11. IMPACTS ON COASTAL AREAS

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ABSTRACT

The main problems of climate change in coastal areas are related to potential changes in the frequency and/or intensity of storms, and to a possible rise in mean sea level (MSL). With regard to sea level, the estimates by the IPCC for the end of the century have been reduced as more reliable data has become available, from 50-90 cm (IPCC 1998) to 13-68 cm (IPCC 2001). The values by the INQUA (International Union for the Study of Quaternary, Sea-Level Change and Coastal Evolution Commission) and by the IGCP (International Geosciences Programme, Projects 369 and 437) are even more modest: 10-20 cm.

For the E and S coasts of Spain, the available data indicate a generalised tendency towards the stability or slight drop in MSL, although local subsidence could camouflage this effect (for example, the Ebro delta). This tendency is seen in coastal progradation, the growth of litoral spit bars, the infilling of estuaries and the disappearance of wetlands. To the contrary, for the N coast, that data indicate a tendency to rise, at rates of 3-4 mm/year in the second half of the 20th century. This is combined with observations that indicate a clear decrease in many confined beaches, retreat of dune fronts and "soft" cliffs or narrowing and/or breakage of litoral spit bars, which cannot exclusively be attributed to a reduction in sediment input, given the fact that recent data indicate, to the contrary, marked increases in sedimentation rates in estuaries throughout the last century.

Furthermore, different studies show that the MSL was almost 1 m above the present one between approximately 5,500 and 2,000 years ago, at times in which climatic conditions were similar to those expected for the end of this century.

Based on these data, it could be considered that a rise of around 50 cm for the end of the century is a reasonable scenario. A pessimistic hypothesis, much less likely but which cannot be ruled out, would involve a rise of 1 m, corresponding to the maximum in certain predictions and with the aforementioned levels in the past. This situation appears to be much less likely on the S and E coast than on the N.

In the case of a generalised rise in mean sea level (MSL), the most vulnerable areas would be deltas and naturally or artificially confined beaches. The part of the Spanish coast with cliffs made up of resistant rocks would present no particular problems. There is potential danger, however, regarding the stability of the coasts with cliffs consisting of non-coherent materials (not very significant). The hypothetical scenario of 0.5 m maximum possible rise could mean the disappearance of 30% of the beaches in the eastern part of the bay of Biscay, considering that no natural or artificial nourishment of sediments takes place. A relative rise in MSL by 0.5 m without an associated sediment response would give rise to the disappearance of around 50% of the Ebro delta.

These hypothetical rises in MSL could cause the flooding of coastal lowlands (deltas, coastal wetlands and agricultural and built up areas in the vicinity of deltas or on coastal alluvial plains). On the eastern part of the Bay of Biscay, this could imply the flooding of some of the lowlands, estimated at 23.5 km^2 for the above-mentioned value. In the Mediterranean and the Balearic Isles, and supposing a maximum of 0.5 m, the most threatened areas, apart from the aforementioned deltas (Ebro and Llobregat), are the Manga del Mar Menor (around 20 km), the Cabo de Gata lagoons (5 km) and, in the Gulf of Cadiz, around 10 km of the coast of Doñana and around 100 km^2 of marshland. Some of these areas are occupied by buildings or infrastructures, but others are devoted to agricultural use or are part of a nature park, and could allow for the formation of new wetlands which would compensate, by displacement, for the foreseeable loss of other wetland areas due to permanent flooding.

However, more precise estimates about the future evolution of this kind of coastal systems should also take into account changes in the height and intensity of waves and meteorological tides.

It should be pointed out that, added to the potential impacts of climate change, other factors of anthropic origin, such as changes in river sediment transport or construction on the coast, have, at least, a similar potential influence in the short-term stability of the coast.

As main prevention or adaptation strategies, immediate action is recommended in relation to human factors affecting the coast. Among these, we could highlight the maintenance of discharge and solid deposits by rivers as a solution to the “origin” of the problem (the lack of sedimentary matter). As a solution to the “symptoms” of the problem (retreat or excessive mobility of the coast), we could mention the stabilisation of beaches and dunes, the construction of structures aimed at limiting the transport capacity of the incoming waves and artificial sediment nourishment. In another category are actions for protecting natural values (strict land planning aimed at ensuring the maintenance and recovery of valuable areas). It is also considered necessary to delimit and make an inventory of the areas and elements that could be affected by a rise in sea level, meteorological tides and changes in direction, height and frequency of swell, in order to define where to apply abandonment and retreat strategies, or ones aimed at protection. In any case, acting upon these factors will contribute to attenuating the future impacts of climate change, regardless of the uncertainties related to the magnitude thereof.

11.1. INTRODUCTION

The coastal area constitutes the interphase between the atmosphere, the hydrosphere and the lithosphere, which makes it particularly sensitive to climate changes. The status of interphase gives the littoral great diversity with regard to environments and resources, and makes it a particularly attractive area for human settlement, both for residence and because of the great variety of productive activities that can be established therein. The result is that around 60% of the population is concentrated on the coast, most of this quite close to the coastline (Nicholls and Branson 1998).

11.1.1. Types of coasts

Within the littoral, the vulnerability of the coastal area to the potential impacts of climate change depends on the characteristics of the sectors or large "environmental units" it consists of. In this analysis, the following large types of coastline have been distinguished:

Coastal lowlands associated with river mouths

In which the interaction between human activity and/or changes affecting the ocean or river flows and natural systems could give rise to particular problems.

Estuaries, bays and rías. Embayments of very different dimensions. They are usually flanked, at least in part, by coastal lowlands with wetlands, tidal flats and beaches at the estuary mouth and also inland. These are the areas with the greatest potential impact, both due to their characteristics and to the settlements they contain.

Deltas. Protuberances formed at the mouth of water courses where the sediment input exceeds the redistributing capacity of sea currents and waves. They do not exist on the North coast, due to the predominant geomorphological and climatic features.

Wetlands (marshlands) and coastal lagoons.

Areas of coastal lowlands, not associated with estuaries or deltas, usually separated from the sea by systems of litoral spit bars or beach barriers and which can present marshland vegetation, can be found along the whole Spanish coastline.

Beaches.

Confined beaches: limited at the upper part by a) cliffs or artificial structures, restricting or preventing migration inland or b) at their sides by natural structures (capes) or artificial ones (groins) limiting longitudinal dynamics.

Unconfined beaches: such as litoral spit bars or beach barriers made of sand adjacent to coastal lowlands, with possibilities for displacement inland. When the sediment volume and wind climate allow, they are associated with aeolian dune fields.

Both typologies occur along all sectors of the Spanish coastline.

Cliffs.

"Hard" cliffs. Comprising compact rocks, resistant to erosion. These areas do not present significant problems in this sense, and will consequently not be analysed.

"Soft" cliffs": Comprising materials that are not very coherent, easily eroded and that currently present annual coastal retreat rates measured in decimetres to tens of metres or higher.

The former type predominates on the North and Northwest coasts, in the South and in certain parts of the Spanish Mediterranean. The latter abound in the Southwest of the Peninsula and in parts of the Levant.

Ports.

Rigid areas protected by vertical or sloped groins or jetties, which would require a re-evaluation of their structural reliability in relation to possible local climate change.

11.1.2. Relative distribution

The Mediterranean coast is made up of a succession of stretches with cliffs (usually "hard" ones) and coastal lowlands, in which torrential, wadi-like rivers called by locals "ramblas" or "rieras" flow, some of these forming deltas. The biggest delta is the Ebro. On the coast of Valencia, there are abundant fan deltas of the rivers Mijares, Palancia and Belcaire, which cause coastal progradation. On the South coast, into which flow big ramblas, deltas have also formed, some of the main ones being the Andarax and Adra deltas (Almería) and that of the River Vélez (Málaga).

In the lowlands there are wetlands (marshlands) and coastal lagoons, of varying sizes, separated from the sea by spits accumulated due to coastal drift. In some cases, one can find wetlands and lagoons associated with the deltas. In general these are highly populated areas, with highly-developed tourism, maintained practically throughout the whole year, and which also present a high ecological value.

The South Atlantic coast (Gulf of Cádiz) and particularly the coast of Huelva, is formed by cliffs comprising mainly soft materials, interrupted by river mouths constituting estuaries that are practically silted up. All of these include systems of sandy spits formed in favour of a general drift in the E-SE direction, which enclose, landwards, marshland systems, the biggest of which is that of the river Guadalquivir, which contains the Doñana National Park. There are also big bays, the largest of which are those of Cádiz and Algeciras.

In the Canary Isles, there is a clear predominance of "hard" cliffs, and the beaches tend to be quite short (many of them are stony), and large ones are usually only found in the S of Gran Canaria and in Fuerteventura.

In Galicia and the Bay of Biscay the coast mostly comprises cliffs, with a high proportion of "hard" cliffs. On the west coast of Galicia, the predominant elements are rías, whereas in the Bay of Biscay, there are many bays or rías, with large intertidal areas and marshlands in the vicinity. Most of the main towns and cities in this area are located by bays or estuaries.

11.1.3. Values and problems

The main values of the coastal area include the peculiarity and scarcity of certain units of great ecological interest (dunes, marshes and intertidal areas, some cliffs), and other resources that serve as a base for important economic sectors, in particular the landscape and the beaches, which are the mainstay of the tourism and recreation sector.

The problems considered with regard to the preservation and sustainable use of the aforementioned resources lie in the pressure applied upon them by the different activities involved therein, which, furthermore, often enter into mutual conflict.

Thus, the extent and state of several units of high value for conservation have become very deteriorated as a result of the pressure applied by housing development (related to a great extent to tourism), especially, but not only, on the Mediterranean coast, the Gulf of Cadiz and the Archipelagos. There are also evident pollution problems affecting some of these environments, particularly *albuferas* (lagoons), marshlands and intertidal areas, as a consequence of agricultural, industrial or residential activity (for example, the *albufera de Valencia*, Mar Menor, vicinity of Doñana national park, estuaries in Cantabria, etc.).

In some cases (Almeria, Cantabria), the aeolian dune fields have been totally eliminated by sand mining and in many other cases they have been destroyed by building directly upon them. The elimination of the exchange role played by dunes and beaches, along with the regulation of river basins, which has clearly reduced sediment supply, and the construction of different coastal infrastructures, are the main causes of the instability of unconsolidated coastlines (beaches, deltas), particularly in the Mediterranean.

Artificial desiccation and fill of marshlands and intertidal areas for various uses were the main factor of degradation of these important units throughout the last century, especially on the coast of the Bay of Biscay. Fortunately, in recent years, certain actions aimed at inverting this process have been implemented.

The overexploitation of aquifers and the resulting saline intrusion constitutes another problem affecting many sectors of the E and S coasts.

Lastly, we should point out the serious deterioration of landscape quality (a resource of great importance, both for the tourism sector and for the population's own quality of life), which has occurred as a consequence of building along the coast, a process which is particularly evident on the Mediterranean coasts, in the Gulf of Cadiz and the Archipelagos.

In general terms, land-use planning (distribution of uses and activities) together with the construction of infrastructures, impose rigidity upon the coastline which needs to be made compatible with the inherently dynamic nature of the land-sea interphase.

The problems indicated also represent the main threats for the coastline in the near and mid-term future, and it is in this context that we ought to consider the possible impacts of climate change, in order to assess the importance of these in comparison with the former ones.

11.2. SENSITIVITY TO THE PRESENT CLIMATE

11.2.1. Present climate. State of reference

The present climate in the Galicia-Bay of Biscay area is characterised (averages for the 1971-2000 period) by mild temperatures with annual averages ranging from 13.2º C (San Sebastián-Igueldo) to 14.8º C (Pontevedra), averages of from 16.2º C (Igueldo) to 19.1º C (Pontevedra) and averages of minimums from 9.4º C (Bilbao-Sondica) to 11.4º C (Coruña). Annual rainfall ranges from 971 mm (Gijón) to 1909 mm (Vigo).

The Atlantic coast of the Gulf of Cadiz has a Mediterranean-type climate with Atlantic influence and mean annual temperatures of around 17-19º C, with summertime maximums of between 35º and 40º C. Average annual rainfall is below 600 mm, with two maximums (November-December and springtime).

The current climate of the South and Southeast of the Mediterranean coast is semiarid with average temperatures in summer (July) increasing from the coast of Valencia (24.6ºC) to the coast of Malaga (25.6ºC), decreasing once again towards Gibraltar (24.4ºC) due to the proximity of the Atlantic. The annual averages for winter (January) maintain the same tendencies: Valencia (10.3ºC), Malaga (12.5ºC) and Gibraltar (12.4ºC). On the Balearic Isles, mean annual temperature is around 17º C, with wintertime averages of 10º C and summertime ones of 24.5º C.

In the Mediterranean, the minimum annual mean rainfall (200-300 mm) is recorded on the coasts of Alicante and Almeria, and the highest averages (500-750 mm) on the Valencia and Malaga coasts. On the Balearic Isles, average rainfall is around 500 mm and is concentrated between September and May. A peculiar feature is the appearance of abnormal deviations of rainfall values, with downpours that discharge a large amount of water in very few hours, sometimes one third or a half of mean annual rainfall.

Winds and waves/swell

The prevailing winds have a great influence upon the direction of the incoming waves and therefore upon coastal currents and the associated transport of sediment. On the coast of Catalonia, the prevailing winds and swells are easterly (more energetic storm swell, on having a greater area of generation), southerly, (commonly known as “Garbo”) and northerly (“Tramontana”) to north-westerly (“Mestral”). The annual mean significant wave height is below, although close to, 1.0 m and the storms can give rise to maximum significant wave heights of close to 6.0 m, with individual waves of up to 10.0 m (Gómez *et al*. 2001). On the Alicante coast and in eastern Murcia, the most influential winds are the “Levante” (easterly) and the south-easterly winds, although we must also take into account the westerly and north-westerly (“Mistral”) winds. Of great importance towards the South, is one of the most characteristic winds of the western Mediterranean: the “Sirocco” or “*lebeche”,* a south-westerly wind which is very hot in summer and of moderate temperature in winter and which, between *La Nao* Cape (Alicante) and *Gata* Cape (Almeria), gives rise to dust storms that deposit a red sediment known as “Saharan dust” that clearly affects the life cycles of the flora and fauna of the coastal wetlands. Of great relevance between Almeria and Malaga are the south-westerly winds associated with winter storms. They are usually accompanied by rains and cause over-elevation of local sea level, which favours coastal erosion.

In the Gulf of Cadiz, the prevailing winds blow from the SW, causing a general littoral drift towards the E on the coast of Huelva, where it contributes very much to the formation of sand bars which create big spit bars. Southeasterly and easterly winds are also important, due to the role they play in the processes of coastal erosion associated with storms.

In the Balearic isles, and depending on the orientation of the coast, the most influential winds are those from the North (“Tramontana”), the Southwest and the Southeast. These winds accumulate dune fields and cause more or less permanent littoral drifts that favour the growth of spit bars in the Alcudia and the old Palma lagoons, now silted up. The storms associated with southerly winds can pile up waves over 5 m high to the South of Majorca.

In Galicia and the Bay of Biscay coast, the prevailing winds affecting the stability of the coast are from the NW, and the associated storms cause swell of great height which frequently give rise to erosion of the beaches, and even the breakage of some sand spits. On the confined beaches of this coast, a notable loss of sand can often be observed, caused by storms from the NW, which tends to recover with a change in conditions. Indeed, there are numerous cases of this kind of beaches disappearing or being seriously reduced in the winter, and returning in the spring-summer, with the reduction of these storms. On the coast of the Rías Bajas there are also big storms associated with winds from the SW.

Tides

On the Galicia-Bay of Biscay coast, the tidal ranges vary from somewhat less than 1.5 m in neap tides and over 4 m in spring tides, and these level differences can be accentuated in the event of over-elevation due to meteorological effects (storms from the NW, low pressure).

The Gulf of Cadiz is mesotidal, with a mean astronomic tidal range of 2 m (Dabrio *et al*. 1980).

The Mediterranean coast is microtidal and the astronomic component is around 8-10 cm but, combined with the daily breeze, it can raise the mean level by around 30 cm in good weather (Dabrio and Polo 1987).

During storms and prolonged wind events involving the *Levante* and *Poniente* winds, the over-elevation caused by the meteorological tide can exceed one metre on the coastal segments oriented towards them. The return period of these exceptional events can vary from ten years for an over-elevation of 1 m to 100 years for 1.5 m (Sánchez Arcilla and Jiménez 1994).

11.2.2. Effects of climatic variability on the coast, based on their past evolution

The change tendencies established for the Cantabria area during the Holocene (Figure 11.1); according to Menéndez Amor 1961a,b,c, 1963; Menéndez Amor and Florchutz 1961, 1963, 1964; Mary 1968, 1973, 1975, 1979, 1985, 1992; Mary *et al*. 1975; Mariscal 1983, 1986, 1987; Peñalba 1989; Cearreta *et al*. 1990; Salas 1993; González *et al*. 1996 1999), indicate that around 5500 BP a relative temperature maximum was reached, accompanied by a decrease in mean annual rainfall. In the early centuries of our Era, there was a new episode of relative warming, followed by a cooling phase that ended in the Little Ice Age, after which the warming tendency started, and continues at present. Projections by the available models suggest that similar conditions to those "climate maximums" of the Holocene could be reached during this century.

Although the available data on fluctuations in sea level in these times are not very conclusive, as they present certain apparent contradictions among the different areas (Table 11.1), in the Cantabrian Holocene there are evidences of transgressive phases, according to what has been observed in numerous analyses (palinology, anthracology, palaeontology, archaeology, morphology, sedimentology, etc.) carried out by different authors in emerged coastal deposits and in estuarine infills (Altuna *et al*. 1989; Cearreta 1992, 1993, 1994, 1998; Cearreta and Murray 1996; Edeso 1990, 1994; Flor 1983, 1995; Hoyos Gómez 1987; Mary 1968; 1975, 1979, 1985; Mary *et al*. 1975; Moñino 1986; Moñino *et al*. 1988; Mosquera *et al*. 1994; Rodríguez Asensio and Flor 1980; Rivas and Cendrero 1987; Santos Fidalgo *et al*. 1993; Santos Fidalgo and Vidal Romaní 1993a, Vidal Romaní *et al*. 1997). The first marine incursion corresponds to the Flandrian transgression, which has been clearly identified and dated in other parts of Europe. At this time, sea level could have reached elevations of between 1 and 3 m above the present level (according to different authors). The marine transgression after the start of the Christian era appears to have been of lesser magnitude.

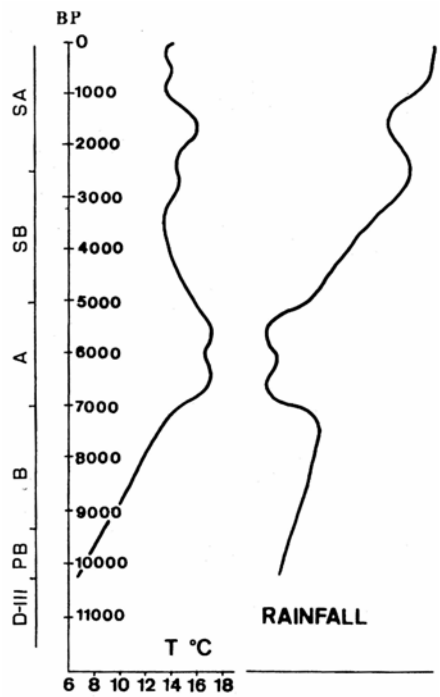

Fig. 11.1. *Change tendencies established for the Cantabrian area during the Holcene (González et al. 1996)*

Table 11.1. *Dated Holocene coastal deposits around the Bay of Biscay. Note: the elevations indicate the position of the deposits in relation to the current intertidal mean level, and not the sea level at the date on which this was indicated*

Sample	Situation	Site	Age BP	Height	Author
Plant remains	Estuary IS 1	Bidasoa river	7810±130	- 25 m	Cearreta *et al*. 1992
Plant remains	Estuary IS 2	Bidasoa river	6590±120	-15.5 m	Cearreta *et al*. 1992
Plant remains	Estuary IS 2	Bidasoa river	6630±120	- 2 m	Cearreta *et al*. 1992
Peat	Beach	Gerra I	5880±130	Intertidal	Mary 1979
Tree trunk	Beach	Gerra IIIa	5850±200	Intertidal	Mary 1979
Organic matter	Estuary	HerrikoBarra	5810±170	Intertidal	Cearreta *et al*. 1990
Peat	Beach	Gerra II	5300±120	Intertidal	Mary 1979
Tree trunk	Beach	Gerra IIIb	5250±90	Intertidal	Mary 1979
Organic matter	Estuary	HerrikoBarra	4920±100	+ 2.5 m	Altuna *et al*. 1990
Peat	Beach	Bederna stream	4770±110	Intertidal	Mary 1979
Peat	Beach	Ares	4350±90	Intertidal	Santos-Vidal, 1993
Tree trunk	Beach	Trengandín	4070±100	Intertidal	Cearrera 1993
Peat	Beach	Ares	3970±50	Intertidal	Santos-Vidal, 1993
Wood	Beach	Ares	3450±100	Intertidal	Santos-Vidal, 1993
Wood	Beach	Trengandín	3080±100	Intertidal	Cearrera 1993
Tree trunk	Beach	Trengandín	2890±70	Intertidal	Salas *et al*. 1996
Wood	Fluvial	Besaya river	2780±80	- 0.5 m	Salas *et al*. 1996
Plant remains	Estuary IS 2	Bidasoa river	2740±90	- 5 m	Cearreta *et al*. 1992
Vegetal carbon	Estuary	Xivares	2150±110	+ 1 m	Mary 1968
	Marine terrace	Fontías	1920±120	+ 1 m	Mary 1975

On the coast of the Gulf of Cadiz, the pollen sequences from the records found in cores in coastal and estuary lagoons (Zazo *et al*. 1996, Yll *et al*. 2003), show no appreciable temperature changes during the mid- and recent Holocene, but they do show a tendency towards aridity after ca. 5000 BP (Zazo *et al*. 1999). This general tendency was interrupted by short episodes (at a scale of hundreds of years) of greater aridity between 2700-2400 BP and 900-800 BP (Borja *et al*. 1999).

With regard to variations in sea level, studies of estuary fills (Dabrio *et al*. 2000) and of litoral spit bar systems (Zazo *et al*. 1994, Goy *et al*. 1996, Zazo *et al*. 1996) suggest that, once the Holocene maximum was reached (ca. 7000 cal BP), the general tendency was towards a drop in MSL, interrupted by short intervals of relative rises, of a magnitude of less than one metre around 2700 BP and 500 BP.

Rodríguez Ramírez *et al*., (2000) studied the litoral spit bar systems in the Gulf of Cadiz, and observed that the coastal progradation continues, and that in the last four decades (1956-1996) five new beach ridges have been formed.

On the Mediterranean coast, the pollen analyses from cores drilled in river mouths on the Almeria coast (Yll *et al*. 1994, Pantaleón-Cano *et al*. 1996, Jalut *et al*. 2000) record a radical change in plant cover that indicates a change from humid conditions to arid ones in ca. 5400 cal BP. The tendency towards aridity has lasted to the present, although it was interrupted several times by periods of extreme aridity of secular duration at around 4200 cal BP, 2700 cal BP and 1900 cal BP (Goy *et al*. 2003).

The litoral spit bar systems of Almeria provide data on the changes in relative sea level. There is a general tendency towards relative drop in MSL , which allows for the maintenance of progradation on the coastal plain, but several episodes of a relative rise in MSL of secular duration were detected. The magnitude of these rises, recorded in 5400 cal BP, 3100 cal BP, 1900 cal BP and 500 cal BP, is less than one metre.

Fernández Salas *et al*. (2003) studied the prodelta of the river Guadalhorce (Malaga), deducing that the deposit of sedimentary units subsequent to the trangressive maximum (ca. 7000 BP) is controlled by eustatic changes that present two small-range cycles (few metres) and a periodicity of around 3,000 years. Within one cycle, the greatest duration corresponds to the progradation period (drop in MSL) when there is more sediment input to the coast, whilst the periods of relative rise in MSL are usually shorter, with a very marked one around ca. 3000 BP.

In the Ebro delta, a markedly subsiding area, Somoza *et al*. (1998) described the eustatic oscillations for the last 7,000 years. More recent indirect estimates of subsidence rates range from 1.0 mm/year to 5.00 mm/year (Sánchez-Arcilla *et al*. 1998). The range of the estimates varies with the type of methodology used to obtain them (sediment balance, topographic levelling/survey, old levees) and with the thickness and age of the delta area considered.

In the Balearic Isles (Burjachs *et al*. 1994), the pollen analyses from core drills to the North of the Albufera de Alcudia (Majorca) record humid conditions during the Holocene climatic optimum (7100-6000 BP), with abundant sediment input to the coast. After 6000 BP there is evidence of a change towards aridity which is accentuated around 2400 BP. The Holocene marine terraces and the litoral spit bar systems in the bays of Alcudia and El Prat (Majorca) also record the relative drop in MSL after 7000 BP (Goy *et al*. 1997), within a tendency interrupted by short episodes of relative elevation around 4400 BP, 3000 BP, 1800 BP and 500 BP.

11.2.3. Present coast. State of reference

The sedimentary coastal response to the climate changes predicted for the future should be analysed from the perspective of the present situation and the evolution of this in the past. If a state of reference is not established no comparison will be possible.

The past evolutionary history reveals a general tendency towards progradation on the South-Atlantic coast, recorded in the litoral spit bar systems (figura 11.27: H units by Zazo *et al*. 1994 and Dabrio *et al*. 1996) integrated by a certain number of small ridges and swales. The study of the evolution of these litoral spit bar systems in the last few decades (Rodríguez Ramírez *et al*. 2000) suggests a continuous tendency towards progradation.

Likewise, the tidal flats, which tend to disappear, reached in their natural state a maximum development around 2400 BP (Dabrio et el. 2000), due to the increase in the rates of coastal progradation and vertical accretion of the sedimentary units inside the estuaries.

Furthermore, part of the Gulf of Cadiz coast is currently undergoing an accelerated process of erosion (figure 11.2). Clear evidence of this are the watch towers along the coast, the construction of which dates from the 16th century to the start of the 17th, the bunkers from the 30s, and the tangible retreat of the soft cliffs in El Asperillo (Huelva), Sanlúcar de Barrameda, Chipiona and other parts of the Bay of Cadiz in the last quarter century (figure 11.3). Recent research along the whole coast of Cadiz, based on aerial photography and continuos monitoring of beach profiles in 34 stations (Del Río *et al*. 2002) revealed that the two main causes of coastal erosion involve human intervention: river dams that reduce sediment supply to the coast, and coastal structures (dikes, groins, ports and other constructions) which alter littoral dynamics.

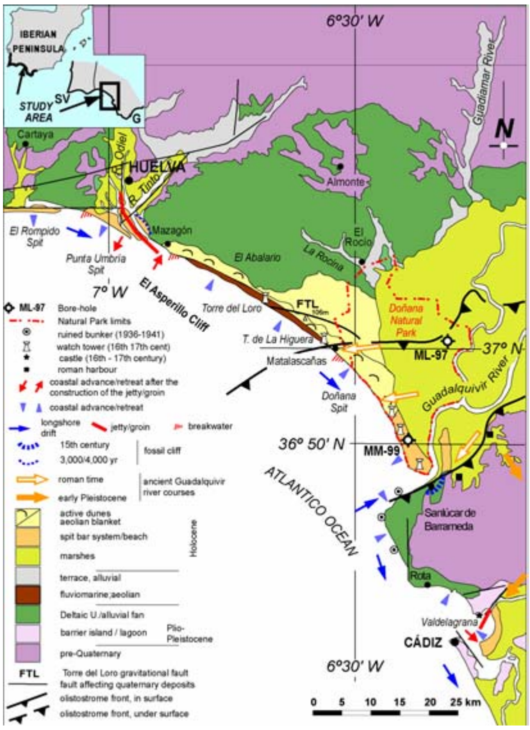

Fig. 11.2. *Present erosion conditions along the coast of Cadiz (Zazo et al. 1987, mod.)*

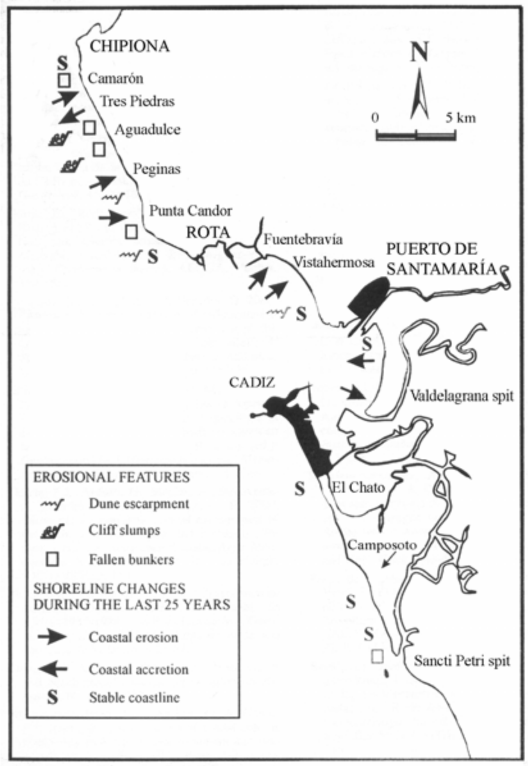

Fig. 11.3. *Retreat of soft cliffs in the Bay of Cadiz (Del Río et. al. 2002)*

In the Mediterranean area, erosion has greatly increased as a consequence of the drastic reduction of fluvial sediment input due to the regulation and reforestation of river basins and the construction of dams. The coastal evolution of the Ebro delta clearly shows this tendency (Sánchez-Arcilla *et al*. 1998). Most of the areas affected by accelerated erosion are the result of the construction of ports that interrupt littoral drift, and the situation is exacerbated by urban development and the construction of infrastructures as well as by the associated coastal defence structures. In some cases, this has involved the erosion of the barriers separating coastal wetlands from the sea, such as the one between Puçol and Massalfasar, as a result of the port of Sagunto, the spit of the lagoon between Valencia and Cullera, due to the Valencia port, and the closing barrier of Santa Pola lagoon, a consequence of the Santa Pola port (Alicante). In other cases, the erosion of beaches and coastal plains has been radically accelerated, like in Puerto de Mazarrón (Murcia) and Carboneras (Almeria).

The conatruction of walls or coatings in areas where retreat is now an established fact (for example, in the Manga del Mar Menor) breaks the natural summer/winter sediment balance and causes two negative effects: it inhibits the growth of the beach in summer by waterproofing the swash area, and prevents the erosion of the upper part of the beach in winter, and consequently, the formation of the sediment bar which acts as a reserve in the area of transition to the shoreface. In all these cases, the estimate of transports, both longitudinal and transversal, presents multiple uncertainties with regard to the present climate (Sánchez-Arcilla *et al*. 2001), and even more for future climate scenarios.

On the northern coasts, the situation is different, as the basins flowing to these have not generally been subjected to any great regulation. On these coasts, there is evidence of appreciable increases in sediment deposits in recent times, most likely as a result of human intervention (Cendrero 2003; Remondo *et al*. 2004; Méndez *et al*. 2004, Cendrero *et al*. 2004).

The retreat of beaches and dune fronts, however, is perceptible in many places, or even the accelerated erosion of "soft" cliffs (Rivas 1991; Rivas and Cendrero 1991, 1992, 1995).

11.2.4. Spatial scales

In order to analyse possible future change, it is necessary to combine the spatial and temporal scales at which the morphodynamic processes are acting. The definition of these scales must be based on the available knowledge of the driving mechanisms and coastal response observed. The main problem lies in the fact that an agent (for instance, swell) acts at different scales and in different ways. At the main scale of the considered process, the agent will be a "controller" whereas at other scales, it will play the role of "noise" or boundary condition (de Vriend 1991). As a matter of illustration, let's consider the longitudinal transport of sediments induced by the swell on the coast of the Ebro delta (Figure 11.4). The "natural" scale of the longitudinal transport is medium-term, that is, a few years. If this scale coincides with the study period, longitudinal transport will be the main component of this study and the role it plays is illustrated in figure 11.4b, which shows how annual net transport rates account for the corresponding sediment balance. This also means that the long-term volumetric changes will be controlled mainly by the net longitudinal transport pattern.

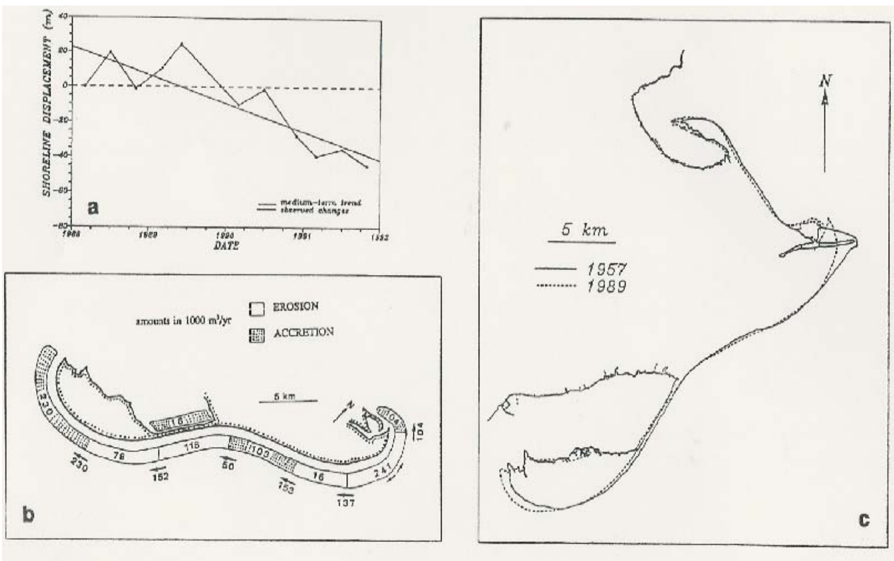

Fig. 11.4. *Role played by sediment transport along the coast according to different time scales: (a) short-term, (b) medium-term and (c) long-term (adaptaded from Jiménez and Sánchez-Arcilla 1993).*

When the study period is smaller than the temporal scale of the process, this will act as a boundary condition as indicated in figure 11.4, in which the movements of a coastal profile in the Ebro delta appear "against" the medium-term tendency. The classical seasonal variations in the transversal behaviour of the strandline can be observed. The mean tendency shown in this figure is associated with the positive gradient in longitudinal net transport average, which gives rise to erosive behaviour and therefore represents an external boundary condition

Finally, when the time scale of the study is greater than that of the process considered, this will have a residual or "noise" effect. Figure 11.4 illustrates this fact. The long-term evolution of the coast of the Ebro delta presents a reshaping that could be defined in terms of the corresponding sediment balance. Longitudinal sediment transport cannot be considered responsible for this balance, as the system is almost “closed”, at least for the sand fraction (Jiménez *et al*. 1993). The observed reshaping , however, is due to net longitudinal transport, and these processes at this long-term scale will therefore have a residual effect as a reshaper but will not contribute to sediment balance at this scale.

Coastal response depends on the climatology, geomorphology and structures existing in each coastal sector and it has multiple scales. For analysis of the coastal response to a possible climate change at local range, three scales are usually considered:

1. Long-term scale, which is the one most directly related to changes at global scale (area, profile and sedimentary balance) and which is controlled by agents such as: sediment input from rivers, changes in relative land-sea level, sediment transport at the internal limit of the platform, sediment exchanges between the strandline, coastal strip and the adjacent land (due, for instance, to wind transport) and variations in climatic factors at decadal scales. The residual effect of longitudinal sediment transport can also be considered as an agent.

2. Medium-term scale, which is associated with systematic coastal changes in the order of kilometres and with temporal variability in the order of years. The main coastal response that can be observed at this scale is the remodelling of the coast and the main controlling factor involves net sediment transport (longitudinal and transversal). The changes in the coast are the result of integrating the different swells acting upon a coastline, although the way of averaging those, is far from being universally accepted.

3. Episodic scale, which is associated with the actions of extreme driving mechanisms that act for a limited number of days and have an approximate return period of decades. These agents cause great changes of impulsive type in the coastal area, and in the case of our Mediterranean coast, two of them are essentially considered: a) the action of storms simultaneously characterised by meteorological tides and high-energy waves (which will cause accentuated erosion and the eventual breakage of the more fragile coastal sections) and b) extreme floods providing a big sediment supply over a short period of time and, simultaneously, the intense re-shaping of the area close to the river mouths. These extreme events are characterised by an immediate coastal response, through which the coastal section affected will subsequently recover at a different temporal scale, which can be considered as medium-term. Possible climate change will undoubtedly affect the distribution of these extreme events. Its study is therefore particularly important in order to characterise the impact of climate change upon our coasts.

The coastal response observed in each case will depend on the time scale chosen for the study. The vulnerability of the different types of coastal responses to climate change will depend, as has already been mentioned, on the existing geomorphology, climatology and structures. In this sense, coasts with cliffs will be less vulnerable and less dynamic, whereas the sedimentary coasts with a limited granular volume will be the most vulnerable ones. Sedimentary coasts with an “undefined” volume of material, although they may be susceptible to big changes caused by the impact of climatology, will present less vulnerability. The two types of coasts that are in a more fragile balance (due to being the result of the balance between land, sea and atmospheric factors) and are therefore more vulnerable to possible local climate changes, are deltas and estuaries, which will be dealt with in detail in this chapter.

11.3. FORESEEABLE IMPACTS OF CLIMATE CHANGE

The factors shaping coastal areas are related, on one hand, to processes taking place in river basins and, on the other, with marine dynamics. Among the former are those affecting the generation and transport of sediments towards the coast (changes in land cover and land use, construction of reservoirs, changes in rainfall regime, etc.). Among the latter, we can highlight changes in mean sea level and the intensity, frequency and prevailing direction of winds and swells. All of these influence the balance between erosion and sedimentation, but also the area and condition of wetlands and the erosion rates of the cliffs.

The impacts of climate change themselves (changes in temperature, rainfall, tendency towards humidity or aridity, changes in sea level, etc.) do not appear to be specific to coastal areas, except, naturally, with regard to the interaction between the atmosphere, the ocean and the coast, and the consequences for the related activities. For example, a temperature increase by a few degrees and a decrease in rainfall could have a positive impact on the North and Northwest coasts, due to the resulting greater climatic comfort and attraction for tourism, but there would be the opposite effect on the East coast, exacerbated by the *torrentialisation* of the water courses and the subsequent destabilisation of coastal dynamics.

An essential aspect of the study of driving factors involves determining their possible variation in time and even their recurrence and, in this case, the periodicity with which the events occur. This could be attempted with the use of drill-cores in ice, sea bed, lagoons and coastal or inland wetlands, high-resolution seismic studies on the continental platform and morpho-sedimentary analyses of coastal units, all of this backed up by radiometric dating. This is vital in order to distinguish between natural climate change, which obviously fluctuates, and that caused by human action.

The present situation and the change tendencies observed in the recent past, together with the projections made by climate models (see chapter on “The climate of Spain: past, present and future climate scenarios for the 21st century”), suggest that in the last third of this century, we may encounter mean and maximum temperatures that exceed current ones by between 2 and 3 degrees on the N coast and by 4 and 5 degrees on the E and S coasts. Seasonal rainfall will increase in the N and NW, with slight increases in the rainfall accumulated in autumn-winter and more evident decreases in spring-summer. In the south and East, to the contrary, decreases in rainfall are to be expected in all seasons (although not very marked ones). No significant differences have been indicated with regard to changes in the intensity, frequency and direction of winds.

We therefore find a scenario in which the magnitude of the changes to be expected in comparison to the present situation of the climatic variables affecting swells, tides, water and sediment input, and therefore, the stability of the coast (fundamentally of the beaches) has to be added to the effects that human action has previously had and can have on these processes.

11.3.1. Mean sea level

The term “mean sea level” indicates a theoretical situation and refers to a point on the coast considered to be fixed and stable. In Spain, this point is officially set in Alicante. On speaking of “mean level”, a certain vertical variability is accepted, which is considered as “normal” and which takes into account certain periodic oscillations longer than the long-term waves present on the coast.

Three components are usually considered in these oscillations:

1. The periodic component associated with the astronomic tide
2. The non-periodic component associated with the meteorological tide
3. A slower variation component associated with the relative variation in land-sea levels

The astronomic component plays a vital role on the mesotidal and macrotidal Atlantic coasts of Spain, but on the Mediterranean microtidal coast, they have very little effect, because their range does not usually exceed 25-30 cm.

The meteorological tide is caused by the combined effect of atmospheric pressure (inverted barometric effect) and the tangential pressure of the wind. Over-elevations of around 1 m have a return period of about 10 years, whereas those of 1.5 m have a return period of approximately 100 years. If we add a possible rise in MSL related to climate change, the return periods of the big over-elevations are clearly reduced: for a rise of 0.46 m, the return period of the 1.5 m high waves is reduced from 100 years to 9 years in the Ebro delta. To the contrary, the coasts with the highest tide ranges are less exposed to these effects.

The third component is related to the land-sea relative level and refers to the superposition of the eustatic variation (the change in MSL) and vertical local displacements of the substrate. This relationship is what enables the coastline to be shaped. This component is usually calculated with the use of data from tide registers and reflects the combined effect of the eustatic level and the local change in the land base on which the register is located (Emery and Ausbry 1991; Pirazzoli 1991). This means that much care must be taken in the extrapolation of the values to nearby coasts, in particular to the delta areas in which local subsidence (sinking) exceeds the eustatic component, as was documented by Suanez (1997) and Morhange (1994) who compared data from Marseilles (elevation 1mm/year) and from the Ródano delta (3 mm/year). In the Ebro delta, the rise is estimated at between 2 and 5 mm per year (Smith *et al*. 2000).

In relation to relative sea level, there has been a general tendency towards a drop since 5,300 cal BP. These are centimetric variations related to the greater or lesser entry of surface water from the Atlantic into the Mediterranean, reinforced by the winds and probably by the NAO (North Atlantic Oscillation). The litoral spit bar systems are constituted by beach ridges and swales, the generation period of which is related to the sunspot cycle (Zazo *et al.* 1994; Goy *et al.* 2003).

On the Atlantic coasts (Gulf of Cadiz), coastal progradation is represented by the development of litoral spit bars, and the start of estuary filling (Zazo *et al.* 1994, Goy *et al.* 1996), Dabrio *et al. 2000,* Lario *et al.* 2002) occurs from de ca. 2700 BP, indicating a general tendency towards a drop in sea level from that time up to the present. The most recent data (Rodríguez-Ramirez *et al.* 2003), covering the last 4 decades (1956-1996), indicate a close relationship between the periodicity of the SW winds, the number of storms and the formation of the ”mini beach ridges” that constitute Doñana’s spit bar system.

Existing data on variations in sea level on the North coast (Gómez Gallego 1994) during the last century indicate that between 1972 and 1990 there could have been a rise of 6-7 cm, (figure 11.5), although these values present some uncertainty.

With regard to the fluctuations in sea level in previous periods, the available data are not very conclusive, as they present certain contradictions. Table 11.1 summarises the existing data for sea levels in the Bay of Biscay. Figure 11.6 presents an approximate reconstruction of the variation in sea level during the Holocene, based on existing data on the N coast of Spain.

In accordance with the previously presented set of historic data, a rise in sea level of more than 1 m can be considered as a maximum hardly to reach in this century. Recent projections consider a set of much lower values (figure 11.7).

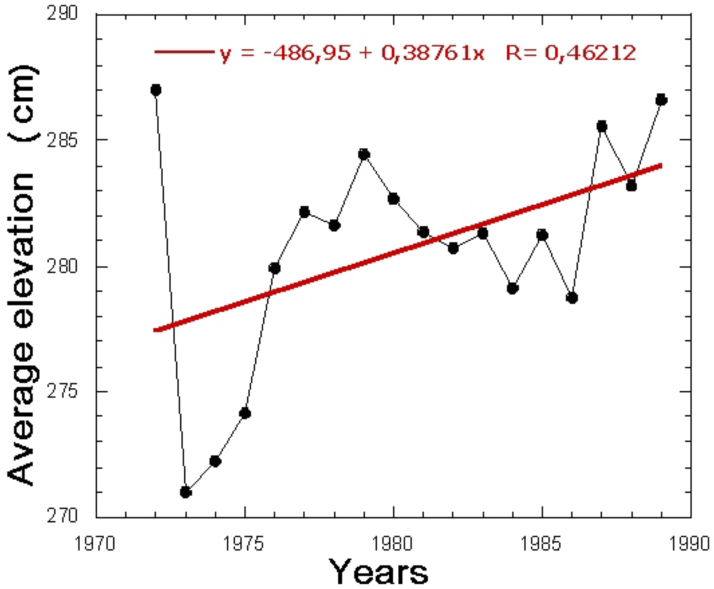

Fig. 11.5. *Variation in sea level based on the Santander Port tide register (Gómez Gallego 1994)*

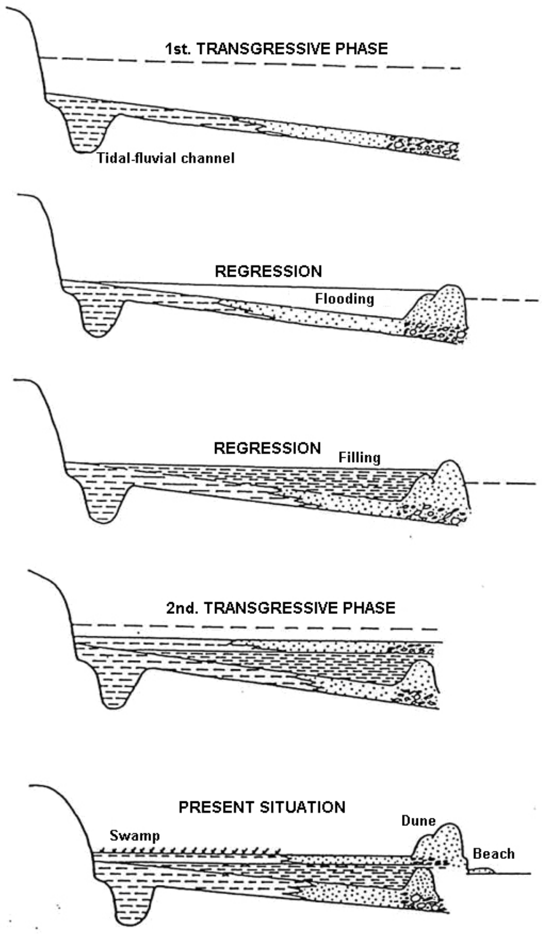

Fig. 11.6. *Reconstruction of the variation in sea level during the Holocene, estimated using existing data on the N coast of Spain. (Edeso 1994)*

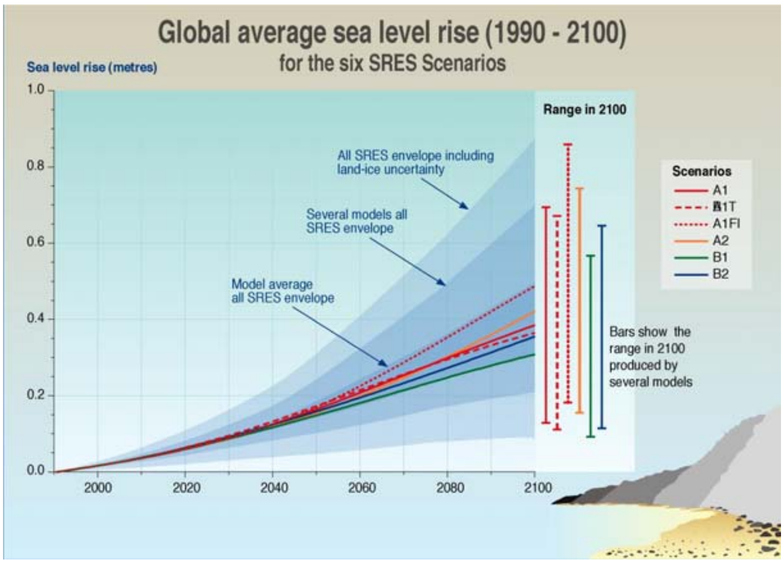

Fig. 11.7. *Recent projections under different scenarios of a rise in MSL (source: IPPC)*

11.3.2. Swell

Swell is one of the most important factors shaping the coast at the different scales considered. The swell climate is obtained from records, visual observations and numerically obtained data, and provides characteristic values of the wave height, period and direction. Wave height partly characterises transversal transport, which varies with the height of the wave to the power of between 2 and 5, which requires the correct determination of the probabilistic distribution of this variable. The longitudinal current generated and the corresponding transport depend upon the second and third variables.

In the *long term,* an essential component of the swell climate is the transport in the border area between the continental platform and the active coastal area (Wright 1987). Its value is only known in some areas of our coastline (Jiménez *et al*. 1997, 1999), but it has partly substituted the lack of fluvial supply in recent times, and has mitigated the erosive effects that might be expected.

At *decadal scale,* transport depends on the elevation and wave period and can be estimated through the analysis of tendencies, as shown in figure 11.8 (Jiménez *et al*. 1997).

At *medium-term scale (a few years),* the main factor is net longitudinal transport, which requires accurate knowledge of the mean wave height of each frequency interval. It has been seen empirically that on the Mediterranean coast the best results are obtained using a CERC-type formula with a proportionality coefficient that varies according to sedimentary characteristics and the coastal structures present (Sánchez-Arcilla *et al*. 2001).

Episodic events giving rise to the highest transport rates are associated with certain conditions of temperature, swell and meteorological tides and are the main "impulsive" reshapers of the Mediterranean coastline (Sánchez-Arcilla and Jiménez 1994). In order to study the swell climate of these episodes, intervals are used, because errors associated with the extremes of the probabilistic distribution intervene. The joint probabilistic distribution of significant wave height, the temperature and the maximum meteorological tide associated with "this" storm (for the Ebro delta coast) appear in figure 11.9, in which the asterisk indicates the conditions that caused the breakage of the ”Barra del Trabucador” in 1990, and therefore, an “impulsive” morphological change.

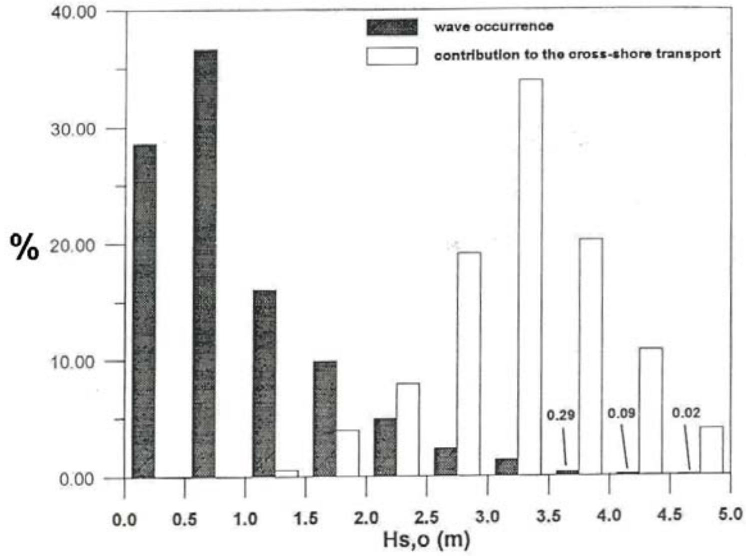

Fig. 11.8. *Contribution of wave height to transversal sediment transport (Jiménez et al.,1997)*

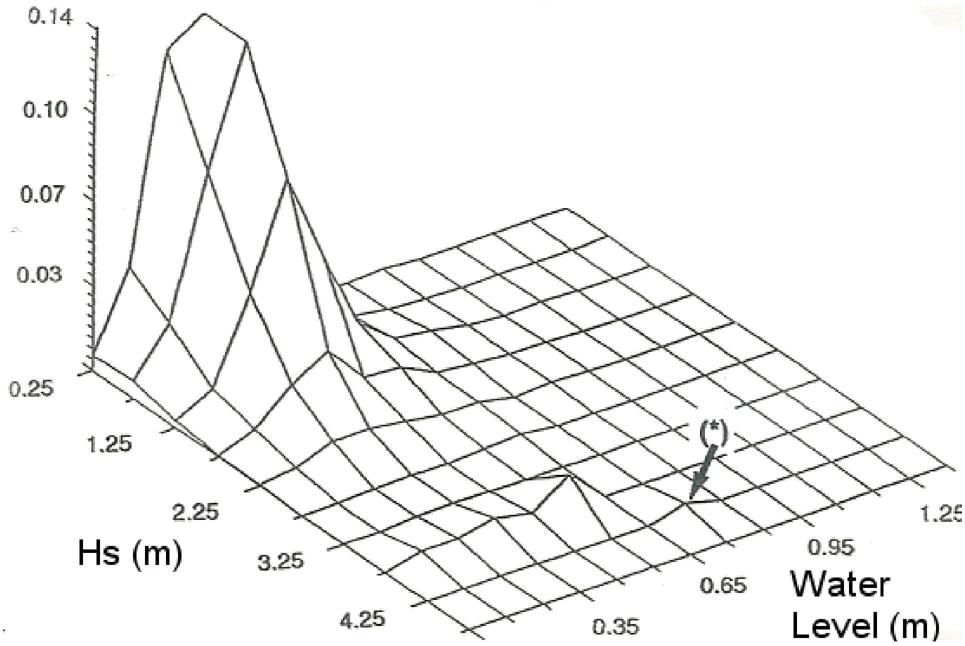

Fig. 11.9. *Joint probabilistic distribution of significant wave height (Hs) and mean sea level (Z). Note: the asterisk (*) indicates the conditions that broke the “Barra del Trabucador”*

A study to evaluate possible the effects of climate changes on coastal areas has been developed under a project carried out by the Universidad de Cantabria (Medina *et al*. 2004) for the Oficina Española de Cambio Climatico (Spanish Office of Climate Change) and the Dirección General de Costas (General Coastal Office of the Ministry of Environment). The study has been carried out by reanalysing datasets spanning 44 years (1958-2001) obtained by numerical simulation in which relevant metereological and oceanographical variables have been considered.

The analysis has allowed to study such variables and to perform a forecast of their future evolution. Considering 12 relative homogeneous areas, the mean, maximum and minimum values of the following variables have been calculated: direction of average flux of swell energy, wave height surpassed 12 hours per year and significant wave height. The results of the mean probability distribution are plotted in Figure 11.10. The extreme probability distribution has also been studied.

The study reveals that there is an evident increase of the swelling energy reaching to the Cantabrian Coast. The prevailing direction of the swelling tends to present an enhanced West component, with more intensity on the Western Coast. On the Galicia coast, the Cape Finisterre becomes the border between two zones with significant differences in the magnitude of the studied parameters. This gives rise to a smoother marine climate in the Rias Bajas; the swell energy tends to increase.

On the Mediterranean coast, although no relevant changes in the magnitude of swelling energy are detected, some marked peculiarities are obvious around Cape de la Nao due to its geographical position and, in addition, on the Costa Brava due to its proximity to the Gulf of Leon. On the Costa Brava, similar tendencies to the Northeastern Balear area are observed, displaying a reduction of the mean swell energy. Respect to the predominant swell direction, variations are found in the Ballearic Islands and on the Costa Brava, in which a tendency to a clockwise turn of swell has been obtained, resulting in a more eastern component of the predominant direction.

The Gulf of Cádiz displays a clear negative tendency for all the studied parameters, confirming the smoother maritime climate in such an area.

Finally, the results for the long-term variations indicate an increase of storms in the North and a tendency to an energetic reduction and a clockwise turn in the swell direction in the South. Changes in the wave height will affect the coastal flooding level, the sediment potential transport and to the extent of the beach active profile, among others. The variation of the angle of the mean flux energy may contribute to modifications in the beach shape and, in consequence, additional retreats together to the ones produced by sea level rise may occur.

11.3.3. River discharge

Liquid and solid discharge by rivers controls the biological productivity and quality of the water on the surrounding coast and the type and availabilty (volume) of unconsolidated sediment. Fluvial transport constitutes the main supply of sediments to the coast and is of particular relevance in the delta areas. There is a non-linear relationship between liquid discharge and sediment supply, but the present-day regulation of river basins has broken this (especially with regard to the sand fraction), and they will therefore be treated separately. It is very useful, however, to record liquid discharge in the form of velocities averaged on a daily basis, because these provide more information than those measured on a monthly or annual basis, which tend to camouflage specific processes. Indeed, there can be monthly measurements below the transport limit for a given sediment fraction, and, at the same time, the daily value can surpass this. Likewise, the impact of a possible climate change can go unnoticed within the averaged process but can be perceived with more “instantaneous” values. In this context, it should be pointed out that water management or use policies for river basins can accentuate, attenuate or eliminate the possible effects of climate change.

Liquid supply

The *long-term* discharge, in the context of this chapter, involving just a few decades, can only be estimated with the corresponding records, but taking into account actions aimed at regulation. For instance, for the river Ebro, they can only be taken into account after 1957, when the Ribaroja and Mequinenza reservoirs started functioning (figure 11.11)

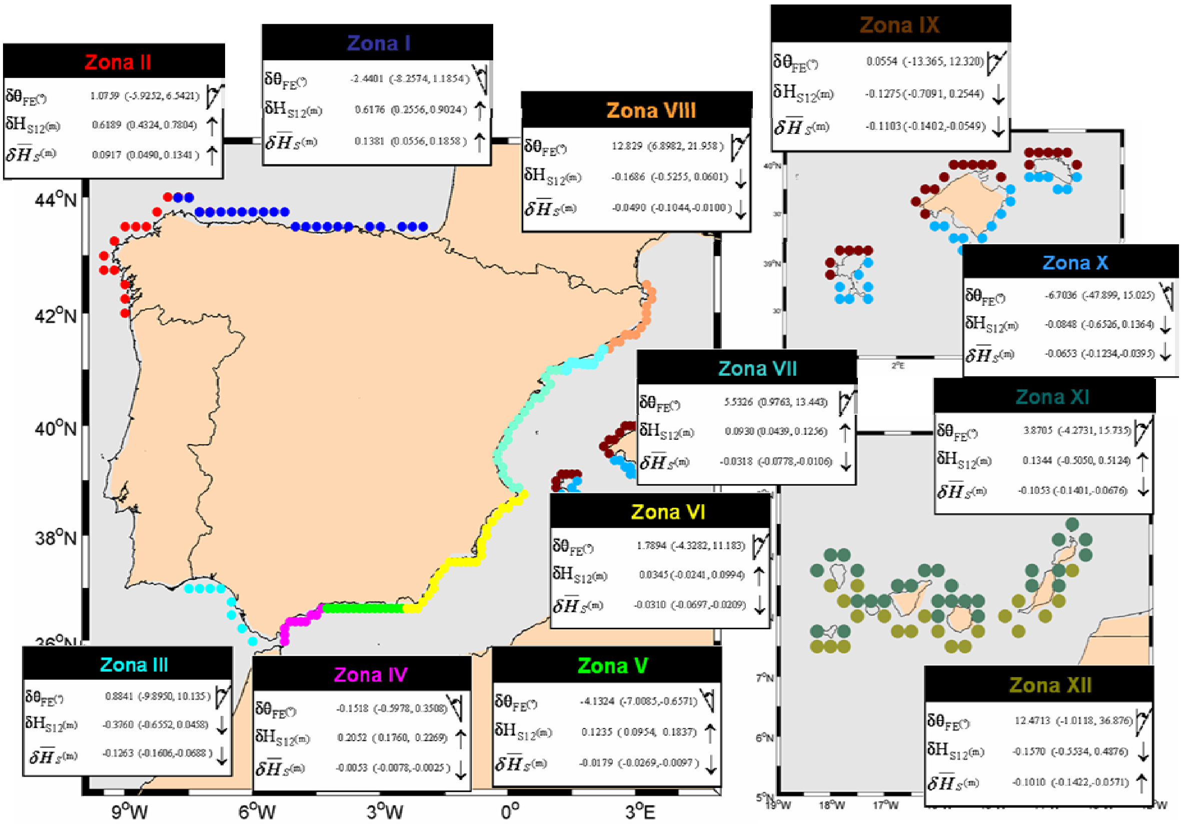

Fig. 11.10. Variations obtained for the values related to mean probability distribution of the swell (Medina et al. 2004)

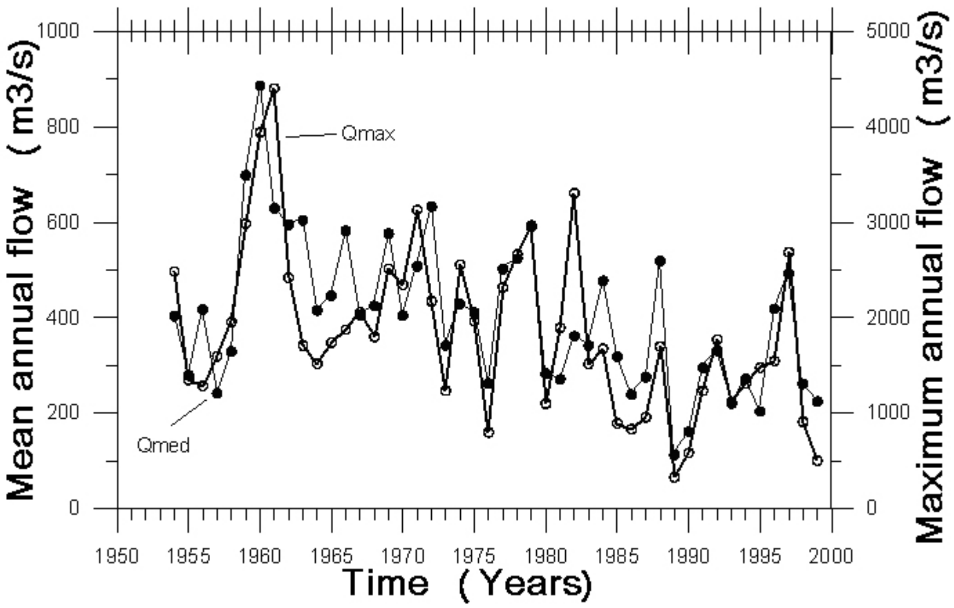

Fig. 11.11. Temporal evolution of the discharge of the river Ebro (Qmed = annual average and Qmax = annual maximum)

At *decadal scale* (figures 11.12 and 11.13), estimates of fluvial discharge are made with the use of trend analyses (Mitosek 1995) non-parametric tests (IPCC 1995) or in a simplified manner with the use of minimum squares regression analyses. Mean monthly and annual discharges are considered (Jiménez and Sánchez-Arcilla 1997). Trend changes in the context of decades should be analysed with care, because these can be of multiple origin: changes in climatology (and therefore in rainfall and surface runoff of the basin) changes in river regulation policy, changes in land management in the basin itself, etc. In strictly regulated rivers, as is the case of most Spanish ones, the impacts of possible climate change might very well go unnoticed.

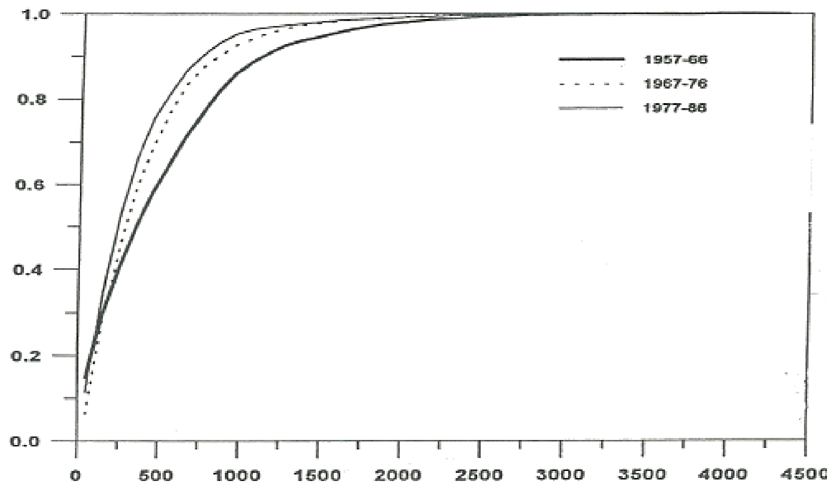

Fig. 11.12. *Probabilistic distribution of the discharges by the river Ebro, using flow- gauge records from 1957-1987*

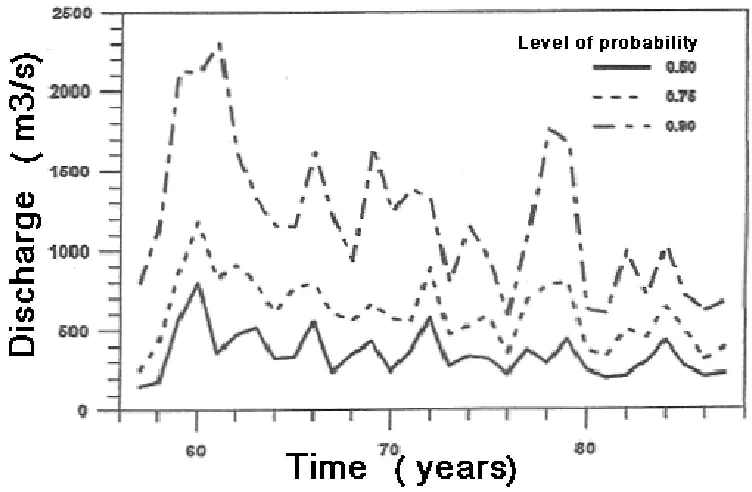

Fig. 11.13. *Variations in discharges by the river Ebro for a given probability*

In the *medium term* (a few years) shorter time series are required to analyse the underlying trends. We can generally expect a decreasing trend of the discharge in most (if not all) rivers of Spain. This is a serious disadvantage, because it hinders the choice of mean annual discharge, especially when this variable is taken as the "control" one. An example is given for the river Ebro in figure 11.14 (Jiménez and Sánchez-Arcilla 1997).

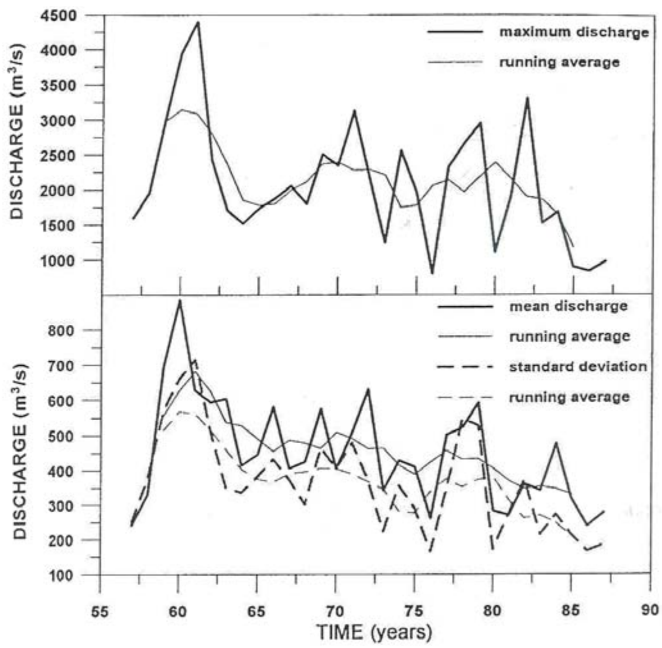

Fig. 11.14. *Temporal evolution of the liquid discharge of the river Ebro; (a) mean annual discharge; (b) annual maximums*

Espisodic events constitute the main contribution of the river to the volume and characteristics of the sediments on the coast, because they are the most efficient ones with regard to mobilising a solid discharge and, besides, it is precisely these that are most affected by local or regional climate change. It is difficult to quantify them, however, because even the episodic events in the present situation must be estimated using river discharge distribution extremes, which involves a high degree of uncertainty. Figure 11.15 presents an estimate for the river Ebro based on the annual maximums recorded since 1957 and using a Gumbel-type distribution. Any variation in discharge will lead to an increase or decrease in the solid discharge and a notable variation in the associated return periods.

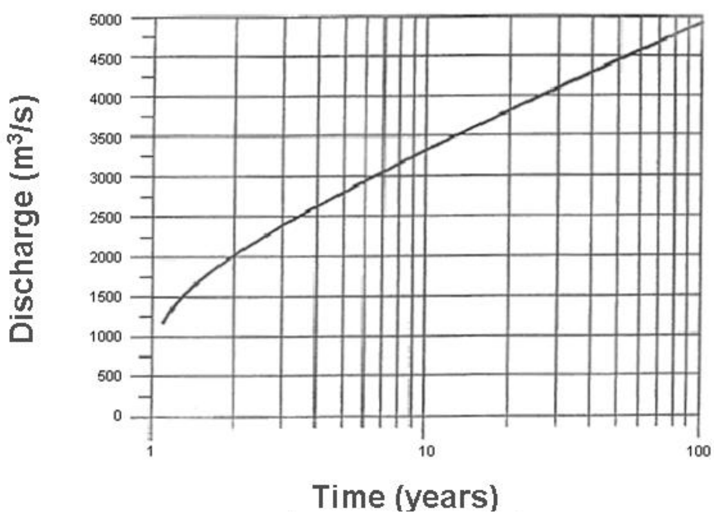

Fig. 11.15. *Regimen extremal for the discharges of the river Ebro*

The data on the liquid discharge of the rivers flowing to the South and East coasts are usually expressed in annual averages, taking their regulation system into account. With recent data from Water Basin Boards and other sources (Vanney 1970, Van Geen *et al*. 1997, MIMAM 2000), the mean discharges appear in table 11.2:

Table 11.2. *Liquid flows of rivers flowing to the coast*

River or basin	Discharge	Regulated (%)
Catalonia basins	1115	72
Ebro	12998	71
Júcar	1985	77
Segura	725	85
Sur	504	47
Barbate + Guadalete	842	44
Guadalquivir	7230	26
Tinto-Odiel	630	--
Guadiana	2525	75

Solid deposits

The solid discharge most directly affecting "external" coastal dynamics is the sand fraction or higher, transported as bed load by the river. The finer material is not stable on the coastline directly exposed to wave action, but it can contribute to the vertical dynamics of coastal lowlands and of the coasts of protected bays.

It is not easy to evaluate transport as bed load (Jiménez and Sánchez-Arcilla 1997) or to quantify it using direct measurements, because there is a very high degree of uncertainty (van Rijn 1993). Many formulae have been proposed, but the reliability and applicability of these are very limited and, in any case, they only indicate the theoretical transport capacity of the river in "ideal" conditions, without taking into account sediment availability or other limitations of real cases, an idea of which we attempt to establish using calibration parameters the value of which is unknown for our rivers. To this end, we can only consider the discharges in terms of order of magnitude. We can only obtain a time series of bed load discharges with the use of several formulae (Jiménez and Sánchez-Arcilla 1997).

In any case, and as we have already mentioned, it must be remembered that sediment supply by rivers in the recent past has been more conditioned by human activity in the basins or in the watercourses themselves than by climatic factors. We can expect the same thing to occur in the future.

By way of an illustration, the mean solid supply of the river Ebro was estimated for the sand fraction at 30,000 m3/year. The mean supply of the river Guadiana for the different sediment fractions and in the last four decades was estimated at 1 Hm3/year.

11.3.4. Precipitation

The possible effects in the coastal area of changes in the rainfall regime are more related to rainfall in the river basins than with rainfall on the coast itself. Projections by climate models indicate a decrease in total annual rainfall and a small variation in the frequency and/or intensity of torrential rainfall, which is more significant from the point of view of possible effects, as the coincidence of intense rainfall and storms establishes the ideal conditions for cliff slides. These processes, however, are restricted to relatively small sectors of the cliffs, of which only some present human structures in risk areas. Furthermore, the increase in the frequency and/or intensity of storms in the river basins can give rise to an increased risk of flooding in the lower courses and areas close to the river mouths, particularly the coastal lowlands in the vicinity of the estuaries. These effects will naturally be exacerbated with a local over-elevation of sea level due to meteorological causes, low pressure or spring tides, or in a permanent and general manner, due to a rise in mean sea level (MSL). .

Obviously, changes in the rainfall regime (and possible related flood events) could affect river supply of sediments and other substances to the coastal area. With regard to sediments, the available data suggest that the alterations resulting from human activity are much greater than those caused by climate changes. In some estuaries in the North of the Peninsula, sedimentation rates have increased one order of magnitude during the 20th century (Remondo *et al*. 2003). Climate changes detected in this period are very slight and do not reasonably account for this increase; increased human activity seems to be the most reasonable explanation. We could expect this to be valid, too, for deposits of pollutant substances (livestock farming and agriculture, industrial or urban), which are much more conditioned by the type and intensity of present and future economic activities and of the corresponding preventive or corrective measures, than by changes in rainfall patterns.

11.4. MOST VULNERABLE AREAS

11.4.1. Vulnerability and risk

A detailed analysis of the risks for the whole coast is not among the objectives of this study, but we can make a qualitative evaluation of these and present quantitative estimates for certain specific cases.

What is understood as vulnerable areas are those that can suffer some kind of damage as a direct or indirect consequence of climate change, due to being subjected to some type of risk, risk being understood as total predictable material losses. In the context of this analysis, it would be of interest to estimate the risk in vulnerable areas, which obviously depend upon the processes acting in each area, and upon the intensity of these.

Losses (risk in the context of this analysis) are estimated according to the *exposure* (existence of damagable elements in areas that could be affected by processes representing a potential danger), the *vulnerability* (sensitivity of the existing elements to these processes, or fraction of their total value that would he damaged) and the *hazard* (probability of occurrence and magnitude of a dangerous process in a given period of time, or recurrence period thereof, in a given land unit).

11.4.2. Probability of failure or risk

The risk or probability of failure of the system should be quantified taking into account the temporal and spatial scales considered, and the uncertainties involved in the calculation. Likewise, damage assessment should consider these scales of time and space and use a procedure that incorporates both the positive and negative response of the system. The negative response, or susceptibility, indicates the degradation of the system, or the incapacity of this to deal with modelling agents in their current state. The positive response, or “resilience”, implies an improvement in the system or its capacity to deal with the impulsive agents.

Here we should consider, on one hand, the likelihood of short-lived violent episodes (storms and tsunamis) in the future. And, on the other, the probability that, within the temporal horizon considered in this analysis (decades, centuries), there will be a rise in sea level of a given magnitude. This probability can be estimated with the use of two procedures: a) empirical, based on the analysis of change trends in the last century and the extrapolation of these according to different scenarios; b) deterministic, based on climate models.

As a whole, it could be said that we are now faced with a “high risk and high uncertainty” situation. The potential damage caused by failures in the coastal systems resulting from climate change is very great, but there is also considerable doubt with regard to the magnitude of these changes. The main uncertainty refers to possible changes in the frequency and intensity of storms and the magnitude of the rise in MSL.

11.4.3. Damage

As we mentioned previously, the vulnerability of coastal areas to climate change essentially involves two types of units: beaches and coastal lowlands in the vicinity of estuaries and deltas.

The vulnerability of these areas basically corresponds to three types of situations or characteristics: a) presence of structures or property with market value that represent “capital subjected to damage”; b) existence of natural elements of no market value, but which are the basis of economic activities and which could be negatively affected; c) existence of valuable natural units, not necessarily directly associated with economic activities, but which could suffer deterioration.

The first area fundamentally corresponds to areas at risk of potential flooding, in a permanent or intermittent way, in which the value of land and crops, buildings or infrastructures existing therein could be affected. These areas mainly exist in the vicinity of deltas and estuaries, and in many cases, correspond to old wetlands or desiccated intertidal areas. There are also certain areas, not very numerous, situated above all at the upper part of beaches, with buildings or structures that could be affected by a rise in sea level and/or more intense storms or tsunami-type events.

The second group essentially comprises confined beaches, which could suffer a considerable area reduction or even totally disappear.

The third group includes wetlands and supra- or intertidal areas, which could disappear as a result of a rise in sea level, although this disappearance would probably be partially compensated by the appearance of new wetlands in coastal lowlands such as the ones previously described. The degree of vulnerability of the dune fields associated with beaches is lower, although in some cases, their area might be reduced or they might disappear as a consequence of a rise in mean sea level or more intense storms.

Analysis of likely damage should take two aspects into account: On one hand, possible losses of “capital” (damage to infrastructures or buildings, loss of land, etc.). On the other hand, we should also consider the losses caused by the different disturbances that can affect various types of economic activities. The former is easier to deal with, as it refers to material elements existing in the territory, whereas the latter involves much greater uncertainty, especially if we take into account the great difficulty involved in making predictions with regard to the economic activities that will take place several decades from now.

11.4.4. Delta areas

The delta areas, currently out of balance due to the shortage of river sediment supply that generated them in the first place, are a good example of threatened areas presenting a high risk of disappearance. The concentration of human values (e.g. Llobregat delta) and natural ones (e.g. Ebro delta) existing on them account for their degree of vulnerability.

In order to apply these concepts to a coastal process, the appropriate temporal scales must be introduced. It is also convenient to use a vulnerability index summarising this information, which is often fuzzy and inaccurate, through a limited set of parameters. Sánchez-Arcilla *et al*. (1998) have proposed a partial vulnerability index:

$$Vi=Qi \cdot Si \cdot Lc+Ri \cdot Lc$$

Where *Si* is the susceptibility index, *Ri* is the resilience index, *Lc* is a local control factor that acts as 1 or 0 (eventually an intermediate value) and *Qi* is an index that reflects the area of the process analysed.

An illustration of the binary evaluation of susceptibility or resilience indices for certainsection coastal sectors appears in table 11.3. An application of this methodology to long-term susceptibility or resilience indices for a delta area (the Ebro delta) appears in table 11.4.

Table 11.3. *Susceptibility (SI),and resilience (RI) indices and response by the associated system used, to be used in the vulnerability analysis.*

Analysis type	Measure	Response	SI	RI
Absolute	Change of "resource"/	Decrease	-1	0
	Stock	Maintenance/increase	0	1
Relative	System under scenario/	Worsening	-1	0
	Reference	Improv./no change	0	1

Table 11.4. *Susceptibility (SI) and resilience (RI) indices in the long term for agents affecting geomorphological vulnerability and processes associated with this scale. "?" means that an a priori assessment cannot be completed without knowledge of the final consequences.*

Agent	S.I.	R.I.	Response
River discharge	-1	0	Decreased transport capacity
	0	1	Increased transport capacity
RSLR	-1	0	Vertical accretion < RSLR
	0	1	Vertical accretion = RSLR
RSLR	-1	0	Coastal erosion
	0	1	Stability/coastal accretion
Barrier processes	-1	0	Limited rollover
	0	1	Increased rollover
	-1	0	Transport capacity increases
Wave climate	0	1	Transport capacity decreases
	?	?	Transport direction changes

The assessment in the case of episodic events, the most determinant ones for remodelling the physical substrate in any section of coast, appears in table 11.5 for the Ebro delta area. A schematic representation of these indices, with their corresponding area of spatial definition for this same delta area, appears in figure 11.16. An assessment of the corresponding vulnerability at medium-term scale appears in figure 11.17. As can be seen, the vulnerability map changes appreciably according to the time scale chosen.

***Table 11.5.** Susceptibility (SI) and resilience (RI) indices at episodic scale for agents affecting geomorphological vulnerability and processes associated with this scale*

Agent	S.I.	R.I.	Response
Fluvial switching	-1	0	Abandoned lobe
	0	1	New lobe
Fluvial switching	-1	0	Deposit of "protected" sediment
	0	1	"Exposed" deposit
Floods	-1	0	*wash-out* sediment
	0	1	Deposit sediment
Wave storms	-1	0	Erosion / breakage
	0	1	deposit hinterland sediment

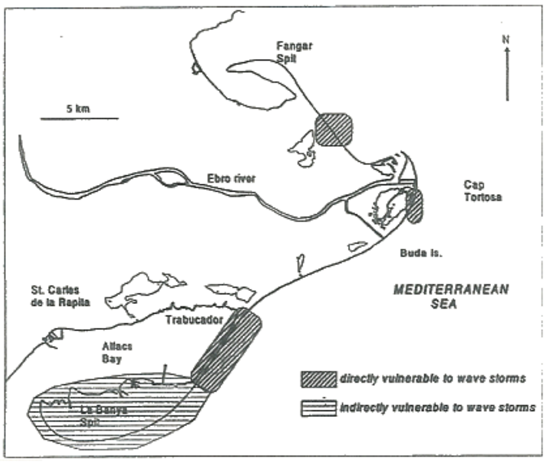

***Fig. 11.16.** Qualitative vulnerability index at "episodic" scale for the Ebro delta*

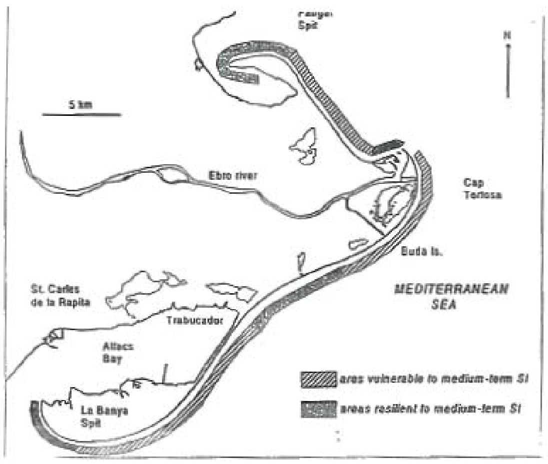

***Fig. 11.17.** Vulnerability caused by changes brought about by sediment transport along the coast in the medium-term in the coastal area of the Ebro delta*

Evaluation of the joint vulnerability of the system, taking its different components into consideration, requires a wider analysis framework. It is therefore necessary to schematise the coastal section and to specify the impulsive agents, and the corresponding associated processes, as both of these affect the uses and resources in the coastal sector. Figure 11.18 shows a conceptual diagram applied to the Ebro delta coastal area. The key point of this diagram is the identification and subsequent quantification of the flows linking some elements with others. These flows vary in magnitude and even in definition with a change in time scale. For instance, irrigation practices and the construction of dams and reservoirs do not affect short-term coastal erosion, but they play a determinant role in coastal dynamics in the medium and long term. This is due to the control both elements have over the solid supply that the river transports to the coast.

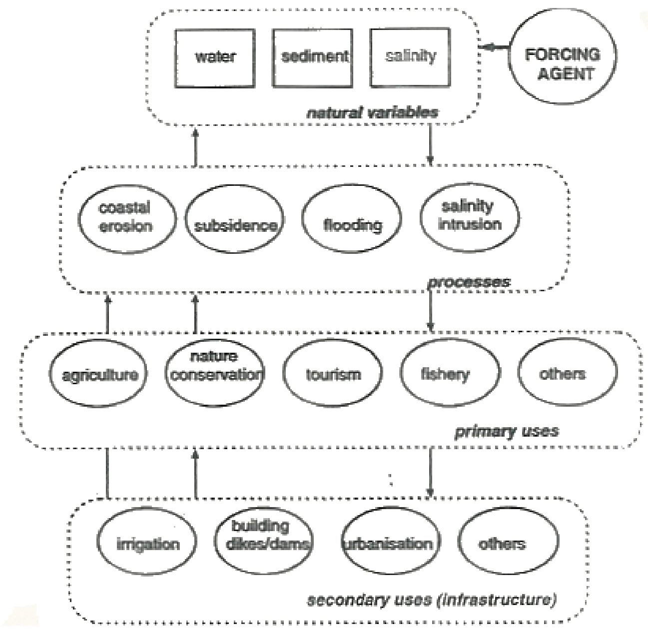

Fig. 11.18. *Diagram of the delta system according to main processes and uses (adapted from Otter et al. 1996)*

11.4.5. Beaches and coastal lowlands

The values and functions of beaches differ with regard to both their nature and location. The biotic communities they contain are not especially rich or varied, but they are very specific to these environments. Due to their diversity, scarcity and endemic condition, the communities of the dune fields associated with some beaches should be highlighted. Furthermore, their importance as a base for the development of activities related to the tourism and recreation sector is well known. We must also consider the coastal geotopes or physical support on which these ecosystems become established. These geotopes contain sediments and morphologies that can easily be dated, and represent sources of information needed to decipher the climatic history of the last few centuries or millenia, and thus help to estimate future change trends

A rise in sea level will bring abaout a displacement of beaches or a retreat caused by erosion, with a reduction of their total useful area. This retreat will depend on the specific characteristics of each beach and it is not possible to present a detailed analysis of each case. By applying Bruun's rule (1962, 1986, 1988), which establishes an advance by erosion of 1 m for every centimetre of rise in sea level, and considering the confined or unconfined condition of beaches, as well as their width, it can be estimated that a rise of 0.5 m could cause the disappearance of 22 km of the length of the beaches in the Basque Country and Cantabria, which is the equivalent of approximately 30% of the total (Table 11.6). As is logical, this disappearance will fundamentally affect narrow confined beaches with gentle slopes. Wider beaches (>50 or 100 m) will be reduced in area, without disappearing. This estimation is based on a hypotetical absence of additional supply of sediments by natural or human-induced causes. Obviously, an increase in the sediment response will reduce the values of table 11.6.

On unconfined beaches, especially spit bars and sand ridges associated with dune fields, the areas loss can be expected to be much less or even nil, although the adjacent dune fields will probably be reduced.

However, it is worth remarking that the assessment of climate change effects based exclusively on the sea level rise is an obvious simplification. A more precise analyse should include the effects derived from the variations in swell height, period and direction.

Table 11.6. *Summary of the characteristics of the beaches in Cantabria and the Basque Country, along with a semi-quantitative estimate of the the likely effects of two scenarios of a rise in sea level on the beaches of Guipúzcoa, Vizcaya and Cantabria, by applying Bruun´s rule (modified from Rivas and Cendrero 1995).*
(1) Spit bars or beach ridges. Some of these are confined along some of their length by cliffs (e.g. Oyambre) or by artificial structures (e.g. Zarauz) and a part of these beaches will therefore also disappear with a rise in sea level.
(2) The reduction will be even greater, as the average width of the beaches has been taken into account, but the width of many of these, along much of their length, is much less than this average figure.

	Confined beaches			**Unconfined beaches (1)**
	Present	Rise 50 cm		
Number of beaches	95	33	35 %	17
Guipúzcoa	17	12	70,6%	2
Vizcaya	22	10	45,4%	3
Cantabria	56	11	19,6%	12
Lenght (km) (2)	45	23,6	51,9%	25,4
Guipúzcoa	9,42	6,6	70%	2,85
Vizcaya	9,2	5	53,4%	1,5
Cantabria	26,37	12,15	46,1%	21,1

The strip of sand constituting the natural border between land and sea in these coastal lowlands in the Mediterranean environment has been gradually disappearing over the last few decades, mainly due to the alteration of the sediment balance in the coastal area, the net result of which is the alarming decline in sediment input, and, as a consequence, the retreat of the coastline and the loss of beaches.

The main inputs of material involve supply by rivers, transport of material along the coast by longshore drift, sediment exchange between the beach (*backshore*) and the dune systems due to the action of the wind, and the seasonal exchange of sediment between the sub-aerial "beach" (*foreshore*) and the submerged "beach" (*shoreface*). All of these have been modified by human intervention.

The progressive decrease in fluvial sediment load due to the construction of dams, river regulation and the fight against erosion in drainage basins, together with the construction of coastal and port structures have led to a drastic decrease in the natural evolutionary capacity of the coast, as they limit the capacity for movement of the different sediment masses from one coastal segment to another. This has unleashed erosion processes and the retreat of the coastline. Furthermore, the occupation of the upper part of the beach prevents the recovery of the profile following the highly erosive storms that occur mainly in wintertime.

The occupation of *backshore* and dune belts, subsequent to massive development along much of the Mediterranean coast, has not only used up a large part of the beaches' natural sand reserves, but has also altered wind dynamics, creating real "corridors" between the higher buildings, through which the wind is channelled, thus increasing aeolian erosion in certain parts of the beach.

The construction of port and coastal structures, apart from contributing to the rigidity of the shoreline, has limited coastal dynamics and the capacity of the system for natural recovery following storms and floods. Such structures act as sediment traps upstream from the drift, leading to erosion downstream, as an attempt by the coastal system to recover sediment balance.

This is the case on the Atlantic coast of the Gulf of Cadiz, where the many existing structures (in an area of high natural variability, resulting from the presence of large inlets, interfere with longshore drift and increase the erosion of the soft cliffs in favour of some beaches, such as those to the west of the Guadiana and Odiel-Tinto estuaries.

The degeneration processes began with the development of tourism and of the economy in the 60s (for example, the Ribaroja-Mequineza complex, which affected the whole Ebro delta, or the housing development in La Manga del Mar Menor). In short, the intervention policy along the coast, together with the obstruction of natural dynamics (fight against river and sea flooding and prevention of the associated silting processes) has accelerated erosion processes on a strandline subjected to great pressure by urban, recreation, port and infrastructure uses. A good example of this is the Maresme coast in Barcelona, made up of a quasi-continuum of housing development and "rigidised" by a railway line and a road running close to the shoreline, and often separated from this only by a longitudinal rockfill.

Furthermore, the high level of occupation of the coastal fringe, particularly of the partially consolidated sand barriers in the coastal lowlands (for example, from Guardamar de Segura to Torrevieja in Alicante and La Manga del Mar Menor) causes increased subsidence due to overload.

On the coastal lowlands of Malaga and, above all, Almeria, the problems lie in the use of the natural coastal alluvial plains for greenhouse crops, with the consequent re-mobilisation of the natural soils and the overexploitation of the aquifers, which cause salinisation.

Another problem involves the loss of environmental quality of the waters, which damages the fields of *Posidonia sp.* and other ecosystems, the loss of which might eventually affect climatic balance. One of the points most affected is the area facing La Manga del Mar Menor. This area should be carefully monitored, especially with regard to the construction of new coastal and port infrastructures or water desalinisation plants. The possible impact of a rise in MSL in the near future should be carefully estimated here.

11.4.6. Estuary areas

These units present a high diversity of socioeconomic and natural values, and therefore greater vulnerability. Estuaries contain some of the main ports along the N, NW and SW coasts and also many of the main population settlements, and much of the economic activity takes place in those areas. There is a considerable potential for tourism and recreational activities, thanks to the landscape value of many of the estuaries and bays, the associated beaches (both inside and at the river mouths), possibilities for sailing, etc. The estuaries are associated with large intertidal areas and wetlands with high biodiversity and biological productivity, and these are very important for the fisheries sector, both directly (traditional fishing, shellfishing, aquaculture) and indirectly, as they are the breeding and/or feeding grounds of many species. However, throughout much of the XIX and XX centuries, the desiccation and infill of many wetlands and marshlands was carried out in order to use them for urban areas, industrial estates, infrastructures, agriculture, etc. This generated large areas that sustain considerable public and private real estate capital (high-value land, buildings, infrastructures, services, etc.). This pressure caused by occupation probably constitutes the main threat affecting these areas at present.

The predicted damages in the vicinity of estuaries or much smaller-area lowlands, associated with snad bars not linked to the mouths of significant water courses, are due, above all, to the rise in mean sea level and to the risk of flooding of old wetlands and intertidal, desiccated wetlands, which were not filled, or which were only filled with a thin layer (Cendrero and Díaz de Terán 1977; Cendrero *et al*. 1981). Many of these areas are occupied by buildings (residential, industrial, services, infrastructures); some of them are less than 1 m above current spring high tides, and a rise in sea level would therefore seriously affect them. One way of estimating the risk for these areas is to consider certain scenarios of sea-level rise, delimiting the areas that would be affected by these rises and making an inventory of the property existing therein (“capital at risk”).

An estimate was made of the potential damage a rise in sea level would cause along the coasts of the Basque Country and Cantabria (Rivas and Cendrero 1991, 1995). The procedure used is illustrated, for a small estuary, in Figure 11.19. A representation of the areas that could be affected (for a scenario of a 1.5 m rise, greater than what is considered to be reasonable in this study) is shown in figure 11.20. It is estimated that in the Basque Country and Cantabria, rises of 0.5 and 1 m would affect, respectively, around 25 and 79 km^2. The estimated value of the “real estate” capital at risk for all three provinces analysed would be, respectively, 820 and 8370 $x10^6$ US$ (1991 figures not updated to 2004 prices; Cendrero *et al*. 1981; Rivas and Cendrero 1991,1995). These figures consider the total loss of the land, buildings and infrastructures existing therein. The real loss of capital, considering that most of the buildings have a limited useful life, generally shorter than the end-of-century horizon contemplated, would be less.

With regard to the marshlands and intertidal areas that maintain their ecological values, two cases should be highlighted: if there are adjacent coastal lowlands, these areas will be displaced inland as sea level rises; this could particularly affect areas that were previously desiccated but that had not been filled. To the contrary, when wetlands cannot be displaced inland, they can be expected to diminish or disappear. It is therefore very important to identify the possible prevention or mitigation alternatives.

A rise in sea level of the magnitude previously mentioned would most likely lead to the recovery of a large area of wetlands and intertidal areas, which would represent a positive impact. Some of the areas below 0.5 m are simply isolated and desiccated or used for agriculture or forestry, or even are not used, and they could therefore recover their original functionality as wetlands or intertidal areas in a period of a few years, either through spontaneous recovery processes set in motion by abandonment, or as a result of deliberate restoration actions (for example, breakage of the existing barriers), even without any change in sea level. In the case of a rise in sea level, practically all of these areas would become wetlands. If there were to be a rise of 1 m, the areas that could be recovered as wetlands would probably exceed 30 km^2. Although there are no detailed analyses that could enable us to quantify this effect, it seems unlikely that the net result will involve a big change in the total wetland area, and these would essentially be displaced.

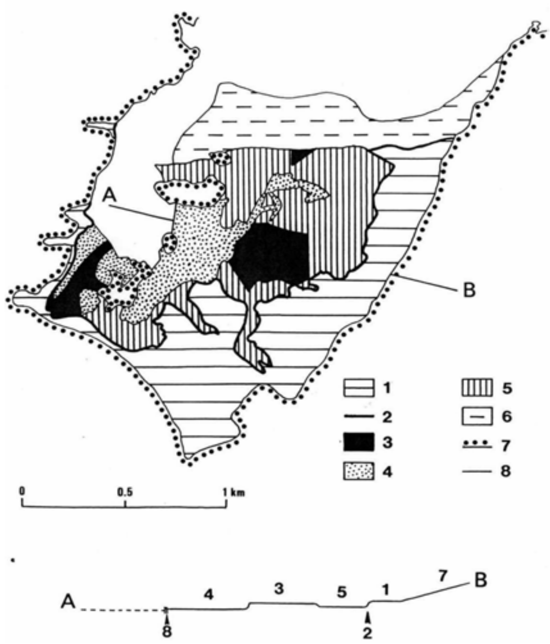

Fig. 11.19. Procedure for identificationand mapping of areas at risk in the vicinity of a small estuary (Rivas and Cendrero 1991)

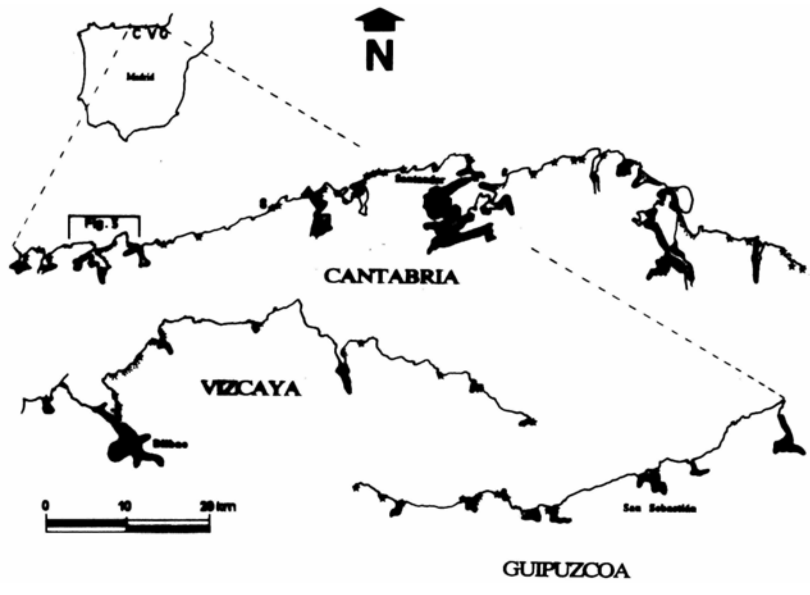

Fig. 11.20. Areas that could be affected by a scenario of a 1.5 m rise, greater than what is considered to be reasonable in this analysis (Rivas and Cendrero 1990)

Special mention should be made of the beaches associated with estuaries. As has been explained before, some of these beaches may disappear, but others, such as sand spits at river mouths, will be more frequently subjected to *overwash* events (in storms with very high waves) and lateral displacement of harbour mouths, and finally displacement inland. This apparently contradicts the results by Rodríguez Ramírez *et al*. (2000) who observed that, in the last few years, the growth of beach crests, that is, the progradation of the litoral spit bars occurs during periods of higher sea level. The explanation is that there are small rises of little duration after which the usual situation of "low sea level" is re-established. However, in the case of the supposed rises in MSL in the scenarios of this study, the magnitude of the rise is greater and, besides, the level will remain high and the over-elevations will occur when these high values are reached.

Furthermore, they are also vulnerable to changes in the rainfall regime, fluvial discharge and floods, especially if these increase and coincide with a rise in MSL. This would cause an increase in the frequency and/or magnitude of the floods. We must also take into account changes in the supply of sediments or other substances (nutrients, pollutants) that can derive from changes in river regimes. Lastly, an increase in mean sea level will give rise to greater penetration of the saline wedge into the water courses and to an advance of the freshwater/saltwater interphase of the aquifers.

11.4.7. Soft cliffs

The potential threat in the areas with cliffs depends very little on climate change, and mainly involves the growing pressure from housing development along their length. In the few sectors with "soft cliffs" presenting significant retreat rates and which contain buildings or structures, changes in the oceanic climate and sea level can lead to an increase in these rates, with the consequent risk for the adjacent buildings.

In the case of cliffs, even of the "soft" typology, a rise in sea level of around 50 cm or 1 m would not have any significant effects. In the case of the coasts of Cantabria and the Basque Country, a total of 9 km of cliffs with a marked erosion rate has been identified, and in only two places a problem might arise, one in Cantabria and another in Vizcaya. It has been indicated that in the first of these (Oyambre beach), an acceleration of the retreat rates has been detected since 1946, up to values of several metres per year in the 90s (Rivas 1991; Rivas and Cendrero 1995).

On the Atlantic coast of the Gulf of Cadiz, soft cliffs represent over 50% of the coastline, and are subjected to intense erosion which, in the Mazagón area, presents a rate of between 1.25 and 2.2 m/year (Rodríguez-Ramírez 1998). This is mainly due to the interference of the Dique de Juan Carlos I (Juan Carlos I Pier) which, with a length of 14 km, has interrupted logshore drift and accelerated erosion downstream and favoured the accumulation of a 4 km-long beach attached to the pier upstream, in the old "Banco del Manto".

11.5. MAIN ADAPTATIONAL OPTIONS

Classical coast management strategies, also applicable to a future climate change at regional scale causing a relatively rapid rise in MSL or a change in the characteristics of storms, include retreat, adaptation and defence.

The *retreat strategy* requires, in the first place, the necessary available space to re-locate activities and resources in the coastal sectors cocerned. If space is available, this strategy is the one that is most in concordance with the big uncertainties in relation to the prediction of climate change at regional scale and, furthermore, it does not reduce degrees of freedom for future decisions in the area.

The *adaptation strategy* requires a different approach for erosion and flooding as well as social and economic flexibility, given the degree of uncertainty of the predictions. In the first case, the strategy for combating erosion, from the adaptation point of view, requires the emplacement of certain soft structures and flexible use of the land-sea interphase. At present, the most commonly used strategy involves the use of vegetation for support and dissipation, aimed at reducing erosion risks. In the second case, the risks and costs associated with flooding can be predicted, although with a certain degree of uncertainty, and, in any case, all the users and managers of the coastal area must be familiarised with them. It should not be forgotten that flooding defences would require continuous maintenance and eventual re-growth, if the coastal sector were to suffer subsidence or if there were to be a eustatic rise. This practice is applied in countries like Holland, which wage a secular war against this type of problems.

The *defence strategy* is the one that society usually prefers, due to its “apparently” monolithic nature in relation to erosion or flooding. This involves initially high costs, but we should also remember that it requires maintenance costs, as can be seen, for example, in the history of the defence and protection structures on the Maresme coast. This defence strategy can therefore only be considered for certain coastal sectors, always keeping the time factor in mind and, what is very important, the degree of uncertainty of the structural resistance of the solution adopted, like, for instance, its functional design.

The best solution for any temporal scale chosen consists of combining the three elements, all of this within a framework of an integrated plan for the coastal area.

11.5.1. Beaches

In *unconfined beaches*, the most recommendable strategy, in general, is the one involving retreat, as this is the natural behaviour to be expected in the case of beaches and associated dune fields. In certain cases, this might involve the invasion of areas containing elements of interest.
The strategy of non-structural intervention involves the prompt establishment of land planning laws aimed at preventing new structures or activities in vulnerable areas. Initially, this should be a task at municipal level, and should be based on town planning revision, with the help of specialists and technical advice by the appropriate organisations, in order to delimit the vulnerable zones. It would therefore be necessary to set a time limit for municipalities to carry out this task.

This strategy should provide for the progressive abandonment of the buildings, infrastructures, croplands, etc., located in the vulnerable areas, and this presents two limitations: accurately determining the areas that will be affected, and, in particular, when the damage will occur. We should therefore work within the range of possibilities corresponding to the “optimistic”, “pessimistic” and “most likely” predictions. Given that abandonment represents a “de facto” transfer of private property to the public domain, indemnity, compensation or expropriation plans should be drawn up, and the impact of the limitation of the owners’ rights to use should be compensated for.

When the migration of the beach and/or the dune inland represents a loss which is considered to be unacceptable, the strategy of artificial nourishment or structural intervention should be implemented. In both cases, a line of maximum retreat should be indicated, in order to allow for better planning of the coastal area. Thus, apart from delimiting the areas that could be affected by the migration (considering the different scenarios), vulnerable property or elements existing therein should be inventoried and valued, in order to determine what requires protection and compare their value with the cost of necessary protection measurements. This analysis should obviously be made for each case in a detailed manner, within the context of the aforementioned revised town planning.

The situation is very different for *confined beaches* because if there is no structural intervention, the useful area of some of them will be reduced and will disappear in other cases. On the beaches that have been stabilised with the use of groins, piers and other coastal structures, the impact of local climate change is difficult to predict. The behaviour of the coastal structures will vary appreciably (Sánchez-Arcilla *et al*. 2004) with any change in mean sea level or in wave climate. The functional design of coastal protection should therefore be reassessed, and the durability of artificial sediment nourishment should also be included.

The urgent need to promptly establish a strategy in this sense is clearly illustrated by the data presented in section 11.4.5.

11.5.2. Soft cliffs

The options in this case are more simple, given the fact that in very few cases are there structures or buildings that could be affected by cliff erosion, and, in any case, this would be clearly of lesser magnitude than the migration of beaches.

One exception is the cliffs of the Costa Brava which, due to their high density of fractures and high level of housing occupation, constitute a coastal problem of increasing importance.

The retreat strategy, aimed at allowing nature to follow its course, would have implications similar to those described for beaches susceptible to migration. It would also be necessary here to delimit the areas that might be affected, to inventory and value existing property, establish use limitations in certain areas and provide for the abandonment of buildings, etc. (and the consequent compensation).

If the abandonment of certain structures subjected to potential risk is considered to be unacceptable, the installation of protection elements will have to be provided for (for example, block barriers at the foot of the cliffs). The valuation of the property to be protected and the comparison between this and the protection costs will obviously be used as a base to decide which strategy is to be implemented in each case.

Given the existing uncertainties with regard to the materialisation of the threat, follow-up and monitoring systems should be put into practice in order to determine to what extent the risk is real and requires intervention. These systems can range from the simple placement of set of reference points, perpendicular and parallel to the cliff edge, and *in situ* visual surveillance, to continuous register systems or detailed photogrammetry at regular intervals.

11.5.3. Coastal lowlands

The situation of delta coastal lowlands is very much threatened by the lack of sediment supply. The remodelling capacity of climatic factors is maintained, while the volume of the sedimentary body diminishes steadily. The adaptation strategy based on maintaining a dynamic border between land and sea allows the duration of the delta sedimentary body to be maximised. Mitigation is more complex to implement in practice. Local mitigation with the use of sand, partial fixation with the use of vegetation or total, rigid fixation using structures is costly and difficult to sustain. A general mitigation system for the delta body based on sediment supply, for instance, through natural peak discharges or controlled reservoir discharges, is therefore considered to be more advisable.

From the point of view of mitigation strategies, the situation of wetlands and intertidal areas is comparable to that of beaches and dunes. Some of these wetlands, both the ones associated to estuaries and the few that exist outside them, can migrate inland, occupying the adjacent coastal lowlands. The retreat strategy will surely be the most suitable one in most cases, as it will generally allow the total area of these to be maintained. If this option were to be taken, the abandonment of the land and structures that could be affected would need to be provided for. If this option were to be considered unacceptable, due to the existence of buildings, structures, etc., that need to be maintained, protection walls or dykes would need to be built, along with pumping systems to avoid a rise in the phreatic level ("Dutch solution"). In certain areas, additional filling and elevation of certain structures could be considered (for instance, the airport runways of Fuenterrabía and Santander).

In other cases, the migration of wetlands inland becomes impossible, due to the presence of different types of barriers. If there is no alternative the final result will be a reduction of the area of wetlands, which will become totally or partially submerged. In other cases, it will be possible to eliminate the barriers, (for example, in areas that have simply been closed off and drained), thus facilitating the migration and/or regeneration of areas previously occupied by wetlands. It has been estimated that on the coast of the provinces of Guipúzcoa, Vizcaya and Cantabria there could be around 30 km^2 of areas with these characteristics, that is, potentially recoverable.

11.5.4. Ports

The local climatic impact on port infrastructures essentially refers to the levels of infrastructures and their capacity for resistance. The first point is illustrated by the level of dyke tops (which condition the overflow volumes) or by the area of dykes exposed to more rigorous conditions. The point of resistance capacity is therefore based upon a change in MSL and on the intensity, duration and recurrence of storm surges. All of this requires re-evaluation of the reliability of coastal structures.

11.6. REPERCUSSIONS FOR OTHER SECTORS OR AREAS

11.6.1. Interaction with the hinterland of the coastal area, including the drainage basin of rivers

A rise in mean sea level would cause a rise in the base level of rivers, which would lead to increased sedimentation in the lower courses of these, especially in estuaries, which will have repercussions for the maintenance of ports. It is not possible to evaluate the relative importance of this factor in comparison with the variations in sediment supply caused by changes in land uses in the river basins. It will also cause greater penetration of the salt wedge into the estuaries, displacing the sedimentation zone inland, through flocculation.

An increase in MSL will probably also determine greater frequency and intensity of flooding in the lower courses of rivers, and this effect will be accentuated if the intensity and frequency of torrential events were to increase.

11.6.2. Interaction with fisheries

A reduction of wetlands and intertidal areas would affect biological productivity, as these are high-production areas and are fundamental for the reproduction and/or feeding of different species of interest. It is therefore important to facilitate as much as possible the migration of these areas landwards, in order to maintain (or even increase) their total area.

11.6.3. Interaction with tourism

The tourism sector is the one that will probably be the most affected, due to the reduction or disappearance of many beaches. It will be necessary to plan ahead, in order to gradually implement beach protection or regeneration actions, or to develop types of “sun and sand tourism without sand”. The example of Puerto de la Cruz (Tenerife) or the more recent bathing area in the Barcelona Forum enclosure, are examples of adaptation of the traditional tourism use of the coast to beachless environments.

11.7. MAIN UNCERTAINTIES AND KNOWLEDGE GAPS

11.7.1. Recent variations in sea level

In relation to changes in sea level (figure 11.21), data from tide gauges and from field data indicate that in the last 150 years, the rise in MSL has been around 1 mm/year (Mörner 2003), but “models of glacial loading” (Peltier and Tushingham 1989; Lambeck *et al*. 2003) enable it to be estimated at between 1.8 and 2.4 mm/year. Fundamentally based on these latter data, the predictions of rises in sea level for the next 100 years (year 2100) published by the IPCC have varied from values of 50-95 cm (IPCC 1998) and 23-49 cm (IPCC 1999) to 13-68 cm (IPCC 2001). Compared with these relatively alarmist estimates, the predictions by the INQUA – Sea Level Change and Coastal Evolution Commission, in their reports from 1993 to 2003 range from 10 to 20cm at the most. But in any case, the most interesting fact is that no acceleration of the rise in sea level has been recorded in the last 100 years.

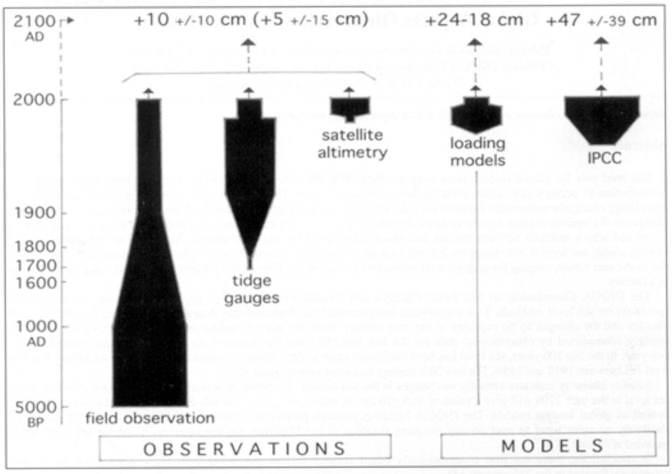

Fig. 11.21. *Means or techniques for recording or estimating changes in sea level, and for making predictions for the next century (Mörner 2003)*

The first satellite data (GEOSAT) on variation in MSL between 1986 and 1988, were not sufficiently accurate but, following the TOPEX – POSEIDON mission, the records improved (figure 11.22) and between 1993 and 1996 the level remained stable, with a noise of ±0.5 cm. Between 1997 and 1998 big oscillations in global sea level were recorded, coinciding with ENSO episodes (*El Niño Southern Oscillation*). Between 1998 and 2000 the register is irregular, showing no clear trend, but there is a possible small rise of less than 0.5 mm/year between 1999 and 2000.

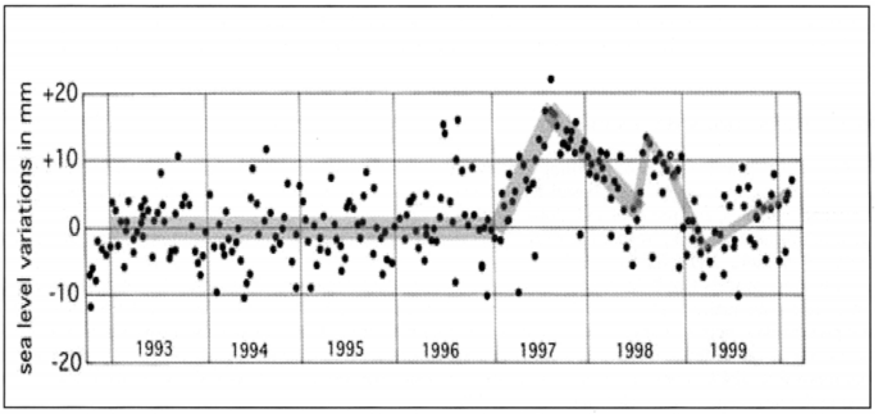

Fig. 11.22. *Measurements of variations in MSL by the TOPEX-POSEIDON satellite (Mörner 2003)*

11.7.2. Driving factors; Holocene climatic variations

The current Holocene Interglacial period (last 11,000 years) corresponds to a warm period which, until recently, was considered to be stable, especially when compared to the extreme variability of the last glacial period. Studies in the last decade, however, have revealed quite a different picture.

Ice cores in Greenland (GRIP, GISP) enabled Dansgaard *et al*. (1993) to recognise climate changes at a scale of thousands of years during the last glacial period, with temperature variations which Bryant (1997) establishes at between 6 and 7º C. Subsequently, Bond *et al*. (1997) recognised these oscillations in oceanic drillings in the North Atlantic, and extended them to the present time. They were less pronounced (only 2º C) during the Holocene, recognising cold events (Bond Events) of little duration (100-200 years) with a periodicity of between 1 and 2 Ka, the peaks of which date from 10.3 Ka, 9.5 Ka, 8.2 Ka, 5.9 Ka, 4.3 Ka, 2.8 Ka and 1.4 Ka (calibrated ages).

Different causes have been suggested for these climatic oscillations: variations in orbital parameters (cycles of 900 years, Loutre *et al*. 1992), oscillations in the ocean-atmosphere system (cycles of 1500 years, Bond *et al*. 1999), changes in solar activity (cycles of 2500 years, Stuiver and Reimer 1993) and fluctuations in the thermohaline circulation in the North Atlantic (cycles of between 550 and 1000 years, Chapman and Shackleton 2000). This climatic variability appears to of a global nature and must surely affect the climate in the North Atlantic (Arz *et al*. 2001).

In the Atlantic-Mediterranean connecting area, Cacho *et al*. (1999, 2001 y 2002) studied core drills in the Gulf of Cadiz (off the Huelva-Cadiz coast) and the Alborán Sea (off the Almeria coast), recognising events of sea surface temperature (SST) rise of a magnitude that is not well established and a periodicity of 750 years and harmonics. In Alborán, they are recognised at 8.2, 5.36 and 1.4 Ka, but in the Gulf of Cadiz, only at 8.2 Ka. Regardless of the exact value of the oscillations, there is evidence of a general cooling tendency during the Holocene in the Northeast Atlantic and in the Mediterranean (Marchal *et al*. 2002), which could be related to the transition of the hypsithermal interval (9-5.7 Ka BP) to the Neoglaciation (ca. 5.7 a = Ka BP).

11.7.3. Coastal response

Study of coastal units on the Mediterranean coast and in the Gulf of Cadiz has highlighted the existence of sedimentation and erosion trends which, once dated and calibrated, reveal a cyclical character comparable to the previous ones, observed at different temporal scales.

Decadal scale. The beach ridges are associated in double pairs separated by throughs or *swales* of greater range, and this grouping is called a *set*. In ideal conditions, the dating of mollusc valves collected in successive swales allows the time required for their accumulation to be estimated. In practice, only some of these swales can be dated, so that the time lapse separating them is divided by the number of ridges accumulated between both of them, to calculate the average accumulation time of a ridge.

In the Gulf of Cadiz (Doñana Spit bar) the duration of a set is 400 years (figure 11.23), that is, each ridge accumulates in about 100 years (Zazo *et al*. 1994), whereas in Roquetas (Mediterranean coast of Almeria) the corresponding values are 45 and 11 years (Goy *et al*. 2003), (figure 11.24). This difference is presumably due to differences in the tidal range, wave energy, sediment size and availability, without excluding the lower degree of conservation of the sand ridges formed on the coast of the Gulf of Cadiz. According to previous authors, the cyclicity of Roquetas appears to be related to simple sunspot cycles and with the NAO oscillation, whereas in Doñana, it is considered to be linked to secular sunspot cycles.

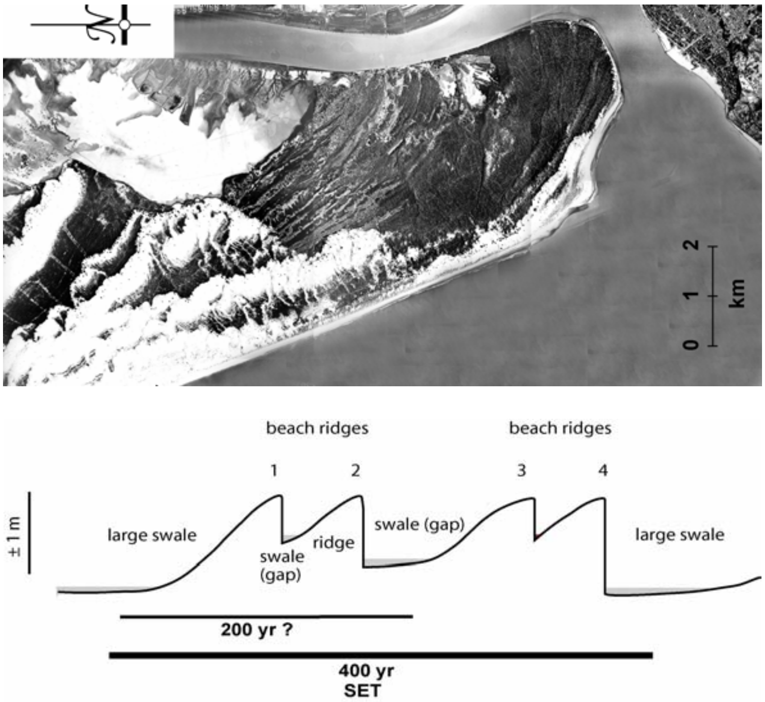

Fig. 11.23. *Doñana Spit (Cadiz) and accumulation diagram for approximately 100 years (Zazo et al. 1994)*

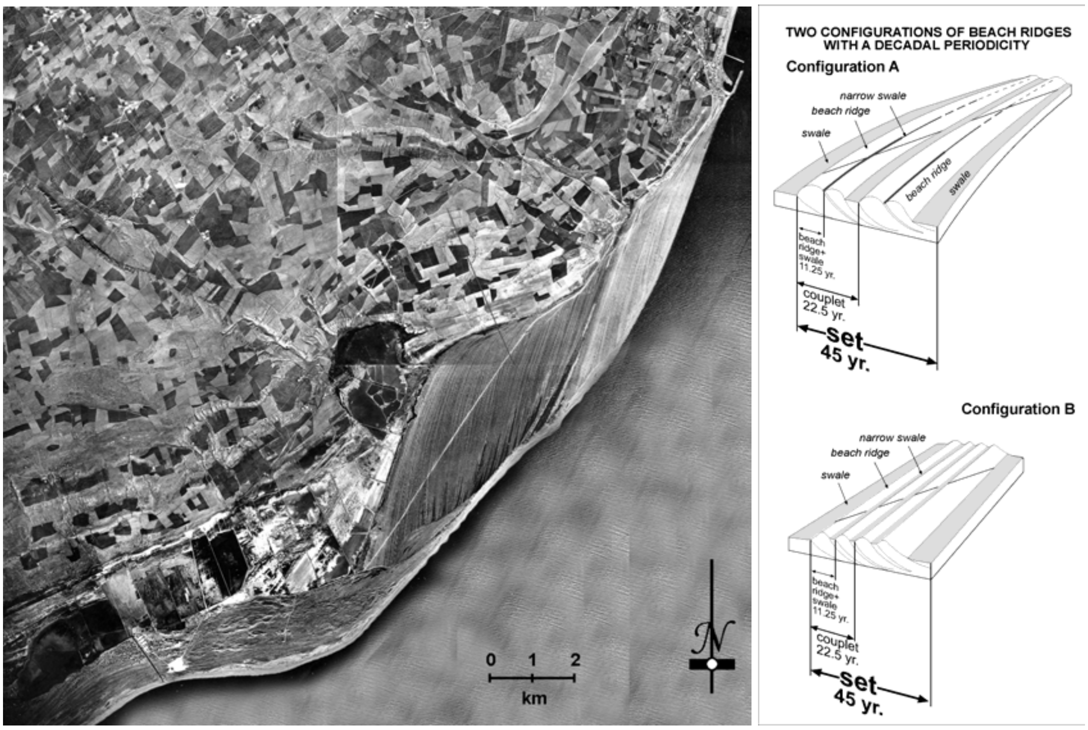

Fig. 11.24. *Roquetas Spit bar system(Almeria coast) and accumulation diagram every 11 and 45 years (Goy et al. 2003)*

In the recent records made by Rodríguez-Ramírez *et al*. (2000) on the litoral spit bars in Huelva for the last 40 years, the formation of very small (figure 11.25) beach ridges has been related to intensification of SW winds (storms), negative NAO index and a lower number of sunspots (figure 11.26).

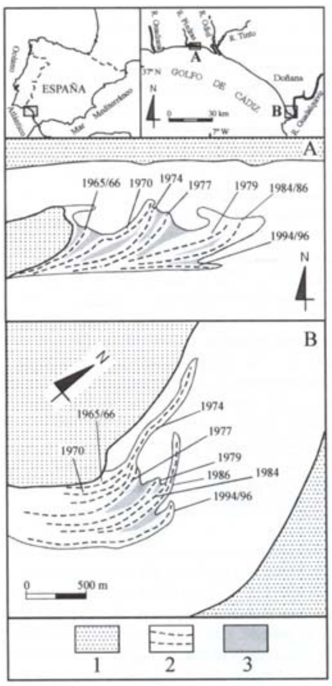

Fig. 11.25. *Beach ridges and swales. Growth chronology between 1956 and 1996 for the beaches of El Rompido (A) and Doñana (B) in the Gulf of Cadiz (Rodríguez Ramírez et al. 2000)*

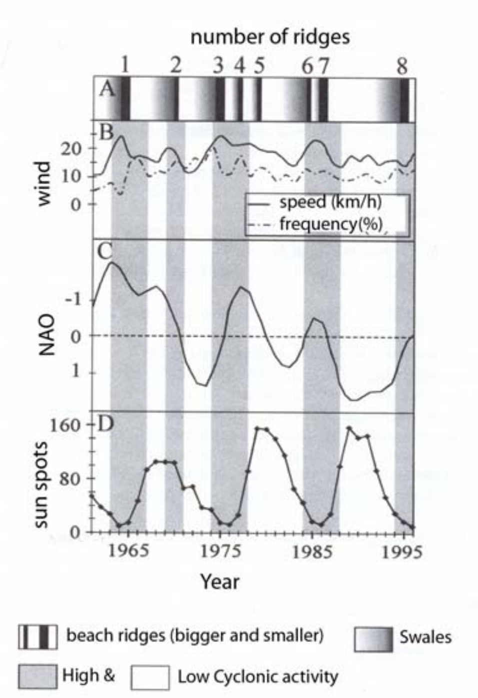

Fig. 11.26. *Relationship between the formation of beach ridges with sunspots, Negative NAO index and intense SW winds (Rodríguez Ramírez et al. 2000)*

Secular scale ("centennial"). The trend towards progradation, that is, coastal advance, generalised on the previous coastlines, is interrupted periodically (figure 11.27). Erosional surfaces have been identified resulting from the increased intensity of storms together with a small rise in MSL, estimated at between 0.5 and 0.8 m (Goy *et al*. 2003). The duration of these episodes is very short (a few decades), but they cause very visible effects in the organisation of the morph-sedimentary units. Between 6000 and 3000 BP the erosion episodes took place approximately every 600 years, but since 2700 BP the interval was reduced to 400 and 200 years. This change coincided with a relevant modification in the regime of prevailing winds, which changed from Westerlies to Southwesterlies, modifying the longshore drift and causing erosion (Zazo *et al*. 1994, Borja *et al*. 1999, Dabrio *et al*. 2000, Goy *et al*. 2003).

At a *scale of thousands of years*, episodes of coastal progradation can be recognised which last between 1200 and 1500 years and which Zazo *et al*. (1994) termed "H" units: units of prograding spits that make up the spit bar systems. The have been recognised in the spit bars of Piedras, Punta Umbría and Doñana (Huelva), Valdelagrana (Cadiz), Calahonda (Granada, Lario *et al*. 1999), Roquetas (Goy *et al*. 2003) and Albufera de Alcudia (Mallorca, Goy *et al*. 1996). They are separated by intervals during which no beach ridges accumulated, or, if they did so, they were smaller and were deposited at topographically lower elevations, which is interpreted as the result of a transitory drop (of secular duration) in the estimated MSL of between 0.5 and 0.8 m, together with reduced storm activity. These ridgeless episodes, also called *gaps,* were formed in a short period of time, between 200 and 400 years. Those of approximate ages of between 5.5, 2.7 and 0.7 Ka are easily recognisable, and that of ~4.2 Ka is much more difficult to obseve.

The *gaps* or interruptions are interpreted as the result of periods of extreme aridity within the general trend towards aridity. These conditions appeared to be dominant, with prolonged periods of positive NAO and less intense entry flow of surface water from the Atlantic into the

Mediterranean (Goy *et al*. 2003). Comparing these results with the data on the Alborán Sea and the North Atlantic obtained with the use of other *proxies*, it can be seen that they coincide with Bond cold events at 5.9, 4.3 and 2.8 Ka and at least one (5.36 Ka) of the surface sea water cold events (SST) described by Cacho *et al*. (2001).

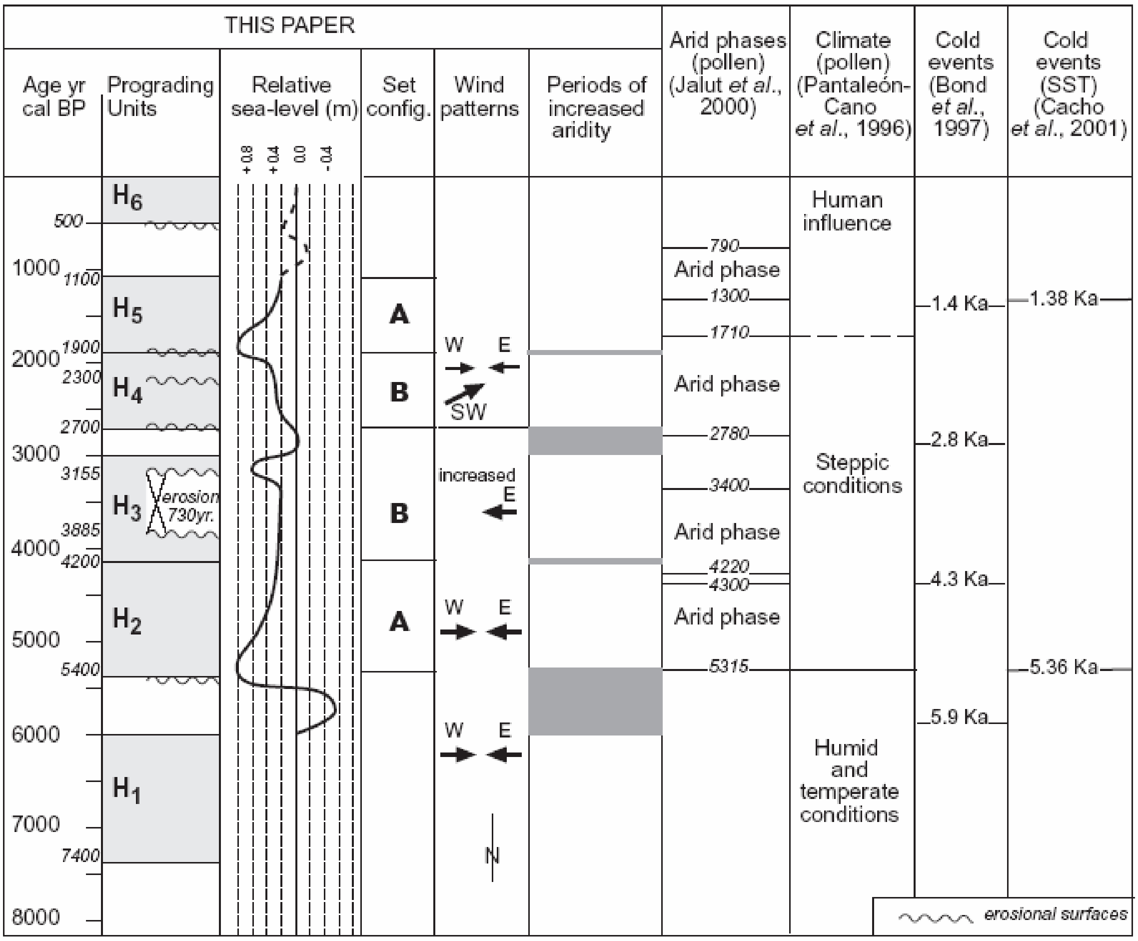

Fig. 11.27. *Progradation tendency interrupted by erosional surfaces resulting from increases in the intensity of storms and small rises in MSL (Goy et al. 2003)*

11.7.4. Interactions

The treds and cyclicities described overlap, each one with a specific periodicity, and in theory, they ought to produce harmonics and interferences. The period of the cycles, however, is not very constant and has a very appreciable margin of error at human life scale. The most general cyclicities involve changes in the atmosphere-ocean system and are at millenial scale, with periodicities of between 1200 and 1500 years. This is seen in the so-called Bond events, and is manifested in the North Atlantic by cold periods (short, with a duration of centuries). According to recent records in Roquetas (figure 11.27), we are about to experience one of those events which, at our latitudes (Atlantic-Mediterranean connecting area), would involve a drop in sea level, extreme aridity, greater frequency and intensity of Saharan winds and a prolonged positive NAO index. In theory, this effect is the opposite of what is usually attributed to anthropic action (global warming and a rise in sea level).

Furthermore, in relation to the cyclicity of 600 years (or somewhat less in the last two millennia), we approach one of the short NAO periods (of around two centuries), predominantly negative, which cause an increase in precipitation and in sea level and a radical increase in coastal erosion, marking the end of the progradation phases (in this case, the H6). In theory, these effects would be added to those triggered by human-induced climate change, which is usually invoked, and relative sea level would rise.

In theory, both cyclicities could coincide and their relative effects could be cancelled out. The margin of variation of each one, however, is wide enough to present great uncertainty with regard to what is really occurring.

With all this in mind, and in order to consider adaptation and mitigation strategies, two scenarios of a rise in MSL are recommended for the end of the century, one which is considered "most likely", of 50 cm (coherent with most of the projections and with data on the Holocene) and another one of 1 m or "pessimistic scenario". The latter corresponds approximately to the maximum predictions of several models and also to the rises detected at different points of the coast around 5500 and 2000 years ago. The chances of this scenario materialising are smaller, particularly on the S and E coasts.

11.8. DETECTING CHANGE

11.8.1. Driving factors

Detection of change in the driving factors or agents (temperature, precipitation, winds, waves, currents), will need to be based on the corresponding meteorological or oceanographic observations. In the specific case of the coastal area, the regular measurement of sea water level and temperature is of interest, at a sufficient number of points (horizontally and vertically). Also of interest are continuous measurements of wind speed and direction, and of swales and circulation.

The most important point, common to all the aforementioned variables, is the continuity and accuracy of the records. Otherwise, it will not be possible to reliably detect the "weak" sign of climate change at decadal scale.

11.8.2. Geomorphlogical response

The most sensitive elements to changes in coastal dynamics are beaches and coastal lowlands. The detection of changes in the area, shape or position of these, with the use of profiles with regular or continuous follow-up, based on remote sensing techniques, including aerial or satellite images, can be used to detect variation trends in sea level or other driving factors, which are difficult to detect in a direct way.

11.8.3. Response by the ecosystems

In an analogous manner, monitoring systems of variations in the area or position of particularly sensitive ecosystems, such as coastal wetlands, can be set up. Some properties of coastal waters (temperature, salinity, etc.), as well as the nutrient content of these, could be affected by local changes in climatology. Saline penetration into terrestrial aquifers is an indicator of noteworthy socio-economic interest, although it is difficult to accurately predict.

11.8.4. Socio-economic response in uses and management thereof

As we have pointed out, the main resources to be considered are of the “non-consumable” type, such as beaches, dunes and wetland ecosystems. In recent years, changes in uses in these units have been almost exclusively determined by types of human activity that do not depend on climate change. This will probably continue to be the determinant factor in the coming decades. Monitoring of these changes can be done easily through remote sensing, based on aerial or satellite images.

11.9. IMPLICATIONS FOR POLICIES

Most of the problems described here as likely consequences of climate change are also caused by unrelated human activities. From the point of view of coastal policy, it is of interest to deal with these problems, not with climate change itself. We therefore present a series of recommendations for a coastal conservation, protection and management policy which will be useful, not only as actions for the prevention and mitigation of the impact of climate change, but also in the event that this change were to occur much more slowly than expected or did not occur at all.

11.9.1. Anticipation in decision-taking

Although there are solutions (whether these be of the structural or non-structural type) for practically all the problems identified, it is impossible to act along the whole coast in a sufficiently short period of time to deal with them, albeit due to the lack of sufficient financial resources. It is therefore very important to take the corresponding decisions in due time. In the first place, these decisions should involve those interventions that will be beneficial in any case (many of these have already been described), regardless of the magnitude and rhythm of climate change.

11.9.2. Policies "from above" or participatory policies

The main problems described can be divided into two main categories: a) those relating to the stability of beaches and coastal lowlands comprising incoherent materials; b) those relating to floodable coastal lowlands, wetlands and intertidal areas. Both types of coastal units are mostly of public ownership, but the displacement of these could also affect private property.

In the case of measures only affecting publicly-owned property (for example, actions aimed at maintaining confined beaches), it is possible to implement policies “from above”, although it is considered very convenient to include all stakeholders in the decision-making process (Central Administration, regional autonomies, municipalities, neighbouring owners, the production sectors affected, conservationist groups), in order to establish agreements, both with regard to the intervention priorities (and investment) and to the technical solutions to be adopted.

When the measures affect private property (for example, abandonment strategies aimed at permitting wetlands to migrate inland), measures of a participatory nature become especially necessary, because the corresponding compensation will have to be provided for.

11.9.3. Intervention criteria

The intervention criteria to be applied derive from the previous point and should consider: a) the potential importance (social, economic, ecological) of the problem; b) the possibility that the measures to be applied might be unnecessary or even counter-productive if the change does not occur in the time period or with the magnitude predicted; c) imminence of the risk or urgency to intervene: d) intervention costs.

It is initially believed that priority should be given to policies that deal with the aforementioned serious problems, with measures that would be of use in any case, regardless of the rhythm of future changes (for example, actions in river basins aimed at ensuring regular sediment supply to the coast, in order to contribute to the stability of beaches and deltas). If, as a consequence of the establishment of monitoring systems, particularly rapid changes are detected in some areas, it will be necessary to act with greater urgency.

11.10. MAIN RESEARCH NEEDS

The research needs identified are related, on one hand, to knowledge of climate variations in the recent past (approximately in the last 10,000 years) and to the reflection of these change in relative sea level and the morphodynamic processes that have affected the coast. Available data indicate that approximately 5,500 years ago, conditions existed that are comparable to those predicted for the end of the century. Detailed knowledge of the evolution of past processes (if possible, with annual or decadal resolution) would significantly help to increase the accuracy of the projections. More in-depth knowledge is also needed of the effects of the climate changes, in particular in MSL, and of other driving factors such as swale, together with the corresponding morphodynmic change, that could take place in coastal ecosystems and in human activities.

Apart from the need for a more in-depth understanding of the processes at play, there is a need for data on the different parameters intervening therein, which at present are quite scarce. This requires the implementation of systematic monitoring and data collection systems in relation to these parameters (in time and in space) which, although they do not strictly constitute research actions, will allow for the establishment of empirical relationships or the design and validation of models.

11.10.1. Driving agents/factors and local climate

It is of particular interest to learn more about the effects of climate change upon the wind and swale regimes and the circulation patterns affecting each area.

11.10.2. Morphodynamic response of the coast

The units most sensitive to the morphodynamic changes that affect the coast are beaches (and associated dune fields) and other coastal lowlands. Deltas are of particular interest and, due to subsidence, are undergoing a relative rise in MSL. In order to increase knowledge of the factors determining these changes, and therefore, prediction and response capacity in relation to these, there is a need to develop and apply models that simulate the behaviour of the main types of beaches (and sand ridges in general), and to establish systems for regular monitoring of the changes.

11.10.3. Response of ecosystems

The most important ecosystems on the coast are constituted by dunes, marshlands and intertidal areas. We must seek a more in-depth understanding of how these have responded to past climate changes (Holocene), and establish systems for monitoring the changes they might be undergoing at present.

11.10.4. Property, resources and uses in coastal areas and estuaries

The main need in this case involves an inventory of the areas that could be affected by the main types of processes described. Given that most of the potential problems derive from an increase in relative sea level or from the effects of storms, there is a great need to avail of sufficiently detailed mapsor Digital Elevation Models (decimetric or centimetric vertical resolution) of the environments that might be affected. This maps or models could be used to demarcate the areas and elements at risk and to quantify the areas and values affected.

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