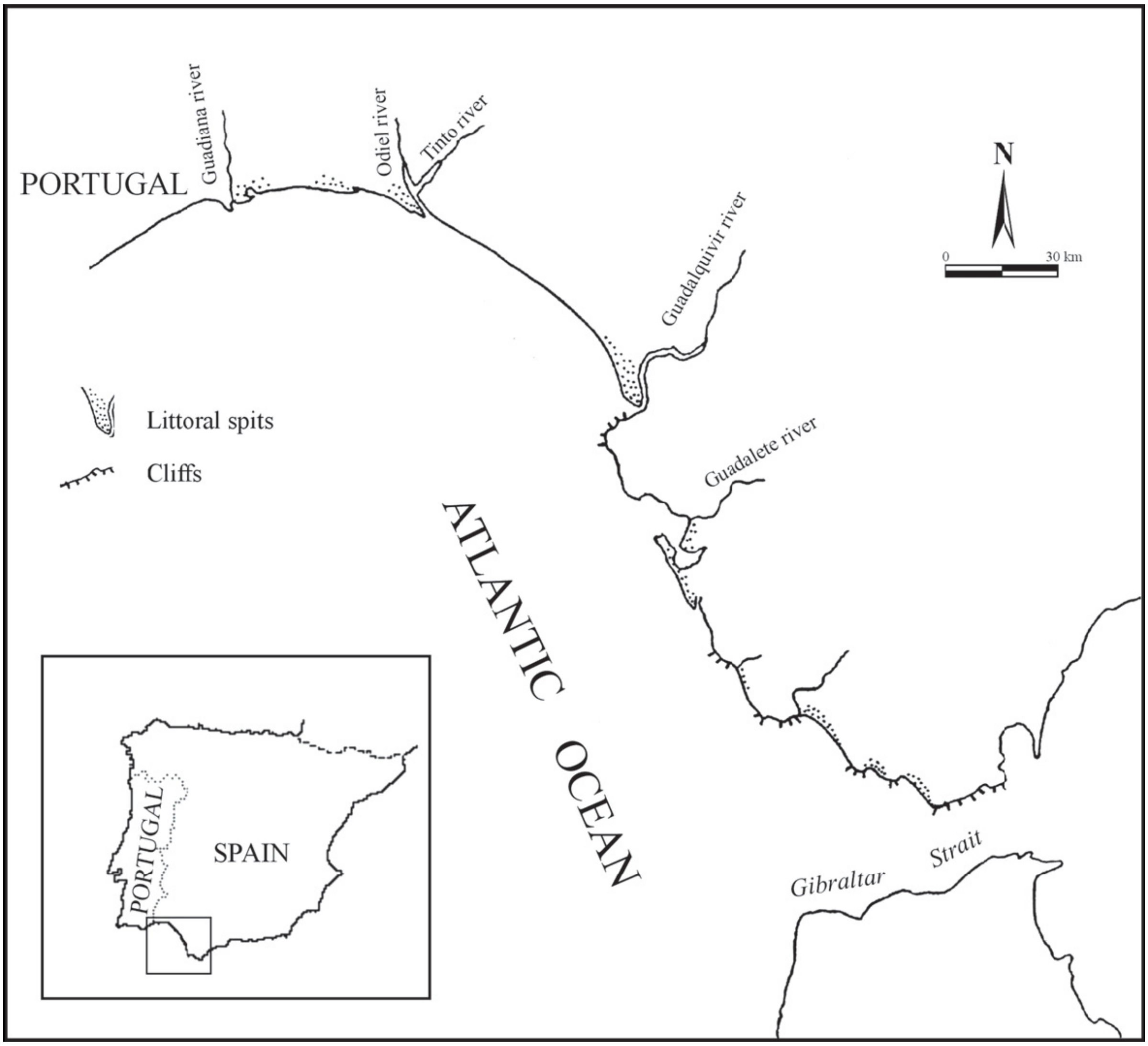
Figure 10. Examples of the effects of winter 2010 storms in the study area. A: Beach and dune erosion in Camposoto beach (31st December 2009). B: Overtopping and inundation of the seafront in Cádiz city (1st January 2010). C: Wave runup reaching the seawall at northern Cortadura beach (1st January 2010). D: Flooding of beach facilities by wave runup in southern Cortadura beach (5th January 2010).

Table captions

Table 1. Topographic elevations of the different types of threshold analyzed in the test sites, corresponding to average summer values.

Table 2. Minimum wave height thresholds for morphological change, overwash, dune foot erosion and damage to infrastructure in the test sites in case of MHWS.

Table 3. Hydrodynamic characteristics of storm events having caused reported damage on coastal infrastructure along Cádiz and/or Huelva coasts. Wave heights have been corrected from HIPOCAS data according to equation (6). Tide type: S (spring), M (mean), N (neap). Newspapers: Diario de Cádiz (1), ABC (2), El Correo de Andalucía (3), Odiel (4), Huelva Información (5) and La Voz de Huelva (6).


PORTUGAL
Guadiana river
Odiel river
Tinto river
Guadalquivir river
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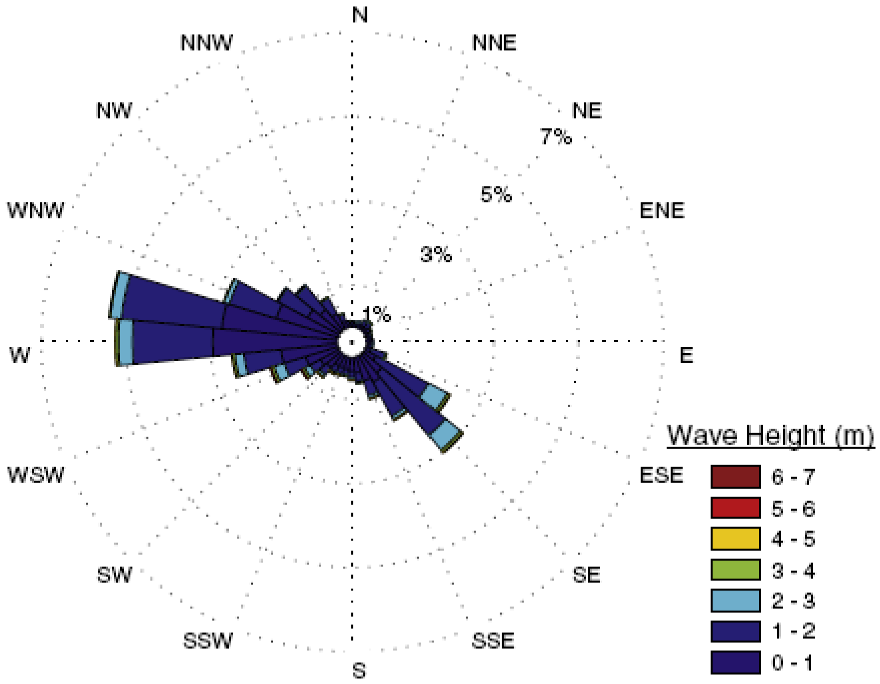
Cliffs
ATLANTIC OCEAN
Gibraltar Strait
PORTUGAL
SPAIN

Figure 1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NNE
NE
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E
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SE
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S
SSW
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W
WNW
NW
NNW
1%
3%
5%
7%
Wave Height (m)
6 - 7
5 - 6
4 - 5
3 - 4
2 - 3
1 - 2
0 - 1

Figure 2

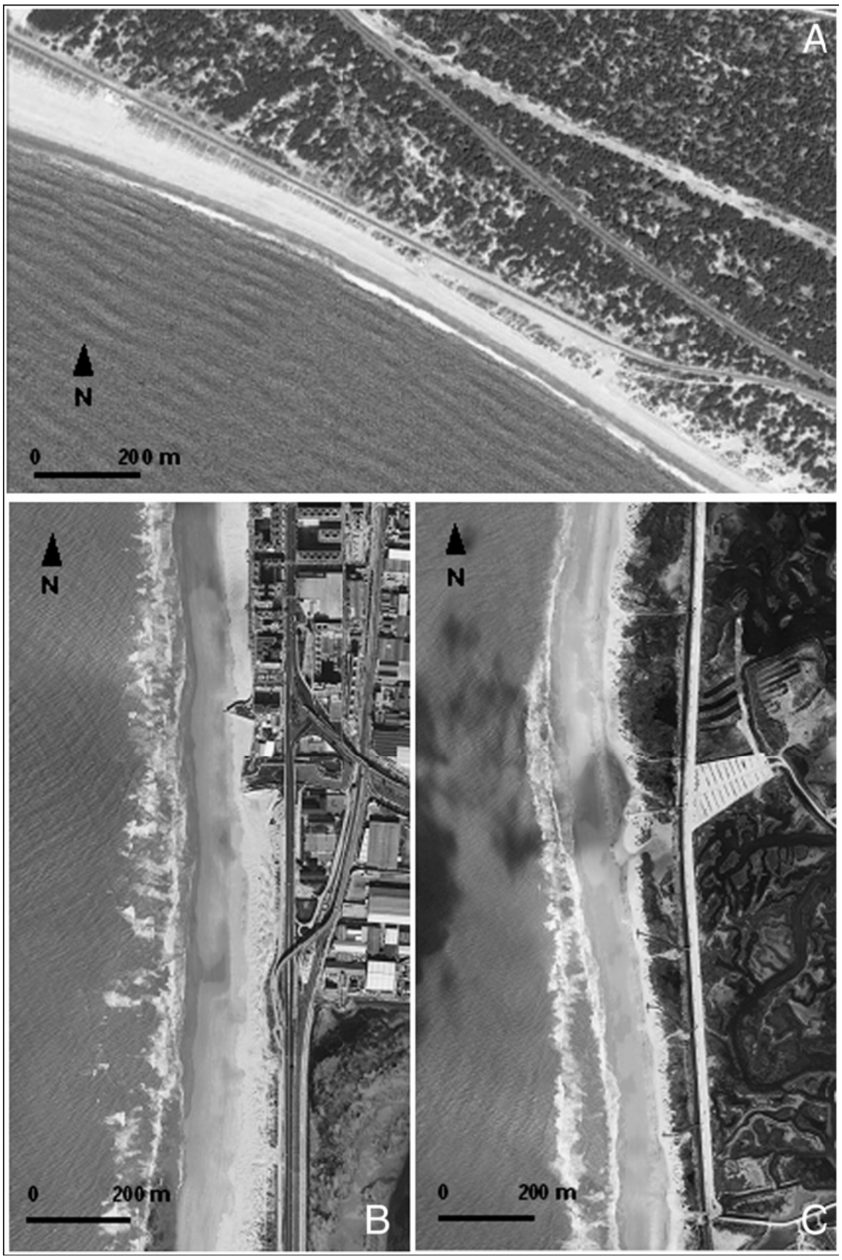
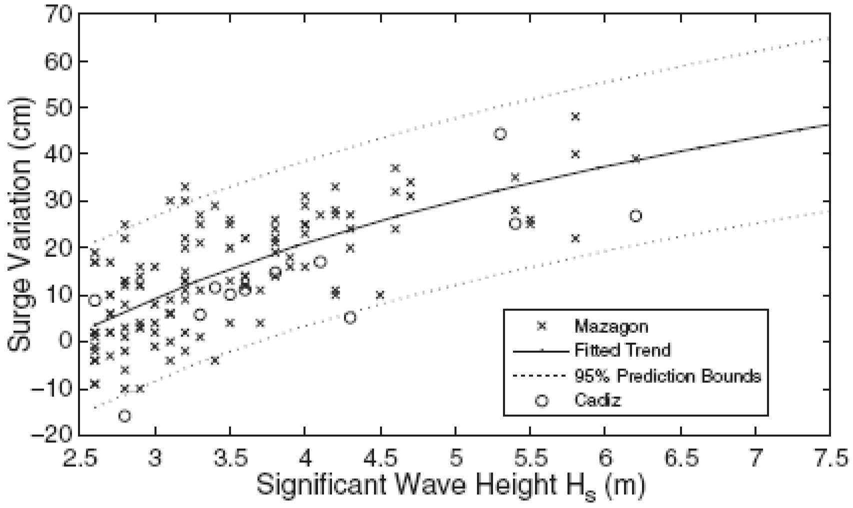


Figure 3



Surge Variation (cm)
70
60
50
40
30
20
10
0
−10
−20
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
Significant Wave Height H_s (m)
Mazagon
Fitted Trend
95% Prediction Bounds
Cadiz

Figure 4

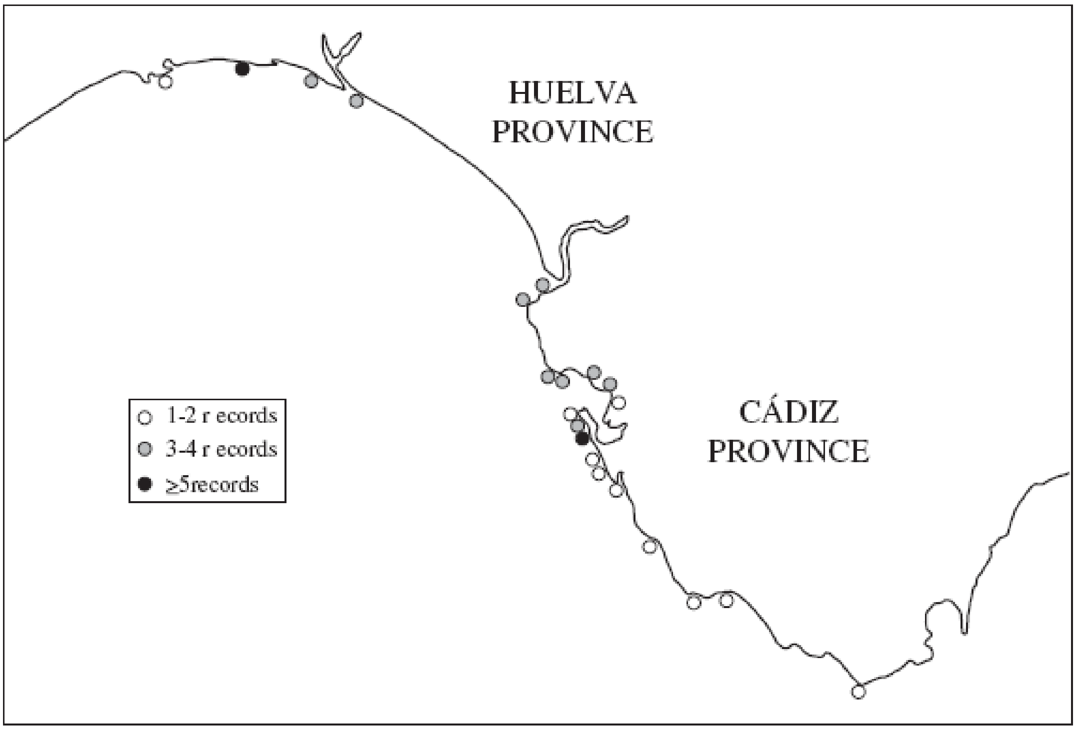
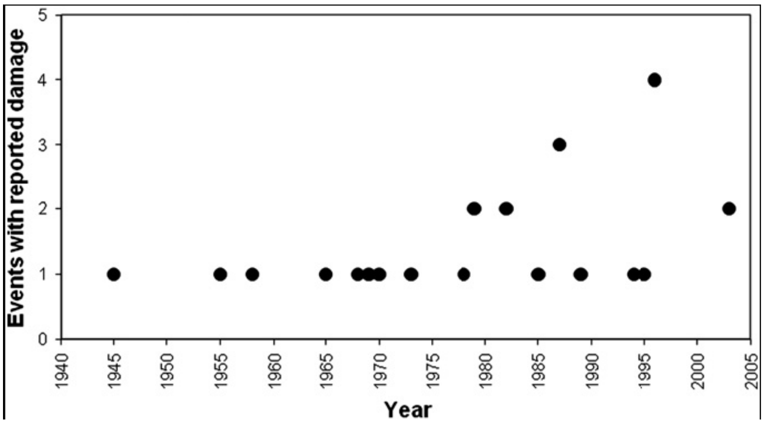

HUELVA PROVINCE
CÁDIZ PROVINCE
○ 1-2 r ecords
● 3-4 r ecords
● ≥5records

Figure 5

894 

895 Figure 6

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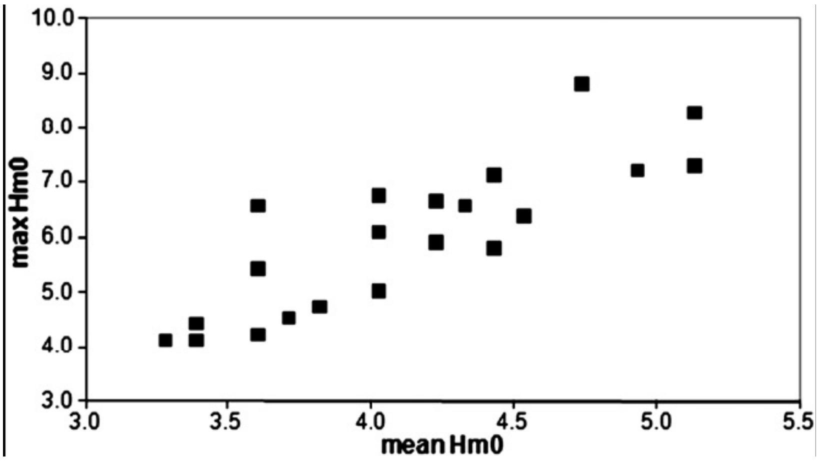

Figure 7

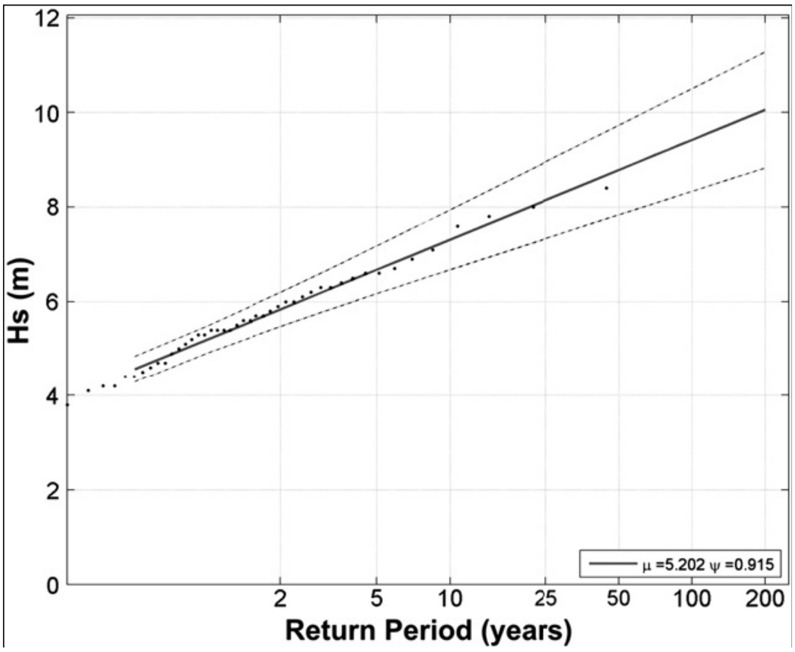
Hs (m)
12
10
8
6
4
2
0
2
5
10
25
50
100
200
Return Period (years)
μ =5.202 ψ =0.915

Figure 8

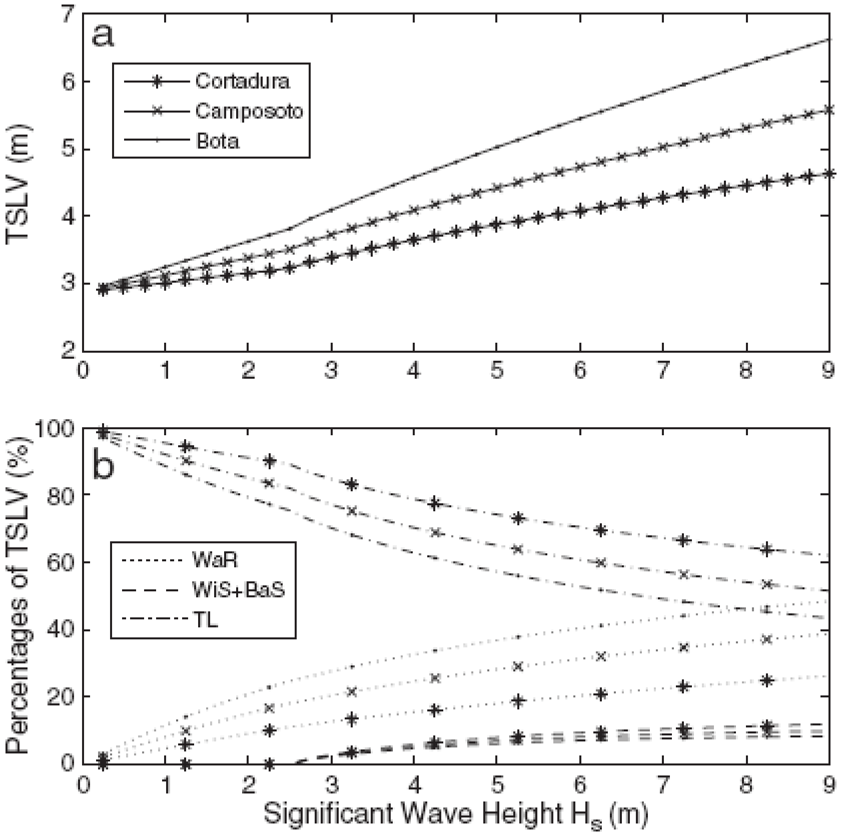
a
TSLV (m)
7
6
5
4
3
2
Cortadura
Camposoto
Bota
0
1
2
3
4
5
6
7
8
9
b
Percentages of TSLV (%)
100
80
60
40
20
0
WaR
WiS+BaS
TL
0
1
2
3
4
5
6
7
8
9
Significant Wave Height H_s (m)

Figure 9

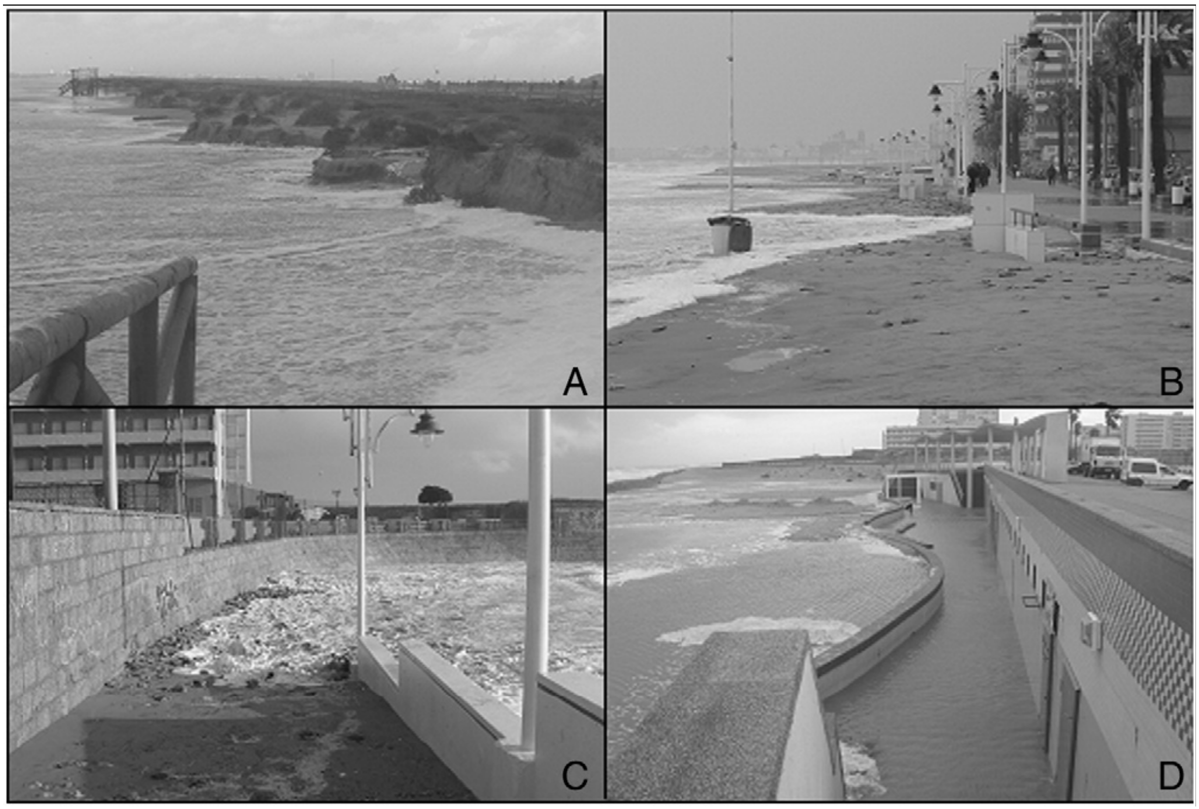

Figure 10

Table 1.

	Berm	**Washover**	**Dune foot**	**Base of seawall**
Bota beach	3.60 m	---	4.26 m	---
Cortadura beach	3.70 m	---	---	4.40 m
Camposoto beach	3.20 m	3.65 m	4.10 m	---

Table 2.

	Morphological change	**Overwash**	**Dune foot erosion**	**Structural damage**
Bota beach	Hs = 2.00 m	---	Hs = 3.33 m	---
Cortadura beach	Hs = 3.75 m	---	---	Hs = 7.19 m
Camposoto beach	Hs = 1.00 m	Hs = 2.57 m	Hs = 3.75 m	---

Table 3

Event nº	Start date	Duration (hours)	Hours H_{m0} > 4 m	Mean H_{m0}	Max H_{m0}	Tide type	Mean W (m/s)	Sea level residual (cm)	Newspaper	Damage type and extent (H: Huelva; C: Cádiz)
1	13/12/1958	240	126	4.9	7.2	N-S	12.3	15.4	1, 2	C: damage in harbour
2	26/09/1965	30	3	3.3	4.1	S	10.5	10.4	2	C: great damage in seafront, damage in beach bars and beach huts
3	31/10/1968	69	3	3.4	4.0	M	10.4	14.1	1	C: damage in a beach hotel
4	01/05/1969	42	6	3.4	4.4	S	9	12.0	1	C: beach huts destroyed
5	02/01/1970	330	108	4.5	6.4	N-S	10.4	19.5	1, 3, 4	H: serious damage and surge flooding in beach restaurants and beach houses, some beach houses destroyed C: great damage in seafront, beach houses, beach restaurants
6	15/01/1973	87	30	4.7	8.8	M-S	12.2	2.3	1	C: damage in cars parked by the seafront
7	23/02/1978	240	30	4.0	6.1	M-S	10.1	10.0	1, 3	C: damage in seawall
8	24/01/1979	114	36	4.4	5.8	M-S	10.7	17.8	1, 4	H: seafront, beach restaurants and houses damaged, pipelines destroyed C: damage in harbour
9	09/02/1979	171	96	5.1	7.3	M	12.2	13.4	1	C: damage in seawall and seafront, stairs of beach access destroyed
10	10/01/1982	48	9	4.0	5.0	S	9.7	15	1, 3, 4	H: damage in beach houses C: damage in seafront and coastal road, access and huts destroyed
11	06/11/1982	60	36	5.1	8.3	M-S	11.2	20	1	C: jetty of harbour damaged
12	06/02/1985	159	57	4.2	5.9	M-S	9.0	3.3	1	C: damage in seafront
13	12/01/1987	72	27	4.4	7.1	M	11.8	10.2	1	C: small damage in seafront fence
14	26/01/1987	117	12	3.8	4.7	M-S	9.4	11.1	1	C: great damage in seafront, damage in beach accesses, beach facilities flooded by surge
15	07/12/1987	27	0	2.9	3.2	M	10.1	23.6	1, 5	H: damage in beach houses C: coastal road flooded
16	26/11/1989	36	0	3.7	4.5	M	8.4	21.1	3, 5	H: damage in beach houses and restaurant, one house destroyed
17	26/02/1994	69	0	3.6	4.2	S	9.1	11.1	1, 3	C: beach facilities and beach restaurant flooded and damaged by surge, damage in PA system, damage in breakwater
18	25/12/1995	129	15	3.6	5.4	M-S	9.6	7.8	1	C: viewpoint destroyed, serious damage in breakwater and seawall, sections of groin collapsed, damage in stairs of beach access

19	04/01/1996	207	66	4.3	6.6	M	9.9	11.2	1, 3, 6	H: damage in beach hotel, beach bars collapsed C: extensive damage in jetty, groins, breakwaters, drainage system, beach accesses destroyed
20	20/01/1996	213	63	4.0	6.8	M-S	10.5	20.8	1, 3, 6	H: beach Yacht Club, tennis courts and wastewater sewers destroyed, beach houses damaged C: extensive damage in seafronts, breakwaters, seawall, beach bars and beach accesses, PA systems destroyed, coastal roads flooded
21	11/11/1996	90	15	3.6	6.6	M-S	9.9	18.2	1	C: damage in seafront and beach access
22	10/12/1996	354	114	4.2	6.7	M-S	10.4	16.4	1, 6	H: beach houses, beach bars and coastal roads flooded C: damage in seafront, beach facilities and beach accesses, coastal roads flooded