| Cuadernos de Investigación Geográfica *Geographical Research Letters* | 2022 | Nº 48 | pp. 219-255 | EISSN 1697-9540 |
| --- | --- | --- | --- | --- |



http://doi.org/10.18172/cig.5451

# THE COMPLEXITY OF STUDYING COASTS: FROM FORMS AND PROCESSES TO MANAGEMENT

**FRANCISCO JAVIER GRACIA PRIETO**

*Guest Editor*

*Dept. of Earth Sciences, Faculty of Marine and Environmental Sciences. University of Cádiz. Puerto Real, 11510 Cádiz, Spain.*

**ABSTRACT.** Coastal environments are characterized by their high dynamism, related to the interaction between marine agents (winds, waves, currents, sea level changes) and continental forms and processes. The present article summarizes the main morphodynamic characteristics of coasts and the resulting environments. Different oscillations of the sea level are considered, depending on their amplitude and frequency: rapid eustatic fluctuations, energetic tsunamis, storm waves and surges, tides and good weather wind waves. Coastal environments are classified in low, sedimentary coasts, including beaches, dunes, barrier islands, lagoons, salt marshes and river mouths, and high, rocky coasts. Management of coastal zones needs a deep knowledge of all the processes involved at the littoral, especially at the local scale, since coastal processes vary rapidly alongshore. At present the integrated coastal management intends to involve different socioeconomic sectors interested in the occupation and use of coasts. Coastal management must include the adaptation of human activities to the natural processes and associated coastal hazards and the protection of coastal values, both of natural and historical-cultural character. Public administrations at different levels should consider the knowledge of the coastal processes at different scales and their potential interaction with human activities in order to design laws and regulations accordingly.

## *La complejidad de estudiar las costas: de las formas y procesos a la gestión*

**RESUMEN**. Los ambientes costeros se caracterizan por su gran dinamismo, relacionado con la interacción entre agentes marinos (viento, oleaje, corrientes, variaciones del nivel del mar) y formas y procesos continentales. El presente artículo resume las principales características morfodinámicas de las costas y los ambientes resultantes. Se han considerado las diferentes oscilaciones del nivel del mar, dependiendo de su amplitud y frecuencia: fluctuaciones eustáticas rápidas, tsunamis enérgicos, olas de temporal e inundaciones de marejada, mareas y oleaje de viento de buen tiempo. Los ambientes costeros se han clasificado en costas bajas, sedimentarias, que incluyen playas, dunas, islas-barrera, albuferas, marismas y desembocaduras fluviales, y costas altas, rocosas. La gestión de zonas costeras necesita de un conocimiento profundo de todos los procesos involucrados en el litoral, especialmente a escala local, ya que los procesos costeros varían rápidamente a lo largo de la línea de costa. En la actualidad la gestión integrada de zonas costeras pretende involucrar a diferentes sectores socioeconómicos interesados en la ocupación y uso de la costa. La gestión costera debe incluir la adaptación de las actividades humanas a los procesos naturales y a los riesgos naturales asociados, así como la protección de los valores de la costa, tanto naturales como histórico-culturales. Las administraciones públicas a distintos niveles deberían considerar el conocimiento de los procesos costeros a diferentes escalas y su interacción potencial con las actividades humanas, de cara a diseñar leyes y normativas de acuerdo con ellas.

**Key words:** Coastal environments, morphodynamic processes, natural hazards, integrated coastal zone management.

**Palabras clave:** Ambientes costeros, procesos morfodinámicos, riesgos naturales, gestión integrada de zonas costeras.

Received: 13 May 2022

Accepted: 26 May 2022

**Corresponding author:** Francisco Javier Gracia Prieto, Dept. of Earth Sciences, Faculty of Marine and Environmental Sciences, University of Cádiz, Puerto Real, 11510 Cádiz, Spain. E-mail address: javier.gracia@uca.es

## 1. Introduction

As in any other natural morphogenetic system, the coast is the result of the action of a number of processes acting on a given space, in this case of azonal nature, not strictly controlled by climate. The main difference between coastal zones and other morphogenetic systems is the high energetic gradient existing in a narrow band, where land and sea meet. Oceans spread out along all latitudes, climates and geological situations, and this adds an additional level of complexity to coasts, since marine processes can affect any kind of morphogenetic system reaching the coast. We can find rivers or glaciers arriving to the coast, coastal karst, active oceanic volcanism, coastal deserts, etc. Any of all those systems, with their specific processes, can interact with specific marine processes, a situation exclusive of coastal environments. The result is a high casuistry, which produces great variability and multiplicity of coastal types (Bird, 2010). Another typical characteristic of coasts is their high dynamism: different marine agents (winds, waves, currents, sea level changes) interact with coastal materials to produce erosion, transport and sedimentation of particles, dealing to rapid changes, perfectly perceptible by humans. A corollary of this is the frequency of situations where natural coastal processes interact with human occupations to produce damage (Morales, 2022).

All this complexity makes it difficult to classify coasts, especially when different spatial and temporal scales are involved (Huggett, 2011; French *et al.*, 2016). Following Fairbridge (2004), a given coast can be described by considering three main terms: coastal material exposed to marine agents, coastal agents and their nature (erosive, constructive, physical, chemical, biological and their geographical conditioning factors), and history (geological, climatic, eustatic, occupational evolution). However, not always it is so simple, because sometimes it is very difficult to define where the continent ends and where ocean begins. This is the case of low coasts and coastal wetlands periodically affected by marine flooding, where sometimes they are clearly continental, while others they turn to be marine. A number of classifications have been proposed to cope with this problem, but many of them are useless when applied at a regional/local scale. Pérez Alberti (this issue) presents a new proposal of coastal classification methodology, designed to be applied to any coastal type, based on the quantification of a number of morphometric, topographic and morphodynamic variables. The method, applied to the Galicia coast, results in a detailed inventory and mapping of that region, including different numeric data, which allows grouping the high diversity of coasts into a number of types in a hierarchical manner.

An additional complication is the increasing concentration of human occupations and activities at coastal zones. Only considering coastal zones of low elevation (< 10 m high), more than 600 million people lived at the coast by 2000, and present trends indicate a growth of more than 50% in the following 30 years, to reach almost 900 million by 2030, especially on the less developed countries (Neumann *et al.*, 2015). This situation considerably increases the exposition of people, settlements and social and economic activities to potentially dangerous marine processes, like flooding linked to the ongoing sea level rise, storm surges, high energy waves, coastal erosion, etc. (Elko *et al.*, 2014).

The sustainability of coastal human occupations and activities is only possible with an adequate adaptation to present natural processes acting on the coast and their future trends. This requires a deep knowledge of the coastal environments, the natural agents and processes acting on them, their future trends, the interaction between human activity and coastal processes, and the extreme potentially dangerous events expected to occur in the future. All these complex topics constitute the aims of the present research carried out in coasts, involving a high number of disciplines such as climate and weather forecast, oceanography, coastal geology and geomorphology, coastal engineering, physical and human geography at the coast, economy and population, urban and social sciences, among others.

The present contribution aims to present a succinct state-of-the-art of all those topics, mainly under a morphodynamic scope applied to management. The exposition firstly presents the main agents and processes acting on coasts, secondly the coastal environments and the most common techniques used in their study, and finally a brief discussion about how all this information can strongly condition future trends in coastal management.

## 2. Coastal processes

Coastal processes are mostly related to oscillations and changes of sea level, which fluctuates on very different time scales. Fairbridge (1983) distinguished three-time scales of sea level change: $10^6$-$10^9$ years (broad eustatic cycles), $10^3$-$10^6$ years (tectonoeustatic changes, Quaternary glaciations) and short-term changes, from hours to $10^3$ years, controlled by astronomical, meteorological, oceanographic and climatic factors. The interest of sea level changes for coastal management is restricted to this third set of scales ($\leq$1000 years of periodicity), and can be detailed into more specific processes, like those presented in Figure 1. Obviously, there exist numerous superimpositions between different processes, which produce interactions, counteractions and synergies. The following sections summarize the main aspects of this set of processes.

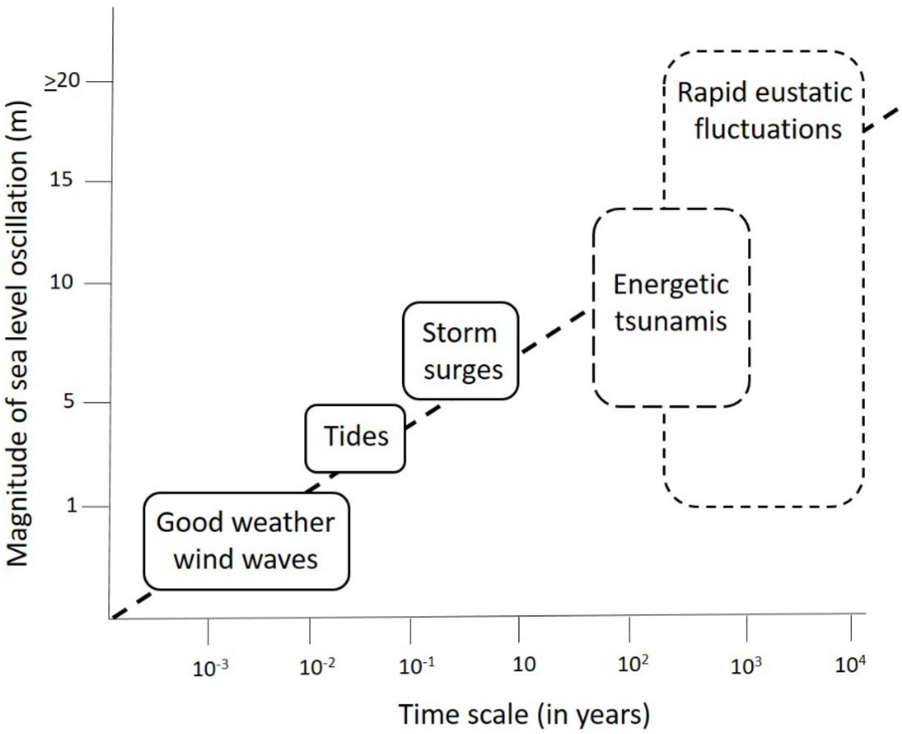


*Figure 1. An example of relationships between sea level fluctuations and time scale of their actuation.*

### 2.1. Rapid eustatic fluctuations

They are commonly triggered by climate oscillations (like those related to the Little Ice Age; Jevrejeva *et al*., 2014), or by rapid vertical movements mostly related to glacio-eustacy, isostacy and tectonism in general (Morhange *et al.,* 2012). Markers of past sea levels can be recognized both as erosional forms on rocky coasts, or through sedimentary records (staircase marine terraces, sedimentary infilling of coastal plains and salt marshes). The first case can be represented by terraced planation surfaces, perched (Kelsey, 2015) or submerged tidal notches (Evelpidou *et al.*, 2012), or more complex cliff profiles, with alternating bevelled and vertical stretches (Trenhaile, 1987), like those studied by Rodríguez-Vidal *et al*. (2004) in the Gibraltar Rock and showed in Figure 2A; these authors sampled and dated the different deposits associated with stepped erosive levels identified in the cliff, to obtain the Late Quaternary relative sea level evolution of that coast; it consisted in a decreasing rate of sea level fall as a consequence of the apparent reduction of tectonic rise of this portion of the Betic Orogen. According to those authors, in recent times sea level trends seem to be lower than -0.005±0.01 mm/yr. Figure 2B includes another example of cliff exhibiting a complex profile as a result of alternating episodes of relative sea-level fall and cliff erosion/retreat in southern Spain.


*Figure 2. Examples of past sea levels indicators. A and B: composite profiles in rocky cliffs including stepped erosion elements due to relative sea level fluctuations; A, eastern side of the Gibraltar Rock; B, western side of the Herradura Bay (Granada, South Spain). C: uplifted Holocene beach deposit (> 90 m above present sea level, a.s.l.), due to glacio isostatic rebound; eastern Baltic coast of Sweden. D: Molluscs accumulations as indicators of former positions of relative sea level (+ 7 m a.s.l.) during historical times; Roman remains at Pozzuoli, SW Italy.*

Tectonic uplifting trends during the Quaternary favoured the generation of terraced coastal landscapes, including stepped erosion surfaces and raised beaches, often forming complex systems with numerous staircase levels, like those of the southern Italian and Sicily coasts (Antonioli *et al*., 2006), or the *rasas* and raised beaches developed along the northern Iberian coast (Flor and Flor-Blanco, 2014; López-Fernández *et al.*, 2020). In high-latitude regions, vertical movements are associated with isostatic readjustments due to the retreat of the great ice caps after the last glaciation. Glacio-isostatic uplift in such regions has produced numerous examples of Holocene raised beaches (Fig. 2C). The process is still active and is responsible for the coastal progradation of sedimentary bodies (commonly beach ridges) in many places of the northern regions (Hansen *et al*., 2011; Nunn *et al*., 2021).

In mid and low latitudes recent (Holocene and historical) sea level fluctuations are mostly recorded in low, sedimentary coasts, where historical beach ridges, and boreholes excavated on sedimentary aggradational plains and wetlands (lagoons, salt marshes), are used to reconstruct vertical relative sea level changes. The ridge systems are studied by means of cartography, high-resolution altimetry and dating (Hansen *et al*., 2011), while the latter are explored through boreholes where different sources of palaeoenvironmental information (pollen, foraminifera, geochemistry, mineralogy) are combined to reconstruct palaeogeographical coastal changes due to relative sea level oscillations. Examples of combination of different sources of data for reconstructing recent sea level trends for the western Mediterranean and the Gulf of Cádiz can be seen in Vacchi *et al*. (2016) and Caporizzo *et al*. (2021).

Apart from erosional forms, like notches (Marriner *et al*., 2014), in recent, historical times, past relative sea levels can be established through the analysis of markers on coastal archaeological remains (Orrú *et al*., 2014). Many examples exist along the Mediterranean coasts, due to the recent to present tectonic vertical movements associated with the active collision between the Eurasian-African plates, and also to a long history of coastal human occupation and urbanization all along the Mediterranean shores, which produced an endless number of coastal archaeological sites. Perhaps the most famous and spectacular markers of historical relative sea level oscillations are those of the coastal Roman ruins of Pozzuoli, located in the Bay of Naples, Italy; the markers are represented by the accumulation of *Lithophaga* burrows and marine organisms fixed on the Roman columns and other remains, presently located several meters above mean sea level (Fig. 2D), and also by submerged Roman constructions (Aucelli *et al*., 2019). The relative sea level rapid oscillations during Antiquity and Middle Ages are in this case produced by the volcanic deformational activity of an underlying caldera (Morhange *et al*., 2006).

If sea level fluctuations during the last millennia were usually lower than a few meters (Kemp *et al*., 2011), at minor time scale climatic oscillations during the last centuries gave rise to subtle sea level variations that can be reconstructed through geo-archaeological and historical techniques (Losada *et al*., 2008), and quantified through the analysis of tide gauges, a method not exempt of uncertainties (Marcos *et al*., 2003; Tsimplis *et al.,* 2011). Historical tide gauge records are mainly available on the northern hemisphere, due to the historical concentration and development of human settlements on the coasts of Europe and North America. This situation gives valuable and detailed data about sea level trends in that region of the Earth, but neglects other world regions, where existing data are very limited. Tidal data are combined with geodetic data for the elaboration of sea level projections, usually by the year 2100 (Vecchio *et al*., 2019). At a global scale, present rates of sea-level change are estimated after applying different climate warming scenarios and geodetical models, always considering that sea level trends are mostly controlled by ice sheet fluctuations (IPCC, 2013). However, this procedure introduces important uncertainties and has been questioned by some researchers (Mörner, 2019). Far for seeking after a global sea level curve and trend, which is by no means non-representative, present research aims to establish local/regional sea level trends (Cronin, 2012), in order to predict the associated coastal changes and their consequences to human occupations and activities at the coast.

Traditionally, it is considered that during a period of sea level rise, like the one presently prevailing in most world coasts due to global warming, sandy beaches will erode and retreat: The increase in the accommodation space prevents sediment return after storm erosion episodes, leading to sedimentary deficit at the shoreface. This relation was expressed mathematically by the Danish civil engineer P.M. Bruun, who proposed a quite simple rule to predict shoreline erosion due to sea level rise (Bruun, 1962), although it received numerous criticism due to a number of arguments, like the absence of geological or oceanographic basis (Cooper and Pilkey, 2004); however, it is still applied due to its simplicity and the absence of an alternative approach.

Cooper (this issue) analyses the response of sandy beaches to sea-level rise, concluding the necessity of enough space behind beaches in order to let them migrate inland. If this possibility exists, then beaches can adapt and face sea level rise maintaining their natural properties. Obviously, human-transformed and artificial beaches usually lack such characteristics, especially those landward limited by rigid structures, which cannot migrate and are condemned to erosion and extinction.

Other coastal sedimentary environments, like salt marshes, can present a comparable behaviour, although bearing a higher vulnerability. If they receive enough sediment supply and include sufficient space inland to migrate, usually inside wide estuaries and bays, they can face a sea level rise if it occurs at not very high rates (Sampath *et al*., 2011; Best *et al*., 2018). Other conditions, like accelerated sea level rise, or decrease in the sedimentary supply to estuaries, however, may progressively submerge salt marshes until their permanent flooding (Hofstede *et al*., 2018; Aranda *et al*., 2020). These environments, and coastal wetlands in general are highly vulnerable systems to rapid sea level rise (Fernández-Núñez *et al*., 2019). Nevertheless, projections of future sea level flooding should consider the possible inland migration of beaches, barrier islands, sand spits, dunes, salt marshes and deltas. This vision requires a dynamic analysis of coastal responses to sea level rise, avoiding any rigid consideration of the present coastal topography; flooding projections uniquely based on a simple, passive, uprising of sea level (Fraile *et al*., 2018) are mostly unreal.

### *2.2. Energetic tsunamis*

The recent catastrophic tsunami events of 2004 in the Indian Ocean and 2011 in Japan have encouraged the study of this type of phenomena that suddenly hit the coasts producing severe damage and casualties. Tsunamis represent the most energetic natural process acting on coasts, capable of producing intense destruction, deep erosion and transport inland huge rock boulders (Figs. 3A, B and C). However, their study is not easy because, fortunately, this is not a frequent process. Prediction of future events, based on a given recurrent period, needs enough historical records for establishing believable trends.

Tsunamis are capable to generate a number of coastal landscapes, both of erosional and sedimentary nature (Bryant, 2008). Historical sedimentary records of past tsunamis are scarce and often difficult to interpret due to the numerous similitudes with coastal storm deposits (Dawson and Shi, 2000; Morales *et al*., 2011; Shanmugam, 2012). In recent times attention is increasingly paid on the diagnostic characteristics of the offshore deposits produced by tsunamis (Costa *et al*., 2021).

Regarding coastal forms and deposits, many places have been reported around the world with outstanding records of historical tsunamis (Scheffers and Kelletat, 2003). Some of them are constituted by boulder accumulations, at places never reached by sea storms; an example of this can be found at Trafalgar Cape, South Spain, where more than 80 large boulders, many of them exceeding 10 tons, lie upon a rocky shore platform; other set of more than 100 rounded cobbles, weighting several hundreds of kg, appear at heights between 8 and 16 m a.s.l. (Fig. 3A). The event responsible for their emplacement is thought to be the tsunami generated by the Lisbon earthquake of 1755 (Whelan and Kelletat, 2005); the presence of mill wheels imbricated within the boulders (Fig. 3B) and other indirect markers would be arguments in favour of this ascription (Gracia *et al*., 2006). Usually big boulders located at high positions and distant from the very shoreline are interpreted as the most typical example of deposit generated by a tsunami, like the case showed in Figure 3C; however, even in such cases, theoretical studies and specific examples demonstrate that big storms can produce the same effect (Barbano *et al*., 2010), like the case showed in Figure 3D, where, according to witnesses, a large boulder was suddenly deposited by energetic storm waves inside the Bay of Sydney (Australia) in the early 20$^{th}$ century (W. Stephenson, pers. com.). Very detailed morphometric determinations are then needed to discriminate the origin of such type of high-energy deposits (Goto *et al*., 2010).


*Figure 3. Examples of boulder accumulations due to high-energy events. A and B, boulders supposedly accumulated by the 1755 tsunami at Trafalgar Cape, South Spain; A, Imbricated boulders at + 8 m a.s.l.; B, historical mill wheel imbricated within the rest of the boulders; C, big boulder deposited by a historical tsunami on a platform more than + 5 m a.s.l. at Bonaire Island (Netherland Antilles); D, the "Mermaid Rock", boulder deposited by a strong storm in the Bay of Sydney, Australia (photo: Wayne Stephenson).*

Much research is still needed for correctly interpreting palaeotsunami markers, both erosional and depositional, related or not to archaeological remains (Goff *et al*., 2012; Röth *et al*., 2015). Although some recent progress has been made in the reconstruction of historical tsunamis in the Atlantic coast, especially along the western European coasts (Scardino *et al*., 2020; Costa *et al*., 2021, Álvarez and Machuca, 2022), one of the best known in the world regarding this topic, the establishment of a credible return period is difficult and proposals in this sense are still controversial (Lario *et al*., 2011; Ruiz *et al*., 2013). The recent catastrophic events that occurred in the Indian and Pacific coasts served as reference for analysing the coastal effects of such phenomenon (Lavigne *et al*., 2009; Ikehara *et al*., 2021), which can be used as a model to a better interpretation of past, historical, events and also to understand how coastal morphology controls the propagation of tsunami waves and the resulting maximum wave height (Umitsu *et al*., 2007).

Taken all these considerations into account, and after combining data from records of historical events, detailed coastal topography and mathematical models for wave propagation, interesting and useful vulnerability analysis can be obtained, with maps of tsunami-flooding hazard that can be used for coastal management in areas exposed to this type of energetic phenomenon (Izquierdo *et al*., 2019). Mathematical models can also be used for theoretically reconstructing the propagation and effects of past tsunamis, in order to compare such results with the real markers and indicators identified in the historical remains (Abril *et al*., 2013). Recent efforts are being made by marine geologists on the specific location and analysis of the submarine faults responsible for the generation of past, historical tsunamis, with present potential activity, in order to refine the existing mathematical models and obtain better flooding maps (Estrada *et al*., 2021; Martínez-Loriente *et al*., 2021).

### *2.3. Storm surges*

Storms are one of the most important natural coastal threats in terms of property damage and lives lost; they produce coastal erosion, coastal flooding and damage to infrastructures (Fig. 4). They are originated by low pressure cells on the ocean and typically produce strong winds; both factors make sea level to rise up (storm surge or set-up). Waves associated with such perturbations are high, steep and with short period. During energetic storms, increasing water level, in coincidence with spring tides, produces coastal surges and flooding of areas which are usually sheltered from water (Vousdoukas *et al.*, 2016). Storm effects can vary considerably alongshore, depending on a number of factors (Guisado-Pintado and Jackson, 2019), including both physical/energetic ones (direction of movement of the storm, occurrence of storm-groups and clusters; Ferreira, 2006, Dissanayake *et al*., 2015), and local/geomorphological ones (coastal outline, soil development, slope changes, beach and dune development and elevation, presence of subaqueous sandbars, etc.). The highest storm surges occur in shallow, gently sloping coastal areas and in semi-enclosed bays and estuaries (Davidson-Arnott, 2010).


*Figure 4. Coastal effects of sea storms in beaches and dunes of SW Spain. A, outcropping of sewage infrastructures after deep beach erosion during a coastal storm in 1996 at El Puerto de Santa María; B, beach flooding and dune undermining at Camposoto Beach (San Fernando) during Emma storm, in 2018 (photo: L. Del Río); C, dune front erosion at Point Candor Beach, Rota.*

Wave energy developed by storms is analysed through statistical approaches, commonly by calculating energetic parameters like significant wave height, storm duration, wave storm direction and energy flux probability of exceedance (Molina *et al.*, 2019), which helps storms to be classified (Anfuso *et al.*, 2015). Wave hindcast can be achieved by applying mathematical models like SWAN (Booij *et al.*, 1999).

All those data are very useful for establishing storm thresholds for a given coast, which represent the minimum wave and tide conditions necessary to produce significant morphological changes and/or damage on beaches, dunes and coastal human occupation (Del Río *et al.*, 2012), which are fundamental for an effective coastal management on exposed coasts. Coastal response to storm impact depends on the natural resilience of the coast: if this can behave without exceeding its system's thresholds, it will maintain its natural dynamics and resist through time; this is quite difficult to be achieved on highly occupied, "developed" coasts (Malvarez *et al.*, 2021).

Storms and hurricanes show a typical seasonal periodicity, although their energy can vary significantly through the years, and extreme wave episodes can hit a given coast unexpectedly (Masselink *et al.*, 2016). Changes in storm frequency and energy should be related to climate trends. However, those relationships are far from simple. In Europe statistical assessment of storminess over the last 30 years evidences an increase in energy variability, although recorded changes are not always directly related to global climate changes (Ciavola and Jiménez, 2013). Only in some specific cases, like the Gulf of Cádiz, a good correlation is obtained between large-scale atmospheric indices (such as the North Atlantic Oscillation, NAO), with a certain increase in the frequency of storms along the 20$^{th}$ century and during the last decades (Ribera *et al.*, 2011). Other regions, like the NW Iberian coast, also record an increased frequency in powerful storm events, and even an alteration in storm approaching directions, which are enhancing erosion of beaches and dunes (Flor-Blanco *et al.*, 2021). In the western Mediterranean coasts, records of the last 40 years show an increase in wave storm durations and direction of approach (Amarouche *et al.*, 2022).

At present, prediction and management of the arrival of storms and their expected energy is assessed through the development of storm early warning systems, an operational oceanography system developed at several coastal sites in Europe (Plomaritis *et al.*, 2012). Apart from hydrodynamic considerations, it is important to evaluate damage and understand the processes responsible for the coastal effects of storms. This can be assessed by post-storm field measurement of changes produced by an energetic event, using high-resolution topographic methods (Almeida *et al.*, 2012; Benavente *et al.*, 2013; Schubert *et al.*, 2015).

More recently, the use of unmanned aerial vehicles (UAV), combined with Structure-From-Motion algorithms, allows detecting and mapping coastal changes through digital elevation models. This method can be used for analysing the response of beaches and dunes to different storm-induced processes, like swash, collision, boulder movement, overwash, beach surface downwearing, dune front retreat, etc. (Pérez-Alberti and Trenhaile, 2015; Talavera *et al.*, 2018; Nagle-McNaughton and Cox, 2020).

## *2.4. Tides*

Tides are periodical metric fluctuations of the sea level mainly produced by the gravitational force of the moon and the sun, with daily vertical sea level variations ranging between low/negligible values (microtidal coasts, average range < 2 m), intermediate values (mesotidal, 2<range<4 m) and high to very high ranges (macrotidal coasts, range> 4 m). In meso and macro tidal regimes tides translate waves and associated currents up and down the nearshore zone, hence modelling their effects (Dey and Shukla, 2019; Héquette *et al.*, 2021).

Tidal currents under macrotidal regimes are strong enough to control beach morphodynamics (Bennett *et al.*, 2019), especially around capes or inside straits, where bottom morphology is the main factor controlling the speed and lateral variations in energy flux (Sánchez Román *et al.*, 2012). Nevertheless, tides can also influence beach dynamics in microtidal coasts under specific morphological circumstances (Chee *et al.*, 2014). Beach and nearshore topography can be used to make computations about direction and speed of tidal currents by applying mathematical models and simulations (Reeve *et al.*, 2019).

In macro and mesotidal environments tidal currents favour the transport and deposition of fine sediments on sheltered coastal areas, commonly bays and estuaries, producing extensive salt marshes (Davidson-Arnott, 2010). In macrotidal coasts human settlements are usually adapted to important sea level fluctuations and are located on places high enough to face such risk. However, in many mesotidal coasts cities, harbour facilities and infrastructures are often located slightly above the high tide level. This situation makes such coasts especially vulnerable to sea level rise. Some approaches to the quantification and mapping of vulnerable tidal coasts and salt marshes to sea level rise emphasize the high exposition of ecosystems, human settlements and activities to the increasing sea level rise (Martínez-Graña *et al.*, 2016; Vázquez Pinillos and Marchena Gómez, 2021). In this sense, larger tidal ranges seem to improve the capacity of coasts to balance sea level rise, due to the role of subtidal gullies as sediment traps, and hence macrotidal coastal flats are considered to be resilient against high rates of sea level rise (Hofstede *et al.*, 2018).

### *2.5. Good weather wind waves*

Determination of wave heights, both modal and energetic, is of prime interest in coastal dynamics. Wave height is usually represented by the significant wave height (average value of the highest third part of a population of data), and is very useful for many purposes related to coastal processes: wave setup, wave-related coastal currents and sediment transport, wave forecasting, atmospheric modelling, ocean circulation, etc.

Measurements of wave heights can be done through a number of methods, although at present satellite radar altimetry is the most accurate source of information about sea surface height, significant wave height and wind speed (López-García *et al.*, 2019). More locally, topo-bathymetric surveys, combined with remote-sensing imagery, can help to understand wave and current dynamics around complex morphologies or bypass processes between adjacent beaches (Da Silva *et al.*, 2021).

When approaching the coast, waves experience a number of processes related to the interaction between the wave base and the sea bottom. From the moment at which the wave base contacts the bottom until the final wave breaking, the wave passes through shoaling processes, which mainly include reduction of wave velocity, increase in wave height, modification of the wave form, and refraction processes that may lead to changes in the approaching direction. All these processes are strongly controlled by the initial wave conditions before reaching the nearshore zone, and especially by the submerged morphology of the sea bottom, mainly slope.

All these physical processes can be predicted with considerable precision through different mathematical equations, which have promoted the generation of mathematic models of wave propagation, very used in coastal studies, like SWAN (Simulating Waves Nearshore; Ris *et al.*, 1999). The accuracy of the results and their correct fitting with natural processes usually depends on the quality of the data feeding the model.

## 3. Coastal environments and their evolution

A quite common, initial and simple classification of coastal environments starts from the division between low, sedimentary coasts and high, rocky coasts. The former ones are constituted by coastal plains or with very low relief, characterized by the accumulation of sediments of varying nature: pebbles, sands and clays, depending on the processes responsible for their sedimentation and their associated energy. They are usually represented by beaches, dunes, lagoons and salt marshes, and also include river mouth systems (estuaries, deltas). The latter are represented by rocky outcrops directly entering the sea through rough relieves, high slopes and cliffs, and also include coastal rocks generated by biochemical processes, like coral reefs. Of course, there exist intermediate cases, like low cliffs modelled on soft rocks, or coastal plains formed by Quaternary deposits (like stepped marine terraces, or beachrocks) that end to the sea through gentle slopes or microcliffs.

### *3.1. Low, sedimentary coasts: beaches and dunes*

Waves and associated currents accumulate particles in favourable places, creating beaches. These sedimentary units can be formed by elements of varied size depending on the average energy of the incoming waves and their competence in the transport of debris. As a consequence, beaches can be formed by boulders and pebbles (named *coídos* in Galicia), or sands, or even very fine sands and silts. One common characteristic of beaches is their high dynamism: they usually respond very rapidly to any change in the energy level of the incoming waves (Pilkey *et al.*, 2011). If storm episodes prevail, boulder and mixed beaches experience micro and mesoscale morphological changes due to the slight movement of boulders and pebbles by energetic waves (Pérez-Alberti and Trenhaile, 2015; Nagle-McNaughton and Cox, 2020; Casamayor *et al.*, 2022). Sandy beaches experience erosion through shoreline retreat, dune front escarpment, overwashing, inland migration of barrier islands, or even erosive planation and dismantling (Carter, 1990; Jiménez *et al.*, 2007; Crowell *et al.*, 2018; Barrantes-Castillo *et al.*, 2020; Ruiz de Alegría-Arzaburu *et al.*, 2022).

In this sense, some recent proposals of mathematical models focus on the energy developed by waves on sandy beaches, and calculate beach profile modifications associated with the different type of waves approaching the coast. There is an interrelationship and feedback between wave type and energy dissipated on the beach, and beach slope resulting from the sediment erosion/deposition by such waves. Some modern mathematic models combine wave physical processes (including surf and breaking processes, runup and overwashing) with continuous beach adaptation to the incoming wave types. One of the most used models is X-BEACH, developed by the Dutch company Deltares (Roelvink *et al.*, 2009). Recent, more advanced versions of this model include interaction between beaches and dunes (Roelvink and Costas, 2019). In a later phase, understanding coastal processes responsible for the changes detected in sandy shores is being recently assessed through the application of sophisticated theoretical models which include multiple response pathways and outcomes (Van Rijn *et al.*, 2007; Payo *et al.*, 2016).

Although the high energy applied on coasts during storm episodes produces rapid changes in beaches (Beckman *et al.*, 2021), beach erosion also occurs at longer, slower rates. Beaches continuously receive and lose sediments, and the volume of sand at a given moment is the result of the balance existing between sediment supply and sediment loss. Sources of sediments to the coast are mainly represented by rivers, and in a much lesser extent by submarine supply and erosion of soft cliffs. Once arrived to the coastal system, fluvial sediments are then transported alongshore by wave-induced currents. Human activities can alter this chain by retaining sediment within the river catchment through dams and reservoirs, and by blocking longshore currents through groynes, jetties and piers (Rodríguez-Ramírez *et al.*, 2008; Hapke *et al.*, 2013). The proliferation of reservoirs in river basins has produced a dramatic reduction of sediment supplied to coastal areas producing a chronic sedimentary deficit in many coasts. This is especially the case of deltas, where the subtle equilibrium between fluvial sediment supply and coastal erosion due to wave action can be rapidly broken in favour of shoreline retreat. Several deltas along the Mediterranean shores exhibit a present trend toward destruction, due to anthropogenic modification of the river catchments (Anthony *et al*., 2014). Historical trends of sandy beaches in river deltas allow predicting the future of their shorelines with significant precision. This is the case of the Ebro River delta (Aranda *et al.,* this issue), where sediment retention on dams threatens the survival of its most valuable ecosystems in the short term.

Urban growth has destroyed many coastal landforms and often has altered the cross-shore sedimentary equilibrium of beaches by dismantling dune ridges, dredging, etc. According to data obtained by Luijendijk *et al.* (2918), about one third of the world coasts are eroding at rates exceeding 0.5 m/yr, and in many places this trend has been maintained for decades (Lira *et al.*, 2016; Pérez-Hernández *et al.*, 2020). The high vulnerability of sand beaches and the important economic income related to their tourist exploitation has made the study of beaches the most important research topic in coastal studies during the last decades. A historical summary of the main advances in this research line during the last 50 years can be found in Jackson and Nordstrom (2020).

Beach processes and trends can be studied under very different spatial and temporal scales (Gracia *et al.*, 2005). At the short term (hours, days) the amount of daily sand erosion and renovation can be assessed in the field by measuring the depth of disturbance (King, 1951) and determining the thickness of the activation layer. This information is of prime interest before facing any artificial beach nourishment work (López *et al.*, 2019). At a medium term (weeks, months), field work is required, although the introduction of RTK-GPS devices (Schubert *et al.*, 2015) and the use of UAV's have greatly simplified procedures, introducing very high resolution outcomes in the topographic assessment of beaches an dunes (Mancini *et al.*, 2013).

Coastal studies on a longer term (years) are very common, since wave energy and storm frequencies fluctuate around multi-monthly to pluri-annual scales. In this case coastal assessment mainly consists on the comparison of vertical images taken at different moments. If the number of images is high enough, projections of future shoreline trends can be established. Traditionally images used for such purpose are vertical aerial photographs, which in some cases can be available for the last 70 years, and allow a first quantification of coastal changes and trends during the last decades (Fig. 5). However, the problem with this method lies in the correct definition of the shoreline, especially on tidal coasts (Boak and Turner, 2005). Another question is the error inherent to the use of such photographs, all of them including image deformations and several sources of uncertainties (Del Río and Gracia, 2013).

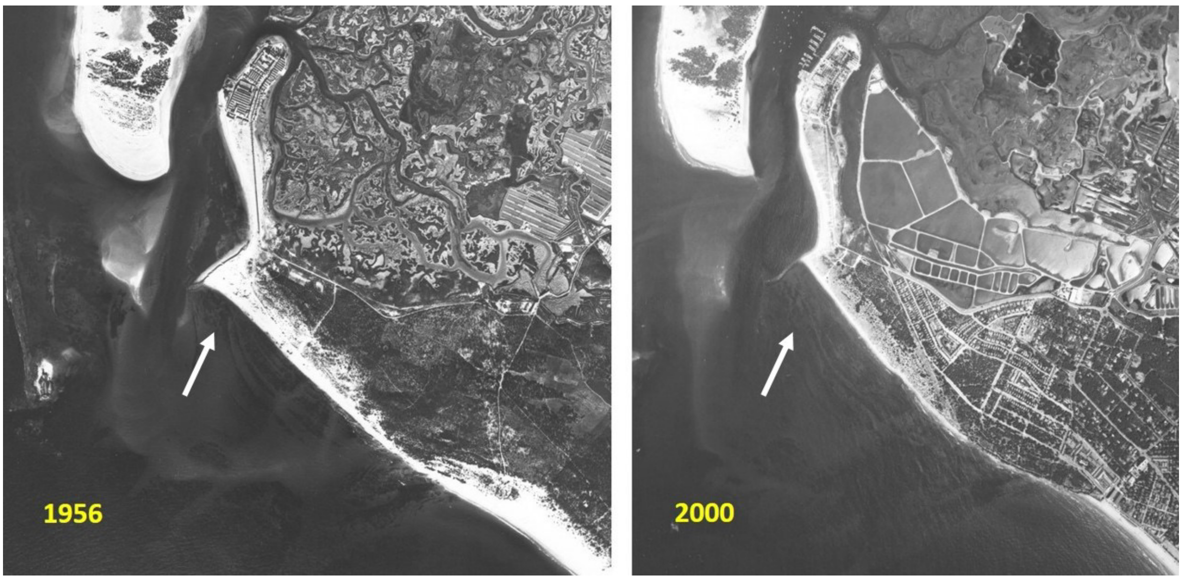


*Figure 5. Aerial photographs showing beach deficit and shoreline erosion at Sancti Petri Beach (Chiclana de la Frontera, SW Spain).*

In recent years a regular monitoring of shoreline changes can be assessed through the high-frequency/high-resolution satellite data displayed by Quickbird and Sentinel-2 imagery (Mitri *et al.*, 2020). The development of sophisticated tools for the pre-processing of images, like the SHOREX system (Sánchez-García *et al.*, 2020) has allowed the improvement of satellite-derived shorelines and the assessment of high-resolution spatial-temporal models. Pardo-Pascual *et al.* (this issue) apply such technique to analyse the morphological changes experienced by a sector of the eastern Spanish coast, between 1985 and 2020. Results, estimated at the sub-pixel scale, show a general erosional trend for all the area, with a sequence of narrow portions with alternating high and low erosion rates. The comparison of coastal trends with the record of wave energy along the last decades indicates a high influence of strong storms on the recent evolution of this coast, although the grouping of minor storms also produces severe damage and coastal retreat (a relation already analysed by Ferreira, 2006). Recent trends on the increasing energy displayed by storms in the Valencia coast are also evidenced, which could be interpreted as another consequence of the ongoing climate change.

Dunes constitute a buffer to coastal erosion since they represent an extra amount of sediment that can be mobilized during energetic events. The erosion of coastal dunes and their vulnerability has focused the attention of research in the last decades (Carter *et al*., 1990; Peña-Alonso *et al*., 2018).

Dune systems can grow significantly if sediment supply is maintained during decades. Strong winds make the dunes active and mobile, producing a net transport inland. These systems, called transgressive dunes, can present different modes of generation and behaviour (Hesp, 2013). Local limiting factors, like the sediment available and its characteristics, control the development of active, mobile dunes. Strong winds associated with storms can favour the generation of transgressive dune systems, rapidly moving, which can interact with human occupation and infrastructures located near the coast. An outstanding example of this situation is the Ria Formosa barrier island, in southern Portugal (Costas *et al*., 2020), where dune invasion of houses and park places is common during wind storms (Fig. 6A).

Coastal dunes are very valuable morphological units to be preserved, not only because of their role in protecting beaches and coastal properties against storms and sea-level rise (Houser *et al*., 2018), or their intrinsic morphological variety and dynamics, but especially because they constitute the base for a number of ecosystems and habitats of great importance. *Psammophytes* are plants adapted to grow upon a sandy substratum affected by wind action. Those plants, of high ecological value, are the main responsible for the partial or total fixation of dunes on coastal environments (Fig. 6B). A subtle equilibrium is established between shoreline progradation/retreat and dune growth, anastomosis of embryo dunes and generation of continuous dune ridges or foredunes (Konlechner *et al*., 2019). Up to 11 different coastal dune habitats are included in the European Directive 92/43, by which states members are committed to establish measures for their preservation (García de Lomas *et al*., 2011).

Dune dynamics is complex due to their sensitivity to different natural and anthropogenic factors. In highly occupied and transformed coasts, dunes develop on specific favourable sites characterized by stability or coastal progradation. Usually coastal erosion produces dune retreat, fragmentation and finally destruction. An outstanding example of the role of different factors in the preservation and trends of beach-dune systems is the Mediterranean coast of Andalucía, studied by Molina *et al*. (this issue). These authors analyse five different photogrammetric flights to quantify recent shoreline trends, and combine those results with the inherent importance of each dune system, taking into account the development of dune habitats. Their results constitute an essential information before facing any management plan on a given low coast.

Present trends in the study of coastal dunes include both field and indirect methods. The former ones are mainly represented by topographic devices: theodolits, electronic levellers, GPS measurements, terrestrial laser scanner, etc. (Labuz, 2016). Wind dynamics and sand transport processes are also investigated through tracers (Wang *et al*., 2017), anemometers and sand traps (Navarro *et al*., 2015). Indirect methods include remote sensed techniques for the acquisition of topographic data and images, and dune mapping (Gonçalves *et al.*, 2018; Grottoli *et al.*, 2021). Holocene and recent historical trends of dune fields can be deduced from historical maps and the analysis of the inner structure through ground penetrating radar surveys (Flor-Blanco *et al.*, 2016).

The status of coastal foredunes is a good indicator of the morphosedimentary health of a given coast. In fact, foredune degradation by sand trampling and urbanization is one of the most important problems in coasts exploited for tourism. Protection and recuperation of dunes can be made through different procedures, like peripheral closures (Fig. 6C) or sand fences (Fig. 6D). A synthesis of dune regeneration methods can be found in Ley *et al*. (2007).


*Figure 6. Coastal dune dynamics. A, dune migration upon coastal buildings and properties at Praia de Faro (South Portugal); B, plant succession on embryo dunes (Bolonia Beach, South Spain); C, dune enclosure for preventing trampling at El Puerto de Santa María (SW Spain); D, wooden dune fences at Tarifa Beach, South Spain.*

### *3.2. Low, sedimentary coasts: barrier islands, lagoons, salt marshes and river mouths*

Active sand sedimentation on low coasts produces accumulations that grow until generating mesoscale sedimentary bodies, often reaching several kilometres long. Beach progradation normal to the shoreline occurs when an abundance of sediment exists. In such a case, slight oscillations in the sediment supply, storminess and sea level changes combine to produce parallel ridges advancing seawards (Taylor and Stone, 1996; Otvos, 2000). Radiocarbon dating of beach ridges gives clues about the Holocene and historical evolution of shorelines, and help to separate local from regional or even global factors controlling coastal evolution (Rodríguez-Ramírez and Yáñez-Camacho, 2008; Rodríguez-Polo *et al*., 2009).

On a different situation, if longshore currents prevail, they transport and accumulate sands forming elongated systems. They can be anchored at one given point of the coast, typically a headland,

and then the longitudinally growing sand body forms a littoral spit whose free limit is usually very unstable and dynamic (Kraus, 1999; Randazzo *et al*., 2015). If the longitudinal body forms at a certain distance from the shoreline, then a barrier island is generated. About 10% of the open-ocean shorelines in the world are represented by barrier islands, especially abundant in the North America coasts. They are very diverse in size, morphology, geological and geomorphological setting, and also in morphodynamic behaviour (Pilkey, 2003). Such systems change in a temporal scale ranging between 10 to $10^2$ years and are very sensitive to changes in external forcing, like sea level, storminess, or climate changes (Cooper *et al*., 2018), and also to human interventions (Paris and Mitasova, 2018; Kombiadou *et al*., 2019).

In microtidal environments the outer sandy barriers can grow enough to close former bays and embayments. As a result, a coastal lake or lagoon is formed (*albufera* in Spanish), characterized by sediment aggradation occasionally affected by storm waves and coastal flooding by sea storms (Adlam, 2014). Sedimentary records in lagoons represent very valuable archives of the recent climate and coastal environmental evolution of the zone, including historical sea level fluctuations (Carrasco *et al*., 2016), and are usually analysed through sedimentological and palynological methods in cores (Ruiz-Pérez and Carmona, 2019). A complete information on the Holocene-historical evolution of a given low coast would be obtained by combining beach ridge data and sedimentary record of coastal lagoons (Sander *et al*., 2015).

In tidal environments, tidal currents usually prevent the closure of inlets and typical tidal deltas form at both sides of the breachings. Tidal currents are usually low and can only transport medium to fine sediments, except at local places where the oceanographic and coastal configurations (macrotidal regime, gently sloping continental shelf, back-barrier plains, straits, channels, etc.) accelerate the tidal flux. As a consequence, the normal result of the tidal dynamics is the accumulation of fine sands, silts and clays at favourable, sheltered places inside bays, estuaries, etc., forming salt marshes (Rahman and Plater, 2014; McLachlan *et al*., 2020). Plants exert a determinant role in the tidal sedimentation process through particle trampling and sediment compaction. The existing interdependences between plant dynamics and morphological evolution of salt marshes are complex and depend on a number of concurrent factors, not always easy to differentiate. As in the case of dune systems, salt marshes are considered as typical cases of biogeomorphological systems, especially under tropical climates (Li *et al*., 2021). In fact, salt marsh reclamation or the removal of vegetation from marshes usually has the same consequence as the effects of strong currents and waves: shoreline erosion and retreat (Brunier *et al*., 2019; Zhang *et al*., 2021; Evans *et al*., 2022).

Sedimentary evolution of salt marshes usually consists in a progressive aggradation, coupled with subsidence due to sediment compaction. The maintenance of this trend in certain areas since the last Holocene eustatic maximum has produced tens of meters of sedimentary record, very useful as geoarchives for palaeoenvironmental and sea-level reconstructions (Zazo *et al*., 2008; Brain *et al*., 2015; Caporizzo *et al*., 2021). Holocene palaeogeographical reconstructions of salt marshes can also be made through detailed geomorphological mapping and dating of inactive elements, like supratidal sedimentary plains, abandoned channels, etc. (Pierik *et al.,* 2016). Historical tidal silting of bays and harbours, sometimes favoured by vertical tectonic movements, can be reconstructed through geoarchaeological techniques (Morhange *et al*., 2012).

The morphological and ecological evolution of salt marshes in the last decades can be analysed through aerial photographs (Aranda *et al*., 2020). Monitoring of salt marsh dynamics and their bio-geomorphological trends are analysed through satellite imagery, LiDAR and high-resolution mapping (Haynes *et al*., 2017) combined with sediment sampling and textural analysis (Chen *et al*., 2018). At present sediment starvation and sea level rise are the most important threats to salt marshes (Fernández-Núñez *et al*., 2017). Most recent research on the topic focus on the resilience of these environments and their role as a natural defence against marine flooding (Day *et al*., 2011; Hofstede *et al*., 2018; Reed *et al*., 2018).

Salt marshes and coastal lagoons are very often related to river mouths, totally or partially closed by outer sand spits or barriers. The palaeoenvironmental reconstruction of such coastal systems is then complicated by the usually complex interaction between tidal and fluvial dynamics (Dabrio *et al*., 2000; Ciavola and Collins, 2004). Tidal currents and fluvial fluctuations control the main paths of sediment transport and accumulations, and the generation of beaches, beach ridges and spits inside these systems (Fortunato *et al.,* 2021). Multi-temporal maps and images help to understand the evolutionary trends of the different environments forming the estuary (Ghosh, 2019; Aranda *et al*., 2020).

River deltas form when fluvial sediment supply is high enough to counteract the erosive action of waves, and sedimentary balance inclines toward sedimentation and coastal progradation. Delta growth usually includes channel migration and capture, closing of embayments by sandy barriers, and rapid shoreline changes, very sensitive to any fluctuation of the energetic forcing (both fluvial and marine). All these processes favour the formation of different fluvial, coastal and mixed environments, including coastal lagoons and wetlands, often of high ecological value (Schmidt, 2011). Apart from accelerated shoreline erosion due to sedimentary deficit, river deltas also present an important issue to take into account: land-surface subsidence, due to sediment compaction and dewatering. This process, active in most deltas during the last millennia, affects the uppermost 5-10 m of sediments, and despite its low rate the associated deformation and faulting produces damage on coastal settlements and increases the zones exposed to marine flooding due to sea level rise (Jankowski *et al*., 2017; Gómez *et al*., 2021).

### *3.3. High, rocky coasts*

Coastal cliffs are typical erosional forms, commonly associated with rocky escarpments subject to different erosive processes, both continental and marine, and represent about 80% of the world coasts (Emery and Kuhn, 1982). As in sedimentary coasts, most part of the marine cliffs in the world has generated and evolved along the last 6000 years, moment at which sea level reached a height broadly similar to the present one (Bird, 2016). Cliff evolution is controlled by a number of factors, like wave energy, sea level trends, and especially their geological characteristics (Trenhaile, 1987; Sunamura, 1992). The geometry of rocky coasts is highly influenced by geological and tectonic processes. Although such relationships are not always evident, mathematical approaches sometimes shed light on this dependency (De Pippo *et al.*, 2004).

A simple subdivision of cliff types could differentiate between those formed by hard or resistant rocks and those constituted by soft rocks (Sunamura, 2005; Carpenter *et al*., 2014). The former ones are affected mainly by erosive processes related to wave breaking at their toe, which produces vibrations and fracturing, undercutting and notch excavation, and falling of unstable elements (Neves, 2008). Mass movements, mostly intermittent due to the seasonality of storminess, affect most cliffs; the material accumulated at the cliff toe is afterwards removed by waves and currents (Granger and Kalaugher, 1987; Del Río and Gracia, 2009; Montoya *et al*., 2012). Only 5% of the world cliffs modelled upon hard rocks experience significant erosion. A common result of cliff retreat is the generation of rock platforms, usually less than 100 m wide due to the rapid wave energy dissipation, that prevents the progression of wave erosion and hence limits the extent of such erosional forms (Trenhaile, 1987). Rock weathering and bio-erosive processes are the main mechanisms of rock downwearing (Trenhaile and Porter, 2007; Moura *et al*., 2011); waves export the resulting products and flatten the surface to the medium sea level through abrasion (Gómez-Pujol *et al*., 2006; Blanco-Chao *et al*., 2007).

In contrast, more than 30% of the cliffs on soft rocks are subject to different erosive processes, and this situation affects to more than 50% of the European cliffs (EUROSION, 2004). As in any other slope, erosive processes are related to gravity (rock falls) and fresh water processes (mainly sheetwash erosion, rilling, gullying and piping). Rock weathering, especially salt weathering (Welman and Wilson, 1965), softens the rocks and make them more vulnerable to such processes. Waves can erode the possible beaches existing at the cliff toe, or directly attack the cliff base (Sallenger *et al.*, 2002; Lee, 2008; Limber and Murray, 2011). Winds can produce both erosion and sand deposition. All those processes present variations along the year, with a typical seasonal behaviour (Fig. 7). At the end, cliffs erode both vertically (downwearing) and horizontally (cliff retreat), the latter reaching very often values higher than 1 m/year (Tsujimoto, 1987).

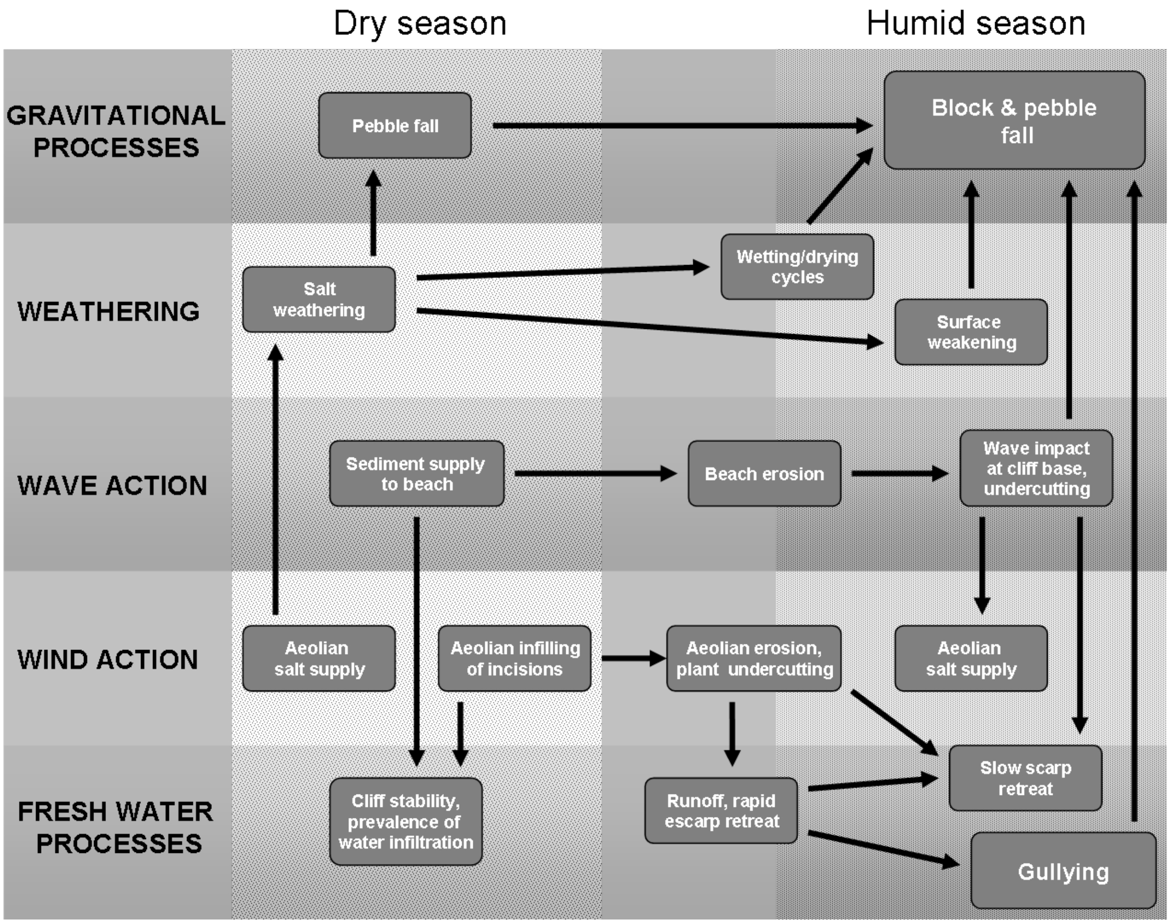


*Figure 7. Seasonality of the main processes dealing to the erosional evolution of coastal cliffs under temperate climates.*

All those processes generate a number of forms that control the final cliff profile morphology and slope. Field indicators/markers of erosive processes on cliffs are numerous and include local gully incisions and generation of small alluvial fans at the cliff toe (Fig. 8A), cracking at the cliff top (Fig. 8B), notching at the cliff toe in the case of resistant rocks, etc. Markers of cliff instability are similar to those recognizable on inland slopes. Such indicators can be used to identify problematic points and subsequently decide to apply protective measures if appropriate (Brampton, 1998). Figures 8C and 8D include examples of defence measures taken in active cliffs of south Spain, like persuasive fences and sign posts of danger.

From a methodological point of view, since middle 20$^{th}$ century a wide variety of techniques have been developed for assessing erosive processes on marine cliffs (Zively and Klein, 2004; Del Río and Gracia, 2009). They include aerial photogrammetry, analysis of historical maps, field measurement and photography, etc. (Young *et al.*, 2009). In the last decades the introduction of a group of advanced techniques has allowed generating high resolution 3D models very rapidly (Wilkinson *et al.*, 2016). One of the most used is the LiDAR sensor (Laser Imaging Detection and Ranging), installed both terrestrial (placed upon the ground) or airborne (on a plane or, preferably nowadays, on a UAV). The terrestrial laser scanner (TLS) is frequently used for assessing rocky escarpments and other coastal forms (Rosser *et al.*, 2005; Sanjosé *et al.*, 2016). A synthesis of the application of this technique to coastal environments can be found in Fairley *et al.* (2016). An alternative technique is the Structure-from-Motion Photogrammetry (SfM), much more economic and giving digital topographic models with a reasonable resolution (Westoby *et al.*, 2012; Del Río *et al.*, 2020). As with LiDAR, image acquisition can be made on the ground or airborne (Gonçalves and Henriques, 2015), and is especially useful in the assessment of coastal cliffs (Warrick *et al.*, 2017).


*Figure 8. Examples of eroding cliffs. A, gully erosion and alluvial fan generation on compacted sands, El Asperillo cliffs (Huelva, SW Spain); B, C and D, unstable cliffs at Conil de la Frontera, Cádiz, affected by mass movements; B, development of fractures at the cliff top; C and D, danger sings and indications at the cliff foot.*

## 4. Towards an efficient management of coastal zones

The growing concentration of human population at coasts and adjacent areas has made these zones be populated with densities nearly 3 times higher than the global average density (Small and Nicholls, 2003). Under this situation, human activities on coasts can directly modify coastal dynamics, both directly and indirectly. Direct interaction with coastal processes includes the modification of the coastal morphology by means of dredging, construction of jetties, docks, harbours, promenades, etc. Those artificial structures modify wave refraction patterns and shoreline currents, block sediment circulation producing sand accumulation at some places and sedimentary deficit in others especially during storm episodes, while changes in the geometry of tidal channels alter the tide dynamics (Rodríguez-Ramírez *et al*., 2008; Manno *et al*., 2016).

Indirect effects include the modification of the quantities and qualities of sediments supplied to the coast through rivers; fluvial basin deforestation increases soil exposure to water erosion processes, increasing the amount of sediment yielded by rivers to the coastal systems; some historical cases of rapid delta progradation are related to this kind of interventions (Anthony *et al.,* 2014). In the opposite situation, regulation of river flows by dam construction, revegetation, irrigation practices, etc., produce sediment trapping and a starvation of sediments to the coast, especially if the reservoir is sufficiently close to the river mouth (less than 50 km). In such a case, sands and gravels are dramatically reduced in the river solid flow, but the suspension fraction (silts, clays) can bypass the barriers and reach the coast, finning the beach sediments and making coastal deposits more erodible (Donadio, 2017).

A common consequence of all these activities is coastal erosion, exacerbated by the ongoing sea level rise. According to EUROSION (2004), 15% of the more than 100 000 km of the European coasts are eroding. In some countries the negative beach sediment budget is being opposed through artificial nourishment, mostly dredged from the nearshore zone, although other alternative methods have been tested and adopted in several countries to protect beaches (Orombelli and Pranzini, 2020). Beach nourishment introduces additional problems, like the burial of shallow reefs and other beach habitats, or the reduction of densities of invertebrates, which represent essential preys for shorebirds, surf fishes, and crabs (Peterson and Bishop, 2005). Additionally, if nourished profile is not strictly controlled, artificial beaches become more susceptible to develop erosive scarps (Van Bemmelen *et al*., 2020). Very specific and exigent requisites must be followed in order to achieve an ecologically sound result (Speybroeck *et al*., 2006).

Dunes are often very active and vulnerable. A simple re-profiling of dunes can derive in a rapid and unexpected change of the dune system, with non-desired results (Gangaiya *et al*., 2017). Dunes are very sensitive to coastal occupation and their naturality is an indicator of the environmental health of the coastal system. Besides, dunes can grow rapidly if the natural conditions are favourable. Unfortunately, many urbanised areas do not allow the development of embryo dunes, due to the seasonal, sometimes daily practices of beach cleaning by mechanical methods, which very often destroy pioneer plants and small aeolian accumulations in the backshore (Fig. 9A). Dune restoration has been addressed in many degraded coasts, by following different methods of sand trampling (Fig. 6C, D), dune coring (Nordstrom, 2019) and replanting (Ley *et al*., 2007). However, as in beaches, dune recuperation must be very carefully performed, always taking into account the subtle equilibrium between plant ecology and sediment accumulation (Houston *et al*., 2001; Jenks, 2018). In this sense, García-Lozano *et al*. (this issue) make an analysis of the response of different types of dunes, both natural and restored, along the Catalan and Valencian shores. These authors show how only sustainable management methods ensure the effective recovering and maintenance of the system.

Another source of coastal degradation is the growing presence of waste materials and litter in beaches and dunes (Fig. 9B). The study of the sources, distribution and consequences of beach debris is a line only very recently addressed in coastal management research (Williams *et al*., 2016), especially due to its possible influence on tourism quality of beaches (Krelling *et al*., 2017; Asensio-Montesinos *et al*., 2019). Regarding impacts on salt marshes and estuaries, urban and industrial settlements eliminate valuable habitats (Fig. 9C), while salt harvesting modifies the geometry of natural tidal channels, altering tide dynamics and sedimentation rates (Gracia *et al*., 2017; Brunetta *et al*., 2019). Nevertheless, the abandonment of traditional salinas maintaining sluice gates open allows the system to rapidly recover its naturalness through plant colonization (Fig. 9D), which favours seabirds nesting (Aguilera and Gracia, 2004).


*Figure 9. Coastal transformations and impacts by human activities. A, destruction of pioneer plants in the upper beach by "beach cleaning" at La Atunara beach (La Línea de la Concepción, South Spain); B, litter accumulation at a stream mouth (Catania, Sicily); C, industrial complex installed upon former vegetated salt marshes (Huelva, SW Spain); D, industrial facilities near abandoned salinas (Cádiz, SW Spain).*

The high dynamism of coastal environments briefly described in previous sections, combined with the dense human occupation and activities on coastal areas, produce numerous situations of hazards. Sea level rise accelerates coastal erosion and increases the risk of flooding on low coasts, like deltas (Fig. 10A), where sometimes drastic measures must be applied in order to protect properties and activities that originally were not threatened by marine processes but at present they are (Fig. 10C). The illogical urban occupation of unstable cliffs also increases the situation of imminent hazard (Fig. 10B). Dense urbanization of low coasts and barrier islands (Fig. 10D) strongly increases the exposition to potentially risky natural processes, like storm waves, overwashing and shoreline retreat.

Coastal hazards must be included in any coastal management plan, through vulnerability analysis of exposed areas and activities and improvement of the coastal resilience. In the last decades this approach is being assessed by means of Coastal Zone Integrated Management, which consists in the articulation of different sectors, communities and agencies involved in the exploitation of spaces and resources at the coast or its vicinity (Quevauviller *et al*., 2017; Puertas and Aparicio, 2020). This strategy is being developed especially in European and South American countries (Barragán, 2005; Rodríguez-Perea *et al*., 2013). Some Spanish regional administrations have included this scheme in their territorial regulations (Oliveros *et al*., 2008; Mas-Pla and Zuppi, 2009).


*Figure 10. Human infrastructures threatened by erosional coastal processes. A, abandoned agricultural facilities affected by shoreline retreat at the Ebro River delta (aerial photo: 2008, Institut Cartografic de Catalunya); B, tourist urban complex on a cliff affected by gullying and mass movements at Santiago de Teide (Tenerife, Canary Islands); C, protecting crops and houses from energetic waves by an artificial earth barrier at the Ebro River delta; D, tourist urban settlement affected by severe beach erosion at Murcia coast (Manga del Mar Menor).*

Coastal protection by stakeholders and policy makers needs to assess the degree of vulnerability and mitigation efforts must be focused in that sense (Wolters and Kuenzer, 2015). Coastal hazards have become an essential element in any approach to coastal management (Rangel-Buitrago *et al*., 2020). Coastal vulnerability is commonly assessed through the application of indices that combine different variables involved in the degree of coastal exposition to risky processes, human impacts on coasts, socioeconomic activities developed on them, etc. (Alberico *et al*., 2017; Bagdanaviciute *et al*., 2019; Alcérreca-Huerta *et al*., 2020). Coastal vulnerability assessment is applied to both natural and historical-cultural heritage elements (Peña-Alonso *et al*., 2018; Mattei *et al*., 2019; Rodríguez-Rosales *et al*., 2021).

As indicated in previous sections, sea level rise produces beach erosion and salt marsh degradation, leading to the deterioration of valuable ecological spaces and the loss of economically profitable beaches, an important source of money in tourist coasts. As a consequence, an important issue in coastal planning must be adaptation to sea level trends and its consequences. Since the latter vary laterally, an analysis of the hazards associated with this phenomenon and its trends is required through the development of coastal response models and databases for assessing the multiple impacts to the socio-economic systems, to the coastal settlements and uses (Wolff *et al*., 2018). In the case of beaches, as Cooper (2022, this issue) points out, policies must prioritise the preservation of their natural features over urbanization and protection of coastal properties; otherwise, many beaches presently considered as important economical sources for coastal communities may degrade severely or even disappear. In the case of coastal wetlands, lagoons and salt marshes, local effects of sea level rise must be specified in order to correctly predict future evolution of the system, including the dynamics and possible impacts on ecosystems (Carrasco *et al*., 2016).

Finally, coastal management must also include the especial protection of the main natural and human values of the coasts. An important component of the coastal value is the historical-cultural heritage, sometimes exposed to hazards like shoreline retreat (Fig. 11A) or erosion due to storm wave impact (Fernández-Montblanc *et al*., 2018; Pourkerman *et al*., 2018; Mattei *et al*., 2019). Another essential aspect of coastal management is the protection of natural areas with environmental interest, a practice that must be compatible with a rational exploitation of coastal resources (Barragán, 2005). Protected habitats (Fig. 11B) must receive an especial attention in laws and coastal regulations (Bartolomé *et al*., 2005). At the same time, coastal active processes can be used to illustrate visitors the dynamism of the coast and the importance of its protection (Fig. 11C). In that sense, the geological and geomorphological aspects of the coast should serve not only for a proper zonation of uses of coastal zones (Flor, 2007), but also for disseminating the heritage value of the abiotic aspects of coasts and their interest as living landscapes (Gracia, 2008). The scenic value of many coasts, combined with their inherent natural values (Fig. 11D) also constitutes an additional task to be included within the integrated coastal management (Mooser and Anfuso, 2018). Protection measures should include the preservation of all these values (Hooke, 1998).


*Figure 11. Four examples of different environmental values taken from the SW Spanish coast. A, historical-archaeological value: remains of a Roman fishery at Cape Trafalgar; B, ecological value: natural salt marshes at the Bay of Cádiz Natural Park; C, geomorphological value: dune ridge affected by a washover fan which lies upon salt marshes, near the Guadiana River estuary; D, faunal and scenic value: a deer walking along the beach in the Guadalquivir estuary, in front of Sanlúcar de Barrameda village (Doñana National Park).*

## 5. Concluding remarks

At a human scale, coastal processes act at very different time scales. The interaction among continental and different marine phenomena produces a quite complex system, sometimes affected by severe risky processes. The combination of dangerous agents (storms, tsunamis, coastal flooding, sea level rise, aeolian sedimentation, accelerated shoreline erosion and retreat, mass movements and water erosion on cliffs, etc.) with an increasing human occupation and transformation of coasts gives as a result a complex casuistry of natural hazard situations. The main consequence of this interaction is the great difficulty to correctly adapt and manage human settlements and activities on the coast and make them compatible with its natural dynamics. This problem converges with the additional uncertainty associated with the political and economic lines followed by governments and stakeholders, which can strongly fluctuate through time.

As Malvarez *et al.* (2021) suggest, another important issue in a correct coastal management is the perception of coastal safety once the administration has dealt with shoreline protection measures against hazardous processes. The false sensation that no more problems will affect the coast once users identify apparently strong and consistent protective structures can deal to encourage more occupation and urban development, increasing exposition of users to future high-energy events.

Education and information seem to be a good tool for making people aware of the real importance of observing and respecting the complex natural processes acting on coasts. Due to the rapidly alongshore changing conditions of coastal processes, more local studies are needed for identifying and understanding them in detail, and all the possible interactions with all types of settlements and human activities at different scales. All the administrative levels (municipal, regional and national governments, supranational associations) should include the study, prediction and prevention of coastal hazards into their regulations, and also the protection and future preservation measures of all valuable components existing at the coastal zone, both natural and historical-cultural.

## Acknowledgements

Thanks to W. Stephenson and L. Del Río for the photographs included in Figures 3 and 4.

## References

Abril, J.M., Periáñez, R., Escacena, J.L., 2013. Modelling tides and tsunami propagation in the former Gulf of Tartessos, as a tool for Archaeological Science. *Journal of Archaeological Science* 40, 4499-4508.

Adlam, K., 2014. Coastal lagoons: Geologic evolution in two phases. *Marine Geology* 355, 291-296. https://doi.org/10.1016/j.margeo.2014.06.005

Aguilera, P., Gracia, F.J., 2004. La degradación de las salinas abandonadas. In A. Pérez Hurtado (Coord.). *Salinas de Andalucía*. Consejería de Medio Ambiente, Junta de Andalucía, Sevilla, p. 274-277.

Alberico, I., Iavarone, R., Angrisani, A.C., Castiello, A., Incarnato, R., Barrera, R., 2017. The potential vulnerability indices as tools for natural risk reduction. The Volturno coastal plain case study. *Journal of Coastal Conservation* 21, 743-758. https://doi.org/10.1007/s11852-017-0534-4

Alcérreca-Huerta, J.C., Montiel-Hernández, J.R., Callejas-Jiménez, M.E., Hernández-Avilés, D.A., Anfuso, G., Silva, R., 2020. Vulnerability of subaerial and submarine landscapes: The Sand Falls in Cabo San Lucas, Mexico. *Land* 10, 27. https://doi.org/10.3390/land10010027

Almeida, L.P., Vousdoukas, M.V., Ferreira, Ó., Rodrigues, B.A., Matias, A., 2012. Thresholds for storm impacts on an exposed sandy coastal area in southern Portugal. *Geomorphology* 143-144, 3-12. https://doi.org/10.1016/j.geomorph.2011.04.047

Álvarez, M., Machuca, F. (eds.), 2022. *Historical earthquakes, tsunamis and archaeology in the Iberian Peninsula*. Springer Nature, Singapore (in press).

Amarouche, K., Akpinar, A., Semedo, A., 2022. Wave storm events in the Western Mediterranean Sea over four decades. *Ocean Modelling* 170, 101933. https://doi.org/10.1016/j.ocemod.2021.101933

Anfuso, G., Rangel-Buitrago, N., Cortéz-Useche, C., Iglesias Castillo, B., Gracia, F.J., 2015. Characterization of storm events along the Gulf of Cadiz (eastern central Atlantic Ocean). *International Journal of Climatology* 36, 3690-3707. https://doi.org/10.1002/joc.4585

Anthony, E.J., Marriner, N., Morhange, C., 2014. Human influence and the changing geomorphology of Mediterranean deltas and coasts over the last 6000 years: From progradation to destruction phase? *Earth-Science Reviews* 139, 336-361. https://doi.org/10.1016/j.earscirev.2014.10.003

Antonioli, F., Ferranti, L., Lambeck, K., Kershaw, S., Verrubbi, V., Dai Pra, G., 2006. Late Pleistocene to Holocene record of changing uplift rates in southern Calabria and northeastern Sicily (southern Italy, Central Mediterranean Sea). *Tectonophysics* 422, 23-40. https://doi.org/10.1016/j.tecto.2006.05.003

Aranda, M., Gracia, F.J., Peralta, G. 2020. Estuarine mapping and eco-geomorphological characterization for potential application in conservation and management: three study cases along the Iberian coast. *Applied Sciences* 10(13), 4429. https://doi.org/10.3390/appp10134429

Asensio-Montesinos, F., Anfuso, G., Corbí, H. 2019. Coastal scenery and litter impact at Alicante (SE Spain): management issues. *Journal of Coastal Conservation* 23, 185-201. https://doi.org/10.1007/s11852-018-0651-8

Aucelli, P.P., Cinque, A., Mattei, G., Pappone, G., Rizzo, A., 2019. Studying relative sea level change and correlative adaptation of coastal structures on submerged Roman time ruins nearby Naples (southern Italy). *Quaternary International* 501, 328-348. https://doi.org/10.1016/j.quaint.2017.10.011

Bagdanaviciute, I., Kelpsaite-Rimkiene, L., Galiniene, J., Soomere, T., 2019. Index based multi-criteria approach to coastal risk assessment. *Journal of Coastal Conservation* 23, 785-800. https://doi.org/10.1007/s11852-018-0638-5

Barbano, M.S., Pirrotta, C., Gerardi, F., 2010. Large boulders along the south-eastern Ionian coast of Sicily: Storm or tsunami deposits? *Marine Geology* 275, 140-154, https://doi.org/10.1016/j.margeo.2010.05.005

Barragán, J.M., 2005. *La gestión de áreas litorales en España y Latinoamérica*. Servicio de Publicaciones de la Universidad de Cádiz, 198 p.

Barrantes-Castillo, G., Arozarena-Llopis, I., Sandoval-Murillo, L.F., Valverde-Calderón, J.F., 2020. Critical beaches due to coastal erosion in the Caribbean south of Costa Rica, during the period 2005-2016. *Revista Geográfica de América Central* 64(1), 123-150.

Bartolomé, C., Álvarez, J., Vaquero, J., Costa, M., Casermeiro, M.A., Giraldo, J., Zamora, J., Hidalgo, R., 2005. *Los tipos de hábitat de interés comunitario de España*. Ministerio de Medio Ambiente, Dirección General para la Biodiversidad, 283 p., Madrid.

Beckman, J.N., Long, J.W., Hawkes, A.D., Leonard, L.A., Ghoneim, E., 2021. Investigating controls on barrier island overwash and evolution during extreme storms. *Water* 13, 2829. https://doi.org/10.3390/w13202829

Benavente, J., Del Río, L., Plomaritis, T.A., Menapace, W., 2013. Impact of coastal storms in a sandy barrier (Sancti Petri, Spain). In: D.C. Conley, G. Masselink, P.E. Russell, T.J. O'Hare (eds.). Proc. 12th Intern. Coastal Symp., Plymouth, England, *Journal of Coastal Research*, Spec. Is. 65, 666-671.

Bennett, W.G., Karunarathna, H., Reeve, D.E., Mori, N., 2019. Computational modelling of morphodynamic response of a macro-tidal beach to future climate variabilities. *Marine Geology* 415, 105960. https://doi.org/10.1016/j.margeo.2019.105960

Best, Ü.S.N., Van der Wegen, M., Dijkstra, J., Willemsen, P.W.J.M., Borsje, B.W., Roelvink, D.J.A., 2018. Do salt marshes survive sea level rise? Modelling wave action, morphodynamics and vegetation dynamics. *Environmental Modelling and Software* 109, 152-166. https://doi.org/10.1016/j.envsoft.2018.08.004

Bird, E.C.F., 2010. *Encyclopedia of the world's coastal landforms*. Springer, Dordrecht, 1493 p. https://doi.org/10.1007/978-1-4020-8640-3

Bird, E., 2016. *Coastal cliffs: Morphology and management*. Springer, 91 p.

Blanco-Chao, R., Pérez-Alberti, A., Trenhaile, A.S., Costa-Casais, M., Valcárcel, M., 2007. Shore platform abrasion in a para-periglacial environment, Galicia, northwestern Spain. *Geomorphology* 83, 136-151. https://doi.org/10.1016/j.geomorph.2006.06.028

Boak, E.H., Turner, I.L., 2005. Shoreline definition and detection: A review. *Journal of Coastal Research* 21 (4), 688-703. https://doi.org/10.2112/03-0071.1

Booij, N., Ris, R.C., Holthuijsen, L.H., 1999. A third-generation wave model for coastal regions: 1. Model description and validation. *Journal of Geophysical Research* 104, 7649-7666. https://doi.org/10.1029/98JC02622

Brain, M.J., Kemp, A.C., Horton, B.P., Culver, S.J., Parnell, A.C., Cahill, N., 2015. Quantifying the contribution of sediment compaction to late Holocene salt-marsh sea-level reconstructions, North Carolina, USA. *Quaternary Research* 83, 41-51. https://doi.org/10.1016/j.yqres.2014.08.003

Brampton, A.H., 1998. Cliff conservation and protection: methods and practices to resolve conflicts. In J. Hooke (Ed.), *Coastal Defence and Earth Science Conservation*. The Geological Society, p. 21-31, London.

Brunetta, R., Paiva, J.S., Ciavola, P., 2019. Morphological evolution of an intertidal area following a set-back scheme: A case study from the Perkpolder Basin (Netherlands). *Frontiers in Earth Science* 7, art. 228. https://doi.org/10.3389/feart.2019.00228

Brunier, G., Anthony, E.J., Gratiot, N., Gardel, A., 2019. Exceptional rates and mechanisms of muddy shoreline retreat following mangrove removal. *Earth Surface Processes and Landforms* 44, 1559-1571. https://doi.org/10.1002/esp.4593

Bruun, P. 1962. Sea-level rise as a cause of shore erosion. Proceeding of the American Society of Civil Engineers. *Journal of the Waterways and Harbours Division* 88, 117-130.

Bryant, E., 2008. *Tsunami. The underrated hazard*. Springer, 330 p., Chichester.

Caporizzo, C., Gracia, F.J., Aucelli, P.P.C., Barbero, L., Martín-Puertas, C., Lagóstena, L., Ruiz, J.A., Alonso, C., Mattei, G., Galán-Ruffoni, I., López-Ramírez, J.A., Higueras-Milena, A., 2021. Late-Holocene evolution of the Northern Bay of Cádiz from geomorphological, stratigraphic and archaeological data. *Quaternary International* 602, 92-109. https://doi.org/10.1016/j.quaint.2021.03.028

Carpenter, N.E., Dickson, M.E., Walkden, M.J.A., Nicholls, R.J., Powrie, W., 2014. Effects of varied lithology on soft-cliff recession rates. *Marine Geology* 354, 40-52. https://doi.org/10.1016/j.margeo.2014.04.009

Carrasco, A.R., Ferreira, Ó., Roelvink, D., 2016. Coastal lagoons and rising sea level: A review. *Earth-Science Reviews* 154, 356-368. https://doi.org/10.1016/j.earscirev.2015.11.007

Carter, R.W.G., 1990. *Coastal environments. An introduction to the physical, ecological and cultural systems of coastlines*. Elsevier, 617 p.

Carter, R.W.G., Hesp, P.A., Nordstrom, K.F., 1990. Erosional landforms in coastal dunes. In K.F. Nordstrom, N.P. Psuty, R.W.G. Carter (eds.), *Coastal dunes: Form and process*. John Wiley & Sons, p. 217-249.

Casamayor, M., Alonso, I., Valiente, N.G., Sánchez-García, M.J., 2022. Seasonal response of a composite beach in relation to wave climate. *Geomorphology* 408, 108245. https://doi.org/10.1016/j.geomorph.2022.108245

Chee, C.L., Singh, A., Persad, R., Darsan, J., 2014. The influence of tidal currents on coastal erosion in a tropical micro-tidal environment – the case of Columbus Bay, Trinidad. *Global Journal of Science Frontier Research* (H) 14, 5.

Chen, Y., Li, Y., Thompson, C., Wang, X., Cai, T., Chang, Y., 2018. Differential sediment trapping abilities of mangrove and saltmarsh vegetation in a subtropical estuary. *Geomorphology* 318, 270-282. https://doi.org/10.1016/j.geomorph.2018.06.018

Ciavola, P., Collins, M. (Eds.), 2004. Sediment transport in European estuarine environments. *Journal of Coastal Research*, S.I. 41, 169 p.

Ciavola, P., Jiménez, J.A. 2013. The record of marine storminess along European coastlines. *Natural Hazards and Earth System Sciences* 13, 1999-2002. https://doi.org/10.5194/nhess-13-1999-2013

Cooper, J.A.G., Green, A.N., Loureiro, C., 2018. Geological constraints on mesoscale coastal barrier behaviour. *Global and Planetary Change* 168, 15-34. https://doi.org/10.1016/j.gloplacha.2018.06.006

Cooper, J.A.G., Pilkey, O.H., 2004. Sea-level rise and shoreline retreat: time to abandon the Bruun Rule. *Global and Planetary Change* 43, 157-171. https://doi.org/10.1016/j.gloplacha.2004.07.001.

Costa, P.J.M., Dawson, S., Ramalho, R.S., Engel, M., Dourado, F., Bosnic, I., Andrade, C., 2021. A review on onshore tsunami deposits along the Atlantic coasts. *Earth-Science Reviews* 212, 103441. https://doi.org/10.1016/j.earscirev.2020.103441

Costas, S., Sousa, L.B. de, Kombiadou, K., Ferreira, O., Plomaritis, T.A., 2020. Exploring foredune growth capacity in a coarse sandy beach. *Geomorphology* 371, 107435. https://doi.org/10.1016/j.geomorph.2020.107435

Cronin, T.M., 2012. Rapid sea-level rise. *Quaternary Science Reviews* 56, 11-30. https://doi.org/10.1016/j.quascirev.2012.08.021.

Crowell, M., Leatherman, S.P., Douglas, B., 2018. Erosion: Historical analysis and forecasting. In C.W. Finkl, C. Makowski (eds.), *Encyclopedia of Coastal Science*, Springer. https://doi.org/10.1007/978-3-319-48657-4_138-2

Dabrio, C.J., Zazo, C., Goy, J.L., Sierro, F.J., Borja, F., Lario, J., González, J.A., Flores, J.A., 2000. Depositional history of estuarine infill during the last postglacial transgression (Gulf of Cádiz, Southern Spain). *Marine Geology* 162, 381-404. https://doi.org/10.1016/S0025-3227(99)00069-9

Da Silva, A.P., Da Silva, G.V., Strauss, D., Murray, T., Woortmann, L.G., Taber, J., Cartwright, N., Tomlinson, R., 2021. Headland bypassing timescales: Processes and driving forces. *Science of the Total Environment* 793, 148591. https://doi.org/10.1016/j.scitotenv.2021.148591.

Davidson-Arnott, R. 2010. *An introduction to coastal processes and geomorphology*. Cambridge University Press, 442 p., Cambridge.

Dawson, A.G., Shi, S. 2000. Tsunami deposits. *Pure and Applied Geophysics* 157, 875-897. https://doi.org/10.1007/s000240050010

Day, J.W., Kemp, G.P., Reed, D.J., Cahoon, D.R., Boumans, R.M., Suhayda, J.M., Gambrell, R., 2011. Vegetation death and rapid loss of surface elevation in two contrasting Mississippi delta salt marshes: The role of sedimentation, autocompaction and sea-level rise. *Ecological Engineering* 37, 229-240. https://doi.org/10.1016/j.ecoleng.2010.11.021

Del Río, L., Gracia, F.J., 2009. Erosion risk assessment of active coastal cliffs in temperate environments. *Geomorphology* 112, 82-95. https://doi.org/10.1016/j.geomorph.2009.05.009

Del Río, L., Gracia, F.J., 2013. Error determination in the photogrammetric assessment of shoreline changes. *Natural Hazards* 65, 2385-2397. https://doi.org/10.1007/s11069-012-0407-y

Del Río, L., Plomaritis, T.A., Benavente, J., Valladares, M., Ribera, P., 2012. Establishing storm thresholds for the Spanish Gulf of Cádiz coast. *Geomorphology* 143-144, 13-23 https://doi.org/10.1016/j.geomorph.2011.04.048

Del Río, L., Posanski, D., Gracia, F.J., Pérez-Romero, A.M., 2020. A comparative approach of monitoring techniques to assess erosion processes on soft cliffs. *Bulletin of Engineering Geology and the Environment* 79, 1797-1814. https://doi.org/10.1007/s10064-019-01680-2

De Pippo, T., Donadio, C., Mazzarella, A., Paolillo, G., Pennetta, M., 2004. Fractal geometry applied to coastal and submarine features. *Zeitschrift für Geomorphologie N.F.* 48(2), 185-199. https://doi.org/10.1127/zfg/48/2004/185

Dey, N., Shukla, P., 2019. Effects of tidal range on the Digha coast: A geomorphological investigation. *Indian Journal of Spatial Science* 10, 79-86.

Dissanayake, P., Brown, J., Wisse, P., Karunarathna, H., 2015. Effects of storm clustering on beach/dune evolution. *Marine Geology* 370, 63-75, https://doi.org/10.1016/j.margeo.2015.10.010

Donadio, C. 2017. Experimenting criteria for risk mitigation in fluvial-coastal environment. *Journal of City, Safety, Energy* 1, 9-14.

Elko, N., Feddersen, F., Foster, D., Hapke, C., McNinch, J., Mulligan, R., Özkan-Haller, H.T., Plant, N., Raubenheimer, B., 2015. The future of nearshore processes research. *Shore & Beach* 83(1), 13-38.

Emery, K.O., Kuhn, G.G., 1982. Sea cliffs: their processes, profiles and classification. *Geological Society of America Bulletin* 93 (7), 644-654.

Estrada, F., González-Vida, J.M., Peláez, J.A., Galindo-Zaldívar, J., Ortega, S., Macías, J., Vázquez, J.T., Ercilla, G., 2021. Tsunami generation potential of a strike-slip fault tip in the westernmost Mediterranean. *Scientific Reports* 11, 16253. https://doi.org/10.1038/s41598-021-95729-6

EUROSION, 2004. *Living with coastal erosion in Europe: Sediment and space for sustainability: PART I – Major findings and policy recommendations of the EUROSION project*. European Commission, Directorate General Environment, 57 p., Brussels

Evans, B.R., Brooks, H., Chirol, C., Kirkham, M.K., Möller, I., Royse, K., Spencer, K., Spencer, T., 2022. Vegetation interactions with geotechnical properties and erodibility of salt marsh sediments. *Estuarine, Coastal and Shelf Science* 265, 107713. https://doi.org/10.1016/j.ecss.2021.107713

Evelpidou, N., Kampolis, I., Pirazzoli, P.A., Vassilopoulos, A., 2012. Global sea-level rise and the disappearance of tidal notches. *Global and Planetary Change* 92-93, 248-256. https://doi.org/10.1016/j.gloplacha.2012.05.013.

Fairbridge, R. W., 1983. Isostacy and eustasy. In D.E. Smith, A.G. Dawson (eds.), *Shorelines and Isostacy*. Institute of British Geographers Special Publication 16, Academic, p. 3-25, London.

Fairbridge, R.W., 2004. Classification of coasts. *Journal of Coastal Research* 20, 155-165.

Fairley, I., Thomas, T., Phillips, M., Reeve, D., 2016. Terrestrial laser scanner techniques for enhancement in understanding of coastal environments. In C.W. Finkl, C. Makowski (eds.), *Seafloor mapping along continental shelves*. Coastal Research Library v.13, Springer, pp. 273-289. https://doi.org/10.1007/978-3-319-25121-9_11

Fernández-Montblanc, T., Del Río, L., Izquierdo, A., Gracia, F.J., Bethencourt, M., Benavente, J., 2018. Shipwrecks and man-made coastal structures as indicators of historical shoreline position. An interdisciplinary study in the Sancti Petri sand spit (Bay of Cádiz, SW Spain). *Marine Geology* 395, 152-167. https://doi.org/10.1016/j.margeo.2017.10.005

Fernández-Núñez, M., Burningham, H., Díaz-Cuevas, P., Ojeda-Zújar, J. 2019. Evaluating the response of Mediterranean-Atlantic saltmarshes to sea-level rise. *Resources* 8, 50. https://doi.org/10.3390/resources8010050

Ferreira, Ó. 2006. The role of storm groups in the erosion of sandy coasts. *Earth Surface Processes and Landforms* 31, 1058-1060. https://doi.org/10.1002/esp.1378

Fortunato, A.B., Freire, P., Mengual, B., Bertin, X., Pinto, C., Martins, K., Guérin, T., Azevedo, A., 2021. Sediment dynamics and morphological evolution in the Tagus Estuary inlet. *Marine Geology* 440, 106590. https://doi.org/10.1016/j.margeo.2021.106590

Flor, G., 2007. La geología en los deslindes de la Ley de Costas. Algunas recomendaciones y ejemplos orientativos. *Tierra y Tecnología* 31, 9-18.

Flor, G., Flor-Blanco, G., 2014. Raised beaches in the Cantabrian Coast. In F. Gutiérrez, M. Gutiérrez (eds.). *Landscapes and Landforms of Spain*. Springer, p. 239-248, https://doi.org/10.1007/978-94-017-8628-7_20

Flor-Blanco, G., Rubio-Melendi, D., Flor, G., Fernández-Álvarez, J.P., Jackson, D.W.T., 2016. Holocene evolution of the Xagó dune field (Asturias, NW Spain) reconstructed by means of morphological mapping and ground penetrating radar surveys. *Geo-Marine Letters* 36, 35-50. https://doi.org/10.1007/s00367-015-0427-1

Flor-Blanco, G., Alcántara-Carrió, J., Jackson, D.W.T., Flor, G., Flores-Soriano, C., 2021. Coastal erosion in NW Spain: Recent patterns under extreme storm wave events. *Geomorphology* 387, 107767. https://doi.org/10.1016/j.geomorph.2021.107767

Fraile, P., Álvarez-Francoso, J., Ojeda-Zújar, J., 2018. Cartografía de la probabilidad de inundación del litoral andaluz a finales del siglo XXI ante la subida del nivel del mar. *Cuadernos Geográficos* 57(2), 6-26. https://doi.org/10.30827/cuadgeo.v57i2.5899

French, J., Payo, A., Murray, B., Orford, J., Eliot, M., Cowell, P., 2016. Appropriate complexity for the prediction of coastal and estuarine geomorphic behaviour at decadal to centennial scales. *Geomorphology* 256, 3-16. https://doi.org/10.1016/j.geomorph.2015.10.005

Gangaiya, P., Beardsmore, A., Miskiewicz, T., 2017. Morphological changes following vegetation removal and foredune re-profiling at Woonona Beach, New South Wales, Australia. *Ocean & Coastal Management* 146, 15-25. https://doi.org/10.1016/j.ocecoaman.2017.05.015

García de Lomas, J., Gracia, F.J., García, C. 2011. Las dunas como hábitats de interés comunitario. Problemas de conservación. In *Las dunas en España* (E. Sanjaume, F.J. Gracia, eds.), S.E.G., p. 585-606.

Ghosh, A., 2019. Monitoring estuarine morphodynamics through quantitative techniques and GIS: A case study in Sagar Island, India. *Journal of Coastal Conservation* 23, 133-148. https://doi.org/10.1007/s11852-018-0643-8

Goff, J., Chagué-Goff, C., Nichol, S., Jaffe, B., Dominey-Howes, D. 2012. Progress in palaeotsunami research. *Sedimentary Geology* 243-244, 70-88. https://doi.org/10.1016/j.sedgeo.2011.11.002

Gómez, J.F., Kwoll, E., Walker, I.J, Shirzaei, M., 2021. Vertical land motion as a driver of coastline changes on a deltaic system in the Colombian Caribbean. *Geosciences* 11, 300. https://doi.org/10.3390/geosciences11070300

Gómez-Pujol, L., Cruslock, E., Fornós, J.J., Swantesson, J.O.H., 2006. Unravelling factors that control shore platforms and cliffs in microtidal coasts: the case of Mallorcan, Catalonian and Swedish coasts. *Zeitschrift für Geomorphologie* SupplBd 144, 117-135.

Gonçalves, G.R., Pérez, J.A., Duarte, J., 2018. Accuracy and effectiveness of low cost UASs and open source photogrammetric software for foredune mapping. *International Journal of Remote Sensing* 39, 5059-5077. https://doi.org/10.1080/01431161.2018.1446568

Goto, K., Miyagi, K., Kawamata, H., Imamura, F., 2010. Discrimination of boulders deposited by tsunamis and storm waves at Ishigaki Island, Japan. *Marine Geology* 269, 34-45. https://doi.org/10.1016/j.margeo.2009.12.004

Gracia, F.J., 2008. Costas bajas de la península Ibérica. In A. García-Cortés, J. Águeda, J. Palacio, C.I. Salvador (eds.). *Contextos Geológicos Españoles. Una aproximación al patrimonio geológico español de relevancia internacional*. Instituto Geológico y Minero de España, p. 192-199, Madrid.

Gracia, F.J., Alonso, C., Abarca, J.M., 2017. Evolución histórica y geomorfología de las explotaciones salineras en marismas mareales. Ejemplos de la bahía de Cádiz. *Cuaternario y Geomorfología* 31 (1-2), 45-72. https://doi.org/10.17735/cyg.v31i1-2.54681

Gracia, F.J., Anfuso, G., Benavente, J., Del Río, L., Domínguez, L., Martínez, J.A., 2005. Monitoring coastal erosion at diferente temporal scales on Sandy beaches: application to the Spanish Gulf of Cádiz coast. *Journal of Coastal Research* S.I. 49, 22-27.

Gracia, F.J., Alonso, C., Benavente, J., Anfuso, G., Del Río, L., 2006. The different coastal records of the 1755 tsunami waves along the South Atlantic Spanish coast. *Zeitschrift für Geomorphologie* SupplBd. 146, 195-220. https://doi.org/0044-2798/06/0146-0195.

Granger, P., Kalaugher, P.G., 1987. Intermittent surging movements of a coastal landslide. *Earth Surface Processes and Landforms* 12, 597-603. https://doi.org/10.1002/esp.3290120603

Grottoli, E., Biausque, M., Rogers, D., Jackson, D.W.T., Cooper, J.A.G., 2021. Structure-from-Motion-derived digital surface models from historical aerial photographs: A new 3D application for coastal dune monitoring. *Remote Sensing* 13, 95. https://doi.org/10.3390/rs13010095

Guisado-Pintado, E., Jackson, D.W.T., 2019. Coastal impact from high-energy events and the importance of concurrent forcing parameters: The cases of Storm Ophelia (2017) and Storm Hector (2018) in NW Ireland. *Frontiers in Earth Science* 7, 190. https://doi.org/10.3389/feart.2019.00190

Hansen, J.M., Aagaard, T., Binderup, M., 2011. Absolute sea levels and isostatic changes of the eastern North Sea to central Baltic region during the last 900 years. *Boreas* 41, 180-208. https://doi.org/10.1111/j.1502-3885.2011.00229.x

Hapke, C.J., Kratzmann, M.G., Himmelstross, E.A., 2013. Geomorphic and human influence on large-scale coastal change. *Geomorphology* 199, 160-170. https://doi.org/10.1016/j.geomorph.2012.11.025

Haynes, T.A., Angus, S., Scanlan, C., Bhatti, N., 2017. Developing a saltmarsh monitoring methodology to meet multiple policy and management objectives in Scotland. *Journal of Coastal Conservation* 21, 445-452. https://doi.org/10.1007/s11852-017-0512-x

Héquette, A., Cartier, A., Schmitt, F.G. 2021. The effects of tidal translation on wave and current dynamics on a barred macrotidal beach, northern France. *Journal of Marine Science and Engineering* 9, 909. https://doi.org/10.3390/jmse9080909

Hesp, P.A., 2013. Conceptual models of the evolution of transgressive dune field systems. *Geomorphology* 199, 138-149. https://doi.org/10.1016/j.geomorph.2013.05.014

Hofstede, J.L.A., Becherer, J., Burchard, H., 2018. Are Wadden Sea tidal systems with a higher tidal range more resilient against sea level rise? *Journal of Coastal Conservation* 22, 71-78. https://doi.org/10.1007/s11852-016-0469-1

Hooke, J. (Ed.), 1998. *Coastal defence and Earth Science conservation*. The Geological Society, Bath, 270 p.

Houser, C., Wernette, P., Weymer, B.A., 2018. Scale-dependent behaviour of the foredune: Implications for barrier island response to storms and sea-level rise. *Geomorphology* 303, 362-374. https://doi.org/10.1016/j.geomorph.2017.12.011

Houston, J.A., Edmondson, S.E., Rooney, P.J. (eds.), 2001. *Coastal dune management. Shared experience of European conservation practice*. Liverpool University Press, 458 p.

Huggett, R.J., 2011. *Fundamentals of Geomorphology*, Third edition. Routledge, 516 p., London.

Ikehara, K., Usami, K., Irino, T., Omura, A., Jenkins, R.G., Ashi, J., 2021. Characteristics and distribution of the event deposits induced by the 2011 Tohoku-oki earthquake and tsunami offshore of Sanriku and Sendai, Japan. *Sedimentary Geology* 411, 105791. https://doi.org/10.1016/j.sedgeo.2020.105791

IPCC. 2013. *Climate change 2013. The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Izquierdo, T., Abad, M., Rodríguez-Vidal, J., Ruiz, F., González-Regalado, M.L., 2019. Análisis de la vulnerabilidad de las poblaciones costeras de la provincia de Huelva (suroeste de España) ante tsunamis. *Revista de la Sociedad Geológica de España* 32 (1), 25-42.

Jackson, N.L., Nordstrom, K.F., 2020. Trends in research on beaches and dunes on sandy shores, 1969-2019. *Geomorphology* 366, 106737. https://doi.org/10.1016/j.geomorph.2019.04.009

Jankowski, K. L., Törnqvist, T. E., Fernandes, A. M., 2017. Vulnerability of Louisiana's coastal wetlands to present-day rates of relative sea-level rise. *Nature Communications* 8, 14792. https://doi.org/10.1038/ncomms14792

Jenks, G.K., 2018. Restoring the natural functional capacity of coastal dune ecosystems: Utilising research records for New Zealand littoral refurbishment as a proxy for analogous global responses *Journal of Coastal Conservation* 22, 623-665. https://doi.org/10.1007/s11852-018-0598-9

Jevrejeva, S., Moore, J.C., Grinsted, A., Matthews, A.P., Spada, G., 2014. Trends and acceleration in global and regional sea levels since 1807. Global and Planetary Change, 113, 11-22. https://doi.org/10.1016/j.gloplacha.2013.12.004

Jiménez, J.A., Sallenger, A.H., Fauver, L., 2007. Sediment transport and barrier island changes during massive overwash events. *30th Intern. Conference on Coastal Engineering ICCE 2006*, 2870-2879. https://doi.org/10.1142/9789812709554_0242

Kelsey, H.M. 2015. Geomorphological indicators of past sea levels. In I. Shennan, A.J. Long, B.P. Horton (eds.). *Handbook of sea-level research*. John Wiley & Sons, p. 66-82.

Kemp, A.C., Horton, B.P., Donnelly, J.P., Mann, M.E., Vermeer, M., Rahmstorf, S., 2011. Climate related sea-level variations over the past two millennia. *PNAS* 108 (27), 11017-11022. https://doi.org/10.1073/pnas.1015619108

King, C.A.M., 1951. Depth of disturbance of san don sea beaches by waves. *Journal of Sedimentary Petrology* 21(3), 131-140.

Kombiadou, K., Matias, A., Ferreira, Ó., Carrasco, A.R., Costas, S., Plomaritis, T., 2019. Impacts of human interventions on the evolution of the Ria Formosa barrier island system (S. Portugal). *Geomorphology* 343, 129-144. https://doi.org/10.1016/j.geomorph.2019.07.006

Konlechner, T.M., Kennedy, D.M., Cousens, R.D., Woods, J.L.D., 2019. Patterns of early-colonising species on eroding to prograding coasts; implications for foredune plant communities on retreating coastlines. *Geomorphology* 327, 404-416. https://doi.org/10.1016/j.geomorph.2018.11.013

Kraus, N.C., 1999. Analytical model of spit evolution and inlets. *Proceedings of Coastal Sediments'99*, ASCE, p. 1739-1754.

Krelling, A.P., Williams, A.T., Turra, A., 2017. Differences in perception and reaction of tourist groups to beach marine debris that can influence a loss of tourism revenue in coastal areas. *Marine Policy* 85, 87-99. https://doi.org/10.1016/j.marpol.2017.08.021

Labuz, T., 2016. A review of field methods to survey coastal dunes – experience based on research from South Baltic coast. *Journal of Coastal Conservation* 20, 175-190. https://doi.org/10.1007/s11852-016-0428-x

Lario, J., Zazo, C., Goy, J.L., Silva, P.G., Bardají, T., Cabero, A., Dabrio, C.J., 2011. Holocene palaeotsunami catalogue of SW Iberia. *Quaternary International* 242, 196-200. https://doi.org/10.1016/j.quaint.2011.01.036

Lavigne, F., Paris, R., Grancher, D., Wassmer, P., Brunstein, D., Vautier, F., Leone, F., Flohic, F., De Coster, B., Gunawan, T., Gomez, C., Setiawan, A., Cahyadi, R., Fachrizal, F., 2009. Reconstruction of tsunami inland propagation on December 26, 2004 in Banda Aceh, Indonesia, through field investigations. *Pure and Applied Geophysics* 166, 259-281. https://doi.org/10.1007/s00024-008-0431-8

Lee, E.M., 2008. Coastal cliff behaviour: Observations on the relationship between beach levels and recession rates. *Geomorphology* 101, 558-571. https://doi.org/10.1016/j.geomorph.2008.02.010

Ley, C., Gallego, J.B., Vidal, C., 2007. *Manual de restauración de dunas costeras*. Dirección General de Costas, Ministerio de Medio Ambiente, 252 p., Santander.

Li, S.H., Ge, Z.M., Xin, P., Tan, L.S., Li, Y.L., Xie, L.N., 2021. Interactions between biotic and abiotic processes determine biogeomorphology in Yangtze Estuary coastal marshes: Observation with a modelling approach. *Geomorphology* 395, 107970. https://doi.org/10.1016/j.geomorph.2021.107970.

Limber, P.W., Murray, A.B., 2011. Beach and sea-cliff dynamics as a driver of long-term rocky coastline evolution and stability. *Geology* 39(12), 1147-1150. https://doi.org/10.1130/G32315.1

Lira, C.P., Silva, A.N., Taborda, R., Andrade, C.F., 2016. Coastline evolution of Portuguese low-lying sandy coast in the last 50 years: an integrated approach. *Earth System Science Data* 8, 265-278. https://doi.org/10.5194/essd-8-265-2016

López, M., Baeza-Brotons, F., López, I., Tenza-Abril, A.J., Aragonés, L., 2019. Factors influencing the rate of beach sand wear: Activation layer thickness and sediment durability. *Science of the Total Environment* 658, 367-373. https://doi.org/10.1016/j.scitotenv.2018.12.211

López-Fernández, C., Llana-Fúnez, S., Fernández-Viejo, G., Domínguez-Cuesta, M.J., Díaz-Díaz, L.M., 2020. Comprehensive characterization of elevated coastal platforms in the north Iberian margin: A new template to quantify uplift rates and tectonic patterns. *Geomorphology* 364, 107242. https://doi.org/10.1016/j.geomorph.2020.107242

López-García, P., Gómez-Enri, J., Muñoz-Pérez, J.J., 2019. Accuracy assessment of wave data from altimeter near the coast. *Ocean Engineering* 178, 229-232. https://doi.org/10.1016/j.oceaneng.2019.03.009

Losada, M., Baquerizo, A., Santiago, J.M., Ávila, A., Moreno, I., Ortega-Sánchez, M., 2008. Sea level variability and coastal evolution. *Proceedings 31th International Conference on Coastal Engineering* (ICCE), vol. 3, 2077-2085. https://doi.org/10.1142/9789814277426_0171

Luijendijk, A., Hagenaars, G., Ranasinghe, R., Baart, F., Donchyts, G., Aarninkhof, S., 2018. The state of the world's beaches. *Scientific Reports* 8, 6641. https://doi.org/10.1038/s41598-018-24630-6

Malvarez, G., Ferreira, O., Navas, F., Cooper, J.A.G., Gracia-Prieto, F.J., Talavera, L., 2021. Storm impacts on a coupled human-natural coastal system: Resilience of developed coasts. *Science of the Total Environment* 768, 144987. https://doi.org/10.1016/j.scitotenv.2021.144987.

Mancini, F., Dubbini, M., Gattelli, M., Stecchi, F., Fabbri, S., Gabbianelli, G. 2013. Using Unmanned Aerial Vehicles (UAV) for high-resolution reconstruction of topography: the structure from motion approach on coastal environments. *Remote Sensing* 5, 6880-6898. https://doi.org/10.3390/rs5126880

Manno, G., Anfuso, G., Messina, E., Williams, A.T., Suffo, M., Liguori, V., 2016. Decadal evolution of coastline armouring along the Mediterranean Andalusia littoral (South of Spain). *Ocean & Coastal Management* 124, 84-99. https://doi.org/10.1016/j.ocecoaman.2016.02.007.

Marcos, M., Puyol, B., Wöppelmann, G., Herrero, C., García-Fernández, M.J., 2003. The long sea level record at Cadiz (southern Spain) from 1880 to 2009. *Journal of Geophysical Research* 116. https://doi.org/10.1029/2011JC007558

Marriner, N., Morhange, C., Faivre, S., Flaux, C., Vacchi, M., Miko, S., Dumas, V., Boetto, G., Rossi, I.R. 2014. Post-Roman sea-level changes on Pag Island (Adriatic Sea): Dating Croatia's "enigmatic" coastal notch? *Geomorphology* 221, 83-94. https://doi.org/10.1016/j.geomorph.2014.06.002

Martínez-Graña, A.M., Boski, T., Goy, J.L., Zazo, C., Dabrio, C.J. 2016. Coastal-flood risk management in central Algarve: Vulnerability and flood risk índices (South Portugal). *Ecological Indicators* 71, 302-316. https://doi.org/10.1016/j.ecolind.2016.07.021

Martínez-Loriente, S., Sallarès, V., Gràcia, E., 2021. The Horseshoe Abyssal plain Thrust could be the source of the 1755 Lisbon earthquake and tsunami. *Communications Earth & Environment* 2, 145. https://doi.org/10.1038/s43247-021-00216-5

Mas-Pla, J., Zuppi, G.M. (eds.), 2009. *Gestión ambiental integrada de áreas costeras*. Rubes Editorial, 284 p., Barcelona

Masselink, G., Castelle, B., Scott, T., Dodet, G., Suanez, S., Jackson, D., Floc'h, F., 2016. Extreme wave activity during 2013/2014 winter and morphological impacts along the Atlantic coast of Europe. *Geophysical Research Letters* 43, 2135-2143. https://doi.org/10.1002/2015GL067492

Mattei, G., Rizzo, A., Anfuso, G., Aucelli, P.P.C., Gracia, F.J., 2019. A tool for evaluating the archaeological heritage vulnerability to coastal processes: The case study of Naples Gulf. *Journal of Coastal Conservation* 179, 104876. https://doi.org/10.1016/j.ocecoaman.2019.104876

McLachlan, R.L., Ogston, A.S., Asp, N.E., Fricke, A.T., Nittrouer, C.A., Schettini, A.F., 2020. Morphological evolution of a macrotidal back-barrier environment: The Amazon Coast. *Sedimentology* 67, 3492-3512. https://doi.org/10.1111/sed.12752

Mitri, G., Nader, M., Dagher, M.A., Gebrael, K., 2020. Investigating the performance of Sentinel-2A and Landsat 8 imagery in mapping shoreline changes. *Journal of Coastal Conservation* 24, 40. https://doi.org/10.1007/s11852-020-00758-4

Molina, R., Manno, G., Lo Re, C., Anfuso, G., Ciraolo, G., 2019. Storm energy flux characterization along the Mediterranean coast of Andalusia (Spain). *Water* 11, 509. https://doi.org/10.3390/w11030509.

Montoya, I., Rodríguez, I., Sánchez, M.J., Alcántara-Carrió, J., Martín, S., Gómez-Ortiz, D., Martín-Crespo, T., 2012. Mapping of landslide susceptibility of coastal cliffs: the Mont-Roig del Camp case study. *Geologica Acta* 10(4), 439-455. https://doi.org/10.1344/105.000001776

Mooser, A., Anfuso, G., 2018. *Playas y paisaje*. Editorial UCA, 301 p., Cádiz.

Morales, J.A., 2022. *Coastal geology*. Springer Nature, 463 p., https://doi.org/10.1007/978-3-030-96121-3

Morales, J.A., Gutiérrez Mas, J.M., Borrego, J., Rodríguez-Ramírez, A., 2011. Sedimentary characteristics of the Holocene tsunamigenic deposits in the coastal systems of the Cádiz Gulf (Spain). In *The tsunami threat–Research and technology* (N.A. Mörner, Ed.), InTech, Rijeka, Croatia, 237-258.

Morhange, C., Marriner, N., Laborel, J., Todesco, M., Oberlin, C., 2006. Rapid sea-level movements and noneruptive crustal deformations in the Phlegrean Fields caldera, Italy. *Geology* 34, 93-96. https://doi.org/10.1130/G21894.1

Morhange, C., Pirazzoli, P.A., Evelpidou, N., Marriner, N., 2012. Late Holocene tectonic uplift and the silting up of Lechaion, the Western harbour of Ancient Corinth, Greece. *Geoarchaeology* 27, 278-283. https://doi.org/10.1002/geo.21388

Mörner, N.A., 2019. Development of ideas and new trends in modern sea level research: The Pre-Quaternary, Quaternary, Present and Future. In M. Ramkumar, R.A. James, D. Menier, K. Kumaraswamy (eds.). *Coastal Zone Management Coastal Zone Management – Global perspectives, regional processes, local issues*. Elsevier, 15-61, https://doi.org/10.1016/B978-0-12-814350-6.00002-1

Moura, D., Gabriel, S., Ramos-Pereira, A., Neves, M., Trindade, J., Viegas, J., Veiga-Pires, C., Ferreira, Ó., Matias, A., Jacob, J., Boski, T., Santana, P., 2011. Downwearing rates on shore platforms of different calcareous lithotypes. *Marine Geology* 286, 112-116. https://doi.org/10.1016/j.margeo.2011.06.002

Nagle-McNaughton, T., Cox, R., 2020. Measuring change using quantitative differencing of repeat Structure-From-Motion photogrammetry: the effect of storms on coastal boulder deposits. *Remote Sensing* 12, 42. https://doi.org/10.3390/rs12010042

Navarro, M., Muñoz-Pérez, J.J., Román-Sierra, J., Ruiz-Cañavate, A., Gómez-Pina, G., 2015. Characterization of wind-blown sediment transport with height in a highly mobile dune (SW Spain). *Geologica Acta* 13, 155-166. https://doi.org/10.1344/GeologicaActa2015.13.2.6

Neumann, B., Vafeidis, A.T., Zimmermann, J., Nicholls, R.J., 2015. Future coastal population growth and exposure to sea-level rise and coastal flooding - a global assessment. *PLoS ONE* 10(3), e0118571. https://doi.org/10.1371/journal.pone.0118571

Neves, M., 2008. Anthropogenic modifications in the erosional rhythm of a coastal cliff. Rocha do Gronho (western coast of Portugal). *Journal of Iberian Geology* 34, 299-312.

Nordstrom, K.F., 2019. Coastal dunes with resistant cores. *Journal of Coastal Conservation* 23, 227-237. https://doi.org/10.1007/s11852-018-0653-6

Nunn, P.D., Creach, A., Gehrels, W.R., Bradley, S.L., Armit, I., Stéphan, P., Sturt, F., Baltzer, A., 2021. Observations of postglacial sea-level rise in northwest European traditions. *Geoarchaeology* (in press). https://doi.org/10.1002/gea.21898

Oliveros, F., Barragán, J.M., Chica, J.A., Pérez Cayeiro, M.L., 2008. *Propuesta de Estrategia Andaluza de Gestión Integrada de Zonas Costeras*. Consejería de Medio Ambiente, Junta de Andalucía, 256 p., Cádiz.

Orombelli, G., Pranzini, E., 2020. Considerations on coastal protection and management. *Rendiconti Lincei. Scienze Fisiche e Naturali* 31, 365-368. https://doi.org/10.1007/s12210-020-00912-y

Orrù, P.E., Mastronuzzi, G., Deiana, G., Pignatelli, C., Piscitelli, A., Solinas, E., Spanu, P.G., Zucca, R., 2014. Sea level changes and geoarchaeology between the bay of Capo Malfatano and Piscinnì Bay (SW Sardinia) in the last 4 kys. *Quaternary International* 336, 180-189. https://doi.org/10.1016/j.quaint.2014.03.054

Otvos, E.G., 2000. Beach ridges – definitions and significance. *Geomorphology* 32, 83-108. https://doi.org/10.1016/S0169-555X(99)00075-6

Paris, P.J., Mitasova, H., 2018. Geospatial contrasts between natural and human-altered barrier island systems: Core Banks and Ocracoke Island, North Carolina, U.S.A. *Journal of Coastal Conservation* 22, 679-694. https://doi.org/10.1007/s11852-018-0601-5

Payo, A., Hall, J.W., French, J., Sutherland, J., Van Maanen, B., Nicholls, R.J., Reeve, D.E., 2016. Causal Loop Analysis of coastal geomorphological systems. *Geomorphology* 256, 36-48. https://doi.org/10.1016/j.geomorph.2015.07.048.

Peña-Alonso, C., Gallego-Fernández, J.B., Hernández-Calvento, L., Hernández-Cordero, A.I., Ariza, E., 2018. Assessing the geomorphological vulnerability of arid beach-dune systems. *Science of the Total Environment* 635, 512-525. https://doi.org/10.1016/j.scitotenv.2018.04.095

Pérez-Alberti, A., Trenhaile, A.S., 2015. An initial evaluation of drone-based monitoring of boulder beaches in Galicia, north-western Spain. *Earth Surface Processes and Landforms* 40, 105-111. https://doi.org/10.1002/esp.3654

Pérez-Hernández, E., Ferrer-Valero, N., Hernández-Calvento, L., 2020. Lost and preserved coastal landforms after urban growth. The case of Las Palmas de Gran Canaria city (Canary Islands, Spain). *Journal of Coastal Conservation* 24(3), 26. https://doi.org/10.1007/s11852-020-00743-x

Peterson, C.H., Bishop, M.J., 2005. Assessing the environmental impacts of beach nourishment. *BioScience* 55, 887-896. https://doi.org/10.1641/0006-3568(2005)055[0887:ATEIOB]2.0.CO;2

Pilkey, O.H., 2003. *Barrier Islands*. Columbia University Press, 309 p., New York.

Pilkey, O.H., Neal, W.J., Kelley, J.T., Cooper, J.A.G., 2011. *The world's beaches*. University of California Press, 283 p., Berkeley.

Pierik, H.J., Cohen, K.M., Stouthamer, E., 2016. A new GIS approach for reconstructing and mapping dynamic late Holocene coastal plain palaeogeography. *Geomorphology* 270, 55-70. https://doi.org/10.1016/j.geomorph.2016.05.037

Plomaritis, T.A., Benavente, J., Del Río, L., Reyes, E., Dastis, C., Gómez, M., Bruno, M., 2012. Storm early warning system as a last plug-in of a regional operational oceanography system: the case of the Gulf of Cádiz. *Coastal Engineering Proceedings* 33. https://doi.org/10.9753/icce.v33.management.54

Pourkerman, M., Marriner, N., Morhange, C., Djamali, M., Amjadi, S., Lahijani, H., Beni, A.N., Vacchi, M., Tofighian, H., Shah-Hoesseini, M., 2018. Tracking shoreline eorison of "at risk" coastal archaeology: the example of ancient Siraf (Iran, Persian Gulf). *Applied Geography* 101, 45-55. https://doi.org/10.1016/j.apgeog.2018.10.008

Puertas, E., Aparicio, J.A. (eds.), 2020. *Turismo azul y seguro. Fundamentos para la gestión de los riesgos costeros*. Círculo Rojo, 132 p., Almería.

Quevauviller, P., Ciavola, P., Garnier, E., 2017. *Management of the effects of coastal storms*. Wiley, 172 p.

Rahman, R., Plater, A.J., 2014. Particle-size evidence of estuary evolution: A rapid and diagnostic tool for determining the nature of recent saltmarsh accretion. *Geomorphology* 213, 139-152. https://doi.org/10.1016/j.geomorph.2014.01.004

Randazzo, G., Jackson, D.W.T., Cooper, J.A.G. (Eds.). 2015. *Sand and gravel spits*. Springer Coastal Research Library 12, 344 p., https://doi.org/10.1007/978-3-319-13716-2

Rangel-Buitrago, N., Neal, W.J., De Jonge, V.N., 2020. Risk assessment as tool for coastal erosion management. *Ocean and Coastal Management* 186, 105099. https://doi.org/10.1016/j.ocecoaman.2020.105099

Reed, D., Van Wesenbeeck, B.V., Herman, P.M.J., Meselhe, E., 2018. Tidal flat-wetland systems as flood defences: Understanding biogeomorphic controls. *Estuarine, Coastal and Shelf Science* 213, 269-282. https://doi.org/10.1016/j.ecss.2018.08.017

Reeve, D.E., Horrillo-Caraballo, J., Karunarathna, H., Pan, S., 2019. A new perspective on meso-scale shoreline dynamics through data-driven analysis. *Geomorphology* 341, 169-191. https://doi.org/10.1016/j.geomorph.2019.04.033

Ribera, P., Gallego, D., Pena-Ortiz, C., Del Río, L., Plomaritis, T.A., Benavente, J. 2011, Reconstruction of Atlantic historical winter coastal storms in the Spanish coasts of the Gulf of Cádiz, 1929-2005. *Natural Hazards and Earth System Sciences* 11, 1715-1722. https://doi.org/10.5194/nhess-11-1715-2011

Ris, R.C., Holthuijsen, L.H., Booij, N., 1999. A third-generation wave model for coastal regions: 2. Verification. *Journal of Geophysical Research* 104-C4, 7667-7681. https://doi.org/10.1029/1998JC900123

Rodríguez-Perea, A., Pons, G.X., Roig-Munar, F.X., Martín-Prieto, J.A., Mir-Gual, M., Cabrera, J.A. (Eds.) 2013. *La gestión integrada de playas y dunas: experiencias en Latinoamérica y Europa*. Monografías de la Sociedad de Historia Natural de Baleares, 19, 401 p.

Rodríguez-Polo, S., Gracia, F.J., Benavente, J., Del Río, L., 2009. Geometry and recent evolution of the Holocene beach ridges of the Valdelagrana littoral spit (Cádiz Bay, SW Spain). *Journal of Coastal Research* S.I. 56, 20-23.

Rodríguez-Ramírez, A., Morales, J.A., Delgado, I., Cantano, M., 2008. The impact of man on the morphodynamics of the Huelva coast (SW Spain). *Journal of Iberian Geology* 34(2), 313-327.

Rodríguez-Ramírez, A., Yáñez-Camacho, C.M. 2008. Formation of chenier plain of the Doñana marshland (SW Spain): Observations and geomorphic model. *Marine Geology* 254, 187-196. https://doi.org/10.1016/j.margeo.2008.06.006

Rodríguez-Rosales, B., Abreu, D., Ortiz, R., Becerra, J., Cepero-Acán, A.E., Vázquez, M.A., Ortiz, P., 2021. Risk and vulnerability assessment in coastal environments applied to heritage buildings in Havana (Cuba) and Cádiz (Spain). *Science of the Total Environment* 750, 141617. https://doi.org/10.1016/j.scitotenv.2020.141617

Rodríguez-Vidal, J., Cáceres, L.M., Finlayson, J.C., Gracia, F.J., Martínez-Aguirre, A., 2004. Neotectonics and shoreline history of the Rock of Gibraltar, southern Iberia. *Quaternary Science Reviews* 23 (18-19), 2017-2029. https://doi.org/10.1016/j.quascirev.2004.02.008

Roelvink, D., Costas, S., 2019. Coupling nearshore and aeolian processes: XBeach and duna process-based models. *Environmental Modelling & Software* 115, 98-112 https://doi.org/10.1016/j.envsoft.2019.02.010

Roelvink, D., Reniers, A., Van Dongeren, A., Van Thiel de Vries, J., McCall, R., Lescinski, J. 2009. Modelling storm impacts on beaches, dunes and barrier islands. *Coastal Engineering* 56, 1133-1152. https://doi.org/10.1016/j.coastaleng.2009.08.006

Rosser, N.J., Petley, D.N., Lim, M., Dunning, S.A., Allison, R.J. 2005. Terrestrial laser scanning for monitoring the process of hard rock coastal cliff erosion. *Quarterly Journal of Engineering Geology and Hydrogeology* 38, 363-375. https://doi.org/10.1144/1470-9236/05-008

Röth, J., Mathes-Schmidt, M., Jiménez García, I., Rojas Pichardo, F.J., Grützner, C., Silva, P. G. Reicherter, K., 2015. The Baelo Claudia tsunami hypothesis - results from a multi-method sediment analysis of late-Roman deposits (Gulf of Cádiz, Southern Spain). *Proceedings 6th INQUA International Workshop on Palaeoseismology, Archaeoseismology and Active Faulting*, 50-53 p., Fucino, Italy.

Ruiz, F., Rodríguez-Vidal, J., Cáceres, L.M., Carretero, M.I., Pozo, M., Rodríguez-Llanes, J.M., Gómez-Toscano, F., Izquierdo, T., Font, E., Toscano, A., 2013. Sedimentological and geomorphological imprints of Holocene tsunamis in southwestern Spain: An approach to establish the recurrence period. *Geomorphology* 203, 97-104. https://doi.org/10.1016/j.geomorph.2013.09.008

Ruiz de Alegría-Arzaburu, A., Gasalla-López, B., Benavente, J., 2022. Morphological response of an embayed beach to swell-driven storminess cycles over an 8-year period. *Geomorphology* 403, 108164. https://doi.org/10.1016/j.geomorph.2022.108164

Ruiz-Pérez, J.M., Carmona, P. 2019. Turia river delta and coastal barrier-lagoon of Valencia (Mediterranean coast of Spain): Geomorphological processes and global climate fluctuations since Iberian-Roman times. *Quaternary Science Reviews* 219, 84-101. https://doi.org/10.1016/j.quascirev.2019.07.005

Sallenger, A.H., Krabill, W., Brock, J., Swift, R., Manizade, S., Stockdon, H., 2002. Sea-cliff erosion as a function of beach changes and extreme wave runup during the 1997-1998 El Niño. *Marine Geology* 187, 279-297. https://doi.org/10.1016/S0025-3227(02)00316-X.

Sampath, D.M.R., Boski, T., Silva, P.L., Martins, F.A., 2011. Morphological evolution of the Guadiana estuary and intertidal zone in response to projected sea-level rise and sediment supply scenarios. *Journal of Quaternary Science* 26(2), 156-170. https://doi.org/10.1002/jqs.1434

Sánchez-García, E., Palomar-Vázquez, J., Pardo-Pascual, J., Almonacid-Caballer, J., Cabezas-Rabadán, C., Gómez-Pujol, L., 2020. An efficient protocol for accurate and massive shoreline definition from mid-resolution satellite imagery. *Coastal Engineering* 160, 103732. https://doi.org/10.1016/j.coastaleng.2020.103732

Sánchez Román, A., García-Lafuente, J., Delgado, J., Sánchez-Garrido, J.C., Naranjo, C., 2012. Spatial and temporal variability of tidal flow in the Strait of Gibraltar. *Journal of Marine Systems* 98-99, 9-17. https://doi.org/10.1016/j.jmarsys.2012.02.011

Sander, L., Hede, M.U., Fruergaard, M., Nielsen, L., Clemmensen, L.B., Kroon, A., Johannessen, P.N., Nielsen, L.H., Pejrup, M., 2015. Coastal lagoons and beach ridges as complementary sedimentary archives for the reconstruction of Holocene relative sea-level changes. *Terra Nova* 28, 43-49. https://doi.org/10.1111/ter.12187

Sanjosé, J.D., Serrano, E., Berenguer, F., González-Trueba, J.J., Gómez-Lende, M., González-García, M., Guerrero-Castro, M., 2016. Evolución histórica y actual de la línea de costa en la playa de Somo (Cantabria), mediante el empleo de la fotogrametría aérea y escáner láser terrestre. *Cuaternario y Geomorfología* 30, 119-130; https://doi.org/10.17735/cyg.v30i1-2.41464

Scardino, G., Piscitelli, A., Milella, M., Sansó, P., Mastronuzzi, G., 2020. Tsunami fingerprints along the Mediterranean coasts. *Rendiconti Lincei Scienze Fisiche e Naturali* 31, 319-335. https://doi.org/10.1007/s12210-020-00895-w

Scheffers, A., Kelletat, D., 2003. Sedimentologic and geomorphologic tsunami imprints worldwide - a review. *Earth-Science Reviews* 63, 83-92. https://doi.org/10.1016/S0012-8252(03)00018-7

Schmidt, P.E. (Ed.), 2011. *River deltas: Types, structures and ecology*. Nova Science Publishers, 186 p., New York.

Schubert, J.E., Gallien, T.W., Majd, M.S., Sanders, B.F., 2015. Terrestrial Laser Scanning of anthropogenic beach berm erosion and overtopping. *Journal of Coastal Research*, 31, 47-60; https://doi.org/10.2112/JCOASTRES-D-14-00037.1

Shanmugam, G., 2012. Process-sedimentological challenges in distinguishing paleo-tsunami deposits. *Natural Hazards* 63, 5-30. https://doi.org/10.1007/s11069-011-9766-z

Small, C., Nicholls, R.J., 2003. A global analysis of human settlement in coastal zones. *Journal of Coastal Research*, 19(3), 584-599.

Speybroeck, J., Bonte, D., Courtens, W., Gheskiere, T., Grootaert, P., Maelfait, J.P., Mathys, M., Provoost, S., Sabbe, K., Stienen, E.W.M., Van Lancker, V.V., Vincx, M., Degraer, S., 2006. Beach nourishment: an ecologically sound coasts difference alternative? A review. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 16, 419-435. https://doi.org/10 1002/aqc733

Sunamura, T., 1992. *Geomorphology of rocky coasts*. John Wiley, 302 p., Chichester.

Sunamura, T., 2005. Cliffs, erosion rates, lithology versus erosion rates. In M.L. Schwartz (Ed.). *Encyclopedia of Coastal Science*. Springer, 240-243 p., Dordrecht,; https://doi.org/10.1007/1-4020-3880-1_72.

Talavera, L., Del Río, L., Benavente, J., Barbero, L., López-Ramírez, J.A., 2018. UAS as tools for rapid detection of storm-induced morphodynamic changes at Camposoto beach, SW Spain. *International Journal of Remote Sensing* 39 (15-16), 5550-5567. https://doi.org/10.1080/01431161.2018.1471549

Taylor, M., Stone, G.W., 1996. Beach-Ridges: A review. *Journal of Coastal Research*, 12(3), 612-621.

Trenhaile, A.S., 1987. *The Geomorphology of Rock Coasts*. Oxford University Press, Clarendon, Oxford, UK.

Trenhaile, A.S., Porter, N.J., 2007. Can shore platforms be produced solely by weathering processes? *Marine Geology* 241, 79-92. https://doi.org/10.1016/j.margeo.2007.03.005

Tsimplis, M., Spada, G., Marcos, M., Flemming, N., 2011. Multi-decadal sea level trends and land movements in the Mediterranean Sea with estimates of factors perturbing tide gauge data and cumulative uncertainties. Global and Planetary Change, 76, 63-76. https://doi.org/10.1016/j.gloplacha.2010.12.002

Tsujimoto, H., 1987. *Dynamic conditions for shore platform initiation*. Science Report, Institute of Geoscience. University of Tsukuba, 8A: 45-93.

Umitsu, M., Tanavud, C., Patanakanog, B., 2007. Effects of landforms on tsunami flow in the plains of Banda Aceh, Indonesia, and Nam Khem, Thailand. *Marine Geology*, 242, 141-153. https://doi.org/10.1016/j.margeo.2006.10.030

Vacchi, M., Marriner, N., Morhange, C., Spada, G., Fontana, A., Rovere, A., 2016. Multiproxy assessment of Holocene relative sea-level changes in the western Mediterranean: Sea-level variability and improvements in the definition of the isostatic signal. *Earth Science Reviews* 155, 172-197. https://doi.org/10.1016/j.earscirev.2016.02.002

Van Bemmelen, C.W.T., De Schipper, M.A., Darnall, J., Aarninkhof, S.G.J., 2020. Beach scarp dynamics at nourished beaches. *Coastal Engineering* 160, 103725. https://doi.org/10.1016/j.coastaleng.2020.103725

Van Rijn, L.C., Walstra, D.J.R., Van Ormondt, M., 2007. Unified view of sediment transport by currents and waves. IV: Application to morphodynamic model. *Journal of Hydraulic Engineering* 133 (7), 776-793. https://doi.org/10.1061/(ASCE)0733-9429(2007)133:7(776)

Vao, K.N., Pandey, S., Kubo, S., Saito, Y., Kumar, K.Ch.V.N., Demudu, G., Malini, B.H., Nagumo, N., Nakashima, R., Sadakata, N., 2020. Paleoclimate and Holocene relative sea-level history of the east coast of India. *Journal of Paleolimnology* 64, 71-89. https://doi.org/10.1007/s10933-020-00124-2

Vázquez Pinillos, F.J., Marchena Gómez, M.J., 2021. Territorial impacts of sea-level rise in marsh environments. The case of the Bay of Cádiz, Spain. *Cuadernos de Investigación Geográfica* 47(2), 523-543. https://doi.org/10.18172/cig.4531

Vecchio, A., Anzidei, M., Serpelloni, E., Florindo, F. 2019. Natural variability and vertical land motion contributions in the Mediterranean sea-level records over the last two centuries and projections for 2100. *Water* 11, 1480. https://doi.org/10.3390/w11071480

Vousdoukas, M.I., Voukouvalas, E., Mentaschi, L., Dottori, F., Giardino, A., Bouziotas, D., Bianchi, A., Salamon, P., Feyen, L., 2016. Developments in large-scale coastal flood hazard mapping. *Natural Hazards and Earth System Science* 16, 1841-1853. https://doi.org/10.5194/nhess-16-1841-2016

Wang, G., Li, J., Ravi, S., Van Pelt, R.S., Costa, P.J.M., Dukes, D., 2017. Tracer techniques in aeolian research: Approaches, applications, and challenges. *Earth-Science Reviews* 170, 1-16. https://doi.org/10.1016/j.earscirev.2017.05.001

Warrick, J.A., Ritchie, A.C., Adelman, G., Adelman, K., Limber, P.W., 2017. New techniques to measure cliff change from historical oblique aerial photographs and Structure-from-Motion Photogrammetry. *Journal of Coastal Research* 33, 39-55. https://doi.org/10.2112/JCOASTRES-D-16-00095.1

Welman, H.W., Wilson, A.T., 1965. Salt weathering, a neglected geological erosion agent in coastal and arid environments. *Nature* 205, 1097-1098. https://doi.org/10.1038/2051097a0

Westoby, M.J., Brasington, J., Glasser, N.F., Hambrey, M.J., Reynolds, J.M., 2012. "Structure-from-Motion" photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology* 179, 300-314. https://doi.org/10.1016/j.geomorph.2012.08.021

Whelan, F., Kelletat, D., 2005. Boulder deposits on the southern Spanish Atlantic coast: Possible evidence for the 1755 AD Lisbon tsunami? *Science of Tsunami Hazards* 23 (3), 25-38.

Wilkinson, M.W., Jones, R.R., Woods, C.E., Gilment, S.R., McCaffrey, K.J.W., Kokkalas, S., Long, J.J., 2016. A comparison of terrestrial laser scanning and structure-from-motion photogrammetry as methods for digital outcrop acquisition. *Geosphere* 12, 1865-1880. https://doi.org/10.1130/GES01342.1

Williams, A.T., Randerson, P., Di Giacomo, C., Anfuso, G., Macías, A., Perales, J.A., 2016. Distribution of beach litter along the coastline of Cádiz, Spain. *Marine Pollution Bulletin* 107, 77-87. https://doi.org/10.1016/j.marpolbul.2016.04.015

Wolff, C., Vafeidis, A.T., Muis, S., Lincke, D., Satta, A., Lionello, P., Jiménez, J.A., Conte, D., Hinkel, J., 2018. A Mediterranean coastal database for assessing the impacts of sea-level rise and associated hazards. *Scientific Data* 5, 180044. https://doi.org/10.1038/sdata.2018.44

Wolters, M.L., Kuenzer, C., 2015. Vulnerability assessments of coastal river deltas – categorization and review. *Journal of Coastal Conservation* 19, 345-368. https://doi.org/10.1007/s11852-015-0396-6

Young, A.P., Flick, R.E., Gutiérrez, R., Guza, R.T., 2009. Comparison of short-term seacliff retreat measurement methods in Del Mar, California. *Geomorphology* 112, 318-323. https://doi.org/10.1016/j.geomorph.2009.06.018

Zazo, C., Dabrio, C.J., Goy, J.L., Lario, J., Cabero, A., Silva, P.G., Bardaji, T., Mercier, N., Borja, F., Roquero, E., 2008. The coastal archives of the last 15 ka in the Atlantic-Mediterranean Spanish linkage area: sea level and climate changes. *Quaternary International* 181, 72-87. https://doi.org/10.1016/j.quaint.2007.05.021

Zhang, M., Dai, Z., Bouma, T.J., Bricker, J., Towned, I., Wen, J., Zhao, T., Cai, H., 2021. Tidal-flat reclamation aggravates potential risk from storm impacts. *Coastal Engineering* 166, 103868. https://doi.org/10.1016/j.coastaleng.2021.103868

Zviely, D., Klein, M., 2004. Coastal Cliff retreat rates at Beit-Yannay, Israel, in the 20th century. *Earth Surface Processes and Landforms* 29, 175-184 https://doi.org/10.1002/esp.1019