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1 **Controls of local geology and cross-shore/longshore processes on** 2 **embayed beach shoreline variability**

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10 **Abstract**

11 Shoreline variability along the 3.6-km long Narrabeen Beach embayment in SE Australia is
12 investigated over a 5-year period. We apply the one-line shoreline change model LX-Shore,
13 which couples longshore and cross-shore processes and can handle complex shoreline
14 planforms, non-erodible emerged headlands and submerged rocky features. The model
15 skilfully reproduces the three dominant modes of shoreline variability, which are by
16 decreasing order of variance: cross-shore migration, rotation, and a third mode possibly
17 related to breathing. Model results confirm previous observations that longshore processes
18 primarily contribute to the rotation and third modes on the timescales of months to seasons,
19 while cross-shore processes control the shoreline migration on shorter timescales from hours
20 (storms) to months. Additional simulations simplifying progressively the bathymetry show
21 how the inherent geology strongly modulates the spatial modes of shoreline variability. The
22 offshore central rocky outcrop is found to limit the rotation. In contrast, the submerged rocky
23 platforms that extend from the headlands enhance the shoreline rotation mode and increase
24 alongshore variability of the cross-shore migration mode, owing to increased alongshore
25 variability in wave exposure. Offshore wave transformation across large-scale submerged
26 rocky features and headland shape are therefore critical to contemporary shoreline dynamics.

27 **Keywords**

28 Embayed beach; shoreline model; local geology; rotation; cross-shore migration; wave
29 transformation

30 **1 Introduction**

31 In the context of climate change and increased anthropogenic pressures, it is critical to improve
32 our understanding and predictive capacity of the spatiotemporal evolution of the land-sea
33 interface. Modelling this shoreline variability is challenging given the myriad of driving
34 processes acting at different timescales. Along wave-dominated open and uninterrupted
35 sandy coasts, shoreline variability on the timescales from hours (storm) to years is often
36 primarily driven by cross-shore processes with the shoreline moving rapidly landward
37 (erosion) during storms, and slowly seaward (accretion) during calm periods (e.g. Yates et al.,
38 2009). On longer timescales, other processes such as changes in sediment supply (Thom, 1983)
39 and sea level rise (e.g. Bruun, 1962; Le Cozannet et al., 2016) become important, as well as
40 longshore processes. However, the typical timescales associated with these processes mostly
41 differ on embayed beaches, where inherent geology (rocky headlands, submerged outcrops
42 and rocky platforms extending from the headlands) greatly complicates shoreline response,
43 with longshore processes also impacting shoreline response on short timescales (Ojeda and
44 Guillen, 2008).

45 Embayed sandy beaches are ubiquitous along hilly or mountainous wave-exposed coasts
46 (Short and Masselink, 1999). The geometry of embayed beaches (headland and beach length)
47 depends on the inherent geology (Fellows et al., 2019), which together with exposure to
48 prevailing wave climate dictate beach morphodynamics (Castelle and Coco, 2012; Daly et al.,

49 2014) and shoreline change (e.g. Turki et al., 2013). A well-known shoreline behaviour along
50 embayed beaches is clockwise/counterclockwise beach rotation (Klein et al., 2002; Short and
51 Trembanis, 2004; Ranasinghe et al., 2004; Ojeda and Guillen, 2008; Thomas et al., 2010; Loureiro
52 et al., 2013; Turki et al., 2013; Van de Lageweg et al., 2013). While rotation has been observed
53 on the scale of individual storm events (e.g. Harley et al., 2013) and more gradually due to
54 seasonal changes in wave conditions (e.g. Masselink and Pattiaratchi, 2001), it has historically
55 been attributed to longshore sediment transport with the dominant direction of sand
56 movement being associated with the dominant incident wave direction. More recently, Harley
57 et al. (2015) suggested a more complex rotation process whereby alongshore variability in
58 cross-shore sediment fluxes may be more significant at Narrabeen-Collaroy embayment (SE
59 Australia). In addition, other modes of shoreline variability can be observed, such as a so-
60 called 'breathing' mode that represents a change in the overall curvature of the embayed beach
61 (Ratliff and Murray, 2014; Blossier et al., 2017). This mode has been shown theoretically to be
62 driven by longshore processes and to typically explain much less variability of shoreline
63 change than the rotation mode (Ratliff and Murray, 2014).

64 Over the last decade, a wealth of numerical models has been developed to simulate and further
65 understand shoreline change within coastal embayments. Most of these models are one-line
66 models where shoreline change is essentially driven by longshore processes (e.g. Turki et al.,
67 2013; Ratliff and Murray, 2014). More recently, shoreline change models coupling cross-shore
68 and longshore processes have emerged (Vitousek et al., 2017; Robinet et al., 2018; Antolínez et
69 al., 2019). Amongst these models, LX-Shore (Robinet et al., 2018) can handle complex shoreline
70 geometries (e.g. sand spits, islands), including non-erodible areas such as coastal defences and
71 headlands. New developments to the model also account for non-erodible submerged rocky

72 structures, providing a unique tool to address the control of geology and cross-shore and
73 longshore processes on shoreline changes in coastal embayments. Although it is well
74 established that both cross-shore and longshore processes combine together to drive shoreline
75 variability along embayed beaches, to our knowledge there is no shoreline modelling study
76 coupling cross-shore and longshore processes and addressing embayed beach dynamics. In
77 addition, most of the modelling studies assume idealized embayed beach bathymetries (e.g.
78 Turki et al., 2013; Ratliff and Murray, 2014). However, it is anticipated that offshore wave
79 transformation over complex bathymetries can have a strong impact on alongshore breaking
80 wave characteristics and, in turn, sediment transport and shoreline response.

81 The objectives of the present study are two-fold: (1) to identify the respective contributions of
82 cross-shore and longshore processes to the different modes of shoreline variability at a real
83 embayed beach; and (2) to investigate the role of the inherent geology in modulating the spatial
84 and temporal modes of shoreline change. This work relies on the combination of a unique,
85 high-resolution dataset collected at the embayed beach of Narrabeen-Collaroy, SE Australia,
86 and the further application of the LX-Shore one-line shoreline change model. The study site
87 and the LX-Shore model physics are described in detail in Sections 2 and 3, respectively. Model
88 results are then analysed both in terms of spatial and temporal variability in Section 4. Results
89 are discussed in Section 5 before conclusions are drawn in Section 6.

90 **2 Study site**

91 The Narrabeen-Collaroy embayment is a 3.6 km long sandy beach (Turner et al. 2016) located
92 in the northern coastal area of Sydney, Australia (Fig 1a,c), which is hereafter referred to as
93 Narrabeen for conciseness. The sediment is nearly uniform along the embayment and consists
94 of fine to medium quartz sand with a median grain size (d_{50}) of approximately 300 μm (Turner

95 et al. 2016). The beach is bordered by two rocky headlands, which extend offshore through
96 large submerged rocky platforms, with the southern headland being the most prominent (Fig
97 1c). Just south of the northern headland, an intermittently-active inlet (typically 50 m wide)
98 occasionally connects an inland lagoon to the ocean, which acts more as a sink than a source
99 of sediment to the beach (Morris and Turner, 2010).

100 The tide at Narrabeen is microtidal and semidiurnal with a mean spring tidal range of 1.3 m
101 (Turner et al. 2016). The beach is exposed to moderate- to high-energy wave conditions with a
102 mean significant wave height (H_s) of 1.6 m and a mean peak period (T_p) of 10 s. The wave
103 climate is dominated by long period swells coming from the SSE (Fig 1.b), generated by
104 eastward-tracking extratropical cyclones south of mainland Australia. The coast is also
105 exposed to storm waves from the S, E and NE generated by intensified extratropical cyclones,
106 east coast lows, and tropical cyclones, respectively. The wave climate is slightly seasonally-
107 modulated owing to decreasing extratropical cyclone and east coast low activity in the austral
108 summer along with more NE sea breezes generating short-period waves. The wave climate
109 offshore of Narrabeen is termed storm-dominated as energetic wave conditions occur all year
110 long (Splinter et al., 2014).

111 Nearshore wave conditions at Narrabeen are non-uniform alongshore due to refraction,
112 bottom friction and depth-induced breaking enforced by the complex inherent geology (Fig.
113 1c). The south headland shelters the southern part of the beach from waves coming from the
114 S-SE (Bracs et al., 2016), leading to up to 30% difference in breaking wave height from S to N
115 for average conditions (Harley et al., 2011a). Within the embayment, the bottom is essentially
116 sandy from the subaerial beach to at least 20-m depth. Exceptions to this sandy bed are made
117 in front of the northern and southern end of the beach, where small rocky outcrops lying in

118 depths from 5 to 10 m disturb the relatively shore-parallel bathymetric iso-contours. Apart
119 from relatively small rocky areas, a large rocky outcrop is observed approximately 1 km
120 offshore in the centre of the embayment, with a minimum depth at its crest of approximately
121 18 m (Fig 1b). Previous wave modelling suggests that, during energetic storm events, this
122 geological feature affects wave propagation through a combination of refraction, diffraction
123 and bottom friction (Bracs et al., 2016).

124 The beach state is modally intermediate-dissipative in the north and progressively transforms
125 into intermediate-reflective towards the S. The subaerial beach width can vary by up to 80 m
126 (70 m) in the north (south). The beach is backed by high natural and vegetated foredunes in
127 the north, while in the central and southern part of the beach intensive urbanization has led to
128 the replacement of natural dunes by sea-facing properties typically protected by buried rubble
129 mound sea-walls.

130 A continuous beach survey program has been led since 1976 at Narrabeen, creating one of the
131 most extensive shoreline datasets worldwide (Turner et al., 2016). Among the numerous cross-
132 shore transects initially defined to support this program, five (PF1, PF2, PF4, PF4 and PF8)
133 have been continuously used to conduct biweekly beach profiles (transects are shown in Fig.
134 1b). Since 2005, this survey program has included monthly three-dimensional topographic
135 surveys of the entire 3.6 km-long subaerial beach using an all-terrain vehicle (Harley et al.,
136 2011b). Previously, Harley et al. (2015) performed an empirical orthogonal function (EOF)
137 analysis on a 5-year period (2005-2010) of this three-dimensional dataset and showed that the
138 two dominant modes of shoreline variability are cross-shore migration followed by rotation,
139 explaining approximately 55% and 22% of the overall variability, respectively. A third mode
140 of variability explaining less than 10% of the total variance was disregarded in their analysis.

141 Below we address the same period as that investigated in Harley et al. (2015), but focussing on
142 shoreline variability from both measurements and model outputs.

143 **3 LX-Shore application**

144 **3.1 Model description**

145 LX-Shore is a two-dimensional planview cellular-based one-line shoreline change model for
146 wave dominated sandy coasts (Robinet et al., 2018). An overview of the model is provided in
147 Fig. 2 and the reader is referred to Robinet et al. (2018) for more details. LX-Shore simulates
148 shoreline change resulting from the combination of gradients in total longshore sediment
149 transport and cross-shore transport driven by changes in incident wave energy (Fig 2a,c). LX-
150 Shore can handle complex shoreline geometries (e.g. sand spits, islands), including non-
151 erodible areas such as coastal defences and headlands.

152 Unlike usual one-line models directly resolving the shoreline position (e.g. Hanson, 1989;
153 Kaergaard and Fredsoe, 2013; Hurst et al., 2015; Vitousek et al., 2017), and in line with Ashton
154 and Murray (2006), LX-Shore computes changes in the relative amount of dry (i.e. land) surface
155 in square cells discretizing horizontally the computation domain and presenting a typical
156 spatial resolution of 10-100 m (Fig. 2b). This relative amount, hereafter referred to as the
157 sediment fraction, ranges from 0 (water cells) to 1 (fully dry cells). The planview shoreline is
158 then retrieved at each simulation timestep using an interface reconstruction method. Change
159 in sediment fraction within the cells can result from longshore transport computed using the
160 formula of Kamphuis et al. (1991), which can be multiplied by a free calibration parameter (f_{cl})
161 when data is available for calibration. Sediment fraction changes also result from cross-shore
162 transport using an adaptation of the equilibrium-based ShoreFor model (Davidson et al., 2013;

163 Splinter et al., 2014). Here the disequilibrium term is computed from offshore wave conditions
164 instead of breaking wave conditions. This cross-shore module is based on three model free
165 calibration parameters (for more detail the reader is referred to Davidson et al., 2013; Splinter
166 et al., 2014): the response factor Φ that describes the ‘memory’ of the beach to antecedent wave
167 conditions; the rate parameter c that describes the speed at which the shoreline
168 erodes/recovers; and a linear trend parameter b .

169 LX-Shore incorporates the direct formula of Larson et al. (2010) to rapidly compute the wave
170 characteristics at breaking at each time step, which is typically used on simple and academic
171 application cases (Robinet et al., 2018). Here the coupling with the spectral wave model SWAN
172 (Booij et al., 1999) is used to account for the complex wave transformation at Narrabeen. LX-
173 Shore, in turn, provides at each time step an updated bathymetry that feeds back onto wave
174 transformation. This updated bathymetry is reconstructed (Fig. 2a) using a method similar to
175 the one used by Kaergaard and Fredsoe (2013), from the current shoreline position and an
176 idealized static equilibrium beach profile (a Dean profile).

177 For the present study, the bathymetric reconstruction method presented in Robinet et al. (2018)
178 has been improved by allowing real non-erodible bathymetric features to be included in water
179 depths greater than a threshold depth (Dt). Beyond this depth, the idealized bathymetry is
180 replaced by the measured bathymetry. Dt must be greater than the depth of closure (Dc) to
181 maintain the equilibrium beach profile which is a fundamental assumption of the one-line
182 modelling approach. Note that a merging is applied over a buffer area between Dc and Dt to
183 ensure a smooth transition between idealized and measured bathymetries. This improvement
184 allows testing the effect of complex local geology such as that observed at Narrabeen on the
185 different modes of shoreline variability.

186 3.2 Data

187 3.2.1 Waves and wind

188 LX-Shore simulations are conducted using offshore wave conditions (H_s , T_p and peak wave
189 direction D_p) measured by the Sydney buoy located 11 km to the southeast of Narrabeen in
190 approximately 80-m depth. Similar to Harley et al. (2015), gaps in buoy measurements were
191 filled using wave conditions extracted from the CAWCR hindcast (Durrant et al., 2014).
192 Inshore wave conditions measured by a waverider buoy deployed at the centre of the
193 embayment in 10-m depth from July 21 to November 14, 2011 were also used to validate the
194 modelled wave conditions close to breaking. As justified in section 3.4, SWAN was also forced
195 by the wind conditions measured at Sydney airport.

196 3.2.2 Bathymetry and seabed type

197 Three different bathymetric data sources were used to generate the bathymetries associated
198 with the SWAN computation grids introduced in Section 3.3.3. The first, most-inshore,
199 bathymetry was sourced from sixteen surveys conducted using a single-beam echosounder
200 mounted to a jetski within the Narrabeen embayment between April 2011 and May 2017. These
201 sixteen bathymetries were averaged to obtain a representative bathymetry of the embayment.
202 Remaining gaps in the bathymetry over the LX-Shore simulation domain were subsequently
203 filled using a second bathymetric dataset of 2-m-spaced iso-bathymetric contours covering the
204 Sydney coastal waters down to 50 m depth digitised from bathymetric charts by the NSW
205 Office of Environment and Heritage (NSW OEH). For even deeper waters, the large-scale
206 coarse-resolution Australian Bathymetry and Topographic Grid (ABTG, Whiteway, 2009) was
207 used. Rocky seabed contours were extracted from the mapping of subtidal habitats provided

208 by the NSW OEH and used to identify the non-erodible rocky patches within and outside the
209 embayment.

210 **3.2.3 Shoreline and rocky contours**

211 Contours of the northern and southern Narrabeen headlands were digitalized manually from
212 Google Earth. For LX-Shore calibration and validation, 44 complete planview shorelines
213 derived from the all-terrain vehicle topographic surveys conducted from July 2006 to July 2010
214 with an average periodicity of 30 days were used (Harley et al., 2015). Following Harley et al.
215 (2015), the mean-sea-level contour was used as the shoreline proxy throughout. The beach
216 topographic survey conducted on July 22, 2005 was also used to compute the initial shoreline
217 position in our simulations as detailed in Sections 3.3.1 and 3.3.2.

218 **3.3 Setup**

219 **3.3.1 General settings**

220 The model is applied over a 5-year period from July 2005 to July 2010, which is the period
221 studied in the reference work of Harley et al. (2015). The simulation timestep is set to 3 hours
222 for both LX-Shore and SWAN. The equilibrium beach profile used in LX-Shore was calibrated
223 using the time and spatial average of the beach profiles measured along transects PF2, PF4 and
224 PF6 (Fig. 1b) down to nearly 14-m depth. PF1 and PF8 were excluded due to the prominence
225 of rocky outcrops at these locations. The depth of closure used in LX-Shore simulations was
226 obtained from the following steps: (i) offshore wave conditions from July 2005 to July 2010
227 were propagated shoreward using SWAN, based on the computation grids and model settings
228 described in Sections 3.3.3 and 3.4, respectively; (ii) wave conditions were extracted in 10-m
229 depth offshore the five historical transects and then used to estimate a few theoretical values
230 of D_c along the beach, based on the formula of Hallermeier (1981); (iii) because estimates of D_c

231 ranged from 6.2 to 8 m, a near average value of 7 m was taken as representative of D_c for the
232 entire embayment. The implications related to the choice of this depth of closure are discussed
233 later in Section 5.2.

234 3.3.2 Initial conditions

235 The rocky contours are considered non-erodible and remain unchanged during the model
236 simulations. The initial shoreline condition is the planview shoreline measured by the all-
237 terrain vehicle on July 22, 2005. However, preliminary tests showed that the mean shoreline
238 planform simulated with LX-Shore tends to slowly converge towards a slightly different shape
239 than that observed, which is a common problem in shoreline change modelling (e.g. Antolínez
240 et al., 2019). Given that the objective of the present study is to investigate the spatial and
241 temporal shoreline variability and not the mean shoreline planform, the deviation from the
242 respective mean of the modelled and measured shoreline was compared. To avoid bias
243 induced by model spin-up from the initial measured shoreline position, a two-step simulation
244 workflow was designed (see Fig. 3). First, a spin-up simulation was run from the initial
245 measured shoreline position to obtain a quasi-converged planview shoreline by averaging the
246 planview shoreline simulated during the last year of the simulation period. Then, this quasi-
247 converged planview shoreline was used as input to a new simulation over the same period.
248 Because the first year of this second simulation still involves some model spin-up, it is
249 removed from further analyses, therefore the results presented here concentrate only on the 4-
250 year period from July 2006 to July 2010.

251 3.3.3 Computation grids and role of inherent geology

252 A modelling strategy using a nested SWAN computation grid was adopted to speed up the
253 simulations (Fig. 4a). The coarser hydrodynamic grid is regular with a mesh resolution of 50 m

254 and is based on a bathymetry computed by merging the 2 m iso-contour bathymetry with the
255 deeper ABTG bathymetry (Fig. 4a). Depths from the 2 m iso-contour dataset are kept from 0
256 to nearly 40 m depth and are then progressively merged with the coarser ABTG bathymetry
257 data down to nearly 50 m depth, below which only ABTG data are used.

258 The nested refined hydrodynamic grid is regular, with a 20-m mesh, and is based on the
259 bathymetry produced iteratively by LX-Shore as described in Section 3.1. The measured
260 bathymetry used in the merging process is made of the combination of the time-averaged
261 jetski-based bathymetries and the 2 m iso-contour dataset. Fig. 4b shows an example of the
262 merged bathymetry produced by LX-Shore. The morphological grid used in LX-Shore (Fig. 4c)
263 has the same spatial extent as the refined hydrodynamic grid but with a cell width of 80 m.
264 The shoreline is discretized into nearly 40 cells. To explicitly test the influence of the inherent
265 local geology on the different modes of shoreline variability at this embayed beach, additional
266 simulations were performed using alternative bathymetries for the refined grid. The central
267 rocky outcrop was removed from the nearshore bathymetry (Fig. 5b) and the bathymetry was
268 also further idealized by removing submerged rocky platform headland extensions and
269 replacing it with a Dean profile along the entire embayment (Fig. 5c), showing large seabed
270 elevation differences (Fig. 5d).

271 **3.4 Calibration**

272 Prior to LX-Shore simulations, a preliminary task consisted of calibrating SWAN parameters
273 to improve wave hindcasts within the embayment. Calibration was made using inshore wave
274 conditions measured at the centre of the embayment in 10-m depth (Fig. 4a,b white triangle)
275 from July 21 to November 14, 2011 (no other observations were available during the simulation
276 period). The default directional spreading of 30° was increased to 45°. The friction was enabled

277 using the expression of Madsen et al. (1988) and a non-uniform bottom roughness length scale.
278 The default value of 0.05 m was used for sandy seabed, but this value was set to 0.5 m for
279 rocky seabed. Finally, the wave generation by wind and dissipation through whitecapping
280 were enabled using the expressions of Komen et al. (1984). Modelled H_s and mean wave
281 direction (D_m) show good skill (Table 1) with a root mean squared error (RMSE) of 0.17 m and
282 10.13° and with a correlation coefficient of 0.94 and 0.75, respectively. Modelled mean wave
283 period (T_m) is less accurate with a RMSE of 1.54 s and a correlation coefficient of 0.60. The
284 present, more-refined, model setup reduces the bias in D_m from 4° to 0.71° in comparison with
285 the reference look-up table used to predict inshore waves at Narrabeen in Turner et al. (2016).
286 The cross-shore model was calibrated by optimizing three free model parameters. Here, a
287 simulated annealing optimization algorithm (Bertsimas et al., 1993) was used as in Castelle et
288 al. (2014) to find the optimal coefficient combination to simulate the cross-shore shoreline
289 positions measured at PF6. The optimized values for these coefficients are as follows: $\Phi = 35$
290 days; $c = 2.5304 \times 10^{-7} \text{ m}^{1.5}\text{s}^{-1}\text{W}^{-0.5}$; $b = 1.4695 \times 10^{-7} \text{ ms}^{-1}$ and were further used for the entire
291 embayment. For the longshore transport model, simulations were conducted by increasing f_{Ql}
292 to 3, 4 and 5. A fair comparison regarding the changes of the overall shoreline orientation
293 (defined as the angle between the north and the linear fit of the northward shoreline positions)
294 was achieved for $f_{Ql} = 4$.

295 **3.5 Post-processing of shoreline position**

296 To ease the analysis of measured and simulated shoreline change, the Cartesian coordinates
297 (x, y) of shoreline positions were transformed into alongshore – cross-shore (s, p) coordinates
298 following the method introduced by Harley and Turner (2008). This transformation relies on
299 a logarithmic spiral baseline obtained by fitting a reference planview shoreline. Here, the

300 average planview shoreline over the study period without model spin-up (July 2006 – July
301 2010) is used as the reference, with p indicating the cross-shore distance from the time-
302 averaged cross-shore shoreline position and s indicating the alongshore distance from the
303 northern end of the beach. Because of the slight differences between the measured and
304 modelled time-averaged shoreline planforms, two distinct logarithmic spirals were used as
305 reference planforms to analyse shoreline variability (one for the model, one for the
306 observations). These two distinct reference planforms were used to more accurately define the
307 longshore and cross-shore directions in the measured and modelled datasets.

308 **4 Results**

309 **4.1 Simulated shoreline changes**

310 Fig. 6a shows the observed and simulated time-averaged planview shorelines. Although the
311 overall shape is fairly well captured by the LX-Shore model, substantial changes of up to 30-
312 40 m cross-shore can be observed (Fig. 6b). The planform curvature is underestimated by the
313 model, resulting in a mean modelled shoreline position located further offshore in the centre
314 of the embayment and further inshore close to its extremities. Although accurately simulating
315 the mean shoreline planform of the coastal embayment is not an objective of the present study,
316 this limitation will be discussed later in the paper (refer Section 5). Hereafter, the cross-shore
317 deviation of observed and modelled shoreline from their respective means $p(s,t)$ is addressed.

318 Fig. 7 shows the space-time diagrams of the modelled (Fig. 7b,c) and measured (Fig. 7d)
319 shoreline deviation from the mean with corresponding time series of the five historical profiles
320 (PF1, PF2, PF4, PF6 and PF8) shown in Fig. 8. A number of erosion events along the entire
321 embayment can be seen. The June 2007 event stands out (Fig. 7b-d), which was caused by an

322 intense east coast low in the northern Tasman Sea on 7-10 June driving high-energy waves
323 from the SE reaching 6.9 m offshore (Fig. 7a), and resulting in 273,000 m³ of sand removed
324 from the subaerial beach (Harley et al., 2015). The shoreline retreat due to this event was
325 observed to be on the order of 30-40 m at all five profiles, except at the southern profile PF8
326 where erosion reduced to approximately 20 m (Fig. 8). Rapid erosion events were followed by
327 slower recovery periods typically extending a few months (Fig. 7d). Overall, shoreline varied
328 more at the north of the embayment than at the south, owing to the larger exposure to the
329 prevailing wave conditions from the SE (Harley et al., 2015). A number of clockwise and
330 counter-clockwise rotation events can be observed (Fig. 7d), which are sometimes not
331 associated with an overall migration of the shoreline.

332 Similar shoreline change patterns are observed with the model (Fig. 7c), which can provide
333 much higher frequency insight into erosion and rotation signals using output at each model
334 time step (Fig. 7b). The model readily captures erosion and subsequent multi-month recovery
335 of the shoreline, as well as rotation events (Fig. 7c-e). Given that the model does not explicitly
336 include surfzone sandbar dynamics, the model does not capture the short-scale, alongshore
337 shoreline variability (e.g. around May 2009), which may reflect the presence of megacusp
338 embayments observed previously at this site (e.g. Harley et al., 2015; Splinter et al., 2018). Fig.
339 7b also shows that shoreline recovery is not a steady process, instead, significant interruptions
340 and reversals in recovery are caused by more or less small storm events. This is further
341 emphasized in Fig. 8. The model systematically explains more than 70% of shoreline variance
342 at all transects (Fig. 8) except at the southern profile FP8 (42%, Fig. 8e), with root mean squared
343 errors systematically smaller than 7.5 m (Fig. 8). Importantly, the model is also able to capture

344 extreme accretion-erosion events, which were typically underestimated north of the beach in
345 previous modelling efforts (e.g. Splinter et al., 2014).

346 **4.2 Temporal and spatial modes of shoreline variability: LX-Shore capabilities**

347 To better understand the different modes of shoreline variability within the embayment, an
348 EOF analysis was performed to decompose observed shoreline variability into linear
349 combinations of statistically independent spatial and temporal patterns (Miller and Dean,
350 2007). Results of the first three EOFs from measured cross-shore shoreline deviation from the
351 mean $p(s,t)$ (Fig. 7d) are presented in Fig. 9. These results indicate very similar modes of
352 shoreline variability to those obtained in Harley et al. (2015). This is in spite of the fact that the
353 former study includes an additional one year of shoreline data that is disregarded here due to
354 model spin-up. The primary modes of shoreline variability are, by decreasing order of
355 importance: (i) cross-shore migration with larger amplitude in the north and accounting for
356 61.3% of the variance; (ii) beach rotation accounting for 19.2% of the variance and presenting
357 a nodal point near $s = 1800$ m and an attenuation of the spatial mode at $s = 800$ m; (iii) a third
358 mode accounting for 6.2% of the variance.

359 A similar analysis was performed with model outputs at time steps concurrent with
360 measurements (Fig. 7c). Results (Fig. 9, red lines/dots) show that the EOF analysis gives, in the
361 same order of importance, very similar spatial patterns (Fig. 9a-c), although the model gives
362 more variance (81.6%) to the first mode (cross-shore migration) than measurements (61.3%). It
363 is however important to note that the model was not calibrated on these modes of variability,
364 and that slight changes in the free parameters could lead to better agreement, which will be
365 discussed later in the paper (refer Section 5). The corresponding modelled temporal modes of

366 variability are also in very good agreement with measurements, particularly for the two first
367 modes ($R^2 > 0.8$) and to a lesser extent the third one ($R^2 = 0.68$, Fig. 9d-f).

368 **4.3 Respective contribution of longshore and cross-shore processes to shoreline** 369 **variability on the timescales from storm to years**

370 Because modelled temporal and spatial modes of shoreline variability are in very good
371 agreement with observations, LX-Shore can be used to further address the respective
372 contributions of cross-shore and longshore processes to the different modes of shoreline
373 variability. For this purpose, cross-shore or longshore processes were switched off
374 alternatively and the impacts on the modes of shoreline variability were investigated
375 systematically. Using model outputs at each model time step (3 hours) instead of only at the
376 time steps concurrent with measurements (~monthly), also provides insight into the shoreline
377 response timescales. The three top panels in Fig. 10 show the first three EOFs with both cross-
378 shore and longshore processes included. Spatial modes (cross-shore migration, rotation and
379 the third mode) are essentially similar in pattern (Fig. 9a,b,c), with the high-frequency
380 temporal modes showing a large number of reversals and short-term large changes
381 highlighting the dynamic nature of the embayment. Visual inspection of Fig. 10h,i,j
382 (comparison of blue lines) also reveals different temporal dynamics for the three modes of
383 variability. While the cross-shore migration mode occurs on scales of hours (storm) to months
384 (Fig. 10h), the rotation mode operates more gradually on annual and interannual scales (Fig.
385 10i). This is in line with Harley et al. (2015) who showed that the first EOF was controlled by
386 waves averaged over ~ 8 days (representing storms) whereas the second EOF was more
387 controlled by wave changes over months to seasons. Regarding the third mode, no

388 predominant timescale arises as both short-term (event scale) and long-term (annual scale)
389 temporal patterns superimpose.

390 Running LX-Shore with cross-shore processes switched off (i.e. longshore only), the EOF
391 analysis shows that the primary modes of shoreline variability in such a configuration (Fig.
392 10d,e) are essentially similar in pattern to the second (rotation) and third modes (Fig. 10b,c).
393 The corresponding temporal modes (Fig. 10k,l) are also essentially the same as for the
394 simulation combining cross-shore and longshore processes (Fig. 10i,j). Running LX-Shore with
395 longshore processes switched off (i.e. cross-shore only), the EOF decomposition leads to two
396 dominant modes of shoreline variability (Fig. 10f,g,m,n). The first mode corresponds to a
397 short-term cross-shore shoreline migration, which is maximized along the northern part of the
398 beach and decreases to close to 0 towards the south (Fig. 10f,m). The negative trend in the
399 temporal EOF, combined with the shape of the spatial EOF, indicates that during the
400 simulation this first mode tends to drive a long-term shoreline retreat, which increases
401 northwards. In contrast, the second mode corresponds to a beach rotation with an amplitude
402 maximized along the southern part of the beach (Fig. 10g,n). The positive trend in the temporal
403 EOF, combined with the shape of the spatial EOF, indicates that during the simulation this
404 second mode tends to drive a long-term shoreline retreat and advance at north and south,
405 respectively. Given that the temporal EOFs of these two modes are similar, and that the first
406 mode shows more variance, the combination of these two modes mostly corresponds to the
407 cross-shore migration mode of the LX-Shore simulation accounting for both cross-shore and
408 longshore processes. In brief, LX-Shore simulations indicate that longshore processes
409 primarily contribute to the second (rotation) and third modes of shoreline variability (Fig.
410 10b,c), while cross-shore processes control the cross-shore migration with more variability at

411 the northern end (Fig. 10a). These results corroborate those of Harley et al. (2011a, 2015) based
412 on extensive field data analysis, showing that LX-Shore can be a powerful tool to address the
413 modes of shoreline variability in complex settings.

414 **4.4 Controls of inherent local geology on the shoreline modes of variability**

415 As shown in Fig. 1b, Narrabeen is bordered by two prominent and morphologically different
416 rocky headlands, which extend offshore through large submerged rocky platforms. In
417 addition, a large rocky outcrop located approximately 1.5 km offshore in less than 20-m depth
418 can be observed. This inherent local geology can affect wave propagation, breaking wave
419 conditions along the embayment and, in turn, the modes of shoreline variability. To further
420 test this hypothesis, two additional simulations (including wave and shoreline modelling)
421 were performed using the same free parameters as in the reference simulation: one removing
422 the prominent central rocky outcrop (Fig. 5b) and a second simulation further removing the
423 headland-facing submerged rocky platforms (including the central rocky outcrop) through a
424 Dean profile along the entire embayment (Fig. 5c).

425 Results from EOF decomposition applied to the outputs of these two additional simulations
426 are superimposed in Fig. 11 onto those from the reference simulation. It appears that removing
427 the central rocky outcrop only slightly affects the overall modes of shoreline variability (Fig.
428 11, red lines). This suggests that the outcrop is too deep to enforce strong wave energy focusing
429 that would cause alongshore gradients in breaking wave conditions large enough to modify
430 both modal wave exposure and longshore sediment transport patterns. This is illustrated in
431 Fig. 12 that shows that even for representative prevailing high-energy waves from the SSE, the
432 wave height patterns alongshore (Fig. 12b) are very similar to those simulated with the
433 reference bathymetry (Fig. 12b,d,e). Two substantial effects can however be highlighted. First,

434 the spatial pattern of the second (rotation) mode is more uniform alongshore (Fig. 11b),
435 suggesting that the presence of this relatively deep central rocky outcrop increases shoreline
436 response complexity. Second, the importance of the rotation mode increases by approximately
437 46% (from 10.9% to 15.9% of the total variance, Fig. 11b) when removing the outcrop,
438 suggesting that the central rocky outcrop is a limiting factor to the rotation signal of the
439 embayment. The simulation for which the bathymetry is further idealized (i.e., with the
440 submerged rocky platforms at the two extremities also removed, refer Fig. 5c) shows much
441 larger changes on shoreline variability (Fig. 11, green lines). The first (cross-shore migration)
442 mode is more uniform along the embayment (Fig. 11a). This observation is consistent with
443 Harley et al. (2015), who suggest that the asymmetric spatial EOF of the cross-shore migration
444 mode is related to alongshore variability in wave exposure, which is indeed reduced when
445 idealizing the offshore bathymetry (see wave field for a SSE swell in Fig. 12c). Overall, the
446 spatial patterns of the second (rotation) and third modes are also more uniform along the
447 embayment without the complex submerged rocky platforms. In addition, the contribution of
448 the second (rotation) mode is reduced by 36% with respect to simulations where only the
449 central rocky outcrop is removed (from 15.9% to 10.1%). This suggests that the prominent
450 submerged rocky platform extensions from the headlands enhances the shoreline rotation
451 mode at Narrabeen. Wave refraction around the prominent platforms resulting in more
452 alongshore non-uniform breaking wave conditions and, in turn, stronger longshore sediment
453 transport gradients, is therefore hypothesized to increase the degree of shoreline rotation.

454 5 Discussion

455 5.1 Respective contributions of inherent geology and cross-shore and longshore 456 processes

457 For the first time our simulations allowed isolating the respective influence of the inherent
458 geology and the cross-shore and longshore processes on the dominant spatial and temporal
459 modes of shoreline variability at a real embayed beach. Although our findings cannot be
460 generalized to all coastal embayments, they provide new insight into shoreline dynamics on
461 real embayed beaches. Overall our results show that longshore processes primarily contribute
462 to the second (rotation) and third modes of shoreline variability at this site, while cross-shore
463 processes control the alongshore-averaged, cross-shore migration, with the inherent geology
464 modulating the modes in space. An important result is that the inherent geology can have a
465 significant impact on shoreline dynamics from the timescales of storms to years. Inherent
466 geology has long been known to influence beach states (Jackson et al., 2005), rip channel
467 morphodynamics (Castelle and Coco, 2012; Daly et al., 2014) or extreme erosion (Loureiro et
468 al., 2012). Here we demonstrate that not only does the headland geometry have an impact on
469 shoreline change, but also more localised submerged rocky outcrops both at the centre and
470 extremities of the embayment. The influence of such submerged non-erodible morphology has
471 been disregarded in previous shoreline change studies, except in a few studies such as Limber
472 et al. (2017) who only investigated the time-averaged shoreline position. These results have
473 implications from the perspective of coastal engineering. Hard structures such as groynes
474 (Hanson et al., 2002) or submerged breakwaters (Bouvier et al., 2017, 2019) are often designed
475 based on their impacts on the adjacent mean shoreline position. Here we show that the design
476 of such structures should also consider their impact on the modes of shoreline variability,

477 including beach rotation and other higher-order modes. These can indeed drive localized time-
478 limited severe erosion on artificial embayed beaches (Ojeda and Guillen, 2008).

479 The third mode of shoreline variability, which is reasonably reproduced by the model (Fig.
480 9c), was suggested by Harley et al. (2015) to potentially be driven by ebb inlet processes
481 occurring at the northern extremity of the beach. The inlet, however, is not included in LX-
482 Shore, which suggests that the influence of the inlet on the shoreline variability is relatively
483 minor and that this third mode is related to other processes. An alternative control of this third
484 mode of shoreline variability is the localized rocky outcrop located in 5 to 10 m depths towards
485 the northern extremity of the beach at around $s = 150$ m. Indeed, when present in the
486 bathymetry, this rocky outcrop is observed to cause substantial localized focusing of breaker
487 wave energy (Fig. 12a,b,d, $s = 150$ m). With this rocky outcrop smoothed within an idealized
488 bathymetry, relatively uniform longshore breaker wave heights are observed (Fig. 12c,d, $s =$
489 150 m), resulting in weakly spatially varying longshore transport. In contrast, such inherent
490 geology, which results in stronger alongshore variability in breaking wave characteristics and,
491 in turn, longshore transport, is likely to drive more complex shoreline variability in its lee. The
492 shape of the spatial EOF of the third mode becomes more symmetrical when idealizing the
493 bathymetry (Fig. 11c) and resembles the U-shaped breathing pattern identified in Ratliff and
494 Murray (2014). The translation of the U-shaped patterns towards the north for the idealized
495 bathymetry might be related to offshore waves predominantly coming from the SE at
496 Narrabeen (Fig. 1b,c,d), whereas in Ratliff and Murray (2014) only symmetrical distributions
497 of wave direction centred around the beach normal are used to force shoreline changes. At this
498 stage it is however not possible to refer to this third mode as “breathing”, which only
499 represents 6.2% of the observed shoreline variability during the period studied here.

500 Both measurements and model results indicate that the cross-shore migration mode is
501 dominant, followed by the rotation mode during the period studied here. However, it is well
502 established that the wave climate at Narrabeen shows strong interannual variability
503 (Ranasinghe et al., 2004; Harley et al., 2010) and that changes in seasonality of storms can have
504 a profound impact on shoreline behaviour (Splinter et al., 2017; Dodet et al., 2019). It is
505 therefore anticipated that the respective contributions of the different modes of shoreline
506 variability to the total shoreline variance may change over time. It will be important to address
507 shoreline variability on longer timescales and explore the genericity of our findings at
508 Narrabeen.

509 **5.2 LX-Shore limitations and opportunities**

510 Our approach presents a number of limitations which are discussed below. First, it is
511 important to remind the reader that, even if LX-Shore relies on an accurate modelling of the
512 waves, it falls into the hybrid shoreline model category, i.e. models based on general principles
513 (e.g. behavioural laws, semi-empirical rules). These models do not use detailed
514 hydrodynamics (nearshore circulation), sediment transport and mass conservation equations.
515 Therefore, while these models can be applied over larger temporal and spatial scales with
516 reasonable computation cost, they also rely on basic assumptions (see Robinet et al., 2018 for
517 detailed assumptions of LX-Shore). Because of this, hybrid models can only be used to
518 investigate the embayed beach mechanisms driven by the processes resolved and at scales at
519 which these processes are meaningful. In contrast, physical-based morphodynamic models
520 have the theoretical potential to explore the full range of mechanisms involved in embayed
521 beach development and dynamics (e.g. Daly et al., 2014, 2015), although they require long and
522 possibly discouraging computation time (Daly et al., 2014). The LX-Shore component

523 resolving longshore processes uses an empirical formula to compute alongshore sediment
524 transport and ensures mass conservation. In contrast, the cross-shore-processes are resolved
525 using an approach relying on a time-varying wave-based equilibrium that does not consider
526 mass conservation. In brief, LX-Shore assumes that the beach cross-shore profile remains
527 unchanged and only translates as the cross-shore shoreline position evolves. This means that
528 deposition or erosion of sediment uniformly spreads along the entire profile from the depth
529 of closure to the top of the active profile. This profile is assumed uniform alongshore, whereas
530 at Narrabeen the mean beach profile characteristics substantially vary alongshore, as does the
531 depth of closure, owing to increasing exposure northwards to the prevailing waves coming
532 from the SE (Harley et al, 2011a). This assumption likely explains a part of the model-data
533 disagreement, in particular the difference in time-averaged shoreline planform in Fig. 6. This
534 depth of closure concept is also challenged along embayed beaches where sediment bypassing
535 (McCarroll et al., 2019; Valiente et al., 2019) and headland rips flushing the surf zone (Castelle
536 and Coco, 2013) have the potential to transport sediment into a nearby embayment and/or well
537 beyond the depth of closure. All these embayed beach specific processes are not taken into
538 account in the present version of LX-Shore.

539 The choice of the depth of closure is crucial in reduced-complexity shoreline change modelling
540 based on the one-line approach (Robinet et al., 2018) as the magnitude of the shoreline
541 response to gradients in alongshore sediment transport depends on this parameter (inverse
542 relation of proportionality). It may also modulate the relative contribution of alongshore
543 processes to shoreline changes in case additional D_c -independent drivers of shoreline
544 variability are included (e.g. cross-shore processes included in LX-Shore). It is therefore
545 essential to use a D_c value that matches the timescales considered and the processes

546 investigated. In LX-shore, the cross-shore processes are resolved on the timescales from storms
547 up to years. The short period used to compute D_c (5 years) ensures a match between the
548 timescales associated with the cross-shore and longshore processes and allows comparing
549 their respective contribution. Addressing long timescales at Narrabeen with LX-Shore (e.g.
550 decades) should imply a re-evaluation of D_c (increased value), which may lead to
551 underestimate on short timescales (storms to years) the shoreline response to alongshore
552 processes relatively to that driven by cross-shore processes. At sites where the number of
553 bathymetric surveys is insufficient, D_c can still be computed from wave-based formulas (e.g.
554 Hallermeier, 1981; Ortiz and Ashton, 2016) or extracted from a new global database of D_c
555 (Athanasίου et al., 2019). The theoretical framework proposed by Ortiz and Ashton (2016),
556 which relies on local wave conditions and few physical parameters, provides an objective
557 method to determine D_c according to the timescales of interest. Based on the average wave
558 conditions simulated along the 10-m depth contour and considering a 5-yr-timescale, their
559 approach gives a D_c ranging from 7.2 to 8.8 m. Given the similarity between these values and
560 those obtained with the formula of Hallermeier (1981) and given the apparent match between
561 measured and simulated modes of shoreline variability (Fig. 9), a D_c of 7 m seems appropriate
562 for the range of timescales involved in this study (storms to years).

563 We performed model calibration on the shoreline position along a single transect and on the
564 change in planview shoreline orientation (linear fit) for the cross-shore and longshore model
565 components, respectively. It was chosen to mimic the classic calibration method, i.e.
566 minimizing the error between simulated and measured values of the latter variables.
567 However, calibrating the model on the amount of variance of the three dominant modes of
568 shoreline variability would likely have further improved model-data agreement. In other

569 words, we willingly decided not to calibrate the model on the end product. Optimization of
570 the cross-shore model free parameters was made at transect PF6 ($s \approx 2500$ in our figures) where
571 the EOF analysis (Fig.9b,e, black curves) revealed a measurable contribution of the beach
572 rotation to the shoreline variability. The best practice is to calibrate the cross-shore model at
573 an alongshore position where the control of longshore processes on shoreline changes is
574 minimized, for instance at s in the range 1000-2000 m at Narrabeen (Fig. 9b, Fig. 10d,e). This
575 would reduce the risk that the cross-shore model free parameters capture part of the shoreline
576 response to alongshore processes. Future applications of LX-Shore to Narrabeen should
577 explore more precisely the effect of the alongshore location used to calibrate the cross-shore
578 model.

579 Breaking wave conditions are critical to sediment transport and resulting shoreline change.
580 Simulating the wave field with SWAN (Booij et al., 1999) was required here to reproduce the
581 wave shadowing from the headland and wave energy focusing patterns through wave
582 refraction across the offshore reef. This is not possible with the direct formula of Larson et al.
583 (2010) that both assumes shore-parallel iso-contours (no focusing) and causes alongshore
584 discontinuities in breaking wave energy at the passage from shadowed to non-shadowed
585 regions and vice versa. SWAN includes a module to simulate the wave diffraction, which can
586 occur near the headlands (Daly et al., 2014) and results in wave energy redistribution toward
587 sheltered areas. However, enabling the SWAN diffraction module in our simulations (not
588 shown) resulted in the development of numerical artefacts in simulated wave fields. It also
589 did not affect the wave conditions along the sheltered southern end of the beach for offshore
590 waves coming from the south whereas it should be the case for such conditions. For these
591 reasons, this SWAN module was not used and no diffraction effects were taken into account

592 in the results presented here. The non-inclusion of the wave diffraction might explain why the
593 overall model performance is degraded at the sheltered southern end of the beach (Fig. 8e, 9b).
594 However, the lack of nearshore wave data in this zone prevents from verifying this speculative
595 hypothesis. It should also be pointed out that wave statistics (H_s , T_p , D_p) were used as offshore
596 wave boundary conditions, although the wave climate off Narrabeen is typically mixed,
597 consisting of locally generated north-easterly waves and swell waves coming predominantly
598 from the SE. Using nested SWAN grids, with the largest grid forced by directional spectra
599 would likely further improve model results, as evidenced by the substantial model
600 improvement by just adding wind effects. Additional simulations (not shown) also indicate
601 that increasing directional spreading, which can reflect an increasingly bimodal wave climate,
602 result in an increasingly curved shoreline planform, i.e. closer to observation at Narrabeen.
603 Therefore, using directional spectra of offshore wave conditions could lead to improved
604 shoreline modelling hindcasts.

605 The analysis of the spin-up simulations (Fig. 3) revealed that the model spin-up is essentially
606 caused by the alongshore processes (not shown). The model spin-up in the simulation where
607 cross-shore processes are switched off (i.e. longshore only; Fig. 10d,e,k,l) is characterized by a
608 progressive planview shoreline readjustment with erosion along the southern end of the beach
609 and accretion north of the alongshore location of transect PF6. The readjustment rate tends to
610 decrease as the planview shoreline approaches an apparent equilibrium shape. Interestingly,
611 the timescales involved for this alongshore-driven readjustment is relatively long in
612 comparison to the timescales on which the alongshore-driven beach rotation acts. The reason
613 is that these modes of shoreline change are driven by different mechanisms. The beach rotation
614 is stirred by the succession of persistent shifts in the incident wave direction occurring on the

615 timescales of month to year in the period investigated here. In contrast, the planview shoreline
616 readjustment might results from a disequilibrium on the timescales of several years between
617 the initial planview shoreline and the incident wave conditions along the beach. Indeed, some
618 approximations made for the SWAN wave propagation (e.g. constant directional spreading,
619 binary values for bottom friction coefficient, homogeneous wind) may have led to breaking
620 wave conditions and longshore sediment transport gradients slightly different to those
621 observed at Narrabeen.

622 Despite the limitations listed above, LX-Shore results show very good agreement with field
623 data. LX-Shore is able to capture even subtle patterns of the dominant spatial modes of
624 shoreline variability. It is important to note that calibration of LX-Shore, which is a one-line
625 model, relies on only four free parameters for the entire embayment. This contrasts with other
626 existing shoreline change models coupling cross-shore and longshore processes (Vitousek et
627 al., 2017; Antolínez et al., 2019), which rely on a specific calibration for every cross-shore
628 transect along the coast. These models therefore require multiple calibration experiments,
629 resulting in a number of free parameters of, at least, an order of magnitude larger than that for
630 LX-Shore. This favours better fitting with field data, but can become a drawback when used
631 for shoreline prediction or at sites with limited shoreline observations. LX-Shore model
632 therefore appears as a relevant and complementary tool to further improve our understanding
633 and predictive ability of shoreline change along real coasts with geological features and
634 exposed to complex wave climates. With both model accuracy and computational power
635 increasing, it is now feasible to simulate multidecadal shoreline change in complex coastal
636 settings. At these timescales sea level rise contribution becomes significant (Le Cozannet et al.,
637 2016) although largely uncertain (Le Cozannet et al., 2019). New developments are being

638 carried out in LX-Shore to account for the effect of sea level change on shoreline variability
639 (Robinet et al., in revision). This includes the possibility of varying the mean sea level
640 throughout the simulation, which drives slow shoreline retreat based on the Bruun rule
641 (Bruun, 1962) and potentially affects the transformation of onshore-propagating waves across
642 non-erodible offshore bathymetry, and, in turn, breaking wave conditions and sediment
643 transport along the coast. Preliminary tests of shoreline change modelling with LX-Shore
644 involving variations in prevailing wave conditions have been done in the frame of Shorecast
645 (Montaño et al., 2019). Such modelling work may provide new insight into embayed beach
646 behaviour in a changing climate.

647 **6 Conclusions**

648 The hybrid shoreline change model LX-Shore was applied to Narrabeen beach, SE Australia,
649 a high-energy 3.6-km long embayed beach. After calibration on a 4-year time series of shoreline
650 change including a large number of rapid erosion events, multi-month recovery periods and
651 clockwise and counter-clockwise rotation events, the model shows very good agreement with
652 observed shoreline behaviour. Model results show that longshore processes primarily
653 contribute to the second (rotation) and third modes of shoreline variability, while cross-shore
654 processes control the first migration mode. The study showed that the inherent geology
655 strongly modulates spatial variability in the three primary modes of shoreline change. The
656 offshore central rocky outcrop is found to limit the rotation signal at Narrabeen beach. In
657 contrast, the submerged rocky platform prominent extensions from the headlands boost the
658 shoreline rotation mode and increases the alongshore variability of the cross-shore migration
659 mode owing to increased alongshore variability in wave exposure. Accounting for accurate
660 wave transformation in shoreline change modelling appears important to accurately account

661 for detailed shoreline variability at sites where complex local geology in the nearshore is
662 present. It is anticipated that such a modelling approach may help improve our understanding
663 of shoreline change in a changing climate, even along complex stretches of coast with large
664 geological influence.

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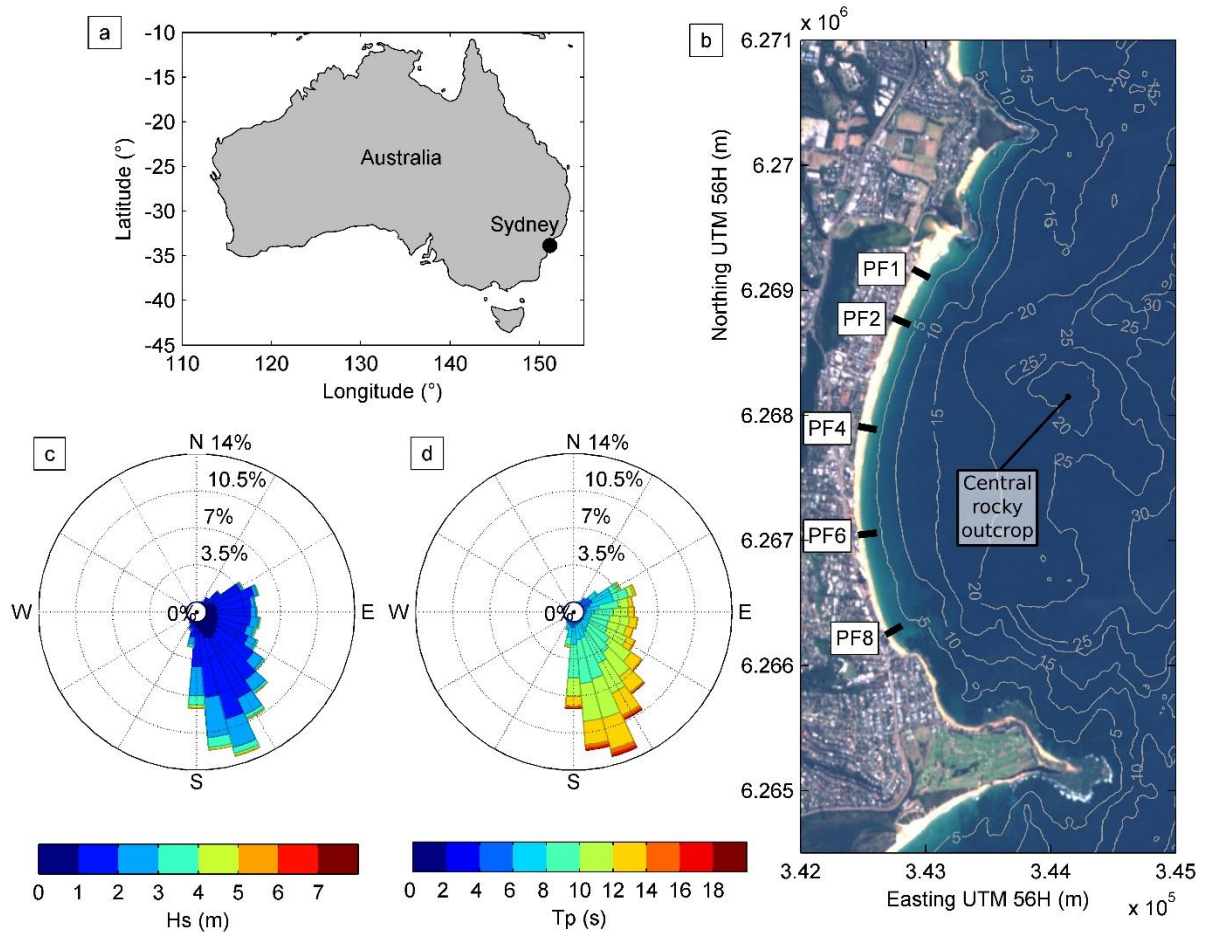
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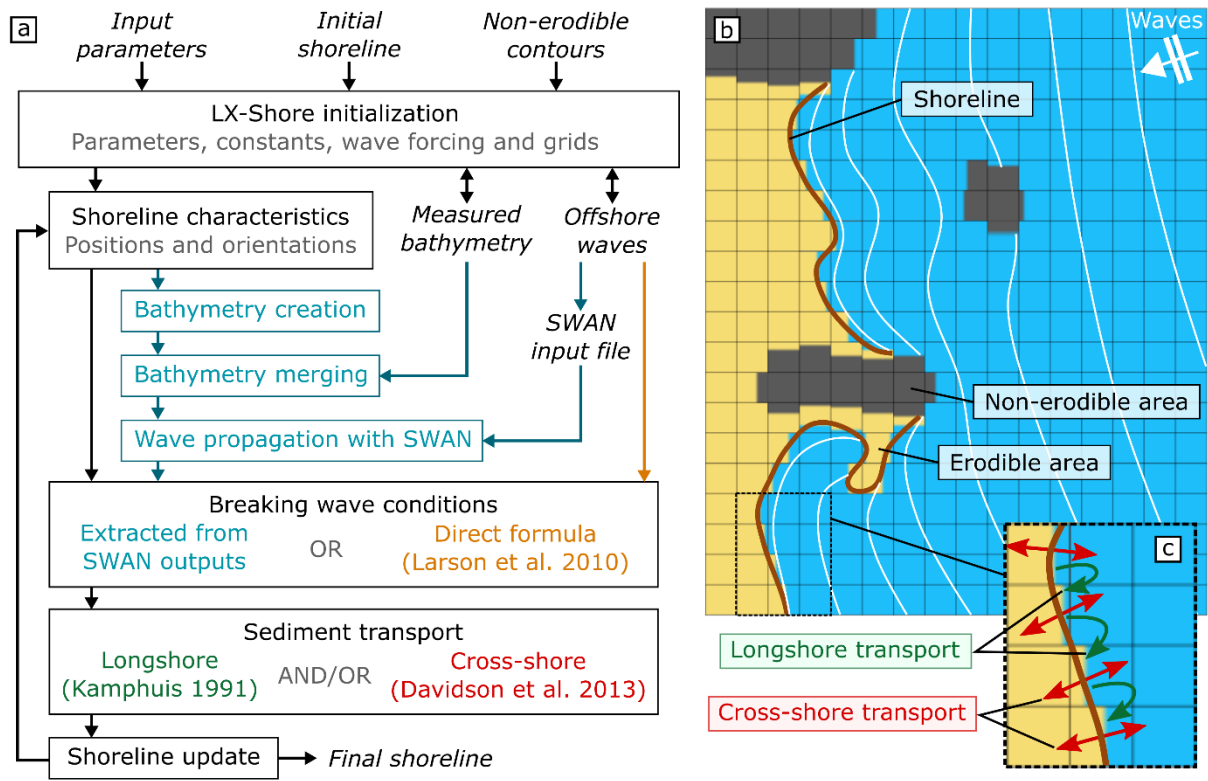
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872

873 *Figure 1 – (a) Location map of (b) Narrabeen beach (Sydney, NSW, Australia) shown by a Sentinel-2 image with*
 874 *bathymetric contours superimposed. The black ticks in (b) indicate the location of five of the historical transects*
 875 *where beach profiles have been acquired since 1976. Wave roses for (c) significant wave height H_s and (d) peak*
 876 *wave period T_p measured at Sydney buoy from July 2006 to July 2010 (for the location of the Sydney buoy, see*
 877 *Fig. 4a).*

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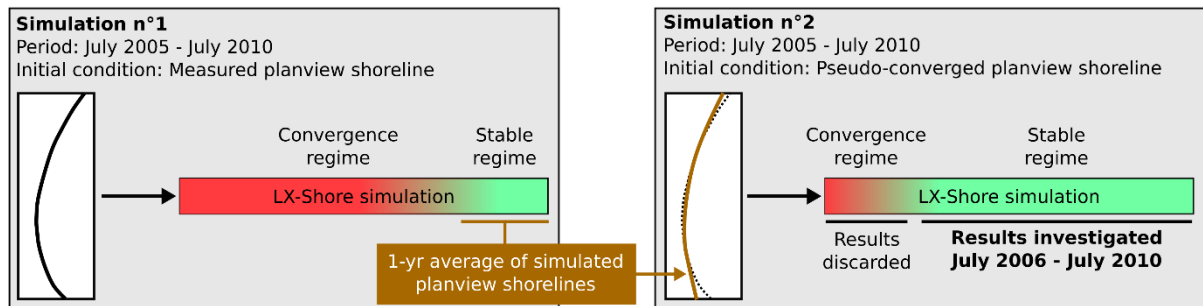


879

880 *Figure 2 – Overview of LX-Shore. (a) Architecture and functionalities. (b,c) Illustrations of the main physical*

881 *processes included in the model. For more detail the reader is referred to Robinet et al. (2018).*

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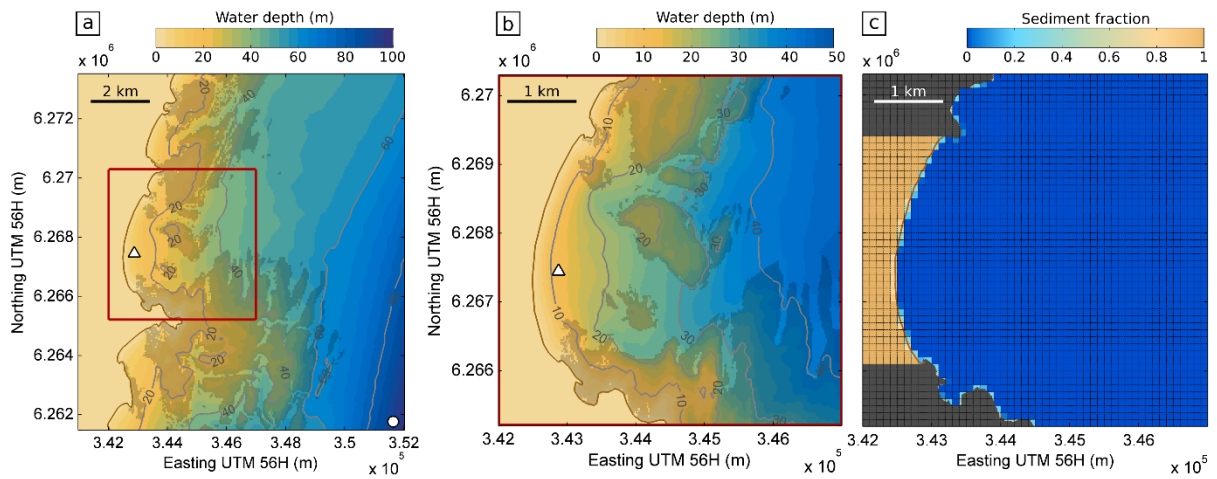


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884 *Figure 3 – The two-step simulation workflow used to reduce the impact of model spin-up from the initial measured*

885 *shoreline.*

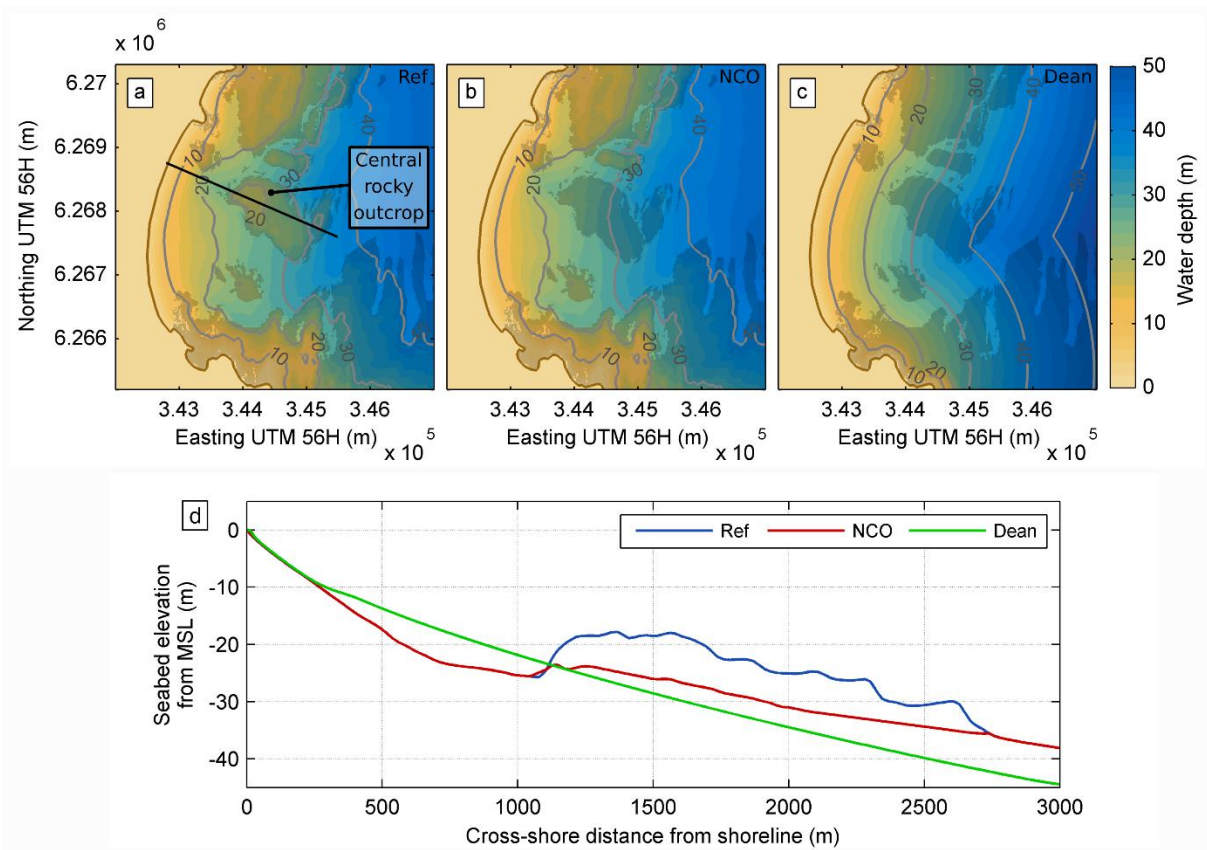
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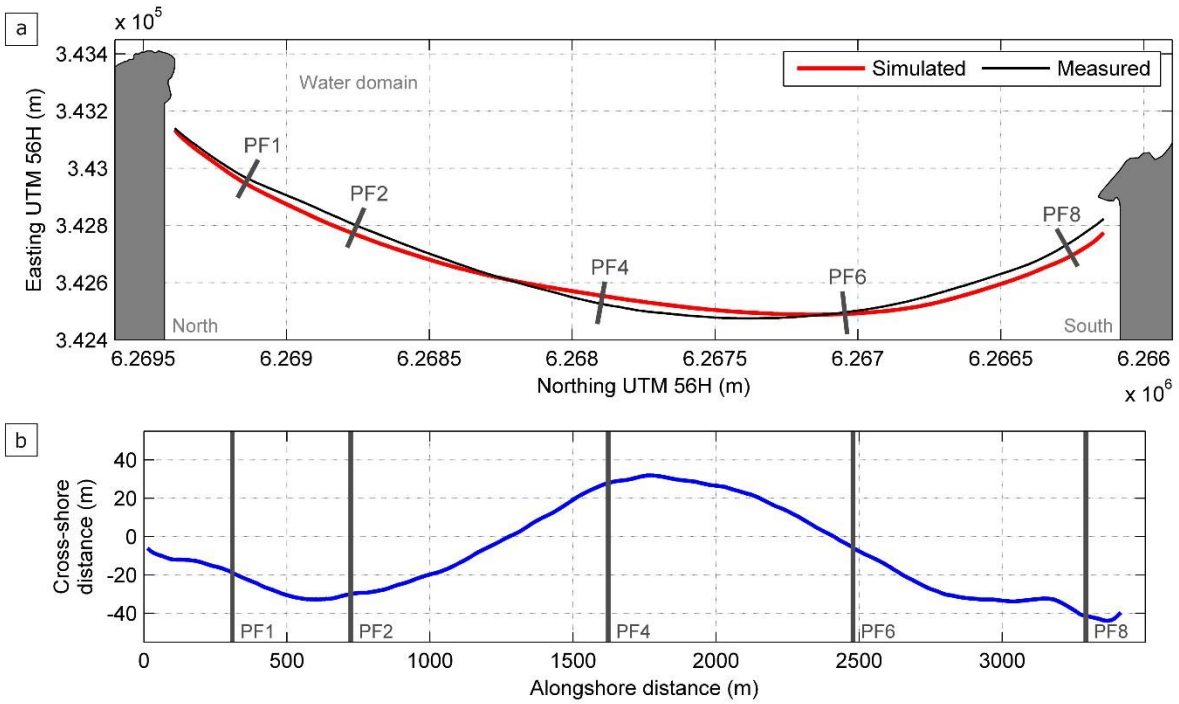
888 *Figure 4 – (a) Coarse and (b) refined nested grid bathymetries used with SWAN. (c) Example of sediment fraction*
 889 *distribution over the morphological grid. The bathymetry shown in (b) is the merged bathymetry produced by LX-*
 890 *Shore on September 20, 2005. The red contour in panel (a) indicates the extent of the refined nested hydrodynamic*
 891 *grid. The white circle in panel (a) locates the Sydney buoy. The white triangle in panels (a,b) locates the inshore*
 892 *buoy location. The shaded areas in panels (a,b) denote the presence of rocky seabed. The dark grey areas in panel*
 893 *(c) indicate non-erodible areas.*

894



895

896 *Figure 5 – (a) Merged bathymetry produced by LX-Shore on September 20, 2005 for the reference simulation, (b)*
 897 *without the central rocky outcrop and (c) further idealizing the bathymetry using a Dean profile along the entire*
 898 *embayment. (d) Seabed elevation extracted from the bathymetries shown in panels (a,b,c) along the PF2 transect*
 899 *extending up to 3 km offshore (black line in panel a). In panels (a,b,c) the shaded areas indicate the location of non-*
 900 *erodible rocky seabed.*

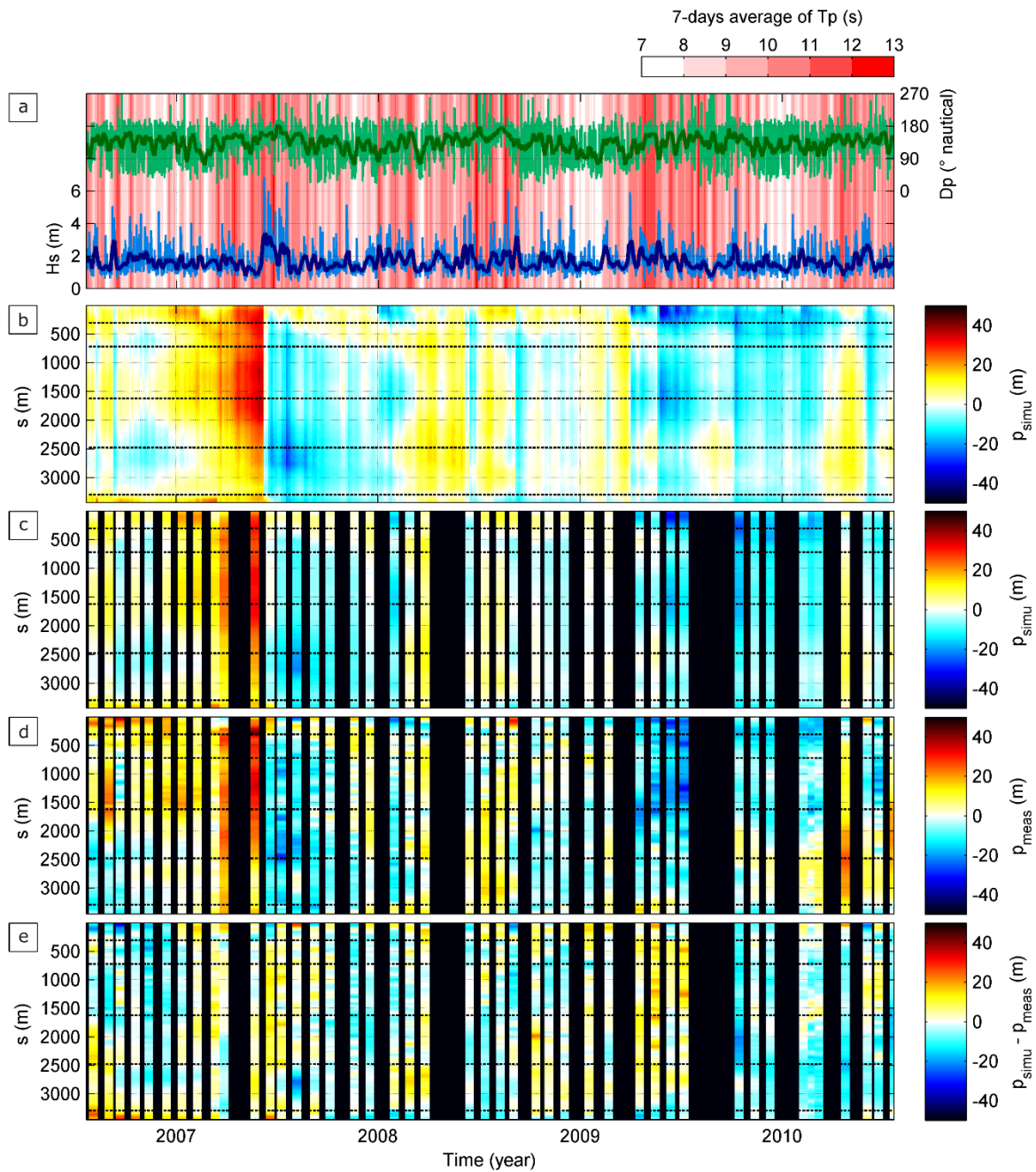


901

902 *Figure 6 – (a) Time average (July 2006 – July 2010) of measured (black) and modelled (red and thick) planview*

903 *shorelines. (b) Cross-shore distance (blue) between the planview shorelines shown in panel (a).*

904



905

906 *Figure 7 – (a) Times series of offshore wave conditions with thin and thick lines indicating respectively hourly and*

907 *7-day-averaged wave conditions for Hs (blue) and Dp (green) and the red background colour indicating the 7-day*

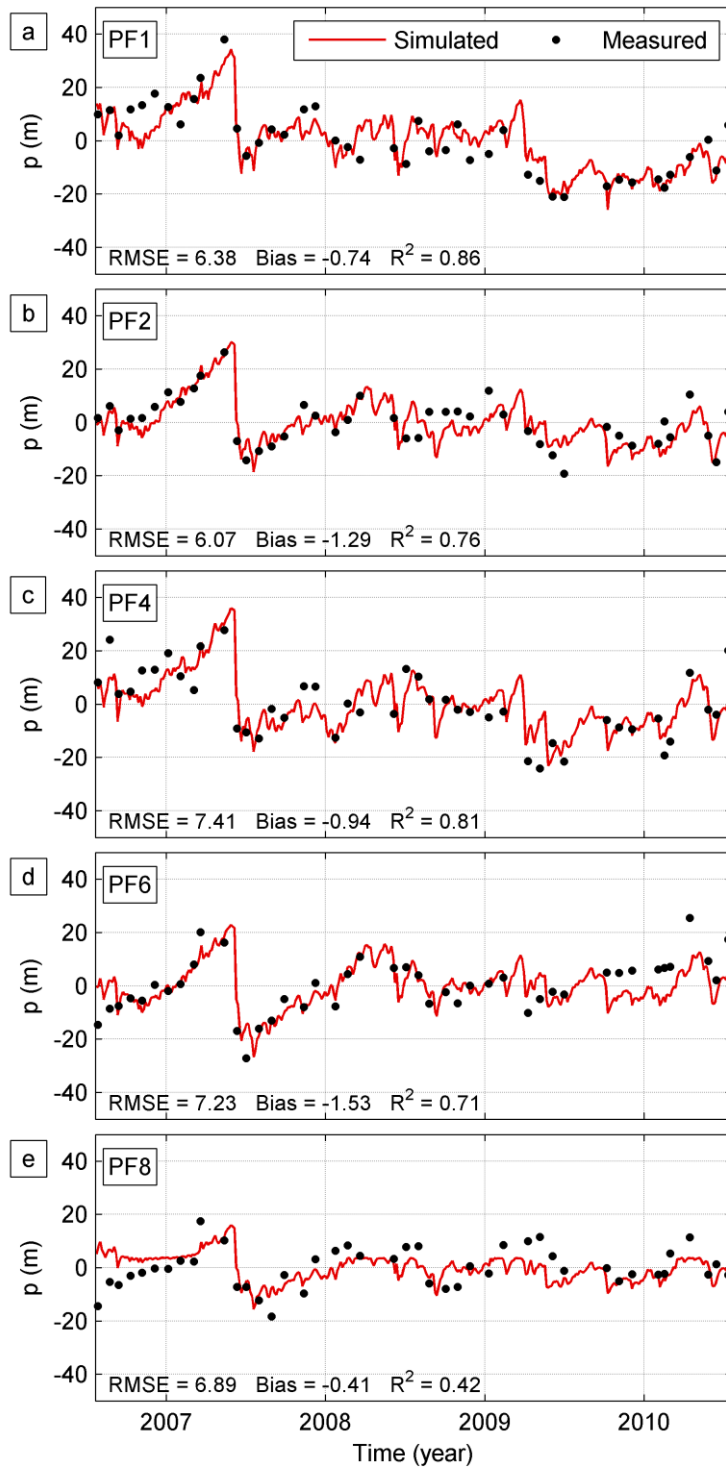
908 *average of Tp. (b,c,d) Shoreline deviation from the mean $p(s,t)$ at Narrabeen beach : (b) modelled with shoreline*

909 *position at each model time step (3 hours); (c) modelled only at the time steps concurrent with measurements; (d)*

910 *obtained from measurements. (e) Difference between the space-time diagrams shown in panels (c,d). In panels*

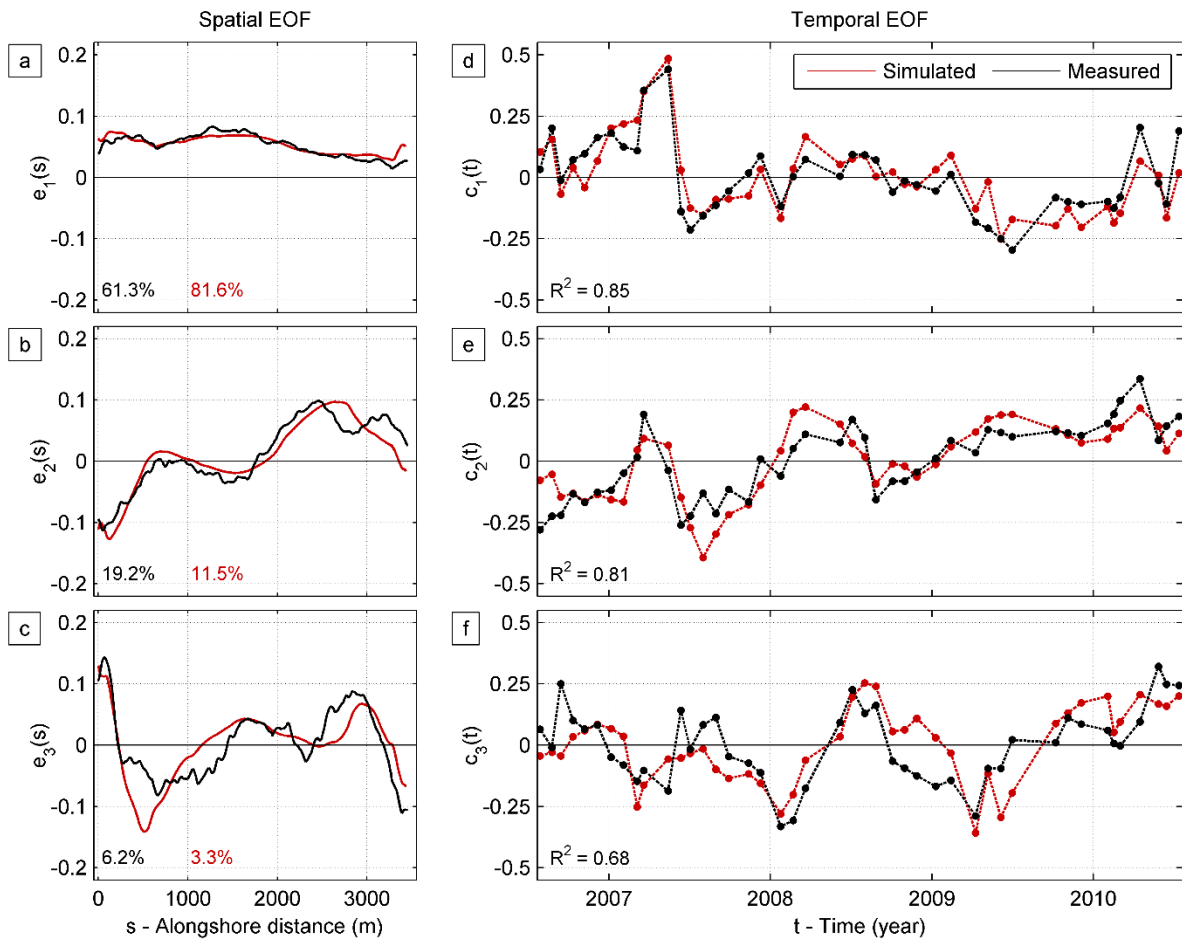
911 *(b,c,d,e) the horizontal dashed lines show the location of the cross-shore transects PF1-8 shown in Fig. 1 and Fig.*

912 *6. In panels (b,c,d,e) the s value of the y -axis indicates the alongshore distance from the north.*



914

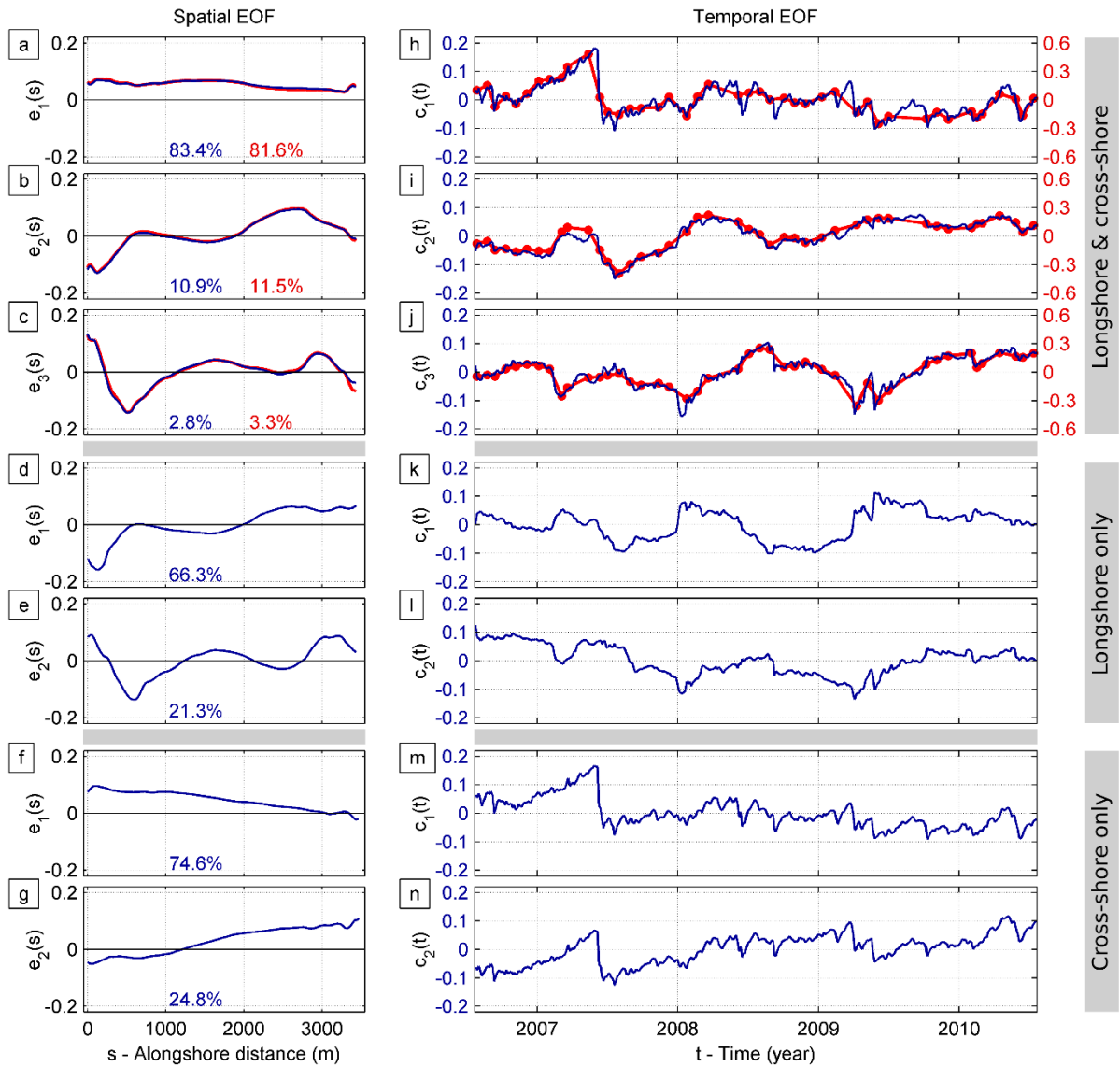
915 *Figure 8 – Time series of measured (black dots) and simulated (continuous red line) cross-shore shoreline deviation*
 916 *from the mean $p(t)$ at profiles PF1 (a), PF2 (b), PF4 (c), PF6 (d), and PF8 (e). For each profile, root-mean-square*
 917 *error, bias and R-squared values are indicated. See Fig. 1 and Fig. 6 for the transect location.*



919

920 *Figure 9 – EOF analyses of the $p(s,t)$ matrices: (a,d) first, (b,e) second and (c,f) third spatial and temporal EOFs.*

921



922

923 *Figure 10 – EOF analyses of the $p(s,t)$ matrices with the dominant spatial and temporal modes of the simulations*

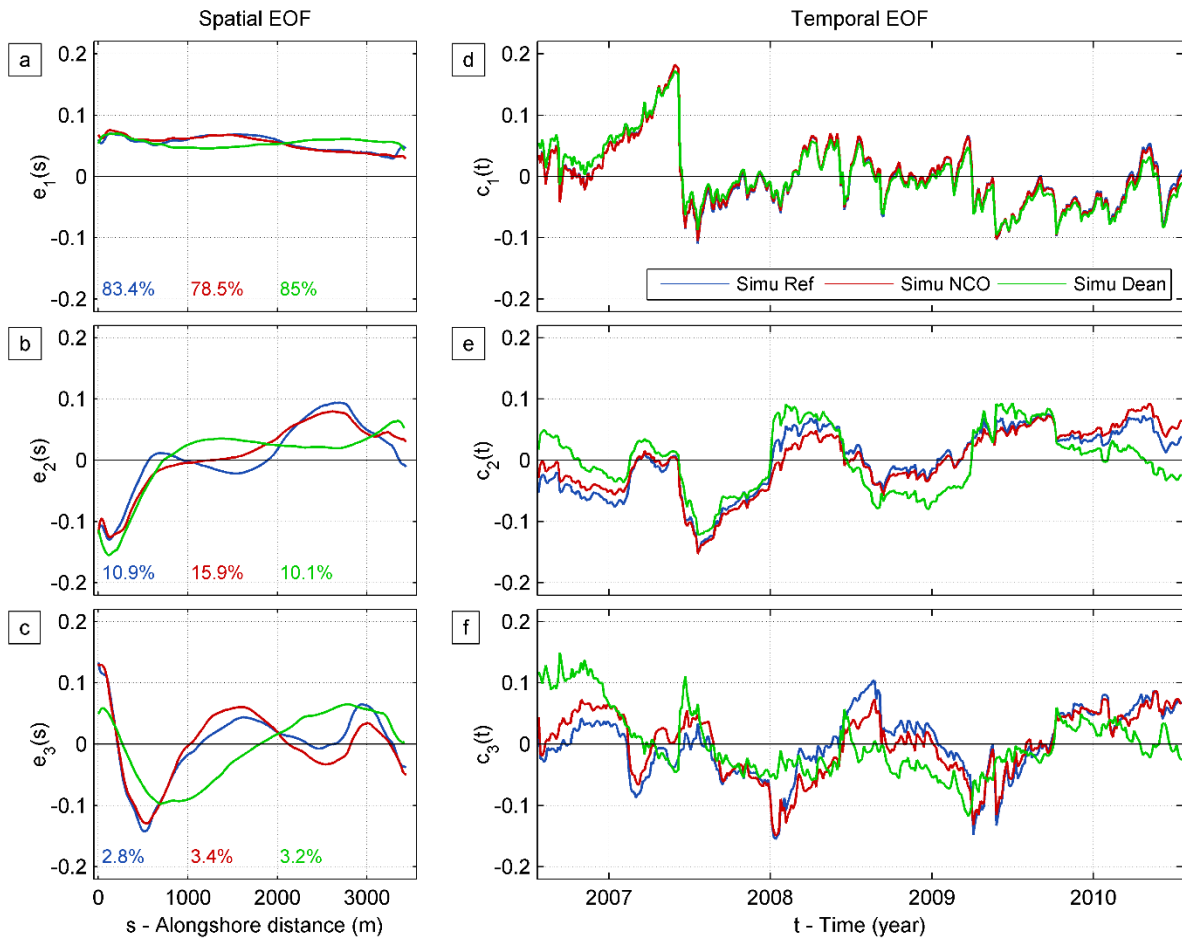
924 *(a,b,c,h,i,j) combining cross-shore and longshore processes; (d,e,k,l) accounting for longshore processes only and*

925 *(f,g,m,n) accounting for cross-shore processes only. Blue (all panels) and red (panels a,b,c,h,i,j) colours are for*

926 *EOF analyses computed using simulation outputs at each model time step and only those concurrent with*

927 *measurements, respectively.*

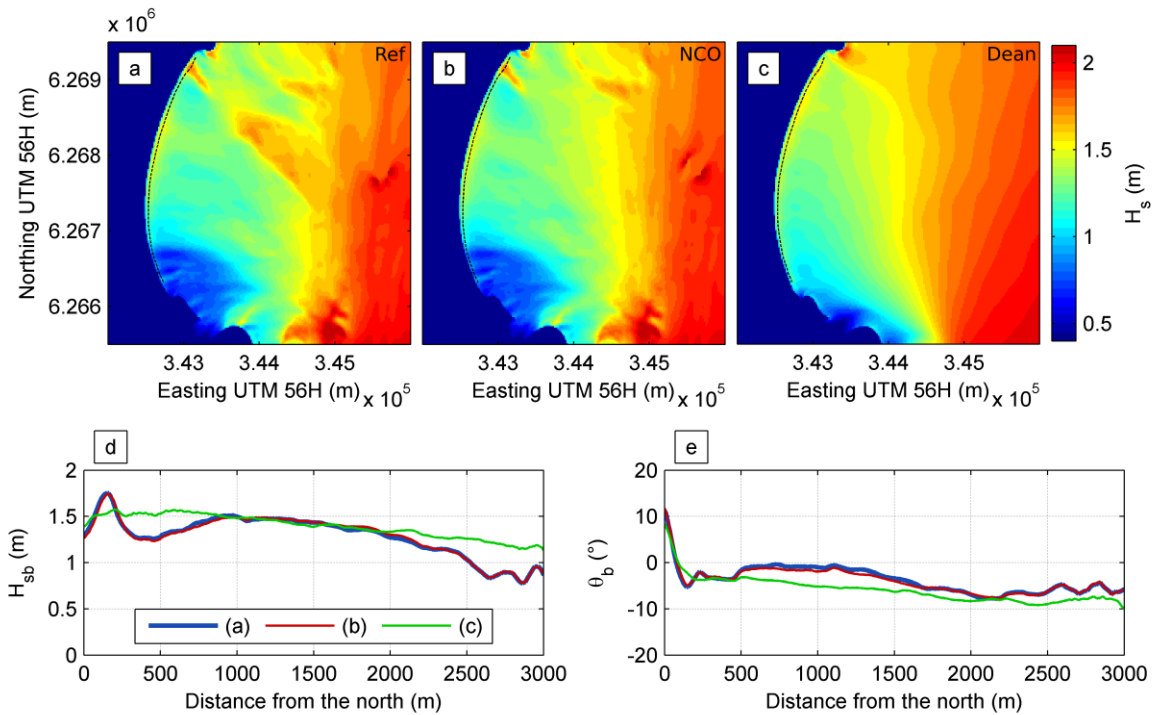
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930 *Figure 11 – EOF analyses of the $p(s,t)$ matrices with the dominant (a,b,c) spatial and (e,f,g) temporal modes of*
 931 *shoreline variability using model outputs at each time step. Reference simulation ('Simu Ref', in blue) without the*
 932 *central rocky outcrop ('Simu NCO', in red) and further removing the submerged rocky platforms extensions from*
 933 *the headlands ('Simu Dean', in green) are superimposed. See Fig. 5 for the corresponding nearshore bathymetries.*

934



935

936 Figure 12 – (a,b,c) H_s field simulated with SWAN for above average offshore wave conditions from SE ($H_s = 2.3$
 937 m, $T_p = 11.1$ s, $D_p = 164$ °TN) using the bathymetry shown in panels (a,b,c) of Fig. 5, respectively. (d,e)
 938 Alongshore distribution of H_s and incidence angle (θ) extracted at breaking corresponding to these simulated
 939 wave fields. Negative values for θ represent wave angles oriented southwards with respect to the local coast
 940 orientation, and vice versa. The thin dotted lines in panels (a,b,c) indicate the breaking line.

941

942 Table 1 – Skill parameters of wave parameters in 10-m depth after SWAN calibration.

	R	Bias	RMSE
H_s	0.94	0.03 m	0.17 m
T_m	0.60	- 0.57 s	1.54 s
D_m	0.75	0.71 °	10.13 °

943