



# Coastline behavior under climate change and sea-level rise scenarios: a western Portuguese littoral case study

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## Abstract

With climate change being addressed as a concern that poses a risk to the coastal communities, alongside with warnings of mean sea-level rise (SLR), the present study aims to highlight the influence of these two factors in the projection of the coastline position, in a time-frame of 20 years. The shoreline evolution of three littoral stretches from the western Portuguese coast (Aveiro, Figueira da Foz and Caparica coast) was analyzed, due to their vulnerability to persistent erosion processes. Coastline projections were simulated with the Long-Term Configuration (LTC) numerical model, calibrated by considering the past shoreline rate-of-change (1958–2010). The behavior of the coastline projection was studied by simulating six different forcing scenarios. Firstly, the coastline was subjected to three different wave climates to depict the effect of climate change: a historical wave climate (1989–2008); and two near future wave climates (2026–2045), assuming the Representative Concentration Pathway (RCP) RCP4.5 and RCP8.5. Secondly, the coastline was projected to simulate an annual increase in the sea water level of 0.75 cm for the three wave climates, isolating the influence of SLR. Considering the shoreline position over time, annual areas of erosion and accretion were measured for the six scenarios. Climate change wave scenarios showed a decrease in waves incoming from the NW quadrant and, an increase from the N and W quadrants when compared with historical data. The global shoreline tendencies were maintained on each study site, but the climate change scenarios influence showed different behavior of the coastline along the Portuguese littoral.

**Keywords** RCP scenarios · Numerical modeling · Shoreline evolution · Coastal erosion · Portugal · SLR

## Introduction

Coastal sandy areas are highly dynamic environments, where sediment transport driven predominantly by wave action defines its morphology. Up to 70% of sandy beaches around the world suffer from erosional problems (Bird 1985) and many of those that are still accretional, are expected to eventually stabilize or even retreat (Leatherman et al. 2000). Adding to the sediment supply reduction to the coastal areas,

variations in the sea-level, wave height and direction are the main physical drivers that trigger the erosive processes, leading to an unbalance of sediment budget (Toimil et al. 2017). Additional risks can be expected from climate change and its undesirable consequences, such as a projected increase in frequency and magnitude of extreme events (SROCC 2019). Managing coastal erosion has become extremely challenging and demands an ever-increasing need for adaptation actions (Toimil et al. 2017; SROCC 2019), since climate change has been occurring for some time now and is being more aggravated by anthropogenic forces (Wong et al. 2014). The effects of climate change due to global warming are recognized as the main driving force for global sea level rise (SLR) and, based on projections by the United Nations Intergovernmental Panel on Climate Change (IPCC), the rate of sea-level rise is accelerating (IPCC 2020). The IPCC adopted different greenhouse gas concentration trajectories, designated as RCP2.6, RCP4.5, RCP6, and RCP8.5 (Representative Concentration Pathway – RCP), to describe different future climates based on the volume of greenhouse gases

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emitted in the future years (IPCC 2014). Global projections of mean sea-level rise (MSLR) predict a rise between 0.47 m (0.32–0.63 m, likely range) under a RCP4.5 scenario and 0.63 m (0.45–0.82 m, likely range) under a RCP8.5 scenario by 2100 relative to 1986–2005 (IPCC 2014). The impacts of global warming in other climatic variables suggest that future change is very likely, where changes in wind climate result in changes of both wave heights and directions, which are expected to contribute primarily to altering future shoreline configurations, since wave conditions are the main regulator of longshore drift rates and direction (Zacharioudaki and Reeve 2011; Luijendijk et al. 2018; Alves et al. 2020; Vousdoukas et al. 2020; Ankrah et al. 2023).

The occidental Portuguese coast is not exempt from this problematic. Being exposed to the wave climate generated in the North Atlantic, which is well known for being very energetic, storms ravage the coast, causing important alterations in the morphodynamics of the beaches, by intensifying the velocity of the longshore drift (Romão et al. 2015). Coastal erosion as well as unsuitable civil development near the foreshore, resulted in the narrowing of the beaches (Coelho et al. 2009). More than 50% of the sandy coast of Portugal is under a significant recess of the coastline (Pranzini et al. 2015), where low-lying sandy coasts are most vulnerable when it comes to storm surges and flood risks (Alves et al. 2011; Santos and Miranda 2006). The Northwest Portuguese coast suffers from the continued high sedimentary deficit caused primarily by the reduction in sediment supply from the Douro River. When dune systems are weakened or destructed, their function of tightening the active beach profile is inhibited by restraining the landward extension of wave swash and, their capacity to protect low-lying coastal areas (Coelho et al. 2009). Due to the current state of coastal erosion along the Northwest Portuguese coast, the anticipated SLR caused by climate change will have a significant effect in the following 50 to 100 years (Silva et al. 2007). Dias and Taborda (1988) found tendencies of increasing mean sea-level based on an elevation time-series of 5 tidal gauges located on the Portuguese coast. For the Cascais station (38.69° N, 9.42° W), which had a time-series long enough for an SLR analysis, the value for SLR was  $1.3 \pm 0.1$  mm/year. A further analysis for a national projection showed a rise of between 0.14 and 0.57 m in the mean sea-level at the end of the twenty-first century (ca. 1–5 mm/year), consistent with the global projections. More recently, Antunes (2019) built an ensemble of 147 projections of SLR for the West coast of Portugal with data from the Cascais tide gauge until the end of the twenty-first century, based on acceleration estimations and their respective initial SLR velocities in the year 2000. In his study, a value around 0.75–0.8 m was calculated for the end of the century, coinciding with the medium RCP8.5 global SLR projection of 0.79 m calculated by Jevrejeva et al. (2014).

The aim of this study is to evaluate the behavior of the shoreline evolution in three coastal stretches from mainland Portugal, selected due to their long-lasting erosional tendencies: Aveiro, Figueira da Foz and, Caparica coast. The Long-Term Configuration (LTC) numerical model was used (Coelho 2005), based on its capacity to project and reproduce the coastline position in a mid-long term, through the application of the equation of continuity to sediment transport (Coelho 2005; Pombo et al. 2022). The shoreline behavior was analyzed through a 20-year projection. A total of six case scenarios were studied, considering a mean sea-level rise of 0.0075 m/year and, three wave climates: a historical scenario with data derived from the WAVEWATCH III spectral model and; two climate change scenarios considering the RCP4.5 and RCP8.5 carbon concentration pathways of the IPCC. The RCP4.5 is described as an intermediate scenario, which assumes that in 2040 it will be reached a maximum of gases emission followed by a decrease in emissions, whereas the RCP8.5 represents the most adverse scenario, considering the continuous increase of greenhouse gas emissions in time, with no decrease afterwards (Meinshausen et al. 2011; IPCC 2014).

## Methodology

A 1-line numerical model, LTC (Coelho 2005; Coelho et al. 2007; Silva et al. 2007; Coelho et al. 2013; Lima and Coelho 2017), was applied in the present study. The LTC allows to project the shoreline position in sandy coasts and enables the establishment of natural and anthropogenic scenarios. Six scenarios were simulated, to highlight the effect of climate change effects in the waves' characteristics and sea-level rise in terms of shoreline behavior due to the persistent erosion occurring in the study area, which includes three coastal stretches.

## Study area

The western Portuguese coast is exposed to a highly energetic wave climate (wave-dominated) and is undergoing severe erosion, especially the sandy coast (Pais-Barbosa et al. 2007). The decades between 1940 and 1970 were characterized by the construction of hydroelectric dams in the main Portuguese hydrographic basins, resulting in one of the main causes for sediment deficit due to the trap of fluvial sediments that would nourish the coastal areas (Dias 2005). The retention was estimated at more than 80% of sand volumes that were transported by rivers in a natural regime (Syvitski et al. 2009; Valle 2014). During the mid-twentieth century, in an effort to reduce erosion along the coastal areas, some anthropogenic solutions were implemented, and consequently, hard coastal structures, such as

groins, seawalls and jetties, were widespread built (Pranzini et al. 2015; Pinto et al. 2020).

The evolution of the coastline along the continental Portuguese littoral between 1958 and 2010, as depicted by Lira et al. (2016), shows a global tendency of erosion of the sandy coasts, with a mean rate-of-change of  $0.024 \pm 0.01$  m/year. The highest rates of erosion were found in the regions of Ovar, Aveiro ( $7.38 \pm 0.2$  m/year), Figueira da Foz – South ( $3.77 \pm 0.2$  m/year) and Caparica coast ( $4.57 \pm 0.2$  m/year) (Lira et al. 2016). The three littoral stretches of the study—Aveiro, Figueira da Foz and, Caparica coast—feature sandy beaches and coastal protection structures, both natural and artificial, as shown in Fig. 1.

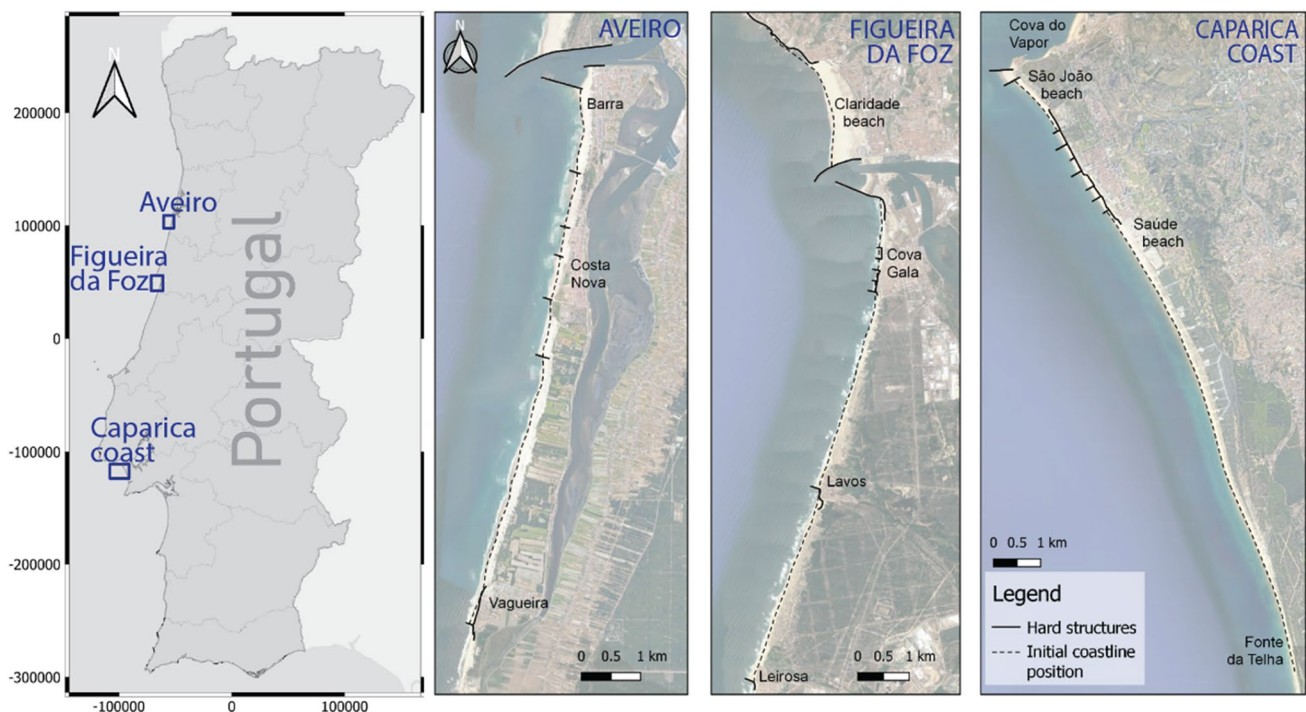
The coastal stretch of Aveiro is oriented NE-SW and composed of medium quartz sand (Narra et al. 2015). The wave climate that reaches the coast of Aveiro is characterized on average by yearly significant wave heights ( $H_s$ ) of 2–2.5 m and, wave periods of 9–11 s corresponding to WNW to NNW swell (Andrade et al. 2002). The coastal area of Figueira da Foz selected in the present study comprises both the northern and southern coasts in relation to the Mondego river, with an orientation of NW–SE at the north shore and NE-SW at the southern coast. The typical wave climate observed at this coast corresponds to NW (71.3% of occurrences) and West (18.8%) swells with  $H_s$  ranging between 2–3 m and, peak period between 11 and 13 s. Storm periods generated in the North Atlantic are frequent during the maritime winter (*i.e.*, from October to March), which

give rise to high amplitude waves, whose significant height frequently exceeds 5 m (reaching  $H_s$  of 8 m) and last up to 5 days, while milder conditions are observed during the summer (Costa et al. 2001; Ferreira et al. 2008). The dominant northwest wave direction, alongside with the NE-SW coastal orientation, results in a predominant southwards longshore sediment transport of  $1 \text{ Mm}^3/\text{y}$  (Silva et al. 2012; Santos et al. 2014; Stronkhorst et al. 2018).

Caparica coast is frequently affected by NNW-SSE moderate wave conditions with  $H_s$  lower than 2 m–3 m and, during the winter season the prevailing swell direction shifts to NW–SE, leading to significant wave heights ranging from 3 to 4 m (Silva et al. 2017). The cape located to the north of the river's mouth provides natural protection to the Caparica coast against NW swells, whilst leaving this coastal area exposed to storms coming from the SW, which can reach significant wave heights of 5 m or more with a 1-year return period (Veloso-Gomes et al. 2009).

### Model set-up

For modeling purposes, hard coastal structures were identified since they restrain the natural evolution of the coastline: groins act as transversal barriers to longshore sediment transport; seawalls fixate the shoreline position hindering its retreat and; rocky areas act as fixed frontiers. A total of four numerical model domains (or grids) were developed based on the identified boundaries. In the present study, the



**Fig. 1** Left: Location of the three coastal stretches in the study; from left to right: Aveiro, Figueira da Foz and Caparica coast

interactions of one grid modeled with the external environment are determined by the boundary conditions and, similar sediment transport conditions were defined for both the north and south borders. Therefore, it was possible to divide the coastal stretch of Figueira da Foz into North and South, in relation to their position off the Mondego river mouth, to facilitate the modeling process due to the difference in the coast orientation. The grids formed a regular mesh of points spaced 20 m oriented E-W and 40 m oriented N-S and, stretching from the -25 m deep referred to chart datum (C.D.) level (the national hydrographic level is 2 m below mean sea-level), as show in Table 1.

With the aim of assessing the behavior of the coastline, within the fixed points represented in the model, the grids were subdivided into different sectors matching the identified boundaries, designated by *s<sub>x</sub>* (being *x* the numerical order of each sector within the grid), as shown in Fig. 2. The initial shoreline position was derived from *Google Satellite* orthophotomaps throughout QGIS software by assuming the wet/dry line as a shoreline proxy, for each numerical domain, and it was later arbitrarily attributed to mean sea-level (+2 C.D.) for reference. The orthophotomaps used for the grids M1, M2 and M3 correspond to the 18<sup>th</sup> June 2018 and, for the grid M4 it was used the one from the 3<sup>rd</sup> October 2018.

The definition of the shoreline rate-of-change through time, in order to calibrate the model, had the study of Lira et al. (2016) as main reference. The initial shoreline position and rate-of-change between 1958 and 2010 are shown in Fig. 2.

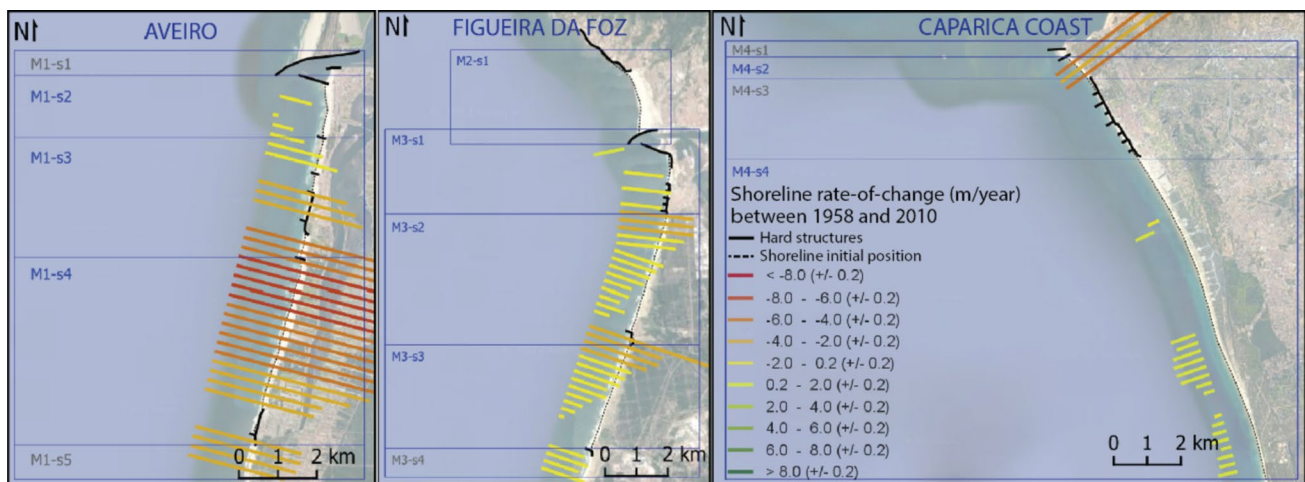
The bathymetry was derived from six transversal profiles obtained in May 2019, under the Portuguese COaStal Monitoring Programme—COSMO (<https://cosmo.apambiente.pt/>, accessed on 6 May 2022), developed and implement by the Portuguese Environment Agency. Real data could not be used for each site since, due to model assumptions, LTC bathymetry and topography can only be assumed steadily increasing landward. For modeling purposes, considering that the LTC is a simplified model for medium to long-term projections that just allows regular bathymetry representation, the COSMO profiles (Pinto et al. 2021) were approximated respectively to the equilibrium beach profiles of Dean (1977) that better represented the real bathymetry. These assume a uniform dissipation of wave energy, following this equation:

$$h = Ax^m \tag{1}$$

where *h* represents depth at a *x* distance, measured at mean sea-level from the shoreline position. The index *m* depends on the type of wave energy dissipation that reaches the beach

**Table 1** Characteristics of the numerical model domain for each coastal stretch

Coastal stretch	Grid	Origin coordinates (ETRS89 / Portugal TM06)		Nº of points		Dimension (km)	
		X	Y	X	Y	X	Y
Aveiro	M1	-60 207.6224	97 987.3492	451	276	9	11
Figueira da Foz-North	M2	-69 167.6224	52 987.3492	351	76	7	3
Figueira da Foz-South	M3	-71 247.6224	42 467.3492	501	276	10	11
Caparica coast	M4	-10 7964.8379	-12 3760.4222	851	326	17	13



**Fig. 2** Location of the grids and subgrids of the modeled sectors. Shoreline initial position (dashed black line) and rate-of-change (m/year) between 1958 and 2010 (following Lira et al. 2016)



under study. Commonly for intermediate beaches, which represents the typical profiles found on the western coast of Portugal (Coelho 2005), this value varies between  $m=1/2$ ,  $m=4/7$  and  $m=2/3$ . This last value was the one applied in the present study, after performing some sensitive analysis to the impact of the different options, and finding that a single  $m$ -value could describe all the profiles.

In order to estimate the bathymetry, it was considered the equilibrium beach profile of Dean (1977) most representative of the real bathymetric profile of the costal stretch, assuming that: i) in the case of being more than one COSMO profile at the stretch (grids M1 and M4), it was considered the mean of the Dean profiles approximated to each real profile and; ii) in the case of being only one COSMO profile at the stretch (grids M2 and M3), this survey was considered alone in the Dean approximation. The values for the  $A$  parameter for the M1, M2, M3 and M4 grids corresponded to 0.090, 0.097, 0.084 and 0.058 respectively. Regarding the topography, due to simplifications of the model, it was considered a representative and constant slope of 3%, defined at the shoreline. Different slope conditions were tested at the beginning of the calibration process, when adopting the representative cross-shore profiles. No significant differences were verified if the slopes were considered different, as the calibration process allows to represent the shoreline evolution at every stretch. The topo-hydrographic models were produced based on the shoreline position and the transversal profile of reference.

For calibration purposes of the LTC model, 50 years of spectral wave data derived from the WAVEWATCH-III (WWIII—GeoFCUL 2021) hindcast model were simulated, for the period between 1959–2008, previously validated by Dodet et al. (2010). It was assumed a constant sea-level equal to the mean level, considered to be +2 m C.D. The LTC model propagates waves in a simplified approach, considering the shoaling, refraction and diffraction effects, assuming an individual wave incidence along the computational time. It also estimates the induced longshore solid sediment transport for each breaking wave, making a sediment balance, for each elementary beach cell, and evaluating the sediment volume in erosion or accretion (Lima and Coelho 2017). The results of this simulation were compared with the results of the shorelines position evolution determined by Lira et al. (2016) for the period 1958–2010. The LTC allows to calculate inner-grids separately, so as to be possible to simulate different conditions in each of them. Grid intersections are made through forcing the outputs of the northern grid in the subsequent grid at south. Sectors M1-s1, M1-s5, M3-s4, M4-s1 and M4-s3 were not considered in the analyses of the results of the present study since they have been artificialized with seawalls (no shoreline retreat allowed) or since they represent frontier sectors, which were only included

for stabilization of the model. The calibration process was determined mainly based on the discussion of the depth of closure and the empirical coefficient  $k$  of the CERC equation (CERC 1984), being this last one modified in order to approximate the results to the rate-of-change from Lira et al. (2016). The  $k_{\text{CERC}}$  is also used to absorb other simplifications of the model, namely the wave propagation approach that considers the linear wave theory when estimating the wave breaking characteristics. The same wave climate was considered in all the coastal stretches, in spite of each sector particular morphological features (bathymetry and topography), as the  $k_{\text{CERC}}$  coefficient allows adapt and calibrate their resulting longshore sediment transport gradients. Therefore, the adopted  $k_{\text{CERC}}$  may be out of the common range of values referred in the literature, but it was possible to obtain consistency shoreline evolution in the 50-year calibrated values for the sectors M1-s2, M1-s3, M2-s1, M3-s1, M4-s2 and M4-s4, according to Table 2, without compromising longshore sediment transport rates. Depending on shoreline orientation and  $k_{\text{CERC}}$  coefficients, average sediment transport rates within the sectors ranged between 70.000 m<sup>3</sup>/year (sector M1-s2) and 1.400.000 m<sup>3</sup>/year (sector M4-s2), with an average value between all sectors of 426.000 m<sup>3</sup>/year.

The  $\Delta_{\text{abs}}$  and  $\Delta_{\text{rel}}$  values in Table 2 represent, respectively, the absolute and relative difference between the shorelines rate-of-change resulting from the LTC model and the registered in Lira et al. (2016). The calibration process showed a maximum relative difference of 8% and, a mean shoreline rate-of-change between +15 cm/year and -7 cm/year.

## Climate change and sea-level rise scenarios

Maritime wave climate can be forecasted (and hindcasted) through numerical models that solve equations describing the wind-waves generation processes (WMO 1988). Therefore, three maritime wave climate datasets (significant wave height,

**Table 2** Calibration parameters of the LTC model during the simulation period 1959–2008

Sector	Mean rate-of-change (m/year)	Maximum rate-of-change (m/year)	$k_{\text{CERC}}$	$\Delta_{\text{abs}}$ (m/year)	$\Delta_{\text{rel}}$ (%)
M1-s2	-0.33	-0.71	0.0320	-0.03	5
M1-s3	-2.69	-6.06	0.0690	0.15	6
M1-s4	-5.14	-8.41	0.0810	-0.07	1
M2-s1	2.14	4.47	0.0090	*	*
M3-s1	-1.23	-1.72	0.0187	-0.01	1
M3-s2	-1.31	-6.73	0.0226	-0.03	2
M3-s3	-1.19	-6.14	0.0158	-0.05	4
M4-s2	-4.25	-6.96	0.0700	-0.01	0
M4-s4	-0.24	-0.65	0.0100	-0.02	8

\* No found values in Lira et al. (2016) work for this sector

peak period, and wave direction) derived from numerical models were considered to characterize the study area, in a scenario based on past events and, two future scenarios considering the effects of climate change. To reproduce the historical period, the wave series used to calibrate the model were considered (see the model setup description). The future scenarios, designated as RCP4.5 and RCP8.5, characterized the future wave climate for the different greenhouse gas concentration trajectories, corresponding to 20 years of records (2026–2045). These wave series characterize the deep-water wave climate offshore of the study area (at a point with coordinates 10°W 40.50°N) and were obtained from wave datasets downscaled using the Wave Watch III model developed by Meteogalicia in the scope of MarRisk research project (Ferreira et al. 2021). The wave data was considered equal for all the coastal stretches, being the eventual difference between stretches adjusted by the calibration process ( $k_{CERC}$  as referred in the model set-up section). Lastly, in an effort to isolate the effect of SLR, each of the previously defined scenarios was then simulated with an increase in the sea water level of 0.0075 m/year, a value calculated by Antunes (2019) for the Cascais tide gauge and, similar to the 0.79 m medium RCP8.5 global SLR projection of Jevrejeva et al. (2014) calculated for the end of the twenty-first century.

## Results

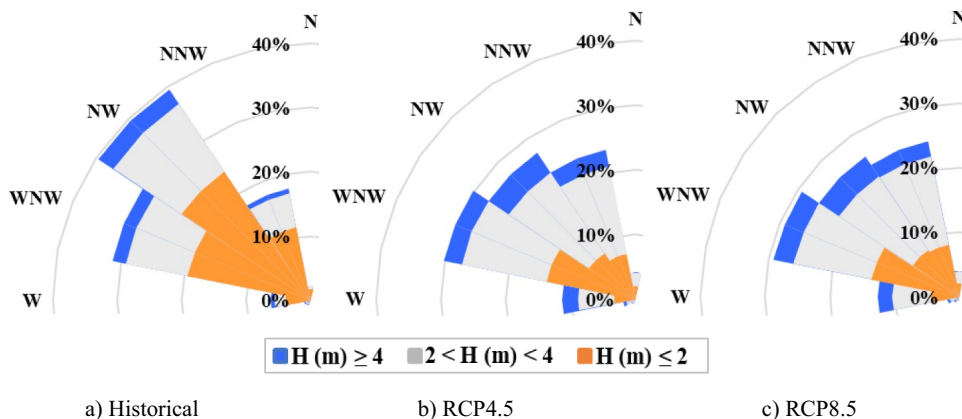
### Wave climate analysis

Table 3 summarizes the average values that characterize each wave series applied in the present study to obtain the

**Table 3** Average values that characterize each wave series

	Historical	RCP4.5	RCP8.5
Hs (m)	2.04	2.61	2.58
T (s)	10.52	10.66	10.57
Dir. (°)	306.94	306.30	306.51

**Fig. 3** Wave roses of significant wave height that characterize each wave series, **a)** Historical, **b)** RCP4.5, **c)** RCP8.5



shoreline projections. The results suggest that on average, the three wave series present a peak period ( $T$ ) of approximately 10.5 s and in the future it is expected an increase of the significant wave height ( $H_s$ ) of approximately 0.6 m, compared with the average wave height obtained for the historical wave series.

The average direction ( $Dir.$ ) offshore that characterizes each series is approximately  $306^\circ$  (angle with North in the clockwise direction). However, the wave rose obtained for each series depicts considerable differences in the dispersion of the waves' directions on the W–N sector, namely between the historical wave series and the RCPs wave series (Fig. 3).

In the historical period, the waves are most frequent from the NW direction (approximately 40%). Additionally, around 60% of the wave records analyzed represented calmness by means of wave height below 2 m. In the RCP4.5 and RCP8.5 wave series is observed a decrease in the waves from NW and an increase in the waves from NNW and W directions. Furthermore, the wave roses show an increase in the frequency of the highest waves in the RCPs series. Based on the study of the Fig. 4, in the RCPs wave series the frequency of the waves with a significant height lower than 2 m decreases approximately by 25%, the frequency of waves in the interval defined by a maximum wave height equal to 4 m and a minimum equal to 2 m increases approximately 20% and the frequency of waves with a significant height equal to or higher than 4 m increases approximately 5%.

### Climate change and sea-level rise influence on shoreline

The influence of wave climate showed a different behavior of the coastline along the Portuguese littoral throughout the 20-year projection (Fig. 5). The coastal stretch of Aveiro is estimated to undergo the greatest erosion among the study areas (Table 4). In a 20-year time frame, it is

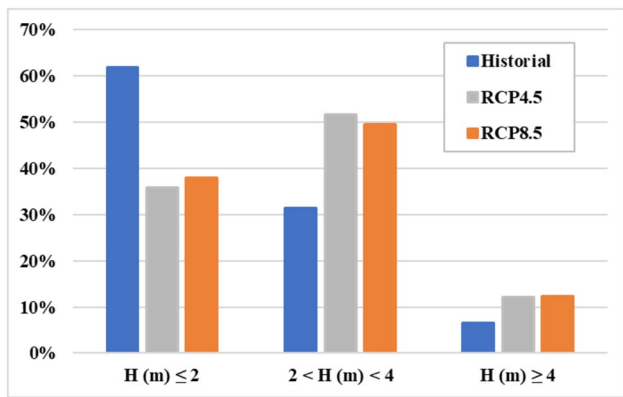


Fig. 4 Significant wave height frequency distribution that characterize each wave series

projected for this stretch a land loss of 50 ha (6.34 m/year) under historical wave climate, whilst under RCP4.5 and RCP8.5 it is projected a loss of 27 ha (3.45 m/year) and 37 ha (4.74 m/year) respectively. The coastal stretch of Figueira da Foz – North is the only among the study area to expect a prevalence of accretion under both historical and RCP (4.5 and 8.5) wave climates, with greater rates due to climate change and, exceeding 10 ha (2.23 m/year) under IPCC’s intermediate scenario. Southern to the Mondego river mouth, in the Figueira da Foz – South sector, it is estimated a similar coastline behavior under RCP8.5 climate change scenario and historical wave climate, with a land loss of 22 ha (1.45 m/year) and 25 ha (1.66 m/year) respectively. It is in this sector that it is predicted an almost double land loss as a consequence of projecting the shoreline behavior under a climate change scenario, RCP4.5, reaching 42 ha (2.79 m/year) after 20 years of simulation. Caparica coast shows the lowest erosion among the study area, being expected a similar behavior of the coastline

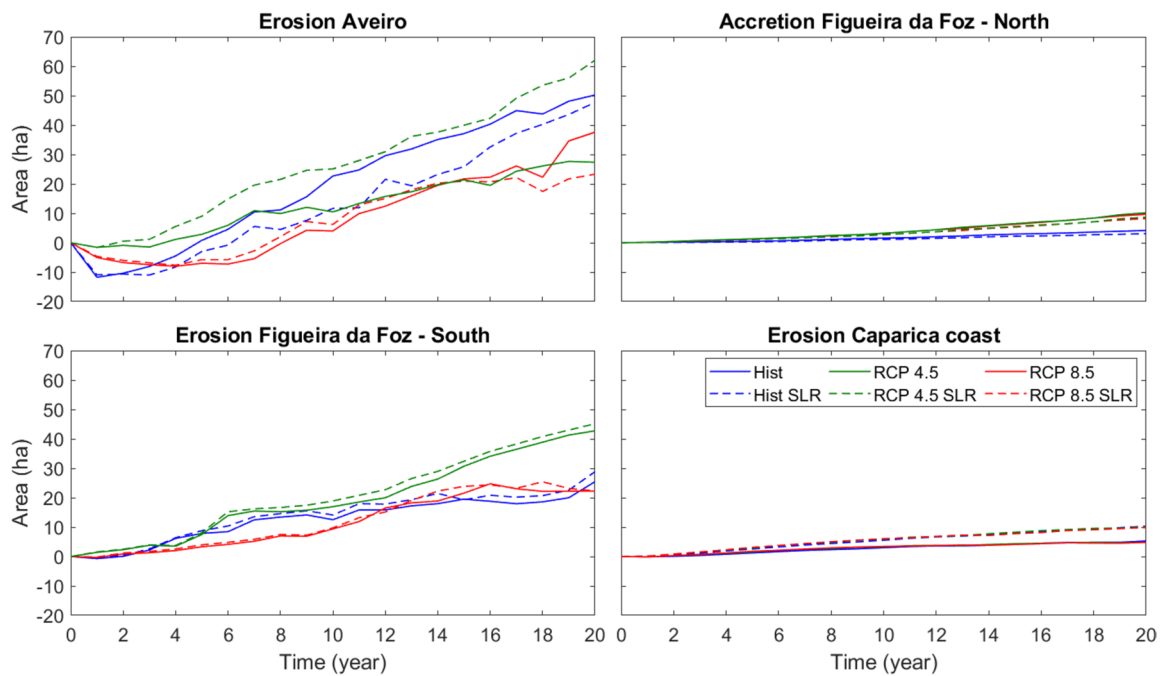


Fig. 5 Yearly predicted erosion and accretion areas under historical (Hist) and climate change (RCP4.5 and RCP8.5) scenarios and; the influence of sea-level rise (SLR) in a 20-year time frame

Table 4 Area of erosion (–) or accretion (+) after 20 years of simulation for the four grids under historical (Hist) and climate change (RCP4.5 and RCP8.5) conditions, with and without sea-level rise (SLR)

Grid	Area (m <sup>2</sup> )					
	Hist	Hist SLR	RCP4.5	RCP4.5 SLR	RCP8.5	RCP8.5 SLR
M1	–502204	–476751	–273545	–620519	–375950	–233180
M2	41841	30892	101850	86773	96864	82181
M3	–254510	–288302	–427378	–451383	–222461	–223102
M4	–53022	–103101	–48320	–101546	–48045	–98681

under historical and climate change scenarios, with values close to 50 ha (1.89 m/year under Hist, 1.73 m/year under RCP4.5 and 1.72 m/year under RCP8.5) of land loss in the three projections.

Regarding the sea-level rise effect in the coastline behavior, in general it results in higher erosion (M3 and M4) or lower accretion (M2). The only exception is Aveiro (M1), where it is expected an attenuation of the eroded land of up to 10 ha during some periods (years 11 and 13 of Hist vs. Hist SLR in Fig. 5) due to the lone effect of sea-level rise, although the difference ceases at less than 3 ha after 20 years of simulation. This result may be related with the wave propagation phenomena considering the local depths resulting from the sea-level rise, changing the potential sediment transport due to different wave refraction effects.

For RCP8.5 climate change scenario accounting for sea-level rise, the region of Aveiro shows an enhancement of the erosion through the first years, whilst after year 15 of the simulation it could be expected a reduction in the areas of erosion when compared to the same scenario without SLR. The influence of SLR shows the highest variability among the scenarios here presented in the projection of the coastline for the RCP4.5 case in the region of Aveiro, with an increasing enhancement of the erosional areas up to 62 ha (7.83 m/year). North to the Mondego river mouth, the accretion tendency is slightly reduced in the order of 11 ha to 15 ha due to the effect of SLR through the 20-year projection. In line with this, for the southern sectors (Figueira da Foz – South and Caparica coast), it is expected that the SLR effect accounts for higher rates of erosion along the coastline simulation.

The results presented in Fig. 5 represent a general trend, but of course, there are years with greater erosion followed by others with less erosion (in accretion, the smaller values show a straighter trend). This is dependent of the adopted wave climate and other wave climate scenarios would represent different evolution. However, if the average wave climate is similar, different scenarios will represent similar shoreline erosion rates at the end.

## Discussion

### Wave climate scenarios

The analysis of the wave series considered in this study (Historical, RCP4.5 and RCP8.5) reveals that the average direction characterizing each series is approximately  $306^\circ$ . However, the wave roses representing significant wave height for the RCP scenarios exhibit a greater

dispersion of wave directions in the W and WNW sectors. Additionally, when comparing the RCP4.5 wave rose to the RCP8.5 wave rose, it is observed that the RCP8.5 series demonstrates a lower frequency of higher waves originating from the NW and NNW directions. The differences in wave direction have implications for the longshore sediment transport. As highlighted in Ferreira and Coelho (2021), sediment transport is highly dependent on the relation between shoreline orientation and wave direction. According to the authors the same shoreline orientation experiences different longshore sediment transport depending on the wave direction and the higher longshore sediment transport rates are not necessarily associated with waves approach the shoreline at a more oblique angle. Also, Murray and Ashton (2013), by means of a semi-empirical equation for alongshore sediment flux, emphasize the impact of the relation between the shoreline orientation and the offshore wave angle in the sediment transport. Through the derivative of CERC (1984) formula, Ferreira and Coelho (2021) highlight that the maximum sediment transport occurs when the offshore wave direction is approximately  $48^\circ$  (angle between the wave and the shoreline). Following the same approach, Ferreira et al. (2023) discuss the longshore sediment transport gradients along the Northwest Portuguese coastal sector. Their study focuses on examining the interplay between wave directions that contribute to higher longshore sediment transport and the orientation of the shoreline. The results highlight the variability of potential littoral drift values along the Portuguese coast, emphasizing the significance of the relationship between shoreline orientation and wave direction. According to the findings presented in these studies, the offshore wave direction that promotes higher sediment transport along the Portuguese West coast is approximately  $32^\circ$ , representing the angle between the wave direction and the shoreline. Furthermore, the results of Ferreira et al. (2023) suggest that Aveiro region and Figueira da Foz are among the stretches that present high potential littoral drift and these territories are close to areas where are observed important dynamics in terms of littoral drift gradients.

Following the discussion presented above, the increased dispersion of wave directions in the W–N sector during future periods and the observed decrease in the frequency of waves with more capacity to transport the sediments in the RCP8.5 scenario (higher frequency of waves from directions close to the ones that promote larger sediment transport, approximately  $32^\circ$ ) could provide support for the findings that the highest rates of shoreline erosion occur in the RCP4.5 plus SLR scenario, both at Aveiro and Figueira da Foz – South sectors.



## Climate change and SLR impacts

Previous studies in the western Portuguese coast have focused on determining the impact of climate change and SLR, although results seem to differ. In 2006, Santos and Miranda suggested that the intensity of erosion that affects the Portuguese littoral will be amplified in a 12–15% by 2100. A year later 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 twenty-first century. They suggested that there will 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. Coelho et al. (2009) concluded that the effects of SLR are less important than the changes in wave action. For Aveiro, the scenarios of SLR are less important than the scenarios of wave-climate change after 25 years and, a slight increase in the relative frequency of higher waves would have greater effects than a pessimistic scenario of the SLR rate. When observing the coastline position in year 20 of the simulation, a different behavior can be spotted on the north side of the groins Aveiro (Fig. 6). Under a historical wave climate, the results show that it is expected accretion (see groins in Costa Nova—Fig. 6) and, under a RCP4.5 scenario it will be expected an erosional process. This effect can also be observed in Figueira da Foz – South, more precisely in Lavos and Leirosa, and does not appear to be influenced by SLR. This process highlights the effect of the rotation of the incoming waves under climate change scenarios, since the NW incoming waves will no longer be prevailing and a higher percentage of waves will reach the coast from a more perpendicular angle (as seen in Fig. 3), a shift in either the volume or direction of the sediment drift could be expected as an outcome of this process.

Protected at north by the Mondego Cape and at south by the extension of the Mondego River breakwater, the Figueira da Foz – North sector presents a peculiar behavior due to its morphological configuration, where the tendency of accretion has been persistent for the last half century (Freitas et al. 2015). There is a strong accumulation of sands retained by the north breakwater from the longshore sediment transport, with north–south direction, resulting in a significant growth of the beach. Between 1962 and 1980 the coastline position advanced between 180 and 440 m seawards in this sector (Vicente and Pereira 1986). Interestingly, the scenarios that aim to explore the effects of SLR show a decrease in the accretion trend, whilst both climate change scenarios enhance this condition. The sediment retention at the north of the Mondego river mouth induced a downdrift coastline retreat, southern of the port of Figueira da Foz (Santos et al. 2014). The climate change scenarios included in this study, showed an increase in the erosion trends for this sector mostly under the RCP4.5 scenario (Fig. 5). Regarding the

coastline behavior at the Caparica coast, the erosional trend appears to be doubled due to sea-level rise (M4 in Table 4), being São João beach the area mainly impacted and corresponding to the highest rate-of-change in the sector (M4-s2 in Table 3). Caparica coast nearshore is characterized by very shallow bathymetry, therefore an increase in the sea-level would allow a further intrusion of the waves in the cross-shore beach profile and, the consequent enhancement of erosion.

## Numerical modelling assumptions

When considering shoreline retreat rates, the general average behaviour could be similar to the real stretch behaviour, although in specific locations the results may exhibit significant differences. Additionally, medium to long-term shoreline evolution numerical projections, it is difficult to simultaneously reproduce the shoreline retreat rates and the sediment transport volumes (Baptista et al. 2014). The simplified LTC wave propagation approach was considered for all the coastal stretches, making important the definition of the  $K_{CERC}$  coefficient on the calibration process (Hanson and Kraus 1989; Sancho 2023). Hanson and Kraus (1989) refer a common range of 75 to 100% of the original  $k$  value, for the CERC formula and, Pilkey and Cooper (2002) refer to the use of a much broader range, with  $k$  values from 2 to 300%. In the LTC this range is broader, as the  $k$  coefficient is also considered as a correction factor of the simplified processes considered in the wave propagation processes. Bathymetric and topographic differences between coastal stretches are also implicit in this  $k$  coefficient. This process proved to be valid for the medium-term projections, as described by Pombo et al (2022). The same assumptions were adopted in the calibration and future scenarios and thus, a relative impact was considered valid, as intended.

In relation to the beach profile behaviour, it is known that the rising water level causes an imbalance in the cross-shore profile. If the equilibrium profile were flat, then rising water level would not change the depth at a given distance from the new shoreline and there would be no imbalance. Without further nourishment of sediments into the system, the only way in which the profile returns to equilibrium is by shoreline recession, yielding sediments to fill the bottom to a depth consistent with the equilibrium profile and the new (high) water level (Bruun 1962). The 1-line shoreline evolution models consider the longitudinal gradients on the sediment transport and thus, the sea level rise is considered in a new position of the altimetric levels and their impact on the wave propagation and consequent sediment transport capacity. This way, sea level rise is considered in the wave propagation impacts and longitudinal sediment transport processes, adding to the new position of the intersection between the sea level and the land surface (shoreline).

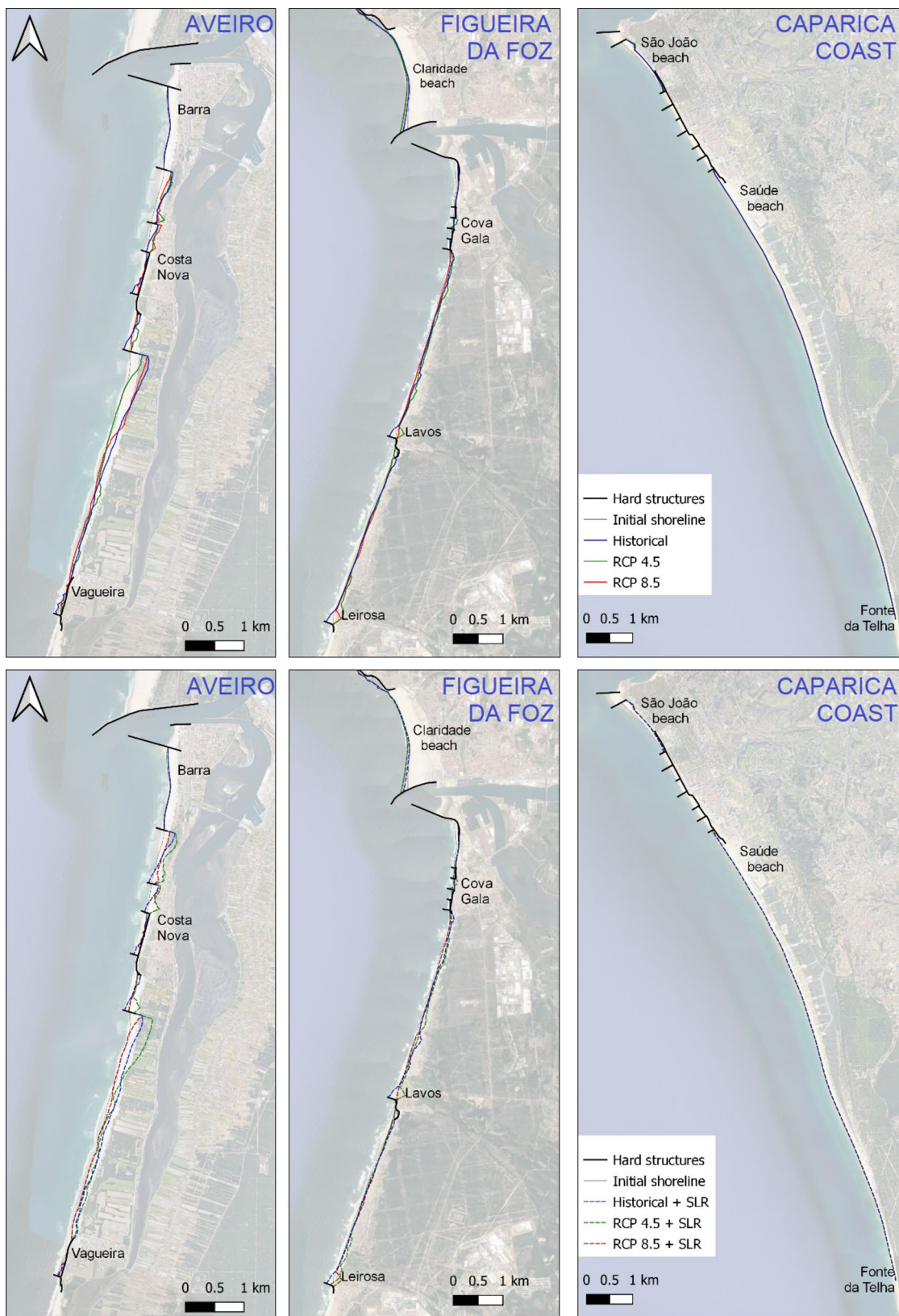


Fig. 6 Shoreline position at year 20 of the simulation under the six maritime climate scenarios: upper without SLR and down with SLR

Finally, numerical modeling simulations have proven to be great tools for accurate shoreline evolution predictions, when compared with *in situ* measurements from monitoring programs (Pombo et al. 2022). The RCP wave climate and sea-level rise values used in the present work are projections based on long-term tendencies. As proved by Pombo et al. (2022), the shoreline evolution model's accuracy is highly dependent of the wave climate adopted to perform the projections. Thus, in order for these shoreline evolution projections to have a good approximation, it is of utmost importance that the wave climate used resembles the uncertain future wave climate.

## Conclusions

While the erosion problem along the Portuguese coast is by now of common knowledge and many initiatives to recess the damages have been implemented through the past decades, the impact of climate change and its subsequent effects, such as sea-level rise, are still to be understood. The present study aimed to analyze the behavior of the western Portuguese mainland coastline, under historical and climate change wave forcing scenarios, as well as the effect of sea-level rise. The numerical model Long-Term Configuration was applied for a medium-term (20-years) shoreline evolution, to three coastal stretches with different erosional tendencies.

Historically, the coast at South of Aveiro suffered from land loss with a maximum of 8.41 m/year (Table 2) and future projections under the same wave regime predict a loss of 50 ha after 20 years. A worse scenario is expected when accounting with an intermediate climate change scenario (RCP4.5) and SLR, reaching values of 62 ha after the same period. However, a westerly rotation in incidence wave angles towards the Portuguese coast will be expected due to climate change. The analysis of future wave directions reveals a higher dispersion of wave directions in the W–N sector, particularly in the RCP8.5 scenario. This dispersion leads to a decreased frequency of waves that have a higher capacity for sediment transport. This factor will allow the waves to approach from a more perpendicular angle to both Aveiro and Figueira da Foz – South sectors, due to their shoreline orientation, changing the longshore sediment transport patterns and the shoreline equilibrium position, allowing higher rates of erosion, mainly caused under RCP4.5 plus SLR. A similar behavior, although of different magnitude, is expected in Figueira da Foz – South, where 45 ha of coastline may be overtaken by the ocean. The Caparica coast presents a different behavior, not only due to its orientation, but also due to the wave refraction. It is suggested by different authors that due to the wave refraction, there is a turning point in the mean sediment flux direction

which works as a counter current, creating a south-north sediment flux that helps stabilize the shoreline position (CEHIDRO 1999; Teixeira 1990; Sancho et al. 2017). Sea-level rise is the main factor to double the erosional tendencies in the Caparica coast, ranging these values between 5 ha without SLR and 10 ha when considering it in the projections. Lastly, the accretional trends in Figueira da Foz – North would be enhanced by climate change reaching 10 ha under RCP4.5, whilst reduced due to SLR with the lowest values observed were 3 ha under historical wave climate.

The uncertainty of future wave climate scenarios and sea-level rise is reflected in shoreline evolution projections. Thus, the obtained results show the importance of defining future forcing scenarios in the projection of the shoreline position over time, representing differences up to about 30% in the areas that may be lost due to coastal erosion. Potential changes in the net longshore sediment transport rates are predictable due to future wave rotation and thus, climate change scenarios may shift the position of the most vulnerable places, but will not necessarily increase the global erosion rates. To mitigate the difficulties in defining adequate forcing climates, several scenarios should be discussed, allowing to define a range of possible shoreline position projections.

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## Declarations

**Competing interests** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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