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# Modelling of embayed beach equilibrium planform and rotation signal

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## Abstract

Embayed beaches are highly attractive sandy beaches bounded laterally by rigid boundaries, which deeply affect equilibrium beach planform and shoreline dynamics. We use LX-Shore, a state-of-the-art shoreline change model coupled with a spectral wave model to address embayed beach shoreline dynamics driven by longshore sediment transport processes. The model is applied to different idealized embayed beach configurations including variations in headland lengths. The model simulates a large range of equilibrium embayed beach planforms and associated spatial and temporal modes of shoreline variability. For short headlands enabling occasional headland sand bypassing, both embayed beach curvature and maximum erosion at the upwave side of the embayment increases with increasing headland length. Beach curvature also increases with increasing headland length for headlands long enough to prevent any headland sand bypassing. In contrast, at the same time, embayed beach becomes increasingly curved and symmetric, with maximum localised erosion within the embayment decreasing in intensity. When there is no headland sand bypassing, rotation signal decreases in amplitude and becomes increasingly symmetric with increasing headland length. The modal (time-invariant) directional spreading of incident waves is critical to embayed beach behaviour, with the envelope and variance of cross-shore shoreline change and time-averaged shoreline curvature all increasing with decreasing modal directional spreading. Embayed beach rotation characteristic timescale increases with increasing embayed beach length, while the narrower the embayment the smaller the cross-shore amplitude of shoreline variability. Our simulations provide new insight into the influence of embayment characteristics and incident wave conditions on equilibrium planform and shoreline dynamics of embayed beaches. This work also implies that the degree of potential headland sand bypassing should be taken into account for modelling of beach rotational dynamics and embayed beach dynamic planform configuration.

## 32 Highlights

- 33 • Embayed beach shoreline response is simulated with a hybrid shoreline model
- 34 • Headland length and headland sediment bypassing control shoreline response
- 35 • Wave directional spreading is critical to both mean shoreline and rotation signal
- 36 • Embayment beach length controls rotation characteristic timescale

37

38 **Keywords:** embayed beach ; hybrid shoreline model ; headland length ; rotation ; equilibrium  
39 beach planform; headland sand bypassing

40

## 41 1. Introduction

42 Embayed beaches are sandy beaches bounded laterally and vertically by rigid boundaries (Loureiro et  
43 al., 2012a), which can deeply affect incident wave conditions and, in turn, breaking wave conditions  
44 (e.g., Daly et al., 2014a), beach morphodynamics (e.g., Castelle et al., 2012; Blossier et al., 2016;  
45 McCarroll et al., 2016) and shoreline variability (e.g. Ranasinghe et al., 2004; Ojeda and Guillen, 2008;  
46 Turki et al., 2013a; Harley et al., 2015; Robinet et al., 2020a). These physical boundaries include  
47 artificial coastal defences like groins, harbour walls and breakwater, and natural rocky headlands and  
48 submerged rocky platforms. Artificial coasts (e.g., approximately 30% of the French coastline, CEREMA,  
49 2017) and hilly/mountainous coasts (Short and Masselink, 1999) constitute a large proportion of the  
50 world's coastlines, making embayed beaches ubiquitous globally. Due to the large natural variability  
51 of wave exposure and headland characteristics (Fellowes et al., 2019), embayed beaches exhibit a  
52 striking planform variability (Figure 1). Therefore, understanding and modelling embayed beach  
53 dynamics is an important but complex research area.

54 Over the last decades, a lot of attention has been paid to describing the time-averaged, equilibrium  
55 planform of embayed beaches (e.g., Yasso, 1965; Sivester, 1970; Rea and Komar, 1975). The  
56 equilibrium beach concept was used to derive a number of static equilibrium models (Hsu et al., 1987;  
57 Hsu and Evans, 1989), which are generally based on a single representative wave direction, a down-  
58 coast control point and a diffraction point. Parabolic bay shaped models (Hsu and Evans, 1989) were  
59 preferred to log-spiral models (Yasso, 1965; Sivester, 1970), and became the most widely used  
60 approach to understanding the stability of embayed beaches (Hsu et al., 2004; Jackson and Cooper,  
61 2010, Hsu et al., 2010). These equilibrium shoreline planform models, however, do not always show  
62 good skill (Gonzalez and Medina, 2001; Klein et al., 2003a,b), for example near estuary mouths or  
63 where there is a strong geological control of beach morphology (e.g., intertidal to subtidal rocky

64 platform, Jackson and Cooper, 2010). Even when general settings are favourable to such model  
65 application, there are still limitations. For instance, a strong underlying assumption is that swell waves  
66 arrive persistently from a narrow range of directions, which is challenged on many coasts with  
67 multimodal wave climates. Such models also assume that alongshore wave height gradient is  
68 controlled by one diffraction point, while on natural coasts many diffraction points can co-exist and  
69 can even migrate across rocky platforms as the tide fluctuates (Jackson and Cooper, 2010). In addition,  
70 as noted by Daly et al. (2014a) diffraction is dominant only for strongly curved embayments when wave  
71 conditions are narrow-banded. Otherwise, refraction typically overwhelms diffraction effects. In  
72 addition, these models do not take into account headland sediment bypassing, which can have a  
73 profound impact on equilibrium shoreline planform as suggested by Goodwin et al. (2013). To  
74 overcome these issues and to address a wider spectrum of natural embayed beaches, equilibrium  
75 shoreline models are still under development (Elshinnawy et al., 2018a,b,c).

76 The processes governing the morphodynamics of embayed beaches on the timescales from storms to  
77 years/decades have been studied for decades (e.g., Klein et al., 2002; Ojeda and Guillen, 2008). Day by  
78 day wave forcing is the primary driver of alongshore and cross-shore sediment transport, leading to  
79 complex patterns of erosion and accretion along the embayment. Clockwise/counterclockwise  
80 rotation of the embayed beach planform has been commonly observed as the dominant pattern of  
81 shoreline variability at embayed beaches (Masselink and Pattiaratchi, 2001; Short and Trembanis,  
82 2004; Ranasinghe et al., 2004; Martins and de Mahiques, 2006; Thomas et al., 2011; Loureiro et al.,  
83 2012a; Turki et al., 2013a; Van de Lageweg et al., 2013; Harley et al., 2013; Robinet et al., 2020a).  
84 Loureiro and Ferreira (2020) reviewed the mechanisms and timescales of beach rotation at embayed  
85 beaches. Beach rotation has long been attributed to longshore transport processes, when enough  
86 sediment moves from one side of the embayment to the other to shift the mean orientation of the  
87 beach (Ratliff and Murray, 2014). However, storms and variations in incident wave energy cause cross-  
88 shore sediment exchange and drive shoreline changes typically by tens of metres (Yates et al., 2009;  
89 Splinter et al., 2014). Harley et al. (2011, 2015) suggested a more complex conceptual model of beach  
90 rotation process at Narrabeen-Collaroy embayment (SE Australia) based on the analysis of an extensive  
91 dataset. They revealed that headland sheltering of oblique waves results in alongshore non-uniform  
92 wave exposure and cross-shore processes that, in turn, contribute significantly to observed beach  
93 rotation. Harley et al. (2015) therefore suggested that beach rotation occurs due to the  
94 complementary and interacting cross-shore and longshore processes at different timescales. Robinet  
95 et al. (2020a) used a state-of-the-art shoreline change model and demonstrated at the same coastal  
96 embayment that cross-shore processes drive a slightly alongshore variable cross-shore migration signal

97 on the timescales from hours (storms) to months, while longshore processes primarily contribute to  
98 rotation on longer timescales of months to seasons at this coastal embayment.

99 In recent years, a new generation of shoreline change models have been developed, offering the  
100 opportunity to simulate shoreline evolution at wave-dominated sandy beaches on the timescales from  
101 hours (storm) to years and decades with reasonable skill (Montaño et al., 2020). Process-based models,  
102 which are computationally expensive, require accurate selection and sequencing of representative  
103 wave conditions to address embayed beach dynamics (Daly et al., 2014b). Instead, the so-called  
104 “hybrid” models are based on general principles (e.g., Yates et al., 2009; Davidson et al., 2013; Vitousek  
105 et al., 2017; Robinet et al., 2018; Antolínez et al., 2019; Tran and Barthelemy, 2020) rather than on the  
106 detailed description of nearshore hydrodynamics, sediment transport and morphological changes  
107 through conservation of mass and momentum. Hybrid models can therefore simulate shoreline change  
108 with low computational cost. Along coastlines that are longshore transport dominated with presence  
109 of rigid physical boundaries such as headlands, one-line models have emerged as a powerful tool (e.g.,  
110 Hanson, 1989; Larson et al., 2002; Szmytkiewicz et al., 2000; Ratliff and Murray, 2014; Hurst et al.,  
111 2015). All these models are essentially based on gradients in longshore sediment transport due to the  
112 alongshore variability in breaking wave conditions, but they vary in terms of numerical implementation  
113 and level of description on wave field transformation. Ratliff and Murray (2014) identified two primary  
114 orthogonal modes of shoreline behaviour around the mean that are the well-known rotation mode  
115 and a newly identified breathing mode, which represents changes in shoreline curvature. Hurst et al.  
116 (2015) examined the behaviour of embayed beaches forced by different directional wave climates.  
117 They showed that embayed beach planform curvature decreases with the spread of wave directions.  
118 However, in both studies headland sediment bypassing and the influence of headland length was not  
119 addressed. In addition, wave transformation was based on simple rules for the diffraction and  
120 refraction of waves where the coast was shadowed from incoming waves.

121 In this paper we use the state-of-the-art shoreline change model LX-Shore, which accounts for the  
122 detailed wave transformation to provide enhanced insight into embayed beach shoreline dynamics.  
123 LX-Shore model (Robinet et al., 2018) can simulate both the equilibrium embayed beach planform and  
124 a large range of spatial and temporal modes of shoreline variability even in complex natural embayed  
125 beaches, even with prominent rocky headland and submerged outcrops deeply affecting the incident  
126 wave field (Robinet et al., 2020a). The model is applied to different embayed beach configurations. We  
127 systematically address the influence of headland length on equilibrium embayed beach planform and  
128 shoreline dynamics on the timescales from hours to decades.

129

130 **2. Method**

131 **2.1. LX-Shore model**

132 LX-Shore is a two-dimensional planview cellular-based one-line shoreline change model for wave-  
133 dominated sandy coasts developed by Robinet et al. (2018), with additional process implementation  
134 described in Robinet et al. (2020a, 2020b). An overview of the model is provided in Figure 2 and the  
135 reader is referred to the aforementioned papers for more details. LX-Shore simulates shoreline change  
136 resulting from the combination of cross-shore transport driven by changes in incident wave energy  
137 and gradients in total longshore sediment transport (Figure 2b). Based on earlier work (Ashton et al.,  
138 2001; Ashton and Murray, 2006) LX-Shore computes changes in the relative amount of dry (i.e. land)  
139 surface in square cells discretizing horizontally the computation domain. The spatial resolution of grid  
140 cells  $\Delta xy$  is typically in the range of 10–100 m. Dry cell fraction ranges from  $F = 0$  (water cells) to  $F =$   
141 1 for fully dry sandy and/or rocky cells. Indeed, LX-Shore also includes non-erodible areas such as  
142 coastal defences and headlands with time-invariant rocky cell fraction ( $F_R$ ) contribution :  $F = F_S + F_R$ ,  
143 with  $F_S$  the sandy fraction. The shoreline is constructed using an interface reconstruction method,  
144 allowing the algorithm to handle complex shoreline geometries (e.g. sand spits, islands). Change in  
145 sediment fraction within the cells can result from longshore transport computed using the formula of  
146 Kamphuis (1991) and from cross-shore transport using an adaptation of the equilibrium-based  
147 ShoreFor model (Davidson et al., 2013; Splinter et al., 2014). The sediment fraction within computation  
148 cells and resulting shoreline are updated at each time step ( $\Delta t$ ).

149 Critical to sediment transport and shoreline changes are the breaking wave conditions, which can be  
150 computed through the direct formula of Larson et al. (2010), which is typically used in LX-Shore on  
151 academic cases or for open beaches with alongshore-uniform offshore bathymetry (Robinet et al.,  
152 2018). Otherwise, breaking wave conditions are computed using the spectral wave model SWAN (Booij  
153 et al., 1999) to address configurations such as when complex wave shadowing or offshore wave  
154 transformation (e.g., energy focusing enforced by refraction, offshore wave energy dissipation through  
155 depth-induced breaking) affect breaking wave conditions and, in turn, sediment transport and  
156 shoreline change. At each time step LX-Shore provides an updated bathymetry that feeds back onto  
157 wave transformation. This updated bathymetry is reconstructed (Figure 2c) from the current shoreline  
158 position and the combination of two different idealized static equilibrium (Dean) beach profiles, for  
159 the sandy shores and for the rocky sectors.

160 **2.2. Simulation set-up and analysis**

161 LX-Shore was run for different embayed beach configurations schematised in Figure 3 with  $x$  and  $y$  the  
162 cross-shore and longshore coordinates, respectively. Embayed beaches were characterised by a length

163  $W$  and headland length  $L$ , with the time-varying shoreline position denoted  $S(y, t)$ , with  $t$  the time.  
164 Periodic lateral boundary conditions were implemented so that headland sediment bypassing that  
165 occurs downdrift feeds the updrift part of the embayment. In other words, we assumed a circular  
166 system with constant sediment budget. This assumption will be discussed in Section 4. All simulations  
167 started from a uniform shoreline position  $S = 0$ . Twenty years of wave hindcast were used, defined by  
168 time series of significant wave height  $Hs$ , peak wave period  $Tp$ , and peak angle of incidence  $\theta$ . A time-  
169 invariant directional spreading  $\sigma_\theta$  of  $40^\circ$  was used, although additional simulations were run for other  
170 values of  $\sigma_\theta$  (see Section 3.3). We used a wave hindcast (Durrant et al., 2014) offshore of Sydney  
171 (January 1, 1994 – January 1, 2014). Such wave climate is known to drive important rotation signal  
172 (Ranasinghe et al., 2004; Harley et al., 2015; Robinet et al., 2020a). Preliminary tests using  $W = 1000$   
173 m (comprising a total headland width of 200 m) and different headland lengths  $L$  indicated that model  
174 spin-up from the initial uniform shoreline typically lasted a few months. Therefore, the two first years  
175 of shoreline evolution were disregarded to insure that the simulated shoreline variability operates  
176 around a true dynamic equilibrium, and the subsequent 18 years (January 1, 1996 – January 1, 2014)  
177 were analysed.

178 Although cross-shore processes are found to affect embayment rotation, earlier work under the same  
179 wave climate as in Figure 3b (Robinet et al., 2020a) shows that cross-shore processes mainly drive a  
180 slightly alongshore variable cross-shore migration signal on the timescales from hours (storms) to  
181 months. In addition, the cross-shore transport module, which is based on ShoreFor (Davidson et al.,  
182 2013; Splinter et al., 2014), uses free parameters that depend on breaking wave conditions. Using a  
183 different headland length, results in different sheltering effects and, in turn, different breaking wave  
184 conditions that require a new calibration effort even under the same offshore wave climate. However,  
185 these calibration data do not exist for such academic cases. For all these reasons, cross-shore  
186 processes were switched off in all our simulations, which will be further discussed in Section 4.

187 Wave transformation was computed by SWAN model with default settings. Diffraction was not  
188 activated given that it shows poor skill unless fine grid resolution is used (Enet et al., 2006), and that  
189 LX-Shore shows very good skill on natural beaches without diffraction (Robinet et al., 2020a). LX-Shore  
190 simulations were run with grid cell size  $\Delta xy = 50$  m and a constant time step  $\Delta t = 3$  hours. SWAN cell  
191 size (“hydrodynamic grid”) was 25 m. The water depth ( $h$ ) was retrieved at each time step using an  
192 equilibrium Dean profile (Dean, 1991) on sandy sectors, given by  $h = \alpha d^\beta$ , with  $\alpha$  and  $\beta$  two free model  
193 parameters. In the present study, we use values representative of Narrabeen beach (Robinet et al.,  
194 2020a), i.e.  $\alpha = 0.25$  and  $\beta = 0.67$ . The profile was projected offshore from the current shoreline  
195 position where  $d$  is the distance offshore from the shoreline. The same applied for rocky shoreline with  
196 a steep profile also following a power law  $h = \alpha d^b$  with  $a = 1$  and  $b = 1$  chosen arbitrary (linear profile,

197 Figure 2c). When transects intersected, specific conditions including weighted averages were applied  
198 (for more detail see Robinet et al., 2018) to produce a consistent and smoothed bathymetry. In all  
199 simulations SWAN offshore boundary was located at  $x = 800$  m in approximately 16-18 m depth. All  
200 simulations were performed for an embayment beach length  $W = 1000$  m (comprising 200 m  
201 headland), although additional simulations were run for shorter and longer embayments (see Section  
202 3.3). Headland length  $L$  was varied from 0 to 700 m, every 50 m, with additional simulations for  $L = 75$   
203 m, 125 m and 175 m to capture subtle changes in embayment shoreline response for this range of  
204 headland lengths.

205 Shoreline response was analysed using a set of variables (Figure 3), including the 18-year average  
206 (denoted  $\bar{(\cdot)}$ ), hereafter referred to as mean, shoreline position  $\bar{S}(y)$ , its most eroded position  $\bar{S}_{min}$   
207 and corresponding longshore position  $y(\bar{S}_{min})$ , and the cross-shore standard deviation of shoreline  
208 position  $\sigma_S(y)$ . We also computed the mean shoreline rotation  $\bar{R}$ , which can also be referred to as  
209 orientation, as the slope of the trend-line fitted to  $\bar{S}$ . In order to address the spatial and temporal  
210 modes of shoreline variability, empirical orthogonal function (EOF) analysis of the shoreline deviation  
211 from the mean, i.e.  $dS = S - \bar{S}$ , was performed on the 18-year period. The analysis was performed at  
212  $150 \text{ m} < y < 850 \text{ m}$  to ignore the influence of spurious shoreline interpolation near the headlands.  
213 Finally, occurrence of headland sand bypassing was detected at each time step as  $F_S > 0$  at the tip of  
214 the northern and/or southern headland(s). In order to address the wave control on embayed beach  
215 rotation we computed the power of the shore-parallel propagating wave component  $Pl$ , which is  
216 indicative of the portion of wave power available to drive alongshore currents in the surf zone (Price  
217 and Ruessink, 2011).

## 218 **3. Results**

### 219 **3.1. Mean embayed beach planform**

220 Figure 4 shows the mean shoreline  $\bar{S}$  obtained for different headland lengths, together with the  
221 alongshore-uniform shoreline without headland ( $L = 0$ ). Results show that mean shoreline planform  
222 varies from a reasonably straight rotated shoreline (e.g.,  $L = 50$  m), to a curved shoreline (e.g.,  $L = 700$   
223 m), through an asymmetric and slightly curved shoreline with large erosion in the southern sector (e.g.,  
224  $L = 150$  m). The mean embayed beach planforms also suggest headland sediment bypassing for certain  
225 headland lengths, e.g. for  $L = 50$  m, for which the mean shoreline position at the northern end of the  
226 embayment coincides with the headland extremity.

227 Figure 5 provides more insight into the influence of headland length on mean embayed beach planform  
228 characteristics and how they relate to headland sand bypassing. Two categories of mean shoreline  
229 planforms can be discriminated, with a separation at headland length of  $L \approx 150$  m. For  $L < 150$  m,



230 both shoreline orientation  $\bar{R}$  and maximum erosion  $|\bar{S}_{min}|$  rapidly increase with increasing headland  
231 length, with the opposite behaviour observed for  $L > 150$  m (Figure 5a,b). Such a threshold is, however,  
232 not clearly observed for the alongshore location of maximum erosion  $y(\bar{S}_{min})$ , which becomes  
233 increasingly close to the centre of the embayment as headland length increases (Figure 5c). The change  
234 in mean shoreline behaviour corresponds to the transition between occasional headland sand  
235 bypassing and no headland sand bypassing (Figure 5d). For  $L = 150$  m headland sediment bypassing  
236 only occurs  $B = 0.2\%$  of the time, which contrasts with shorter headlands (e.g.  $B = 55.3\%$  for  $L = 50$  m  
237 and  $B = 23.7\%$  for  $L = 100$  m), while headland sediment bypassing never occurs ( $B = 0$ ) for  $L > 150$  m.  
238 Overall, when headland sediment bypassing never occurs, the mean shoreline planform becomes  
239 increasingly symmetric and curved, with a less severe shoreline retreat in the embayment, with  
240 increasing headland length (Figure 4b). At the same time, embayed beach orientation and prevailing  
241 angle of offshore wave incidence are increasingly different. In contrast, for  $L < 150$  m as headland  
242 length is decreased allowing more frequent headland sediment bypassing, embayed beach planform  
243 becomes increasingly symmetric with its orientation increasingly deviating from the prevailing angle  
244 of wave incidence, while maximum erosion within the embayment at  $y \approx 200$  m is increased (Figure  
245 4b).

### 246 **3.2. Modes of shoreline variability**

247 Figure 6 provides insight into the spatial and temporal evolution of the embayment shoreline for three  
248 representative simulations: i) short headlands with headland sand bypassing ( $L = 100$  m,  $B = 23.7\%$ ,  
249 Figure 6c,d); ii) intermediate-length headlands with no headland sand bypassing ( $L = 250$  m, Figure  
250 6e,f) and iii) long headlands with no headland sand bypassing ( $L = 600$  m, Figure 6g,h). In the case of  
251 frequent sand bypassing, the mean shoreline is curved, asymmetric, with a more rectilinear form in  
252 the northern section of the embayment. The pivot zone, i.e. where  $\sigma_s$  is minimized, is located at  $y \approx$   
253 600 m, that is, not in the centre of the embayment. The shoreline variability reaches its maximum  
254 against the northern headland, where both  $\sigma_s$  and cross-shore amplitude are locally maximised at  $y \approx$   
255 800 m, and is more homogeneous along the southern section ( $y < 550$  m) of the embayment (Figure  
256 6c,d). In contrast, in the case of intermediate-length headlands with no headland sand bypassing, the  
257 mean shoreline is still strongly asymmetric, but with a pivot zone closer to the centre of the  
258 embayment and with most of shoreline variability approximately equally distributed between the  
259 northern and southern sectors (Figure 6e). The cross-shore amplitude of shoreline position for  
260 intermediate-length headlands is also larger than for the situation with headland sand bypassing, with  
261 an amplitude exceeding 65 m near the embayment extremities (Figure 6e,f). In the case of a longer  
262 headland, still with no headland sand bypassing, both the mean embayed beach planform and

263 shoreline variance  $\sigma_S$  are essentially symmetric (Figure 6g). Shoreline variability is still maximized at  
264 the extremities of the embayment, with a maximum amplitude decreasing to 18 m (Figure 6h).

265 Figure 7 shows the first EOF mode for each of the same three simulations, providing additional insight  
266 into the spatial and temporal modes of shoreline variability for different headland lengths. It highlights  
267 a clear rotation response between the opposite ends of the embayment for both intermediate-length  
268 ( $L = 250$  m) and long ( $L = 600$  m) headlands, with a pivot zone at  $y \approx 600$  m and  $y \approx 500$  m,  
269 respectively. In each case, this rotation signal accounts for more than 95% of the total shoreline  
270 variability, with positive (negative) values of temporal mode  $c_1(t)$  signifying a clockwise  
271 (counterclockwise) rotation of the embayed beach planform. The simulation with intermediate-length  
272 ( $L = 250$  m) exhibits a first temporal mode essentially similar in pattern with the one obtained with the  
273 long ( $L = 600$  m) headland, with a large interannual variability. The first EOF mode of the short headland  
274 simulation ( $L = 100$  m) explains less variability (74.9%) and, contrary to the two previous examples, it  
275 does not correspond to a pure rotation mode as it is associated with a change in curvature (Figure 7a).  
276 This mode of shoreline variability indicates that when the shoreline tends to rotate clockwise  
277 (dominant northerly longshore transport), the shoreline also tends to be stable at the southern end of  
278 the embayment, which is expected to be the signature of headland sand bypassing feeding the  
279 southern sector of the embayment. Compared to simulations with longer headland for which there is  
280 no headland sand bypassing, the temporal EOF mode shows increased amplitude, particularly in higher  
281 frequency variability, although interannual variability is still present.

282 The difference in shoreline behaviour observed with no headland sand bypassing between  
283 intermediate-length (Figure 6e) and long (Figure 6g) headlands can be explained by the difference in  
284 wave shadowing patterns by the upwave headland and resulting different alongshore variability in  
285 breaking wave height conditions. This is illustrated in Figure 8 that shows the wave field for typical  
286 southeast swell conditions on May 16, 1995 ( $H_s = 1.2$  m,  $T_p = 7.72$ ,  $\theta = 132.9^\circ$ ) for different headland  
287 length  $L = 250$  m, 500 m and 600 m. Wave shadowing effects readily increase with increasing headland  
288 length (Figure 8). For intermediate-length headland  $L = 250$  m (Figure 8a) the embayment shoreline  
289 varies from fully exposed to wave conditions in the northern sector to well sheltered at the southern  
290 end of the embayment, maximizing alongshore gradients in longshore sediment transport and  
291 resulting shoreline change (Figure 6e,f). For longer headlands, although wave shadowing and resulting  
292 alongshore variability in breaking wave height are large, the alongshore-averaged breaking wave  
293 height is largely reduced (Figure 8b,c), therefore limiting longshore transport gradients and resulting  
294 shoreline change (Figure 6g,h).

295

### 296 3.3. Influence of directional spreading and embayed beach length

297 Figure 9 shows that for a headland length  $L = 500$  m (no headland sand bypassing) the mean embayed  
298 beach planform is much more curved and asymmetric for a time-invariant directional spreading  $\sigma_\theta =$   
299  $10^\circ$  than for  $\sigma_\theta = 40^\circ$  (Figure 9a,d). Shoreline position also shows larger variance by a factor exceeding  
300 3 (Figure 9c,f). Although the time-invariant directional spreading does not readily affect the temporal  
301 mode of rotation (Figure 9c,f), it affects the spatial mode as the rotation is associated with a slight  
302 change in overall shoreline curvature for  $\sigma_\theta = 10^\circ$  (Figure 9e). This can be explained by an inspection  
303 of the wave field for different directional spreadings. Figure 10 also that changes in directional wave  
304 spreading  $\sigma_\theta$  have a profound impact on the wave shadowing zone and resulting alongshore variability  
305 in breaking wave height, with sharper gradients in breaking wave height for narrow-banded waves  
306 (Figure 10d). This is expected to favour changes in curvature.

307 Figure 11 shows the first temporal EOFs (rotation mode) for simulations with  $W = 500$  m and  $W = 1000$   
308 m both for  $L = 200$  m (no headland sand bypassing around the headland). Results show that the  
309 narrowest embayment respond at much shorter timescales (Figure 11b). Rotation signal for  $W = 1000$   
310 m correlates well with the 1-yr moving averaged  $\tilde{P}_l$  (Figure 11a), while the smallest embayment seems  
311 to respond on the timescales of days, in response to changes in  $Pl$ . Other simulations (not shown)  
312 indicate that for longer embayments ( $W > 1000$  m) the characteristic rotation timescale does not  
313 evolve much, instead it is the spatial mode that slowly evolves from a pure rotation pattern to rotation  
314 pattern associated with a change in shoreline curvature.

## 315 4. Discussion

316 Our simulations indicate that the onset of headland sediment bypassing is critical to both embayed  
317 beach equilibrium planform and the spatial and temporal modes of shoreline variability. These findings  
318 on the underrated role of headland sediment bypassing are in line with earlier observation on mean  
319 embayed beach planform (Goodwin et al., 2013). Our simulations show that, in addition, headland  
320 sand bypassing changes shoreline variability from a pure rotation mode to a more complex rotation  
321 mode where curvature is also modified. Embayed beaches where headland sand bypassing occurs also  
322 show more variability on short timescales. These results will need to be compared with a systematic  
323 assessment of embayed beach response timescales for a wider range of embayed beaches and  
324 headland lengths. Shoreline and embayed beach rotation monitoring techniques from freely-available  
325 satellite imagery (e.g., Vos et al., 2019) will be critical to address such embayed beach behaviour  
326 globally. Overall, hybrid shoreline models like LX-Shore (Robinet et al., 2018, 2020a), and others (e.g.  
327 Hurst et al., 2015), appear as relevant new tools to explore embayed beach shoreline dynamics, in

328 parallel to more empirical approaches (e.g., Gonzales and Medina, 2001; Klein et al., 2003a; Elshinnawy  
329 et al., 2018a) looking at equilibrium beach planshape.

330 Hurst et al. (2015) tested different spreads of schematic and monochromatic wave conditions and  
331 showed that embayed beach planform curvature decreases with the spread of wave directions. Here,  
332 we only used a single time series of realistic wave conditions. Clearly, the considered wave climate  
333 offshore of Narrabeen shows a narrowly peaked angular distribution (Figure 3b), which limits embayed  
334 beach shoreline dynamics. A greater variety of wave climates will need to be considered in future  
335 modelling experiments, ranging from low to high angles waves. It is expected that the alternation  
336 between near shore-normally incident waves, exerting a shoreline straightening influence, and highly-  
337 obliquely incident waves will lead to larger stochastic variations in local effective diffusivity (Ratliff and  
338 Murray, 2014). We also anticipate that it will lead to larger changes in beach curvature and enhanced  
339 breathing mode. The role of multi-modality of wave climate on rotation and breathing modes should  
340 also be investigated. Recent work (e.g. Wiggins et al., 2019a, 2019b) indicate that bimodal wave  
341 climate, which is common on many coasts (Scott et al., 2020), can lead to dramatic beach rotation  
342 events from the timescale of storm to decades. In such bimodal wave climate, the absence of shore-  
343 normal condition resulting in vanishing shoreline diffusivity may also allow for greater-amplitude  
344 fluctuations in shoreline curvature. To the best of our knowledge, the role of such wave climate  
345 bimodality on the spatial and temporal modes of shoreline variability has never been studied. Instead  
346 of addressing the directional spread in wave climate, we investigated the influence of the time-  
347 invariant directional spreading of each incident wave condition. Our results (Figure 9) show that the  
348 embayed beach planform is much more curved and asymmetric for narrow directional spreading,  
349 which is in line with Elshinnawy et al. (2018a) and consistent with the findings of Hurst et al. (2015).  
350 Shoreline position also shows larger variance for  $\sigma_\theta = 10^\circ$  than for  $\sigma_\theta = 40^\circ$ , and rotation signal is also  
351 associated with a change in overall curvature for a narrow directional spreading  $\sigma_\theta = 10^\circ$  (Figure 9e).  
352 This is consistent with the results of Ratliff and Murray (2014) who found an important breathing  
353 signal, reflecting a change in shoreline curvature, at idealised embayed beaches where monochromatic  
354 obliquely incident waves resulted in sharp shadowed-exposed wave energy gradients. However, at this  
355 stage we cannot explain why rotation and curvature change signals are not orthogonal EOF modes of  
356 shoreline behaviour in our simulations, contrary to simulations in Ratliff and Murray (2014) in which  
357 rotation and breathing modes were clearly discriminated. These results have strong implications, as  
358 they suggest that time series of parametric wave conditions ( $Hs, Tp, \theta$ ), which are typical products of  
359 global and regional wave hindcasts (e.g., Poli et al., 2016), are not enough to provide a fair description  
360 of both embayed beach equilibrium planform and rotation signal, and that directional spreading must  
361 also be accounted for.

362 Simulations were run to explore the role of  $W$  on embayed beach response. Model spin-up was found  
363 to dramatically increase with increasing  $W$ , with for instance an approximately 10-yr model spin-up  
364 for  $W = 2000$  m ( $L = 300$  m), compared to less than 2 years for  $W = 1000$  m. Computation cost can  
365 therefore become prohibitive for large coastal embayments. Empirical equilibrium embayed beach  
366 profile approaches (e.g., Hsu et al., 2010), which are computationally cheap, should be preferred in  
367 such situations, bearing in mind they cannot address the time and spatial models of shoreline  
368 variability. Such long model spin-up is also in line with Hurst et al. (2015) who showed that the time  
369 taken for modelled bays to reach equilibrium scales with the square of the distance between  
370 headlands. This also corroborates the results of Ratliff and Murray (2014) who found a diffusing scaling,  
371 similar with the analytical findings of previous studies of e.g. Turki et al. (2013b), whereby increasing  
372 the alongshore length of embayed beach or decreasing the wave heights, will tend to result in  
373 nonlinear increases in the characteristic time scales. This emphasizes that, for a given headland length,  
374 small embayed beaches respond and recover from perturbations more rapidly than larger bays.  
375 Prohibitive model spin-up time for long embayments using our model set-up prevented from running  
376 a comprehensive analysis on this topic.

377 In addition to some model limitations detailed in Robinet et al. (2018), and in Robinet et al. (2020a)  
378 specifically for embayed beaches, here cross-shore processes were switched off. Robinet et al. (2020a)  
379 indicated that cross-shore processes primarily control the cross-shore, slightly alongshore non-  
380 uniform, translation mode of variability at Narrabeen-Collaroy embayment. However, different  
381 embayment widths, headland lengths and wave climate may have a profound impact on the relative  
382 contributions of cross-shore and longshore processes to rotation signal. In addition, other  
383 morphodynamic processes (see review of Loureiro and Ferreira, 2020) can affect embayment rotation,  
384 such as for instance shoreline-sandbar-coupled rotation driven by strong longshore components  
385 during storms (van de Lageweg et al., 2013), or high-energy rips flowing against the headland (Loureiro  
386 et al., 2012b). More shoreline modelling is required on real embayed beaches with different  
387 hydrodynamic and geological settings, in order to better constrain academic modelling experiments  
388 and gain generic knowledge of the processes driving rotation.

389 We found that headland sand bypassing is important to embayed beach behaviour. However, it must  
390 be pointed out that sediment bypass only occurs in our model when the sandy shoreline reaches the  
391 tip of the rocky headland, while it is well established that headland sediment bypassing can occur in  
392 the surf zone or even farther offshore through boundary rips (Castelle et al., 2016; Valiente et al., 2019;  
393 Sous et al., 2020). The degree of headland sand bypassing therefore strongly depends on the surf zone  
394 width relative to headland length (Klein et al., 2020). The critical headland length in the present study  
395 is likely underestimated and the 150 m value should be considered as low bound. Given that surf zone

396 width depends on beach profile characteristics defined by a Dean profile based on Narrabeen  
397 characteristics (Robinet et al., 2020a), changing such profile characteristics should also affect headland  
398 sand bypassing and, in turn, mean embayment planshape and shoreline dynamics. To tackle these  
399 issues, a more realistic contribution of headland sand bypassing (e.g. McCarroll et al., 2020) will need  
400 to be implemented in LX-Shore. We used synthetic headland shapes. However, headland geometry  
401 shows a striking natural variability (Fellowes et al., 2019 ; Figure 1), which deeply affects wave  
402 shadowing regions and accommodation space for sand deposit and, in turn, embayed beach shoreline  
403 behaviour. We used periodic lateral conditions, meaning that the amount of sediment leaving the  
404 domain in the north enters the domain from the south and vice versa. In reality, this perfectly circular  
405 system behaviour does not exist. Different rates of sediment supply/sink due to different lengths and  
406 shapes of the headlands likely impacts the mean embayed beach planform and modes of shoreline  
407 variability. This is however difficult to implement numerically as the amount of sediment entering the  
408 system depends on many updrift beach variables, including headland length, beach width and  
409 orientation, which also depend on the further updrift embayment, and so on. Therefore our work is  
410 complementary to previous ones which disregarded headland sand bypassing and assumed embayed  
411 beaches as closed systems (e.g. Hurst et al., 2015). Our results provide general trends in embayed  
412 beach behaviour but encourage application of such modelling approach to natural embayed beaches  
413 for more quantitative local assessment, such as in Robinet et al. (2020a) at Narrabeen-Collaroy  
414 embayment.

## 415 **5. Conclusions**

416 Our simulations show that headland length controls both the embayed beach equilibrium planform  
417 and the spatial and temporal modes of shoreline variability. For short headlands promoting occasional  
418 headland sand bypassing, embayed beach curvature increases with increasing headland length while  
419 the opposite is observed for headlands long enough to prevent any headland sand bypassing  
420 occurrence. The onset of headland sand bypassing also controls embayed beach rotation signal. When  
421 there is no sand bypassing, rotation signal decreases in amplitude, resulting in less shoreline variance,  
422 and becomes increasingly symmetric with increasing headland length. The modal directional spreading  
423 of incident waves is also critical to embayed beach behaviour, with both shoreline embayment  
424 curvature and shoreline variance increasing with decreasing modal directional spreading. Embayed  
425 beach rotation characteristic timescale increases with increasing embayed beach length, while  
426 shoreline variance decreases across the entire embayment. Our simulations provide new insight into  
427 the influence of embayed beach characteristics and incident wave conditions on equilibrium planform  
428 and shoreline dynamics, implying that the potential occurrence of headland sand bypassing should be  
429 considered in future embayed beach classifications. State-of-the-art models coupling spectral wave

430 and shoreline change modules such as LX-Shore (Robinet et al., 2018) appear as a powerful tool to  
431 describe and further predict embayed beach behaviour, and to design coastal structures (e.g. groins,  
432 jetties), in parallel to the continuous development of empirical embayed beach planform models (e.g.,  
433 Hsu et al., 2010).

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## Figures

634



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636 Figure 1. (a-d) Examples of typical embayed beach planforms from a relatively straight shoreline with

637 (a) low and (c) high indentation at Porto Vecchio (Corsica) and Cassis (southeast France), respectively,

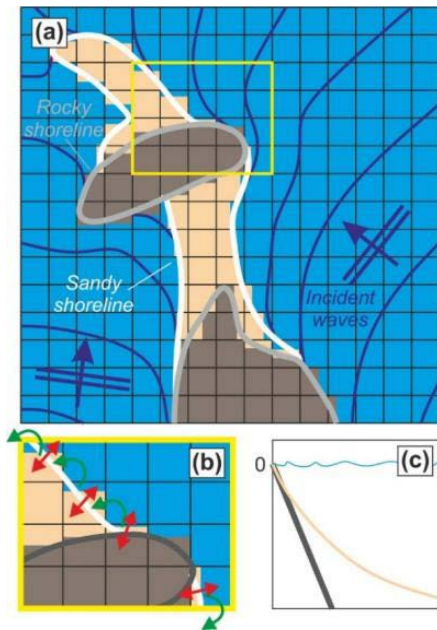
638 to curved embayments at (b) Crozon (Brittany, northwest France) and (d) Guarapari (southeast Brazil).

639 (e,f) Illustration of dramatic variability in shoreline orientation resulting from embayment rotation at

640 Lloret de Mar (northeast Spain) (e) on June 2004 and (f) on March 2014 with in (f) the dotted the

641 shoreline position in (e). Images adapted from Google Earth.

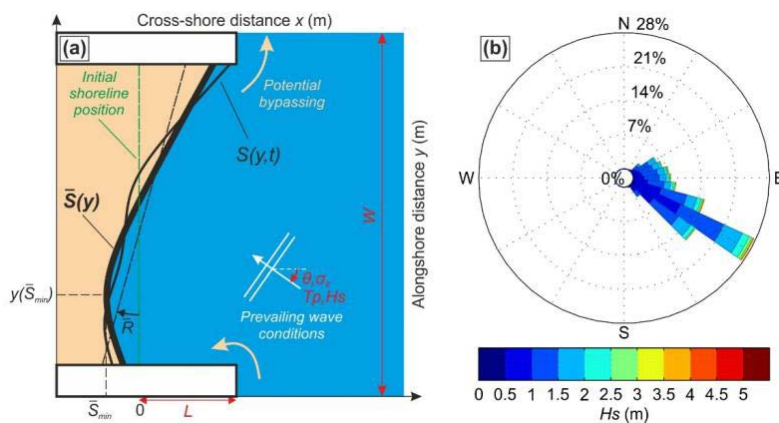
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644 Figure 2. Overview of features and processes included in LX-Shore (adapted from Robinet et al., 2018,  
 645 2020a) with (a) schematic planview coastal area with non-erodible rocky areas, sandy shores and  
 646 incident waves; (b) zoom onto a sandy/rocky area showing where the longshore and cross-shore  
 647 sediment transports are computed; (c) idealised rocky (grey) and sandy (sand) profiles used to design  
 648 the updated nearshore bathymetry feeding back spectral wave model SWAN at each time step.

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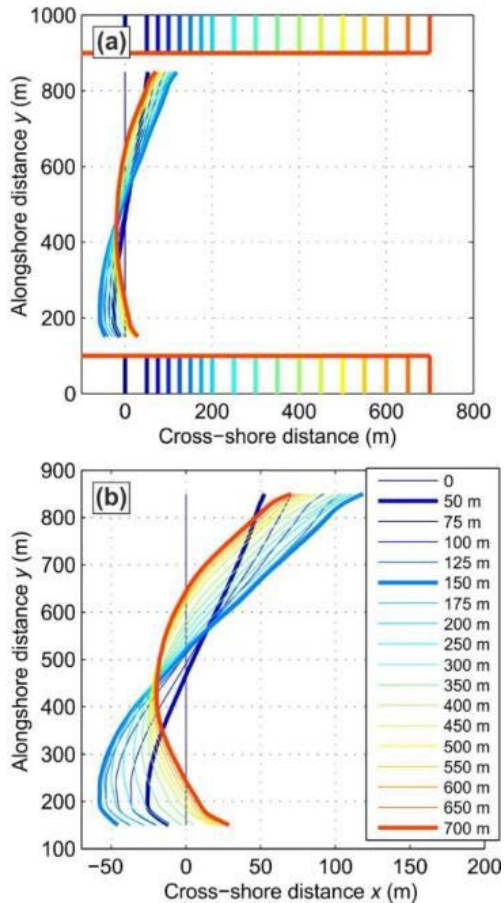
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651 Figure 3. (a) Schematic of embayed beach model set-up with primary input and output variables used  
 652 for analysis and (b) significant wave height  $H_s$  rose of wave conditions used as offshore boundary  
 653 conditions. All variables in (a) are explained in the text.

654 Figure 4. (a) Mean shoreline planform obtained for different headland lengths  $L$  (coloured) with (b)  
 655 zoom to emphasize variability.

656 Figure 5. Mean embayed beach planform variables against headland length  $L$ : (a) rotation  $\bar{R}$ ; (b) most  
 657 eroded shoreline position  $\bar{S}_{min}$ ; (c) corresponding alongshore location  $y(\bar{S}_{min})$  and (d) percentage of  
 658 occurrence of sediment bypass around the headland  $B$ .

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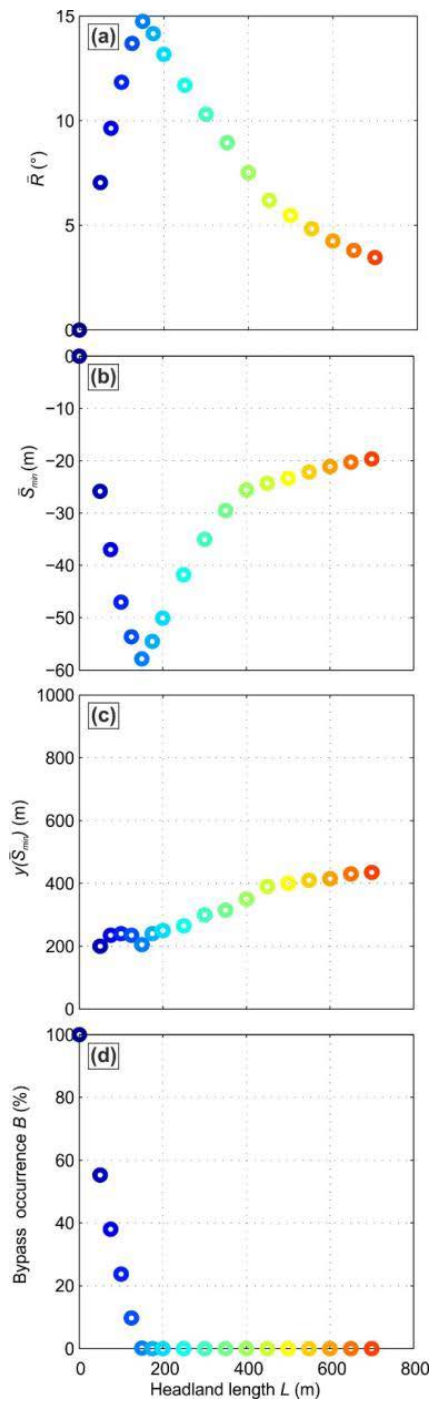


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661 Figure 6. Time series of (a) significant wave height  $H_s$  and (b) alongshore component of offshore wave  
 662 power  $Pl$ . Left-hand panels (c,e,g): mean (black line), cross-shore standard deviation  $\sigma_S$  (grey line) and  
 663 envelope (yellow area) of simulated shorelines; Right-hand panels (d,f,h): time evolution of shoreline  
 664 deviation from the mean  $dS$  for different headland lengths (c,d)  $L = 100$  m; (e,f)  $L = 250$  m; (g,h)  $L =$   
 665 600 m.

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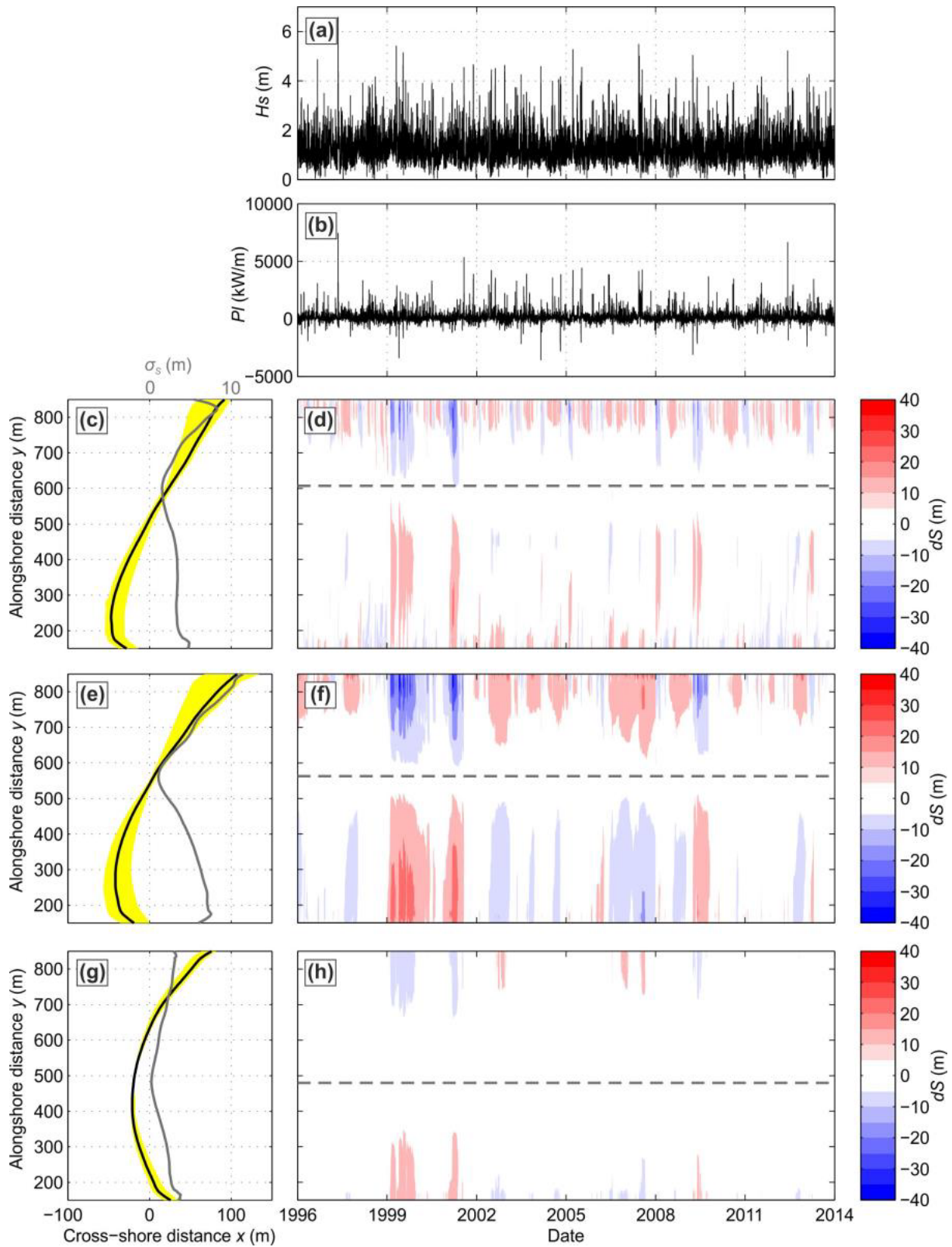




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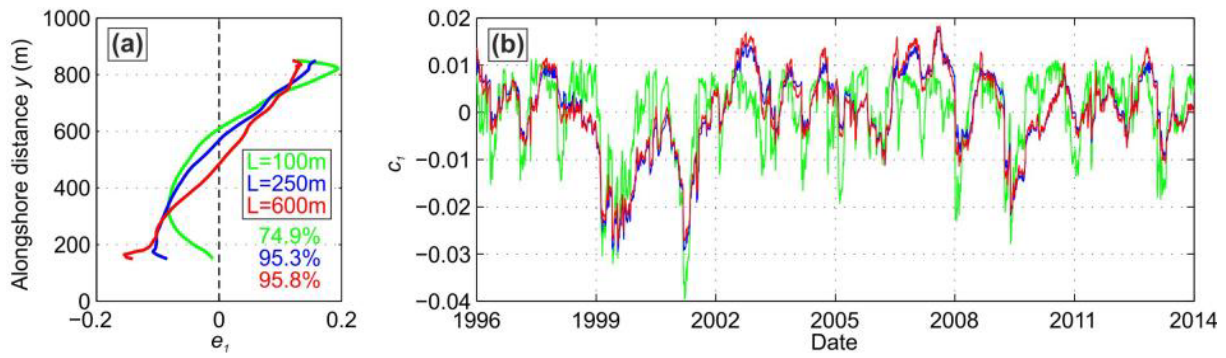
668 Figure 7. EOF analyses of  $dS$  showing the first (a) spatial and (b) temporal EOFs for simulations with  $L$   
 669 = 100 m (green),  $L = 250$  m (blue) and  $L = 600$  m (red).

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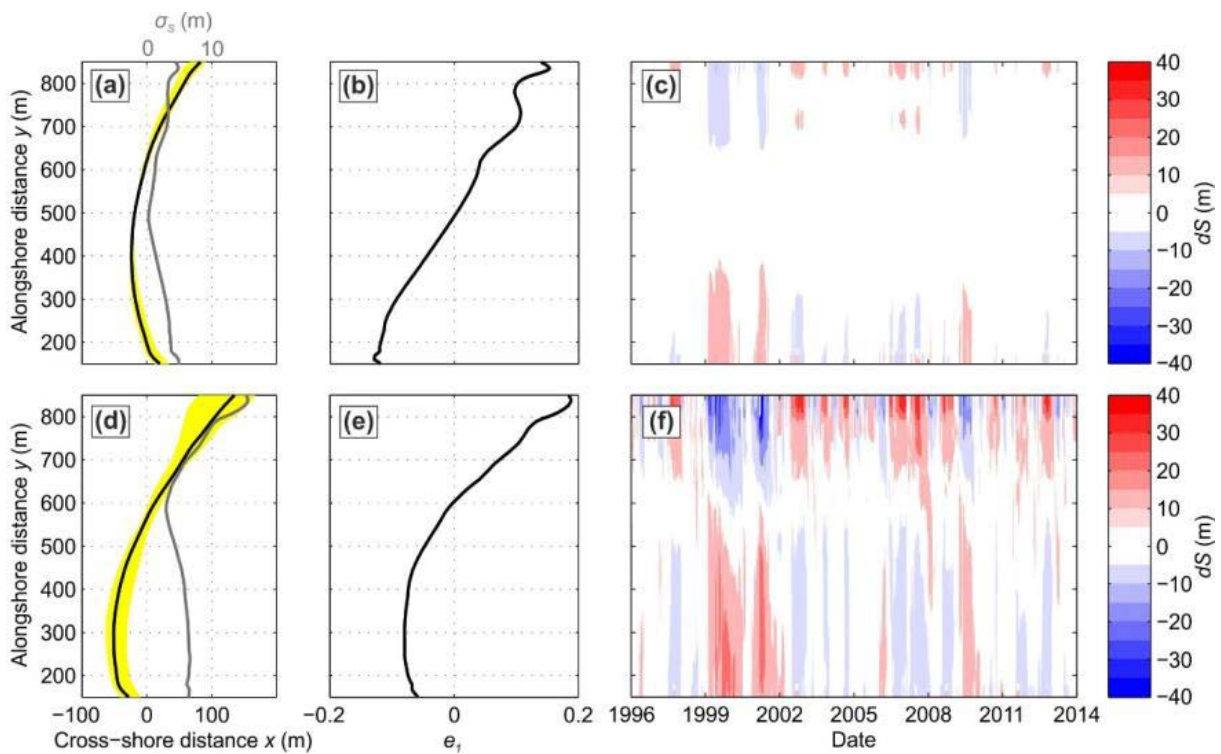
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672 Figure 8. Significant wave height  $H_s$  field coloured on May 16, 1995 ( $H_s = 1.2$  m,  $T_p = 7.72$ ,  $\theta = 132.9^\circ$ )  
 673 for different headland length (a)  $L = 250$  m; (b)  $L = 500$  m; (c)  $L = 600$  m. In all panels, bathymetry is  
 674 contoured in the background (black lines) at 2-m interval, with the thick grey line showing the  
 675 embayment shoreline.



676

677 Figure 9. Left-hand panels: shoreline envelope (yellow area), mean shoreline planform (black line) and  
 678 cross-shore standard deviation  $\sigma_s$  (blue line); Middle panels: spatial component of the first EOF of  $\sigma_s$ ;  
 679 Right-hand panels: time evolution of shoreline deviation from the mean  $dS$  for  $L = 500$  m for different  
 680 wave directional spreading (a-c)  $\sigma_\theta = 40^\circ$  and (d-f)  $\sigma_\theta = 10^\circ$ .

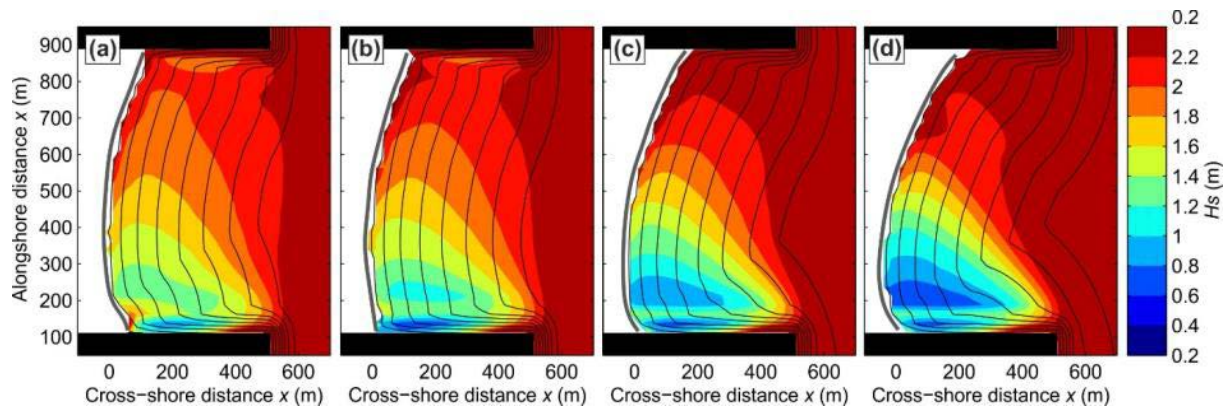


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683 Figure 10. Embayed beach morphology and wave field (significant wave height  $H_s$  coloured) on  
 684 December 26, 1995 for different time-invariant directional spreading values (a)  $\sigma_\theta = 40^\circ$ ; (b)  $\sigma_\theta = 30^\circ$ ;  
 685 (c)  $\sigma_\theta = 20^\circ$ ; (d)  $\sigma_\theta = 10^\circ$ .

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687

688 Figure 11. (a) Time series of alongshore component of offshore wave power  $Pl$  (black) and its 1-yr  
 689 moving average  $\tilde{P}l$  (red); (b) first temporal EOFs of  $dS$  for simulations with  $W = 500$  m (red) and  $W =$   
 690  $1000$  m (blue) both for  $L = 200$  m (no headland sand bypassing).