Potential effects of climate change on northwest Portuguese coastal zones

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Coastal erosion is a common problem in Europe; a result of the dynamic nature of its coastal zones, of anthropogenic influences, such as coastal interventions and littoral occupation, and of the effects of climate change. The increase in the occurrence of extreme events, the weakening of river-sediment supplies, and the general acceleration of sea level rise (SLR) probably tends to aggravate coastal erosion on decadal time-scales. Describing vulnerability and risk patterns for energetic environmental actions is important for coastal planning and management to rationalize the decision-making process. To minimize negative effects, the various processes causing erosion must be understood to assess the possible prediction scenarios for coastal evolution in the medium to long term. This paper describes the application of a coastal (shoreline evolution) numerical model to a stretch of the Portuguese coast to determine the effects of various scenarios of wave action and SLR that might result from climate change over the next 25 years. We conclude that the effects of SLR are less important than changes in wave action. The numerical model was also applied in a generic situation to compare shoreline evolution with and without anthropogenic intervention.

Keywords: beach evolution, erosion, medium to long term, numerical model, scenario assessments.

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Introduction

Coastal zones are dynamic geomorphological regions that respond on different temporal and spatial scales to changes in natural and anthropogenic effects. Natural factors include wave action, winds, tides, and surges, whereas man-made effects result from resource exploitation, construction, and pollution (Figure 1).

The assessment of beach evolution over time is complex. At any given moment, a beach may be changing rapidly because of a short-term disturbance, such as a winter storm, from which it can recover during calm wave conditions, thereby maintaining equilibrium. At the same time, slight changes caused by sea level rise (SLR) could be happening in one or more of the several morphological states that are part of a dynamic equilibrium, cycling over time-scales of years or even decades. Extreme events may also trigger abrupt irreversible changes.

A major challenge in understanding beach evolution is the ability to identify and separate processes beyond any given morphological change. A possible approach to this problem is to group the processes on a beach response scale, namely short, medium, and long term (Stive *et al*., 2002; Figure 2). The causes of medium-term changes are reasonably well understood, because they are readily observed and have been studied for almost a century. Some of the processes and mechanisms behind the short-term changes are the subject of active research (e.g. the relation between bed forms and cross-shore sediment transport in the surf zone; van Rijn *et al*., 2007). Processes and responses at such small scales may not be observable under natural settings (e.g. the intensive sediment transport in a thin boundary layer with a thickness of the order of a few centimetres has only been measured in the laboratory; Nielsen, 2006), and their importance may not be well recognized. Long-term changes may also be difficult to identify, because observational time-series are often too short to allow identification of long-term cycles, and data gaps

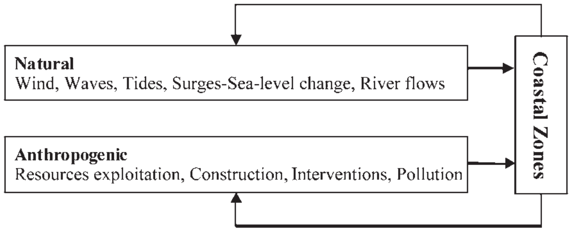

Figure 1. Processes affecting coastal zones.

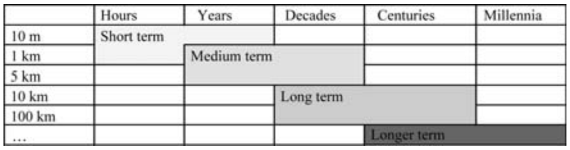

Figure 2. Spatial and temporal scales of change in beach geomorphology.

are frequent. This is the case for the wave dataseries (1993–2003) measured at the Leixões wave buoy (Portugal), where the extreme conditions are often missed, because of damage to or breakdown of measuring equipment during storms (Figure 3).

The factors contributing to small-scale changes in beach morphology (10 m–1 km; hours–years) include the instantaneous response to the direct action of waves, winds, tides, and surges, as well as seasonal changes in the surf zone between storms and calm periods (Komar, 1998). On this scale, nearshore waves and currents induce spatial variations in sediment transport, and these are the most important natural factors contributing to beach change. Artificial replenishment and surf-zone structures interfere with these natural patterns.

On medium scales (1–5 km; years–decades), surf-zone bar cycles, interannual wave-regime changes, or recovery from a major storm event are important processes contributing to modifications of beach morphology. On this time-scale, coastline evolution is usually consistent with predictions obtained from the estimates of sediment volume fluxes, based on knowledge of the alongshore transport in relation to wave height and angle at the break zone. The influence of large surf-zone structures or other coastal structures may also cause changes in beach configuration on this scale (Stive *et al.*, 2002). Other medium-term responses are related to changes in the sediment availability, such as what could result from fluctuations in river input.

On larger scales (10–100 km; decades–centuries), changes often arise where spatial difference in alongshore transport are prevalent (Horikawa, 1988); see for example, the different morphological states in the formation of the Aveiro lagoon (Figure 4). The long-term changes also reveal the effects of SLR and regional wave-climate change, allied with evidence of negative effects of erosion, because of a lack of coastal-zone management.

A hierarchy of action-priority coastal-zone risk assessments can be accomplished with the creation of risk maps. Because the Aveiro region is considered a critical erosion zone along the northwest coast of Portugal, we evaluated it for the potential effect of different scenarios of climate change and erosion, using a numerical model of the medium-term shoreline evolution. Possible effects of climate change could increase medium- to long-term erosion in an already critical situation. The likely increase in the frequency of extreme events (Meehl *et al.*, 2007) would accentuate erosion periods and possibly increase flooding, thereby jeopardizing low-lying lands. Changes in mean annual wave height and direction would have direct implications for potential alongshore transport; larger waves would be expected to increase the potential alongshore transport and result in greater coastal erosion. An indirect influence of SLR on sediment budgets relates to infilling of coastal areas. When sea level rises, lagoon and estuary beds also rise, maintaining equilibrium. The sediments are often derived from the open coast, resulting in increased erosion an order of magnitude greater than predicted by the Bruun model (Woodworth and Blackman, 2004). A decrease in precipitation, with a likely increase in episodes and duration of droughts, could result in reduced river-sediment supply to the shoreline (Nicholls *et al.*, 2007).

We also simulated a generic situation of what has been happening along many stretches of the Portuguese coast with human interventions. Our numerical tests intended to contrast shoreline evolution with and without these interventions.

Northwest Portuguese coast

Portugal is located on the Iberian Peninsula in southwest Europe, facing the Atlantic coast. The northwest Portuguese coast, at latitudes 40–42°N, is a highly energetic region, as may be inferred from the average wave power obtained with data from the wave analysis model archive of the European Centre for Medium-Range Weather Forecasts (Cruz, 2008).

On the Portuguese coast, waves usually arrive from the northwest, with an offshore mean significant wave height of 2–3 m and a mean wave period of 8–12 s. Storms generated in the North Atlantic are frequent in winter and can persist for up to 5 d, with significant wave heights as high as 8 m (Costa *et al.*, 2001). The tides are semi-diurnal, ranging from 2 to 4 m during spring tides. The mean sea level is +2 m chart datum (CD). The strong

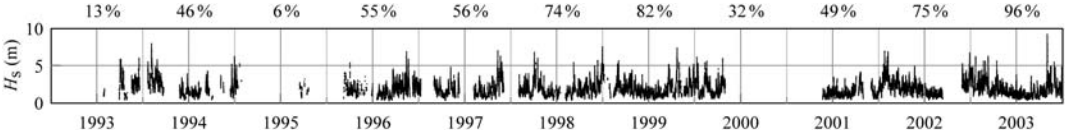

Figure 3. Significant wave-height time-series, obtained from the Leixões wave buoy for the period 1993–2003 (the buoy is located offshore of the northwest Portuguese coast, and owned and operated by the Hydrographical Institute of the Portuguese Navy).

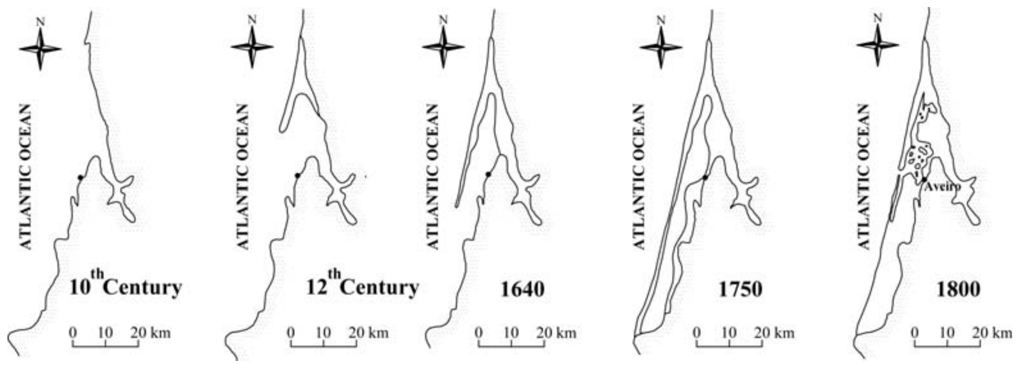

Figure 4. Morphological states of the evolution of the Aveiro lagoon, located on the northwest Portuguese coast (INAG/FEUP, 2001).

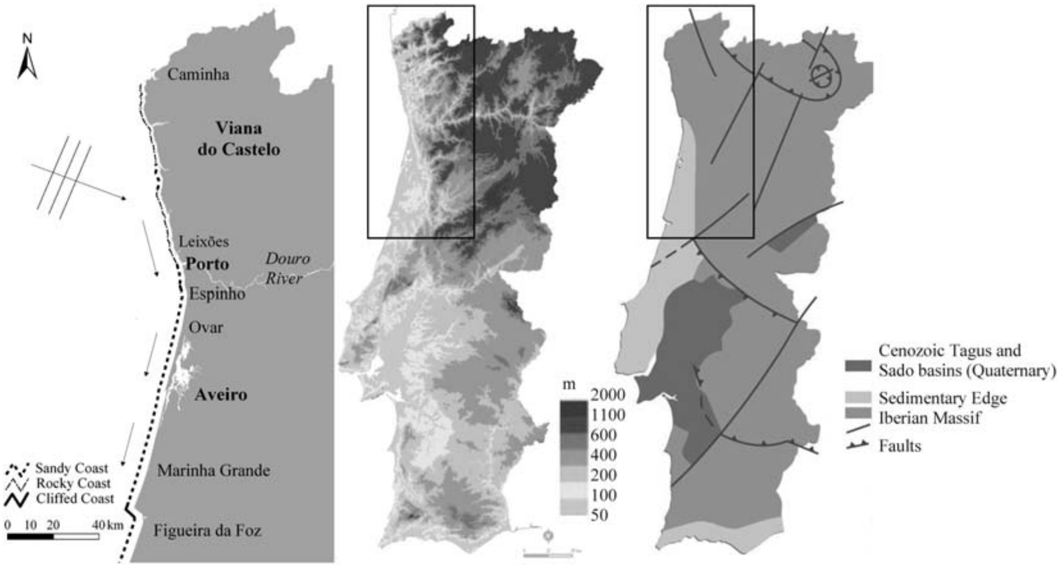

Figure 5. Littoral drift and dominant incident wave directions on the northwest Portuguese coast (left); topographic map of continental Portugal (centre); morphostructural scheme of continental Portugal (right). The maps are from the Atlas de Portugal [Atlas of Portugal—Portuguese Geographical Institute; http://www.igeo.pt/atlas/Cap1/Cap1.html (in Portuguese)].

wave regime induces a southward alongshore transport of $1-2 \times 10^6$ m^3 year^{-1} (Oliveira, 1997).

The Portuguese northwest coast may be divided into two stretches based on the geomorphological characteristics (Figure 5): one, from Caminha to Espinho consists of low rocky formations; the other, from Ovar to Marinha Grande is mostly a low-lying open sandy shore, vulnerable to wave action, and backed by dunes that have already been destroyed in some places. The Douro River estuary and the Aveiro lagoon are important morphological features and are strongly influenced by anthropogenic effects emanating from the cities of Porto and Aveiro (Figure 5).

The principal sources of sediments from Ovar to Marinha Grande are the Douro River and coastal erosion. The former, in its natural regime, used to supply $\sim 1.8 \times 10^6$ m^3 year^{-1}, but this has decreased to $\sim 0.25 \times 10^6$ m^3 year^{-1} (Oliveira, 1997), causing coastal erosion to increase, because alongshore transport has not changed significantly. During the past two decades, the rate of shoreline retreat has increased, reaching 7 m year^{-1} in some stretches of the region (Veloso-Gomes *et al.*, 2006). The reduction in sediment supply has been caused by dam construction and the associated river flow regulation, as well as sand-mining activities in the past.

Coastal structures also contribute to erosion. Harbours, which are essential to socio-economic development, introduce severe perturbations in the littoral drift system, by changing wave propagation with the construction of long breakwaters and by changing the sedimentary dynamics by dredging navigation channels. Consequently, the effects of refraction, diffraction, and reflection of waves are transformed; currents are created that carry sediments offshore to depths where waves are not able to return them to the beach, and the littoral drift is interrupted. In addition, activities related to development (e.g. sand removal from beaches, sand retention, and channel dredging without repositioning downdrift) in other harbours (Viana do Castelo, Leixões, Aveiro, and Figueira da Foz) tend to aggravate erosion.

Coastal erosion and inappropriate civil development too close to the foreshore have caused narrowing of the beaches. The weakening or destruction of dune systems inhibits their function of tightening the active beach profile by limiting the landward extension of wave wash, as well as their ability to protect low-lying areas of the coast. A few simple calculations resulted in the conclusion that the continued high sedimentary deficit in the region is caused primarily by the reduction in sediment supply from the Douro River. Because of the current state of coastal erosion along the northwest Portuguese coast, the anticipated SLR resulting from climate change should have a significant effect in 50–100 years (Silva *et al.*, 2007). Measures aimed at rebuilding and preserving dunes and other natural defences are important, but more severe measures are needed to confront the erosion problem. Under the current erosion regime, defensive measures have had to be implemented, and several structures have already been built along this stretch of coast. The proper management of this coastal zone is essential, because it will have to redress some earlier shortcomings.

Coastal erosion, risk, planning, and management

Coastal erosion is a common problem in Europe (Eurosion, 2004); this can be observed in the medium term. Several causes, each to varying degree, are contributing to it. On the one hand, there are the dynamic nature of coastal zones and climate change, and on the other, there are the anthropogenic influences. To deal with the problem in an effective manner, an adequate understanding of these causes is needed. However, actionable knowledge of coastal-zone dynamics is limited, the effects of climate change over coastal zones are identified in a context of great uncertainty, and the effects of coastal interventions have not been monitored systematically. Nevertheless, although the causes are not clearly identified and understood, it is increasingly clear that people as well as assets are endangered in some littoral urban fronts and that serious damage and high costs can be expected. The situation calls for preventative measures, and it is becoming increasingly important to make scientific and technical information available to decision-makers to support their resolutions. To effect sustainable actions, plans should be conceived based on a medium- to long-term coastal evolution assessment. Because of inherent uncertainty in our knowledge, the assessment of future conditions can only be based on scenario evaluations, for which numerical models comprising the current state of knowledge could be used as a tool. To help rank action priorities, the risk along the coast must also be assessed, and this can be accomplished by crossing vulnerability and degree-of-exposure information in risk maps depicting spatial analysis (a recommendation by the European Union; EU, 2007).

An analysis, based on the spatial classification and weighting of the parameters thought to be of importance for the evaluation of the vulnerability to wave action, has already been done for the Aveiro District on the Portuguese northwest coast (Coelho *et al.*, 2006). Coastal stretches very vulnerable to wave action might not necessarily be considered at risk. An approach similar to the vulnerability analysis was established to evaluate the degree of exposure. For exposure levels, the parameters considered important for classification were population density, economic activities potentially affected by erosion, and ecological, cultural, and historical assets exposed to devastation by sea action (Table 1). Spatial classification facilitates mapping the degree of exposure (Figure 6). Risk maps consist of a classification obtained by crossing vulnerability with degree-of-exposure information (Table 2).

Long-term configuration model

The long-term configuration (LTC) model (Coelho, 2005; Coelho *et al.*, 2007; Silva *et al.*, 2007) was specifically designed for sandy beaches, where the main cause of medium-term shoreline evolution is the alongshore sediment transport. The latter depends on wave climate, water levels, sediment sources/sinks, sediment characteristics, and boundary conditions. The model inputs are the changing water level and the bottom elevation of the modelled area, which is modified during the simulation. The volumes transported are estimated with formulae that take into account the angle of the shoreline to oncoming breaking waves (CERC, 1984; Kamphuis, 1991), the wave breaking height, beach slope, and sediment grain size (Hanson and Kraus, 1989; Kamphuis, 1991). The model assumes that each wave acts during a certain period (the computational time-step). The wave transformation by refraction, diffraction, and shoaling is modelled in a simplified manner, or wave conditions may be imported from more complex

Table 1. Classification of considered parameters for the analysis of the degree of exposure.

Degree-of-exposure parameters	**Very low 1**	**Low 2**	**Moderate 3**	**High 4**	**Very high 5**
Population density (inhabitants km^{-2})	<100	≥ 100 and <200	≥ 200 and <350	≥ 350 and <500	≥ 500
Economic activity (settlements)	Without edification or economic activity	Rural zones with agricultural activities	Urban zones with associated economic activities	Industrial zones	Zones of specific equipment
Ecology	Non-classified	National agricultural reserve	National ecological reserve	Ecological protected zones	Natural parks
Cultural and historical values	Non-existent	Non-classified	Traditional activities and edifications	Regional historical edifications	National historical monuments

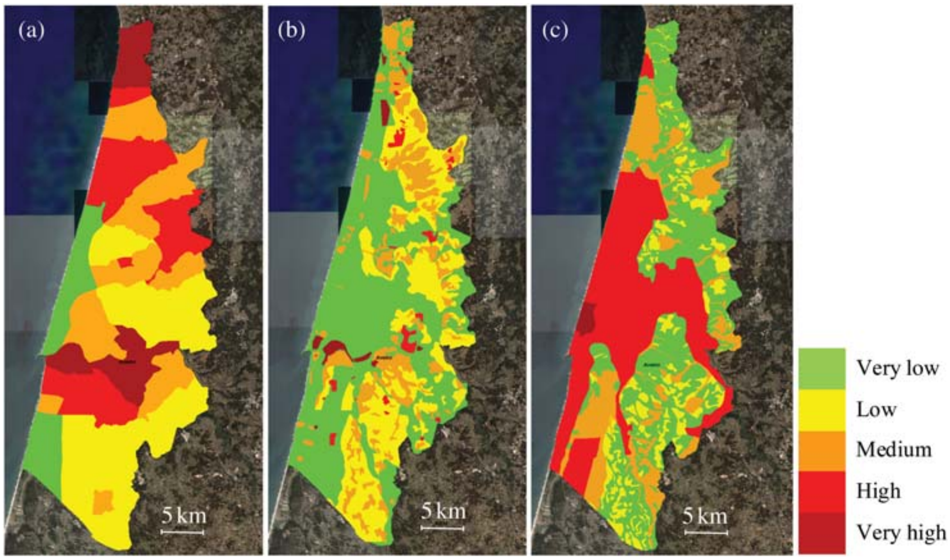

Figure 6. Maps resulting from spatial classification of the degree-of-exposure parameters for Aveiro District, located on the northwest Portuguese coast: (a) population density; (b) economic activity; (c) ecology.

Table 2. Risk classification scale resulting from global vulnerability and global degree-of-exposure classifications crossing.

		Degree of exposure					
		1	2	3	4	5	Risk
Vulnerability	**1**	I	I	I	II	III	I (very low)
	2	I	I	II	III	IV	II (low)
	3	I	II	III	IV	V	III (medium)
	4	II	III	IV	V	V	IV (high)
	5	III	IV	V	V	V	V (very high)

wave models, such as SWAN (Simulating WAves Nearshore, http://vlm089.citg.tudelft.nl/swan). Because of the importance of boundary conditions in the model simulations, several options can be selected, e.g. constant sediment volumes going in or out, constant volume variations in the border sections, or extrapolation from nearby conditions. Moreover, different combinations of coastal protection mechanisms may be considered, almost without limitation for the number of groins, breakwaters, and seawalls; the number of sediment sources/sinks sites or artificial nourishments. This model allows for the assessment of certain medium-term scenarios of combined anthropogenic and natural actions, permitting the modelling of climate-change scenarios.

Numerical models of shoreline evolution (Hanson and Kraus, 1989; Vicente and Clímaco, 2003) are generally based on the calculation of coastal sediment transport with the application of the continuity equation to the volumes of sand moved. The variation in the shoreline position is calculated in each cell of the domain by the differences between the volumes of sediments that enter and exit over a certain time interval. The shoreline position consequently changes, because of the spatial and temporal variations in the longitudinal sediment transport. For this reason, situations of systematic tendency in position changing are better represented (e.g. erosion down-drift of a groin). The effects of the cross-shore transport are usually not considered in medium- to long-term model simulations, because the representation of its evolution remains unrealistic on temporal scales of years to decades. Over a time interval, an analysis along the shoreline for different cells permits establishing the relationship between the volume variation in the cell and the variation in the volume of sediments in transport.

The variation in the volume of sand along the beach represents a variation in the depth level at points along the same profile. Erosion and accretion are distributed along the active cross-shore profile between the closure depth and wave run-up limit. The closure depth is estimated according to the inshore depth limit of Hallermeier (1978). According to Nicholls *et al.* (1998), Hallermeier's approach permits robust estimates of the closure depth both for individual erosive events and for the time-dependent case. This conclusion was based on an analysis of a series of cross-shore profiles measured biweekly and with high precision on a sandy ocean beach.

The main difference between the LTC model and the other one-line models is that near the closure depth in an accretion situation, the angle of repose controls the sediment distribution, and in an erosion situation, the control is applied by the minimum underwater bottom slope. Near the wave run-up limit, the controlling parameters are the angle of repose and the minimum beach face slope for erosion and accretion, respectively. An important improvement is achieved using the LTC model, because different profile evolution slopes may be tested with it under different erosion or accretion situations, thus reducing the limitations of not knowing the profile shape evolution over time.

Climate-change and erosion scenarios

The LTC numerical model was used to evaluate potential effects of certain climate-change effects and erosion scenarios, considering the critical erosion situation of the Portuguese northwest coast and assuming river-sediment-supply reduction as its major cause. The scenarios for climate-change effects were decided based upon the criteria described below.

According to Nicholls *et al.* (2007), the range of potential drivers of physical climate-change effects in coastal areas may be summarized, as in Table 3. Changes in all these drivers are subject to regional variations. Usually, any effects will be the result of the interaction between these climate-change drivers and other drivers of change. Increased occurrence of extreme sea levels because of rises in mean sea level and/or changes in storm characteristics causes widespread concern. The future wave climate is uncertain, although extreme wave heights will likely increase with more intense storms (Meehl *et al.*, 2007). Andrade *et al.* (2007) presented an assessment of projected wave-climate changes expected to affect the west coast of Portugal by the end of the 21st century. They suggested that there would be no change in mean wave heights in the region, but that there would be a clockwise rotation of $\sim 6^\circ$ in the mean wave direction. However, the frequency distributions of these parameters were not provided in the paper. Changes in run-off driven by changes

Table 3. Main climate drivers for coastal systems, their trends because of climate change, and their main physical effects.

Climate driver (trend)	Main physical effects on coastal systems
Sea surface temperature (↑)	Increased stratification/changed circulation; reduced incidence of sea ice at higher latitudes
Sea level (↑)	Inundation, flood, and storm damage; erosion; saltwater intrusion; rising water tables/impeded drainage; wetland loss (and change)
Storm intensity (↑)	Increased extreme water levels and wave heights; increased episodic erosion, storm damage, risk of flooding, and defence failure
Storm frequency (?) Storm track (?)	Altered surges and storm waves and hence risk of storm damage and flooding
Wave climate (?)	Altered wave conditions, including swell; altered patterns of erosion and accretion; re-orientation of beach plan form
Run-off	Altered flood risk in coastal lowlands; altered water quality/salinity; altered fluvial sediment supply; altered circulation and nutrient supply

Trend: ↑, increase; ?, uncertain (adapted from Nicholls *et al.*, 2007).

to the hydrological cycle appear likely, but the uncertainties are large. For the numerical assessment, the drivers considered were sea level, storm intensity, and wave climate.

Projected global mean SLR under the special report on emissions scenarios (Nakicenovic *et al.*, 2000) based on thermal expansion and ice melt are summarized in Table 4; adapted from Meehl *et al.* (2007) in Nicholls *et al.* (2007). These projections do not include any allowance for potential ice-sheet instability, being smaller than those given by Church *et al.* (2001). If recently observed increases in ice discharge rates from the Greenland and Antarctic ice sheets were to increase linearly with global mean temperature change, this would add a 0.05–0.11 m rise for the A1FI scenario over the 21st century (Meehl *et al.*, 2007). Local changes depart from the global mean trend because of regional variations in ocean-level change and geological uplift/subsidence; the relative sea-level change that drives effects and this is of concern. Regional sea-level changes will depart significantly from the mean global trends illustrated in Table 4 (Nicholls *et al.*, 2007).

Table 4. Projected global mean SLR at the end of the 21st century for the six SRES (Nakicenovic *et al.*, 2000) marker scenarios (adapted from Meehl *et al.*, 2007, in Nicholls *et al.*, 2007).

	SLR (relative to 1980–1999)					
SRES marker scenarios	**B1**	**B2**	**A1B**	**A1T**	**A2**	**A1FI**
Best estimate (m)	0.28	0.32	0.35	0.33	0.37	0.43
Range (m)						
5%	0.19	0.21	0.23	0.22	0.25	0.28
95%	0.37	0.42	0.47	0.44	0.5	0.58

Dias and Taborda (1988) performed a mean-sea-level analysis based on an elevation time-series obtained from tidal gauges located on the Portuguese coast (Leixões, Cascais, Lisboa, Lagos, and Angra do Heroismo) and found increasing tendencies for each of the tidal gauges. Yet, the only stations with time-series long enough for an SLR analysis were Cascais (105 years) and Lagos (79 years). For these stations, the values for SLR were 1.3 ± 0.1 and $1.5 \pm 0.2\ \mathrm{mm\ year^{-1}}$, respectively. Using the

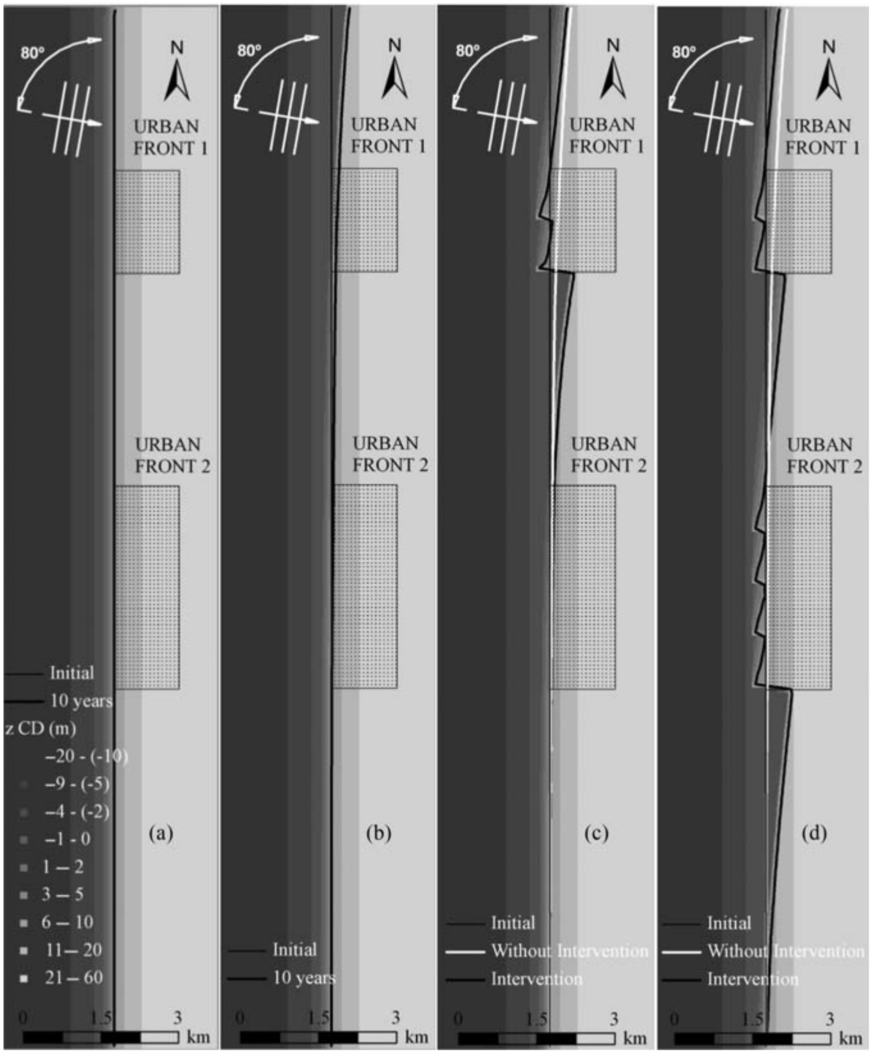

Figure 7. Shoreline evolution under a scenario of a 50% reduction in sediment supply from the north: (a) equilibrium; (b) after 10 years of sediment-supply reduction; (c) four years after the construction of two groins to protect the northern urban front; (d) 10 years after the construction of four more groins to protect the southern urban front.

Table 5. Areas lost in generic numerical tests, for a coastal stretch under a scenario of sediment-supply reduction of 50% from the north.

Time elapsed	**10 years**	**4 years from reference**		**4 + 10 years from reference**	
Intervention	**Reference**	**Two groins**	**Without**	**Four groins**	**Without**
Area lost (m^2)	1 280 000	1 720 000	1 752 000	2 059 000	2 821 000
Rate of area loss (m^2 $year^{-1}$)	128 000	123 000	125 000	86 000	118 000
Relative to reference (%)		−4	−2	−33	−8

Cascais dataseries, Dias and Taborda (1988) projected a rise of between 0.14 and 0.57 m in the mean sea level at the end of the 21st century (ca. 1–5 mm $year^{-1}$), which is consistent with the global projections presented in Table 4.

Numerical evaluation of potential effects

Generic tests

A generic situation was used to represent what has been happening in many stretches of the Portuguese northwest coast: a long, uniform, rectilinear sandy beach in equilibrium acted on by a characteristic wave climate, inducing a potential alongshore transport rate of the same order of magnitude as the river-sediment supply to the stretch. A reduction in the sediment supply was simulated and, in response, the shoreline started to retreat.

The coastal stretch was represented by a computational grid with a 20×100 m^2 resolution, extending over an area of 8×20 km^2, and with a regular bathymetry corresponding to Dean's equilibrium profile (Dean, 1991) for sediments with a median diameter, $d_{50} =$ 0.3 mm, $m = 2/3$, and $A = 0.125$, and a beach face slope of 3%.

The wave climate was represented by an offshore constant wave arriving from 80°W of north, with a 2-m height and a period of 9.3 s. The sediment supply in an equilibrium situation corresponds to an influx of 1.8×10^6 m^3 $year^{-1}$ from the north, which is consistent with the estimated potential alongshore transport on the Portuguese northwest coast. In Figure 7, the shoreline evolution under a scenario of sediment-supply reduction of 50% is illustrated, starting with the equilibrium situation (Figure 7a). In Figure 7b, the simulated beach configuration after 10 years is illustrated. The deficit in the sediment supply is compensated for by coastal erosion; for that reason, the shoreline retreats, jeopardizing the northern urban front. To protect this area, an intervention is needed and two groins are constructed. After 4 years, the southern urban front becomes vulnerable (Figure 7c) and four more groins are needed to protect it. After another 10 years, completing 24 years of continued erosion, the shoreline presents the configuration illustrated in Figure 7d. For comparison, numerical simulations for the beach evolution under the same scenario were performed without any coastal interventions. Figure 7d shows the disparity between the two situations. The shoreline configuration differs much, especially on a radius of 1 km centred on each groin. However, the urban fronts have been spared, and a reduction in total land loss is achieved when the interventions are made. The total area lost because of coastal erosion in the stretch for each of the numerical tests, and the mean areas lost annually are presented in Table 5.

Figure 7 and Table 5 allow certain comments to be made. Despite other generic beach-profile conditions (both emerged and submerged) conducive to naturally different erosion rates, the interventions appear to have reduced the total eroded area in the coastal stretch. For example, the total area lost 4 years after the first intervention was ~1 720 000 m^2, and if the intervention had not taken place, it would have been 1 752 000 m^2; the effect of the sediment-supply reduction was attenuated over time with the shoreline adjustment to a new equilibrium. In the natural evolution situation, 4 years after the reference state, the mean annual area lost was reduced by 2%; after 14 years, it was 8% less. The interventions also appear to have become more effective over time, because 14 years after the reference situation the mean area lost annually decreased by 33% in the stretch where the six groins were constructed.

Table 6. Scenarios considered for the numerical model application to a coastal stretch south from Aveiro, assuming a river-sediment-supply reduction.

Scenarios	**Offshore wave climate**	**SLR (mm $year^{-1}$)**
1	Typical	0
2	Typical	1
3	Typical	5
4	Increase in storminess	0
5	Rotation to the north	0
6	Rotation to the south	0

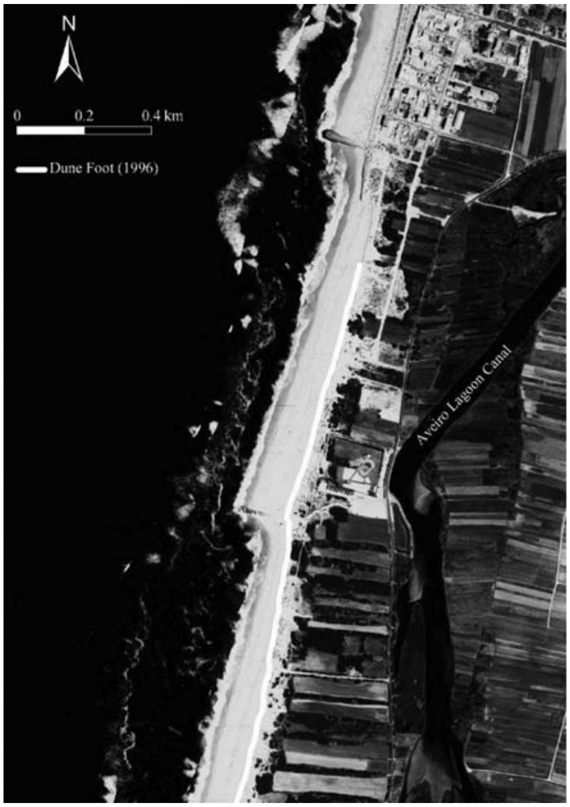

Figure 8. Aerial photograph of the coastal sector near Vagueira settlement included in the model simulation (cf. Figure 9; Ortho photomap from SNIG, 1995).

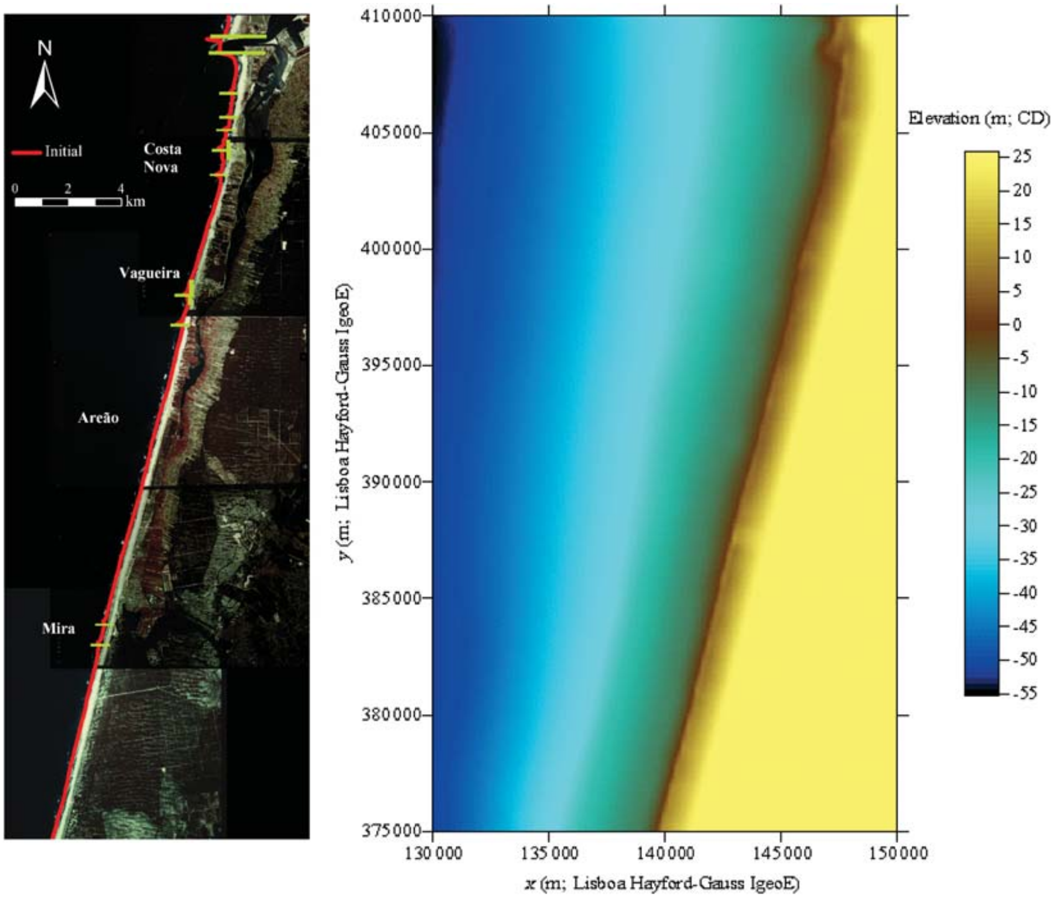

Figure 9. Diagram of the coastal area stretching ~35 km south from Aveiro harbour to which the LTC model was applied. The left panel outlines the existing shoreline with an exaggerated sketch of coastal structures in green. The right panel displays the digital elevation model.

Application to south Aveiro coastal stretch

The LTC model was also applied to a coastal stretch south from Aveiro harbour, assuming a reduction in the sediment supply and the six scenarios presented in Table 6 for offshore wave climate and SLR. The SLR scenarios were selected following Dias and Taborda (1988). The wave-climate-change scenarios corresponded to slight changes in significant wave height and direction, using the available wave data (Leixões wave buoy: 1981–2003).

In this coastal zone, the south sand spit sometimes separates the Aveiro lagoon from the ocean by only 200 m (Figure 8). The primary littoral dune is almost continuous, with a general orientation parallel to the coastline, corresponding to the aerial beach limit. The dune crest ranges from +7 to +18 m CD, but it has been destroyed in some parts, displaying several wind corridors and is highly vulnerable to sea overwashes (Ferreira, 1998). Inland from the primary dune system, there are some low-lying plain zones (+5 to +8 m CD) occupied by urban settlements (Figure 8).

The modelled coastal stretch has suffered from continued erosion for 20–30 years, and it is already protected with several groins and longitudinal adherent structures (Figure 9; left). Bottom elevation information available for the study site [a nautical chart (IH, 2000), as bathymetric support, and an aerial survey (IGP, 1998), as topographic support] was used to generate a regular digital terrain model with a 50×100 m^2 resolution and 20×35 km^2 extension (Figure 9; right). The numerical model applications consisted of 25-year simulations for each of the scenarios listed in Table 6. Tidal variations were not considered, and a mean sea level of +2 m CD was used. Near the northern and southern boundaries of the modelled area, the sediment transport rates were extrapolated from nearby conditions. The CERC (1984) formula was adopted for the calculation of the potential alongshore transport. The results obtained should be taken as indicative and used for comparison.

In scenario 1, the only expected future change was the river-sediment-supply reduction, the wave climate remained unchanged from the typical current situation (Figure 10), and the mean sea level was considered constant. After a 25-year simulation, three critical situations of imminent sand spit disruption become clear in the results: near Costa Nova, south of Costa Nova, and south of Vagueira (Figure 11a, in front of the dark circles). Scenarios 2 and 3 in Table 6 concern the SLR at rates of 1 and 5 mm year^{-1}, respectively, for an unchanged wave climate and a sediment-supply reduction. At 25 years, both scenarios result in an increase of <5% in the mean shoreline retreat rate, Figure 11b. The remaining three scenarios (4, 5, and 6 in Table 6) are related to wave-climate changes. An increase in storm waves is represented by an increase of 6% in the frequency of occurrence of higher waves relative to the more frequent ones (Figure 10; left). Wave-climate changes appear to have greater effects on the shoreline change than the SLR, with an increase in

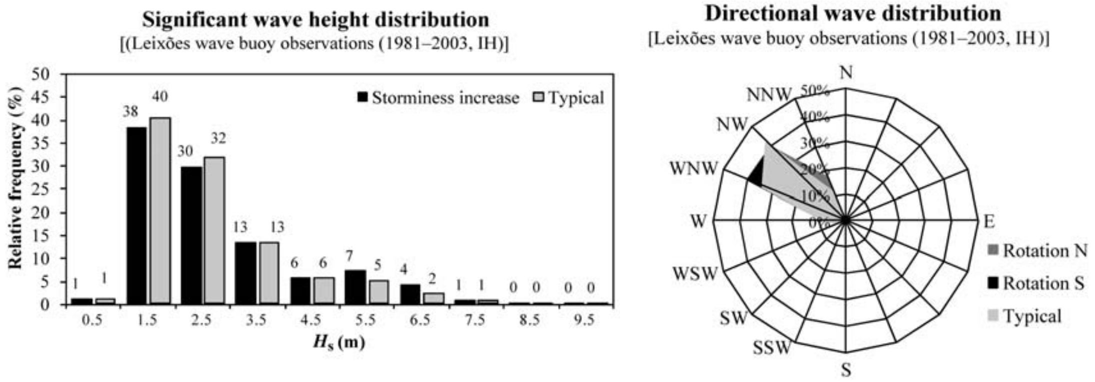

Figure 10. Typical wave climate (based on observations of the Leixões wave buoy between 1993 and 2003; Coelho, 2005) and wave-climate-change scenarios (Table 6) considered in the application of the LTC model to the south Aveiro coastal area.

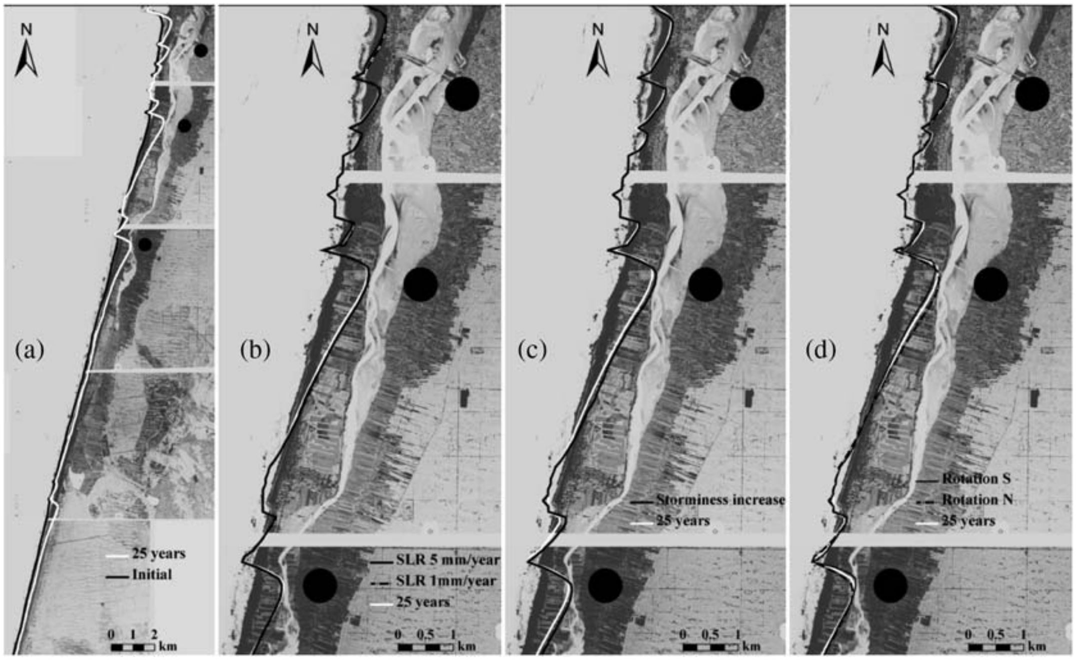

Figure 11. LTC 25-year simulation results for a coastal area located south of Aveiro harbour used in the evaluation of the six different scenarios (cf. Table 6): (a) results of scenario 1; (b) results of scenarios 2 and 3; (c) results from scenario 4; (d) results from scenarios 5 and 6. The results of the simulations are represented on orthophoto maps from SNIG (1995), allied with the initial shoreline [the black dots are pointers to critical sites; in (b), (c), and (d), the area represented is an enlargement of the upper part of the modelled area].

the mean shoreline retreat rate of ∼15% (Figure 11c). A slight rotation in most-frequent waves to the north and to the south (Figure 10; right) results in a maximum increase of 10% in the mean shoreline retreat rate, but the major effects of these scenarios appear to be correlated with a shoreline configuration rotation adjusting to the changes (Figure 11d).

Conclusions

The northwest Portuguese coast suffers from a continued high sedimentary deficit primarily because of the Douro River sediment-supply reduction. The preferable solution to the erosion problem would be artificial sand nourishment, but this solution is not feasible because of the large amounts of sediments in deficit, the high-energy wave climate, and the costs involved. A solution might be found with the construction of coastal-defence structures to protect urban sea fronts, allied with a passive acceptance of erosion in intermediate stretches (Veloso-Gomes *et al.*, 2006).

The situation calls for protection measures to be taken, and it is increasingly important to make scientific and technical information available to decision-makers to inform and support their deliberations. To achieve sustainable actions, plans should be conceived based on a coastal-evolution assessment over the medium to long term. Flowing from an inherent uncertainty in our knowledge, any assessment of future conditions can only be done based on scenario evaluations, for which numerical models comprising the current state of knowledge may be used as a tool. To help create a hierarchy of action priorities, the risk along the coast must also be assessed, and this can be accomplished with risk maps (a recommendation of the EU, 2007).

A numerical model for the medium-term shoreline evolution was used to evaluate potential effects of certain climate-change effects and erosion scenarios, considering the critical erosion situation of the Portuguese northwest coast and assuming that river-sediment-supply reduction is its major cause.

A generic situation was used to represent what has been happening in many stretches of the Portuguese northwest coast where interventions have been made. The generic numerical tests were intended to compare the evolution of the shoreline with and without such interventions. From these tests, some conclusions could be drawn: the interventions seem to reduce the total eroded area in the coastal stretch; the effect of the sediment-supply reduction is attenuated over time, with the shoreline adjusting to a new equilibrium; the interventions also seem to become more effective over time.

The model was also applied to a coastal stretch south of Aveiro harbour to evaluate scenarios about wave-climate change and SLR. After 25 years of reduced sediment supply, critical situations of imminent sand-spit disruption are expected, as well as an ultimate linkage between the sea and the lagoon. The scenarios of SLR are less important than the scenarios of wave-climate change after 25 years. A slight increase in the relative frequency of higher waves would have greater effects than a pessimistic scenario of the SLR rate.

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