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# Dual wave farms for energy production and coastal protection under sea level rise

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## Abstract

Climate change is poised to exacerbate coastal erosion. Recent research has presented a novel strategy to tackle this issue: dual wave farms, i.e., arrays of wave energy converters with the dual function of carbon-free energy generation and coastal erosion mitigation. However, the implications of sea level rise - another consequence of climate change – for the effectiveness of wave farms as coastal defence elements against shoreline erosion have not been studied so far. The objective of this work is to investigate how the coastal defence performance of a dual wave farm is affected by sea level rise through a case study (Playa Granada, southern Iberian Peninsula). To this end, a spectral wave propagation model, a longshore sediment transport formulation and a one-line model are combined to obtain the final subaerial beach areas for three sea level rise scenarios: the present situation, an optimistic and a pessimistic projection. These scenarios were modelled with and without the wave farm to assess its effects. We find that the dual wave farm reduces erosion and promotes accretion regardless of the sea level rise scenario considered. In the case of westerly storms, the dual wave farm is particularly effective: erosion is transformed into accretion. In general, and importantly, sea level rise strengthens the effectiveness of the dual wave farm

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as a coastal protection mechanism. This fact enhances the competitiveness of wave farms as coastal defence elements.

*Keywords:* Renewable energy; Wave energy; climate change; sea level rise; coastal protection; sustainable development

#### 1 1. Introduction

The large-scale exploitation of fossil fuels that started with the Industrial Revolution has caused serious environmental repercussions [1–4], including sea level rise and climate change [5, 6]. One of the most important challenges in the 21st century is to mitigate these repercussions in as much as possible, not least by developing new kinds of sustainable, carbon-free energies [7–19]. In this sense, ocean energies, and wave energy in particular, stand out as one of the most important due to the high resource availability [20–22].

Previous research in wave energy has focused on different aspects related to its exploitation: (i) the development of new technologies [23–29], (ii) the availability of the resource [30–37], (iii) synergies with other types of offshore renewable energies [38–40] and (iv) economic aspects [41–44]. However, the relation between this kind of technology and the incoming sea level rise still needs further research work if wave energy is going to be poised as a functional carbon-free energy in the near future.

Future sea level rise is becoming a threat for coasts across the world, increasing hazards like coastal flooding [45–47]. Among them, coasts near river deltas are being primarily affected, since they allocate places with high economic, social and environmental importance. In addition, anthropogenic interventions on their catchment areas are increasing other hazards as coastal erosion [48, 49].

One of the advantages of wave farms, i.e. arrays of wave energy converters (WECs), is the reduction in wave power in their lee. When waves are transmitted through the farm, part of their energy is absorbed. On these grounds, wave farms can be used to mitigate coastal erosion [50–55] and flooding [56]. In fact, dual wave farms have been defined as those designed to fulfil both functions: carbon-free energy generation and coastal defence [57, 58]. Nevertheless, the wave farm effects on longshore sediment transport (LST), shoreline evolution and dry beach area availability under sea level rise have not been analyzed fo far. This analysis is necessary and relevant since sea level rise is one of the most dangerous consequences of climate change and induces changes on wave propagation and sediment transport patterns.

The objective of this work is to investigate the effects of sea level rise on the 32 functionality of a wave farm for coastal protection against shoreline erosion. To 33 this end, three sea level scenarios were analysed: the present situation (baseline), 34 and the water level in 2100 according to optimistic (RCP4.5) and pessimistic 35 (RCP8.5) projections proposed by [5]. A third-generation wave propagation 36 model (SWAN) was applied to two case studies, with and without a wave farm, 37 on a gravel dominated beach: Playa Granada (Southern Iberian Peninsula). 38 The evolution of the shoreline was computed using a LST formulation [59] and 39 a one-line model [60] in order to obtain the variations in subaerial beach area. 40 The following sections describe the study area (Section 2), methodology (Section 41 3), results (Section 4), discussion (Section 5 and conclusions (Section 6) of this 42 work. 43

## 44 2. Study area

Playa Granada is a 3-km-long beach located on the southern coast of Spain that faces the Mediterranean Sea (Figure 1). The beach corresponds to the central stretch of the Guadalfeo deltaic coast and is bounded to the west by the Guadalfeo River mouth and to the east by *Punta del Santo*, the former location of the river mouth [61, 62]. The deltaic coast is bounded to the west by Salobreña Rock and to the east by Motril Port.

The state of the beach profile is practically reflective and the morphodynamic response of the beach is dominated by the gravel fraction [63, 64]. The studied stretch of beach has been experiencing shoreline retreat and terminal erosion in recent years (Fig. 1c), partly due to anthropogenic interventions in the



Figure 1: (a) Location of the study site in the southern part of the Iberian Peninsula. (b) Aerial photograph of the study site, including the locations of the main geographical features and structures. (c) Storm erosion in Playa Granada. (d) Computational domains used in the numerical model.

Guadalfeo River basin [61, 65]. As a result, artificial nourishment projects have been frequently performed over the past decade [66], but the long-term efficiency of these projects has been very limited [67, 68].

The region is subjected to the passage of extra-tropical Atlantic cyclones and Mediterranean storms [69]. The storm wave climate is distinctly bimodal with the prevailing west-southwest (extra-tropical cyclones) and east-southeast (Mediterranean storms) wave directions [70]. Peak significant wave heights during typical and extreme storm events exceed 2.1 m and 3.1 m, respectively [71]. The astronomical tidal range is  $\sim 0.6$  m (micro-tidal conditions), whereas typical storm surge levels can exceed 0.5 m [63].

## <sup>65</sup> 3. Materials and methods

#### 66 3.1. Modelled wave farm

The influence of wave energy extraction on the wave propagation and sediment transport of Playa Granada was studied modelling a wave farm off the coast, near Punta del Santo (Fig. 2). This wave farm was composed by eleven WECs, arranged in two rows. The location and layout of the wave farm were chosen based on the optimization for coastal defence purposes carried out in previous works [53, 54].



Figure 2: Wave farm location in front of Playa Granada.

The wave energy converter (WEC) selected for the analysis was WaveCat 73 [72, 73]. This device, shown in Figure 3, is a floating and overtopping WEC 74 that comprises two hulls joined by a hinge at the stern [73–75]. For a detailed 75 description of the device, the reader is referred to [25, 76]. Wave farms consisting 76 of WaveCat WECs have been proven to fulfil the dual function of wave energy 77 generators and coastal defence (e.g., Rodriguez-Delgado et al. [57], Abanades 78 et al. [58], among others). This device was included in the wave propagation 79 numerical model through its transmission and reflection coefficients [25]. The 80 inter-device spacing was set to 2D, with D = 90 m the diameter of WaveCat. 81 In order to properly investigate the effects of the wave farm, the baseline (no 82 wave farm) situation was also analysed. 83



Figure 3: Geometry of the WaveCat device at a 1:30 scale (dimensions in mm).

# 84 3.2. Wave and water level conditions

The response of the shoreline was modelled at the storm time scale; more specifically, two sea states were studied, corresponding to westerly and easterly storms – the two prevailing wave directions at the study site. The most frequent values of significant wave height and peak period for storm conditions were selected (Table 1).

Table 1: Parameters of the sea states.  $[H_s: \text{ significant wave height}, T_p: \text{ peak period}, \theta: \text{ mean wave direction}].$ 

	$H_s$ (m)	$T_p$ (s)	$\theta$ (°)
West	3.1	8.4	238
East	3.1	8.4	107

These sea states were applied to three scenarios: the present situation (SLR0), and the optimistic (SLR1) and pessimistic projections (SLR2) of sea level rise in 2100, according to the representative concentration pathways (RCP) 4.5 and 8.5 proposed by [5] for the study site.

## 94 3.3. Wave propagation model

The influence of wave farm and sea level rise in the wave field was computed by means of the third-generation wave propagation model SWAN [77]. This numerical model is able to simulate the effects of obstacles on wave propagation patterns, i.e., reduction of the wave height propagating behind or over the obstacle along its length, reflection of the waves that impinge the obstacle, and diffraction of the waves around its boundaries [37, 78, 79].

The WaveCat WECs were thus included as obstacles in the numerical model, 101 using transmission and reflection coefficients obtained in laboratory experiments 102 [25]. Two computational grids were used (Fig. 1): (i) a coarse grid, covering 103 the region from deep water to the nearshore, with cell sizes that decrease with 104 depth from 170x65 m to 80x80 m; and (ii) a nested grid, covering the inshore 105 region and wave farm area, with cell sizes of approximately 25x15 m. The cell 106 size of the nested grid was adjusted to reproduce properly the effects of each 107 WEC. 108

The spectral resolution of the frequency space consisted of 37 logarithmically distributed frequencies ranging from 0.03 to 1 Hz. For the directional space, the 360° were covered by 72 directions in increments of 5°. This model was previously calibrated and validated in the study area using data from extensive field campaigns [67]. SWAN results were used to obtain wave parameters at breaking, which are the basis of the LST formulation.

## 115 3.4. LST formulation and one-line model

LST rates in the study site for each sea level rise scenario, with and without wave farm, were computed using the formulation of [59] (Eq. 1). This equation has been proved to provide accurate results in a wide range of beach types, from sandy to gravel beaches. More to the point, it has been applied in the study site and successfully validated against field data [67]. The formula can be expressed as follows:

$$Q = 0.00018 K_{swell} \rho_s g^{0.5} (\tan \beta)^{0.4} (d_{50})^{-0.6} (H_{s,br})^{3.1} \sin (2\theta_{br}), \qquad (1)$$

where Q stands for the LST rate,  $\rho_s = 2650 \text{ kg/m}^3$  is the sediment density, 122  $g=9.81~{\rm m/s^2}$  the acceleration of gravity,  $d_{50}=0.02~{\rm m}$  the sediment size,  $\tan\beta$ 123 the slope of the surf zone,  $H_{s,br}$  the significant wave height at the breaking line, 124  $\theta_{br}$  the mean wave direction at breaking and  $K_{swell}$  is a parameter which takes 125 into account the effect of the wave period and varies between 1 and 1.5. This 126 formulation was applied to compute LST rates for 341 beach profiles, evenly 127 distributed, covering the stretch of coast between Salobreña Rock and Motril 128 Port (Fig. 1). 129

The LST rates obtained were used to track changes in the shoreline position of each beach profile using the one-line model [60]. As in the case of the LST formulation, this model has been applied successfully to the study site in previous works [67]. The model equation is:

$$\frac{\partial y_s}{\partial t} = \frac{1}{D} \left( \frac{-\partial Q}{\partial x_s} \right),\tag{2}$$

with  $y_s$  and  $x_s$  the position of the shoreline, t the time, and D a representative length, taken as the summation of the berm height and the depth of closure.

#### 137 4. Results

#### <sup>138</sup> 4.1. Wave farm interaction with the wave field

The changes in significant wave height at breaking,  $H_{s,br}$ , caused by the wave 139 farm in the three sea level rise scenarios, are investigated in this section. More 140 specifically, the ratio of the value of  $H_{s,br}$  with the farm to that without the farm 141 (baseline), hereafter referred to as the wave height ratio. The wave farm reduces 142 the significant wave height at breaking in all cases (Fig. 4). This reduction is 143 more significant in the case of the easterly storm than for the westerly storm: 144 alongshore-averaged ratios range between 0.79 and 0.8 in the three sea level rise 145 scenarios for the easterly storm (Fig. 4b), far smaller than those for the westerly 146 storm, 0.97 - 0.98 (Fig. 4a). 147



Figure 4: Ratio between the significant wave heights at breaking  $(H_{s,br})$  with and without wave farm for the W (a) and E (b) storms.

When sea level rise is considered, the performance of the wave farm as coastal 148 defence element improves slightly. In scenario SLR2, which has the largest sea 149 level rise, the minimum wave height ratio for the westerly storm is 0.93. The 150 corresponding values in scenarios SLR1 and SLR0 (baseline) are 0.94 and 0.95. 151 In addition, with the increase in sea level, the shadow of the wave farm, i.e., 152 the area of wave power deficit and consequently lower wave height, encompasses 153 a greater length of coastline than in the baseline situation (Fig. 4). For the 154 easterly storm, the differences between the optimistic and pessimistic projections 155 for scenarios SLR1 and SLR2 are even smaller, with minimum wave height ratios 156 of 0.63 in both cases. The minimum ratio rises up to 0.65 in SLR0. 157

#### 158 4.2. LST rate variations

LST rates computed using the formulation of [59] are presented in this section. Sediment transport patterns are modified by the wave farm (Fig. 5). Under the westerly storm, these rates are reduced mainly in the eastern part of the study section, whereas the wave farm increases LST rates in the central part (Fig. 5a). Under the easterly storm, LST rates are reduced mainly in the central and western parts of Playa Granada, whereas the impact on the eastern end of the beach is lower (Fig. 5b). The differences between scenarios in the eastern part of the beach under easterly storms are influenced by the effects
of the shoreline horn (Punta del Santo, Fig. 2) on the propagation of easterly
waves.



Figure 5: LST rate alongshore distribution without (a) and with (b) wave farm for the W (1) and E (2) storms.

This influence of the wave farm on LST patterns is readily analysed through 169 the LST ratio, defined as the ratio between the LST rate with and without 170 the wave farm (Figure 6). As described in the previous paragraph, under the 171 westerly storm LST rates are increased in the central part, where maximum 172 LST ratios of 1.53, 1.46, 1.45 are attained in scenarios SLR0, SLR1 and SLR2, 173 respectively. On the contrary, in the western part of the beach the wave farm 174 reduces LST rates, with minimum LST ratios as low as 0.28, 0.29 and 0.26, 175 respectively (Fig. 6a). Sea level rise affects LST much as it does breaking 176 wave heights, slightly increasing the positive impact of the wave farm; indeed, 177 the alongshore-averaged LST ratio is higher in scenario SLR0 (0.95) than in 178 scenarios SLR1 (0.93) and SLR2 (0.92). 179



Figure 6: Ratio between the LST rates (Q) with and without wave farm for the W (a) and E (b) storms.

The modelled wave farm has a more intense impact under easterly storms. The minimum ratios, which are found in the central and western parts of the stretch of coast, are 0.26, 0.21 and 0.21 in SLR0, SLR1, SLR2, respectively (Fig. 6b). Conversely, in the eastern part of the beach, the impact is lower (ratios close to unity in the three sea level rise scenarios). This greater impact under the easterly storm is confirmed by the alongshore averaged ratios: 0.51, 0.50 and 0.52 for SLR0, SLR1 and SLR2, respectively.

## 187 4.3. Shoreline changes

LST rates computed in the previous section were the basis to apply the 188 one-line model and assess changes in the shoreline caused by the sea states 189 considered. The storms were modelled with a duration of 48 hours. The westerly 190 storm causes erosion in the western part of the coast, whereas accretion appears 191 in the eastern part (Fig. 7a1). Sea level rise modifies this behaviour, increasing 192 erosion in the western part and reducing the advance of the shoreline in the 193 central stretch. Maximum accretion is decreased; however, the shoreline advance 194 is higher in the east end. 195

The easterly storm produces accretion in both ends of Playa Granada, with erosion appearing in the central stretch (Fig. 7a2). In this case, sea level



Figure 7: Shoreline advance  $(\Delta y_s)$  after 48 hours without (a) and with (b) wave farm for the westerly (1) and easterly (2) storms. Positive (negative) values mean accretion (erosion).

rise decreases erosion in the central part, turning it to accretion, especially in scenario SLR2. However, accretion in the easternmost part of the beach is decreased in the sea level rise scenarios. For both directions, the results around X-UTM = 450000 m are influenced by the changes in LST patterns and conditioned by the derivative in Eq. 2.

In order to quantify the effect of the wave farm on the variation of the shoreline, the non-dimensional shoreline advance [53] was computed. This indicator can be expressed as:

$$v = \frac{\Delta y_s - \Delta y_{s0}}{\max\left(|\Delta y_{s0}|\right)},\tag{3}$$

with  $\Delta y_s$  and  $\Delta y_{s0}$  the variation in the shoreline position with and without wave farm. Positive and negative values indicate accretion or erosion, i.e., advance or retreat of the shoreline, respectively.

The wave farm produces erosion in a narrow zone in the western part of the beach, and accretion in the central and eastern parts of Playa Granada

under the westerly storm (Fig. 8a). It is clear on the graph that sea level rise 211 enhances the impact of the wave farm. In the case of the erosion, the minimum 212 non-dimensional shoreline advance in scenario SLR0 is equal to -0.46, whereas 213 in scenarios SLR1 and SLR2 this value is -0.54 and -0.57, respectively - in 214 other words, erosion (shoreline retreat) is more pronounced. A similar effect 215 may be observed for the accretion (shoreline advance), with maximum values 216 increasing from 0.51 in scenario SLR0 to 0.56 and 0.61 in scenarios SLR1 and 217 SLR2, respectively. Taking into account the whole stretch of coast, accretion due 218 to the presence of the wave farm dominates, with alongshore-averaged values of 219 v equal to 0.11, 0.10 and 0.09 for scenarios SLR0, SLR1 and SLR2, respectively. 220



Figure 8: Non-dimensional shoreline advance (v) for the W (a) and E (b) storms. Positive (negative) values signify accretion (erosion).

Under the easterly storm, a similar impact is produced by the presence of 221 the wave farm, with erosion again in the western part and accretion growing 222 to the east (Fig. 8b). The effect of sea level rise, strengthening the impact – 223 whether positive or negative – of the wave farm, is confirmed. Attending to the 224 erosion in the western end, the minimum value of v in scenario SLR0 is -0.33, 225 decreasing to -0.69 and -0.79 in scenarios SLR1 and SLR2, respectively. Like 226 erosion, accretion is enhanced by the wave farm, with maximum values ranging 227 from 0.35 in scenario SLR0 to 0.57 and 0.52 in scenarios SLR1 and SLR2, 228

respectively. The alongshore-averaged values of v under the easterly storm are lower: 0.001, 0.035 and 0.003 for scenarios SLR0, SLR1 and SLR2, respectively.

#### 231 4.4. Subaerial beach area variation

The final subaerial beach area obtained for the different sea level rise sce-232 narios and the impact produced by the wave farm are presented in this section. 233 Under the westerly storm, the wave farm produces a positive impact in terms of 234 dry beach area. Erosion dominates without the wave farm in the three sea level 235 rise scenarios, with subaerial beach area variations after 48 hours of: -90.15236 m<sup>2</sup>, -42.83 m<sup>2</sup> and -51.66 m<sup>2</sup> for scenarios SLR0, SLR1 and SLR2, respectively 23 (Fig. 9a). With the presence of the wave farm, this erosion turns into accretion: 238  $\Delta A = 2.31 \text{ m}^2$ ,  $\Delta A = 28.76 \text{ m}^2$  and  $\Delta A = 8.14 \text{ m}^2$  in scenarios SLR0, SLR1 239 and SLR2, respectively. As may be observed in these results, sea level rise de-240 creases erosion without the wave farm, with lower beach area differences, and 241 strengthens the accretionary effect of the wave farm, thus increasing the final 242 subaerial beach area. 243



Figure 9: Subaerial beach area variation ( $\Delta A$ ) after 48 hours without (baseline) and with wave farm for the W (a) and E (b) storms.

The behaviour of the system is accretionary under the easterly storm (Fig. 9b), as shown by the subaerial beach area difference in scenario SLR0 without wave farm (312.6 m<sup>2</sup>). The results depict that this accretion will be attenuated <sup>247</sup> by sea level rise, decreasing the area differences to 205.55 m<sup>2</sup> and 220.38 m<sup>2</sup> in <sup>248</sup> scenarios SLR1 and SLR2, respectively. The wave farm would help to mitigate <sup>249</sup> these effects, increasing accretion in every scenario: 317.56 m<sup>2</sup> (SLR0), 240.74 <sup>250</sup> m<sup>2</sup> (SLR1) and 224 m<sup>2</sup> (SLR2).

However, the effect of sea level rise on the beach cannot be fully understood 251 attending only to its impact on the LST and neglecting the loss of subaerial 252 beach area due to the coastal flooding resulting directly from the sea level rise. 253 Figure 10 depicts the total area of Playa Granada in every scenario studied. 254 The subaerial area available in the present situation is  $101771 \text{ m}^2$ . This area is 25 reduced to 88540 m<sup>2</sup> and 82679 m<sup>2</sup> in scenarios SLR1 and SLR2, respectively. 256 This means that  $13231 \text{ m}^2$  will be lost by 2010 according to the optimistic pro-257 jection, whereas this loss would rise to  $19092 \text{ m}^2$  for the pessimistic projection. 258 The final subaerial beach area after the westerly storm for scenario SLR0 259 decreases to  $101685 \text{ m}^2$ , whereas the wave farm increases this area slightly to 260  $101775 \text{ m}^2$ . Under the easterly storm, the final area for this scenario with 261 (without) wave farm is  $102073 \text{ m}^2$  ( $102061 \text{ m}^2$ ). In scenario SLR1, the final 262 area with (without) wave farm under the westerly storm is  $88570 \text{ m}^2$  (88497263  $m^2$ ) under the westerly storm and 88779  $m^2$  (88741  $m^2$ ) under the easterly 264 one. Finally, the final area for the pessimistic projection (scenario SLR2) with 265 (without) wave farm is  $82685 \text{ m}^2$  ( $82624 \text{ m}^2$ ) under the westerly storm and 266  $82906 \text{ m}^2 (82900 \text{ m}^2)$  under the easterly storm. 267

These results show that due to sea level rise, between 13% and 19% of the subaerial beach surface will be lost by 2100. In all the scenarios considered, the effect of the wave farm is to increase the final subaerial beach area.



Figure 10: Initial and final subaerial beach area for the three sea level rise scenarios without and with wave farm.

## 271 5. Discussion

A number of research works have dealt with the coastal protection perfor-272 mance provided by wave farms. For sandy beaches, [50-52] studied the effects 273 of wave farms on the beach profile in a storm scale. In the case of gravel dom-274 inated beaches, recent works have studied the influence of different parameters 275 and conditions such as the alongshore position [54] or the wave farm layout 276 [53, 57]. However, none of these works have studied the repercussions of sea 277 level rise on the coastal protection againts erosion provided by a wave farm, 278 which is the main motivation of this study. 279

The significance of this work lies in the fact that the results highlight the 280 efficiency of wave farms in coastal protection even in a sea level rise context. In 281 this manner, dual wave farms – for carbon-free energy generation and coastal 282 defence against erosion – become more attractive, since they can contribute to 283 two of the major challenges of the 21st century: the decarbonisation of the 284 energy mix and the mitigation of the impacts of climate change. This fact 285 enhances their interest as coastal defence elements against traditional hard-286 engineering solutions, such as groynes or seawalls, which are not able to maintain 287 the same efficiency under a sea level rise conditions. 288

However, further research is required in this field. To fully take into account the effects of sea level rise, research efforts focused on addressing the sea level rise implications in coastal protection in the long-term scale are required.

#### 292 6. Conclusions

<sup>293</sup>Climate change has repercussions for the world's coastlines, notably through <sup>294</sup>sea level rise and consequent erosion. Recent works have proposed the use of <sup>295</sup>wave farms with a dual purpose: carbon-free energy generation and coastal <sup>296</sup>protection. This work investigated the effects of a so-called dual wave farm on <sup>297</sup>a gravel-dominated beach and, for the first time, considered how these effects <sup>298</sup>were themselves modified by sea level rise. Using a spectral wave propagation <sup>299</sup>model (SWAN), a LST formulation and a one-line model, the final position of the shoreline and final subaerial beach areas were calculated for three sea level rise scenarios: present situation (SLR0), and optimistic (SLR1) and pessimistic (SLR2) projections.

The presence of the wave farm reduces the significant wave height at breaking, with alongshore-averaged ratios with respect to the no-wave farm situation of 0.79 - 0.80 (0.97 - 0.98) for the easterly (westerly) storm. Sea level rise enhances the coastal protection efficiency of the wave farm by reducing the minimum ratios.

The reduction in significant wave height at breaking caused by the wave farm leads to a reduction in LST rates, with alongshore-averaged ratios with respect to the no-wave farm situation of 0.92 - 0.95 (0.51 - 0.52) for the westerly (easterly) storm. Sea level rise contributes to this positive effect of the wave farm, reducing the ratios of alongshore-averaged LST rates, especially for the westerly storm.

The shoreline shows accretion in the eastern part of the beach due to the 314 presence of the wave farm, for both the westerly and easterly storms. However, 315 some erosion appears in the western end. If the final (post-storm) subaerial 316 beach area is considered, the effect of the wave farm is positive, i.e., accretionary. 317 In the case of the westerly storm, the wave farm reverses the behaviour of the 318 coast from an erosive to an accretionary response in every sea level rise scenario. 319 Without the wave farm the subaerial beach area differences are  $-90.15 \text{ m}^2$ , -320 42.83 m<sup>2</sup> and -51.66 m<sup>2</sup> for scenarios SLR0, SLR1 and SLR2, respectively; with 321 the wave farm these differences are  $2.31 \text{ m}^2$ ,  $28.76 \text{ m}^2$  and  $8.14 \text{ m}^2$ . Under 322 the easterly storm, the coastal response is accretionary, and this behaviour is 323 strengthened by the wave farm. 324

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