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# Role of atmospheric indices in describing shoreline variability along the Atlantic coast of Europe

Masselink, Gerd

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# 1 **Role of atmospheric indices in describing shoreline variability along** 2 **the Atlantic coast of Europe**

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4 *Gerd Masselink<sup>1\*</sup>, Bruno Castelle<sup>2</sup>, Aikaterini Konstantinou<sup>1</sup> and Tim Scott<sup>1</sup>*

5  
6 <sup>1</sup>Coastal Processes Research Group, University of Plymouth, Plymouth, PL4 8AA,  
7 UK

8 <sup>2</sup>University Bordeaux, CNRS, Bordeaux INP, EPOC UMR 5805, Pessac,  
9 33600, France.

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11 \*Corresponding author: [gerd.masselink@plymouth.ac.uk](mailto:gerd.masselink@plymouth.ac.uk)

12 Contributing authors: [bruno.castelle@u-bordeaux.fr](mailto:bruno.castelle@u-bordeaux.fr), [a.konstantinou@plymouth.ac.uk](mailto:a.konstantinou@plymouth.ac.uk),  
13 [timothy.scott@plymouth.ac.uk](mailto:timothy.scott@plymouth.ac.uk)

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16

## 17 **Abstract (150 words)**

18 Beaches are highly variable environments and respond to changes in wave forcing, themselves  
19 modulated by climate variability. Here, we analyse three high-quality beach profile datasets to  
20 robustly investigate, for the first time, the link between shoreline change, wave forcing and climate  
21 variability along the Atlantic coast of Europe. Winter wave conditions are strongly associated with  
22 North Atlantic Oscillation (NAO) and Western Europe Pressure Anomaly (WEPA), with WEPA  
23 explaining 50–80% of the winter wave power variability. Shoreline variability during winter is also  
24 strongly linked to NAO and WEPA, with WEPA explaining 25% of the winter shoreline variability.  
25 Winter wave conditions and associated shoreline variability are both unrelated to El Nino Southern  
26 Oscillation (ENSO). In addition to the atmospherically-forced beach morphological response,  
27 shoreline change also depends strongly on the antecedent conditions as evidenced by significant  
28 correlations between summer/winter shoreline response and the shoreline position at the start of each  
29 season.

## 30 **Keywords**

31 Beaches, Atmospheric indices, Shoreline variability, Storms  
32

## 33 **Key messages**

- 34
- 35 • Three beach profile datasets are used to investigate link between shoreline change, wave forcing  
and climate variability along the Atlantic coast of Europe for the first time.
  - 36 • Winter wave conditions and shoreline change are correlated with atmospheric indices NAO and  
37 WEPA, but uncorrelated to ENSO
  - 38 • Antecedent beach morphology is an important factor in determining summer and winter shoreline  
39 response
- 40

## 41 **Plain language abstract (150 words)**

42 Beaches change as a result of changes in the wave conditions, and the weather and climate controls  
43 wave conditions. We surveyed two beaches in SW England and one beach in SW France every month  
44 for more than 15 years and analysed these data to look, for the first time, at the connections between  
45 beach change, waves and climate along the Atlantic coast of Europe. Atmospheric indices are  
46 numbers that tell us about large-scale weather, and the North Atlantic Oscillation (NAO) and the

57 Western Europe Pressure Anomaly (WEPA) are powerful indices that describe the weather in the  
58 north-east Atlantic. We found that especially WEPA is strongly correlated with winter waves and  
59 beach change during the winter months for all three study sites. We also found that beach change over  
60 the summer and winter season depends very much on whether the beach is relatively healthy or  
61 depleted of sediment.

52

## 53 Introduction

54 Shorelines are temporally highly variable and amongst the different timescales of shoreline change,  
55 the interannual and decadal timescales are of particular interest to coastal scientists as they reflect the  
56 integrated system response to the Earth's climate and its natural modes of variability. On these short-  
57 to-medium time scales, wave variability is the main driver for shoreline change and beaches respond  
58 to individual storms (*Harley et al., 2017*), storm clusters (*Dissanayake et al., 2015*), seasonal variation  
59 in wave conditions (*Masselink and Pattiaratchi, 2001*) and inter-annual to decadal changes in wave  
60 forcing (*Castelle et al., 2018*). Shorelines are also expected to change over long-term (> 25 years)  
61 time scales, for example due to sea-level rise, but, even when using decadal data sets, it has been  
62 challenging to identify and isolate the modest and longer-term shoreline trends from the much more  
63 dynamic and short-to-medium term changes imposed by wave climate variability (*Ghanavati et al.,*  
64 *2023*). Both wave-driven cross-shore and longshore sediment transport processes are responsible for  
65 changes in beach morphology and shoreline position, with cross-shore processes generally dominating  
66 seasonal and annual coastal change, whereas longshore processes tend to dominate the coastal  
67 response over decadal times (*Vitousek et al., 2017*).

68 Temporal changes in wave forcing are controlled by large-scale weather patterns and their variability.  
69 Across the Pacific Ocean basin, the El Niño-Southern Oscillation (ENSO) is the dominant mode of  
70 interannual climate variability and is closely associated with wave conditions (*Boucharel et al., 2021*).  
71 In the Indian Ocean, seasonal extreme wave heights are associated with different phase combinations  
72 of ENSO and the Indian Ocean Dipole IOD (*Kumar et al., 2019*). In the north Atlantic, the North  
73 Atlantic Oscillation (NAO) is the dominant mode of atmospheric variability and is strongly associated  
74 with wave conditions, whereby the positive phase of NAO is associated with increased winter wave  
75 conditions across the northeast Atlantic (*Dodet et al., 2010*), whereas the negative phase of NAO is  
76 associated with energetic wave conditions along the south coast of Spain (*Plomaritis et al., 2015*).  
77 These dominant atmospheric circulation patterns can be quantified using indices, generally based on a  
78 measure of spatial variability in sea surface temperature or atmospheric pressure over a region of  
79 interest, and can be correlated with wave parameters to investigate associations.

80 For the northeast Atlantic, *Castelle et al. (2017b)* recently introduced a new atmospheric index, the  
81 Western Europe Pressure Anomaly (WEPA), based on the sea level pressure (SLP) gradient between  
82 the Valentia (Ireland) and Santa Cruz de Tenerife (Canary Islands). The WEPA positive phase reflects  
83 an intensified and southward-shifted SLP difference between the Icelandic low and the Azores high,  
84 driving severe storms that funnel high-energy waves toward western Europe southward of 52°N. The  
85 WEPA index was found to show a very strong correlation with winter wave conditions for the entire  
86 Atlantic European seaboard, from Ireland (52°N) to Spain (42°N), significantly outperforming NAO  
87 as a winter wave height predictor. Within the UK and Ireland, *Scott et al. (2021)* used wave model  
88 data from 63 locations and found that winter-averaged expressions of six leading atmospheric indices  
89 (including NAO and WEPA) were strongly correlated with both total and directional winter wave  
90 power. Notably, the predictive power of the climate indices displayed a strong geographical  
91 dependency, with NAO, and especially WEPA, being the most successful predictor for Atlantic storm  
92 waves. More regionally, *Wiggins et al. (2020)* investigated the characteristics of the strong  
93 bidirectional wave climate along the SE of England. They showed south-westerly wave power was  
94 well correlated to WEPA>0, whilst easterly wave power was well correlated with NAO<0.

95 Since wave height variability is strongly linked to coastal dynamics, it can therefore be hypothesized  
96 that atmospheric indices are also linked to coastal change. *Almar et al. (2023)* used this hypothesis on  
97 a global scale by developing a conceptual global model based on satellite-derived shoreline (SDS)  
98 positions from 1993 to 2019 and a variety of reanalysis products. They argue that global interannual

99 shoreline changes are largely driven by different ENSO regimes and their complex inter-basin  
100 teleconnections, although there is some discussion with regards of the validity of these findings  
101 (*Warrick, 2024*). Nevertheless, extreme coastal erosion along the west coast of the US is  
102 unequivocally associated with strong El Niño events (*Barnard et al., 2011; Barnard et al., 2017;*  
103 *Young et al., 2018*). Recently, *Vos et al. (2023)* used 38 years of Landsat imagery to map shoreline  
104 variability around the Pacific Rim and identified coherent, albeit regionally varying, patterns of beach  
105 erosion and accretion controlled by ENSO.

106 Similar efforts have been made to find associations between atmospheric indices and coastal change  
107 for the Atlantic coast of Europe. *Masselink et al. (2014)* suggested, based on analysis of a decade of  
108 video monitoring data from a sandy beach in SW England, that beach state and bar morphology is  
109 related to NAO. *Wiggins et al. (2020)* analyzed a decade of beach monitoring data from gravel  
110 beaches in SW England and found that beach rotation was related to WEPA for some beaches.  
111 Additionally, the 2013/14 winter, which was the most energetic winter on record in terms of wave  
112 conditions and caused unprecedented beach erosion along the entire Atlantic coast of Europe  
113 (*Masselink et al., 2016a*), was characterized by the highest winter WEPA value since 1948. Finally,  
114 *Castelle et al. (2022)* investigated the 1984–2020 time- and space-evolution of 269 km of high-energy  
115 meso-macrotidal sandy coast in SW France using SDS data and found that the interannual shoreline  
116 variability was strongly correlated with the winter WEPA, outscoring other  
117 conventional teleconnection pattern indices (e.g., NAO). The attraction of identifying causal links  
118 between atmospheric indices and shoreline change is that it may facilitate modelling future shoreline  
119 dynamics without the need for wave modelling (*Robinet et al., 2016*), for example, to obtain season-  
120 ahead forecast of coastal change (*Scott et al., 2021*).

121 This paper builds on previous work along the Atlantic coast of Europe and uses a 17-year dataset of  
122 monthly survey data collected at two beaches in SW England, Perranporth (sand) and Slapton Sands  
123 (gravel), and a 20-year high-frequency dataset of from sandy beach in SW France (Truc Vert) to  
124 investigate the link between atmospheric indices, wave conditions and shoreline change. This is a first  
125 attempt at a wider scale (NW Atlantic coast) assessment of the links between climate patterns and  
126 shoreline change and this work represents a crucial step needed to gain confidence before  
127 investigating climate-shoreline links in larger-scale SDS-based studies.

## 128 **Results**

### 129 **Perranporth**

130 Winter wave power  $\Sigma P$  at Perranporth (Fig. **1a**) is positively correlated with winter NAO (Fig. **1c**;  
131  $r=0.63$ ,  $p=0.01$ ) and WEPA (Fig. **1d**;  $r=0.71$ ,  $p=0.00$ ), indicating that positive phases of both  
132 atmospheric indices are associated with enhanced storminess. No significant correlation was found with  
133 ENSO ( $r=-0.23$ ;  $p=0.36$ ). The monthly time series of shoreline position  $x$  at Perranporth shows a strong  
134 seasonal variation with an amplitude of 20–30 m (Fig. **1b**). No long-term trend is apparent, but a  
135 dominant feature of the time series is a shoreline retreat of c. 60 m during the 2013/2014 winter. All  
136 summers are characterized by shoreline progradation ( $\Delta x > 0$ ) and all winters resulted in shoreline retreat  
137 ( $\Delta x < 0$ ). The seasonality in shoreline change is further demonstrated by the auto-correlation function of  
138 the monthly survey data, which shows a distinct secondary peak at 12 months (Fig. **1e**). Beach  
139 morphological change at Perranporth is forced by variations in the wave conditions, but is also  
140 influenced by the antecedent morphology. A strong correlation between the seasonal shoreline change  
141  $\Delta x$  and the seasonally averaged wave height  $H_s$  is apparent (Fig. **1f**;  $r=-0.83$ ,  $p=0.00$ ), with  $H_s=1.5$  m  
142 broadly separating shoreline advance and retreat. Seasonal shoreline response is also affected by the  
143 shoreline position at the start of the season: winter erosion ( $\Delta x < 0$ ) is encouraged when the beach is  
144 relatively wide at the start of the winter (Fig. **1g**;  $r=-0.54$ ,  $p=0.03$ ), while summer accretion is promoted  
145 by a relatively depleted beach at the start of summer (Fig. **1h**;  $r=-0.42$ ,  $p=0.10$ ).

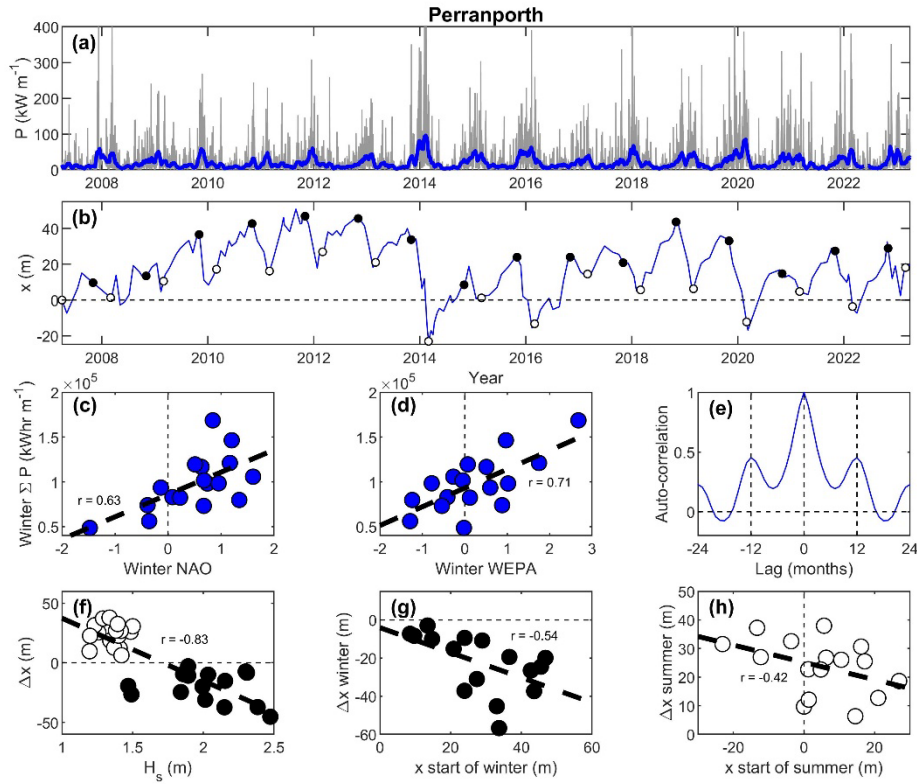


Fig. 1. Wave conditions and shoreline response for Perranporth: (a) time series of wave power  $P$  (grey line) and 30-day moving average of the wave power (blue line); (b) time series of monthly shoreline position  $x$  (0 m ODN) relative to start of the survey period with start of winter (1 December) and summer (1 April) marked by black and white circles, respectively; (c,d) scatter plot of winter wave power  $\Sigma P$  versus winter NAO and WEPA; (e) auto-correlation function of the monthly survey data; (f) shoreline change  $\Delta x$  versus season-averaged significant wave height  $H_s$  with black and white circles representing winter and summer, respectively; (g)  $\Delta x$  over winter season versus  $x$  at the start of winter; and (h)  $\Delta x$  over summer season versus  $x$  at the start of summer. Dashed lines in (c), (e), (f) and (g) represent lines of best fit with Pearson  $r$  indicated in the plots.

## 146 Slapton Sands

147 The wave climate at Slapton Sands is bi-directional with 70% of the winter wave power generated by  
 148 southerly swell waves from the Atlantic and 30% by easterly wind waves generated across the  
 149 Channel (Fig. 2a). Southerly wave power from the Atlantic  $\Sigma P_{south}$  is positively correlated with winter  
 150 WEPA (Fig. 2d;  $r=0.89$ ,  $p=0.00$ ), whereas easterly wave power  $\Sigma P_{east}$ , is correlated with winter NAO  
 151 (Fig. 2c;  $r=0.53$ ,  $p=0.03$ ) indicating that large  $\Sigma P_{east}$  values are associated with negative NAO). No  
 152 significant correlations were found with ENSO (with  $\Sigma P_{south}$ :  $r=-0.1$ ,  $p=0.70$ ; with  $\Sigma P_{east}$ :  $r=-0.34$ ,  
 153  $p=0.20$ ). Shoreline changes at Slapton Sands are characterized by an antiphase relationship between  
 154 the south and north end of the beach (P01 and P18, respectively) (Fig. 2b), representing a rotational  
 155 response. Over the whole survey period, the southern profile shows a shoreline retreat of 15 m,  
 156 whereas the northern profile displays a shoreline advance of 30 m. Seasonal shoreline variation is not  
 157 obvious, but the largest shoreline changes are generally associated with winter waves. Both winter  
 158 waves and summer waves can result in a shoreline advance, as well as retreat. The lack of seasonality  
 159 is further demonstrated by the absence of a 12-month peak in the auto-correlation function of the  
 160 monthly survey data for both transects (Fig. 2e).



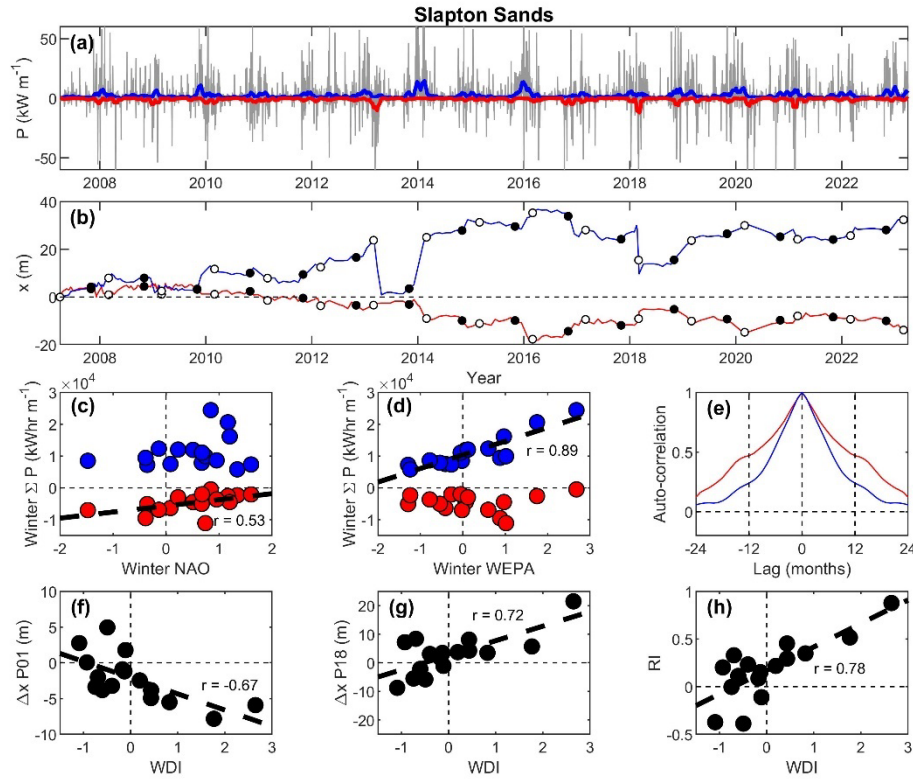


Fig. 2. Wave conditions and shoreline response for Slapton Sands: (a) time series of wave power  $P$  (grey line) and 30-day moving average of the southerly ( $> 135^\circ$ ; blue line) and easterly ( $< 135^\circ$ ; red line) wave power; (b) time series of monthly shoreline position  $x$  (0 m ODN) for P01 (red) and P18 (blue) relative to start of the survey period with start of winter (1 December) and summer (1 April) marked by black and white circles, respectively; (c,d) scatter plot of winter wave power from the south  $\Sigma P_{south}$  (blue) and the east  $\Sigma P_{east}$  (red) versus winter NAO and WEPA; (e) auto-correlation function of the monthly survey data for P01 (red line) and P18 (blue line); (h,i) winter shoreline change  $\Delta x$  at P01 and P18 versus winter Directional Power index  $WDI$ ; and (j) Rotation Index  $RI$  versus  $WDI$ . Positive and negative values for  $WDI$  represent above-average contribution of southerly and easterly wave power, respectively, and positive and negative values for  $RI$  represent clockwise and anti-clockwise beach rotation, respectively. Dashed lines in (c), (d), (f), (g) and (h) represent lines of best fit with Pearson  $r$  indicated in the plots.

161 The more complex beach volume changes at Slapton Sands, involving longshore redistribution of  
 162 sediment, require consideration of the directional wave energy fluxes for the opposing ends of the  
 163 beach. Large values of the seasonally integrated southerly wave power  $\Sigma P_{south}$  are associated with  
 164 shoreline retreat ( $\Delta x < 0$ ) and advance ( $\Delta x > 0$ ) for P01 and P18, respectively (Fig. S8a,c), and a  
 165 clockwise beach rotation. The beach response to the seasonally integrated easterly wave power  $\Sigma P_{east}$   
 166 is not obvious (Fig. S8b,d). A better way to parameterize the bi-directional wave conditions at  
 167 Slapton Sands is through the Wave Directional Index  $WDI$  (see **Methods** section in Supp. Mat.),  
 168 which quantifies the seasonal balance between the two directional wave components compared to the  
 169 long-term average balance.  $WDI$  is significantly correlated with  $\Delta x$  at P01 (Fig. 2f;  $r = -0.67$ ,  $p = 0.00$ )  
 170 and at P18 (Fig. 2g;  $r = 0.72$ ,  $p = 0.00$ ). By combining the shoreline responses at the opposing ends of  
 171 Slapton Sands in the Rotation Index  $RI$  (see **Methods** section in Supp. Mat.) and relating this to  $WDI$   
 172 provides an even better explanation of the rotational beach response (Fig. 2h;  $r = -0.78$ ,  $p = 0.00$ ): for  
 173  $WDI > 0$ , southerly waves are more common than average and/or easterly waves are less common than  
 174 average, and the beach at P01 and P18 retreats and advances, respectively, and the reverse is true for  
 175  $WDI < 0$ . So, clockwise ( $RI > 0$ ) and anti-clockwise ( $RI < 0$ ) rotation are associated with  $WDI > 0$  and  
 176  $WDI < 0$ , respectively.

## 177 Truc Vert

178 The relationship between atmospheric indices, wave forcing and shoreline dynamics at Truc Vert is  
 179 very similar to that at Perranporth, despite the more energetic waves and smaller tides. Winter wave  
 180 power  $\Sigma P$  is positively correlated with winter NAO (Fig. 3c;  $r = 0.43$ ,  $p = 0.05$ ) and WEPA (Fig. 3d;

181  $r=0.88, p=0.00$ ), and no significant correlation was found with ENSO ( $r=-0.09, p=0.71$ ). The  
 182 shoreline at Truc Vert shows no long-term trend, but has a strong seasonal variation with an amplitude  
 183 of 10–20 m (Fig. 3b) and the auto-correlation function of the monthly survey data shows a distinct  
 184 secondary peak at 12 months (Fig. 3e). The 2013/2014 winter caused the largest shoreline retreat,  
 185 and it is further noted that five of the 20 winters were characterized by shoreline progradation and that  
 186 shoreline retreat occurred over three of the 19 summers. In common with Perranporth, beach  
 187 morphological change on Truc Vert is also influenced by antecedent morphology. A strong  
 188 correlation between the seasonal shoreline change  $\Delta x$  and the seasonally averaged wave height  $H_s$  is  
 189 apparent (Fig. 3f;  $r=-0.80, p=0.00$ ), but the  $H_s$  value separating shoreline advance and retreat is not  
 190 very distinct. Winter erosion ( $\Delta x < 0$ ) is encouraged when the beach is relatively wide at the start of the  
 191 winter (Fig. 3g;  $r=-0.52, p=0.02$ ), while summer accretion is promoted by a relatively depleted beach  
 192 at the start of summer (Fig. 3h;  $r=-0.49, p=0.04$ ). The shoreline response on Truc Vert is more  
 193 complex than at Perranporth and this is likely related to the more energetic conditions at the former  
 194 site over the summer period (April–November).

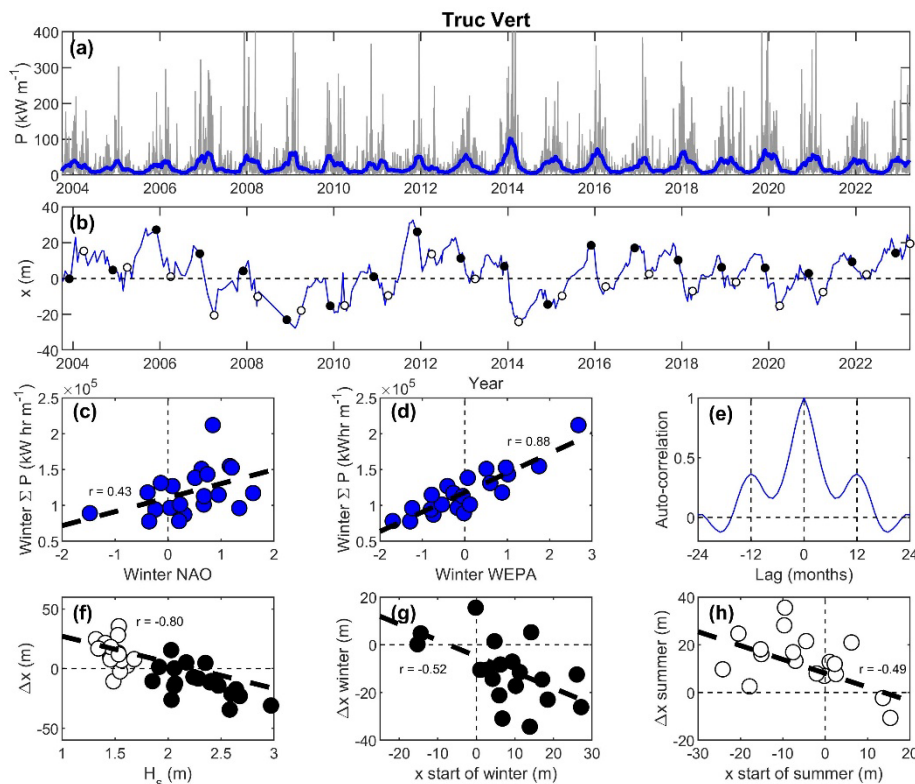


Fig. 3. Wave conditions and shoreline response for Truc Vert (for caption, cf. Fig. 1).

## 195 Role of atmospheric indices

196 As the winter-averaged atmospheric indices NAO and WEPA are strongly correlated to the winter  
 197 wave climate and the shoreline dynamics are strongly related to the wave climate, it seems  
 198 appropriate to address the relationship between shoreline change  $\Delta x$  and atmospheric indices for the  
 199 winter season (Fig. 4). The strength of the correlations between climate indices and wave forcing and  
 200 shoreline response (Pearson  $r$  and associated  $p$ -values) are listed in Table S2.

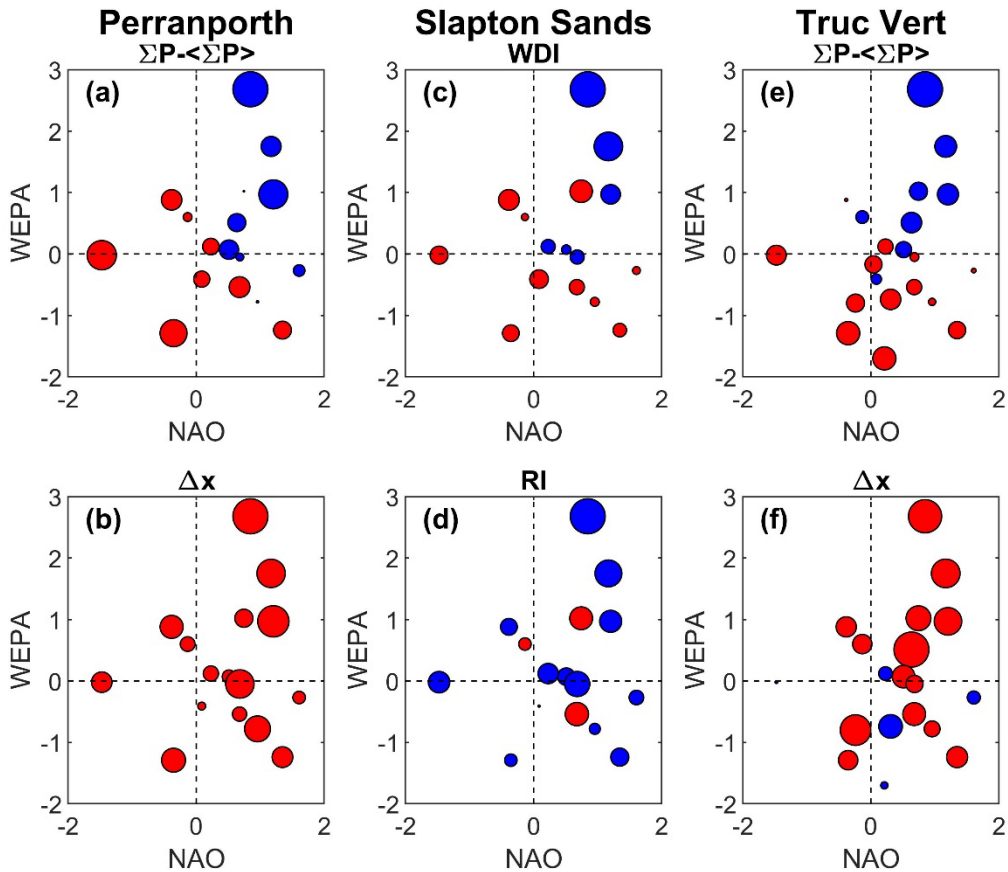


Fig. 4. Wave and morphological response parameters representing the winter season plotted in NAO-WEPA parameter space: (a) winter wave power  $\Sigma P$  minus winter-averaged wave power  $\langle \Sigma P \rangle$  for Perranporth; (b) shoreline change  $\Delta x$  for Perranporth; (c) Directional Power index  $WDI$  for Slapton Sands; (d) Rotation Index  $RI$  for Slapton Sands; (e) winter wave power  $\Sigma P$  minus winter-averaged wave power  $\langle \Sigma P \rangle$  for Truc Vert; and (f) shoreline change  $\Delta x$  for Truc Vert. The size of the symbols is scaled by the absolute value of the plotted parameters, and red and blue symbols represent negative and positive values, respectively.

201 The winter wave forcing conditions ( $\Sigma P - \langle \Sigma P \rangle$  for Perranporth and Truc Vert, and  $WDI$  for Slapton  
 202 Sands) are plotted in a NAO-WEPA parameter space in Fig. 4a,e,c, respectively (no significant  
 203 correlations were found with ENSO). The NAO+/WEPA+ quadrant is associated with the most  
 204 energetic winter wave conditions at Perranporth and Truc Vert, and the largest positive  $WDI$  values  
 205 for Slapton Sands. Both results are attributed to more energetic and/or frequent Atlantic storms under  
 206 such climatic conditions (Castelle et al., 2017b). The other NAO/WEPA quadrants are characterized  
 207 by more benign and below-average winter wave conditions for Perranporth and Truc Vert, and  
 208 smaller positive or even negative  $WDI$  values for Slapton Sands. As  $WDI$  represents the balance  
 209 between southerly and easterly wave power, negative  $WDI$  values could be due to less energetic  
 210 Atlantic wave conditions and/or more frequent easterly storm wave activity.

211 The winter beach response ( $\Delta x$  for Perranporth and Truc Vert, and  $RI$  for Slapton Sands) are also  
 212 plotted in the NAO-WEPA parameter space (again, no significant correlations were found with  
 213 ENSO). The most extensive winter shoreline retreat on Perranporth and Truc Vert is associated with  
 214 the NAO+/WEPA+ quadrant (Fig. 4b,f) and, of the two atmospheric indices, WEPA shows stronger  
 215 correlations with  $\Delta x$  than NAO (Table S2). At Perranporth, all winters result in shoreline retreat (Fig.  
 216 4b), but the calmest winters at Truc Vert are associated with shoreline advance (blue symbols in Fig.  
 217 4f). For Slapton Sands, the NAO+/WEPA+ quadrant is characterized by the most pronounced  
 218 clockwise rotation, quantified by  $RI$ , and the two winters with the largest  $RI$  values (2013/14 and  
 219 2015/16), plot at the top of the NAO+/WEPA+ quadrant (Fig. 3d). Of the two climate indices, WEPA  
 220 shows stronger correlation with  $RI$  than NAO (Table S2).

## 221 Discussion and conclusions



222 The findings of this study, based on three European Atlantic coast observational data sets consisting  
223 of (bi-)monthly observational beach profile data collected over >15 years, confirm and expand  
224 previous studies on these three beaches (*Castelle et al., 2020; McCarroll et al., 2023*). Winter wave  
225 conditions for all three sites are strongly associated with Atlantic climate indices NAO and WEPA,  
226 and are unrelated to ENSO. Perranporth and Truc Vert, which are representative of exposed Atlantic  
227 sandy beaches, experience a unidirectional and strongly seasonal wave climate, which drives a  
228 dominantly cross-shore and seasonal beach signal. Slapton Sands, which is a representative gravel  
229 beach on the south coast of England, experiences a bidirectional wave climate, which drives a  
230 dominantly rotational beach response caused by a longshore redistribution of sediment. The  
231 morphodynamics on all three beaches are strongly linked to Atlantic climate indices NAO and  
232 WEPA, and unrelated to ENSO. In addition to the strongly forced response, as testified by the link  
233 between beach change and wave conditions and climate indices, beach response on the exposed  
234 beaches (Perranporth and Truc Vert) also depends strongly on the beach state/volume at the start of  
235 each season.

236 The strongest statistically significant (at  $p < 0.05$ ) correlations are found between WEPA and winter  
237 shoreline change; however, winter WEPA only explains c. 25% of the shoreline variability. There are  
238 other factors that are also important in driving shoreline change over the winter period. Firstly,  
239 pronounced shoreline response is not necessarily the result of sustained storm wave activity related to  
240 an exceptional atmospheric condition parameterized by an extreme value for a climate index (e.g., the  
241 2013/14 winter), and can be the result of a single event in an otherwise unremarkable winter. For  
242 example, the pronounced anti-clockwise rotation that occurred in the 2018/2019 winter on Slapton  
243 Sands (Fig. 2) was the result of a single easterly storm (*McCarroll et al., 2019*) that occurred in a  
244 winter characterized by a positive NAO of 0.74. Secondly, the shoreline dynamics on the exposed and  
245 cross-shore dominated beaches of Perranporth and Truc Vert showed relatively muted storm  
246 responses on beaches depleted due to previous energetic conditions, strongly suggesting the  
247 importance of antecedent conditions and an equilibrium-type beach response (*Yates et al., 2009;*  
248 *Splinter et al., 2014; Davidson, 2021*). The shoreline response of Slapton Sands appears also to be  
249 associated with disequilibrium, but operating over a decadal time scale. Over the 2004–2023 survey  
250 period, the shoreline at Slapton Sands exhibited a considerable clock-wise rotation and this has been  
251 suggested to be related to a multi-decadal trend in the balance between southerly and easterly wave  
252 power (*Wiggins et al., 2017*). Finally, the role of water levels during storm conditions should be  
253 considered as storm impacts are maximized if peak wave conditions coincide with extreme water  
254 levels (*Masselink et al., 2016b; Young et al., 2018*). As the Atlantic coast of Europe is not surge-  
255 dominated coast, coincidence of peak storm and extreme water level is due to chance (*Haigh et al.,*  
256 *2016*), and not related to atmospheric indices.

257 In this study, the position of the intertidal shoreline (0 m ODN for Perranporth and Slapton Sands and  
258 1.4 m amsl for Truc Vert) was selected as the key Coastal State Indicator (CSI) for characterizing  
259 beach morphological response. It was found to be highly correlated with the intertidal beach volume  
260 (Fig. S4) and a similar analysis to that presented in this paper for the SW England beaches using  
261 beach volume as the key morphological change parameter yielded near-identical results (*Masselink et*  
262 *al., 2024*). The attraction of a shoreline-based CSI is obvious as it can be derived through remote  
263 sensing (aerial photography, video, satellites). Nevertheless, changes in the intertidal shoreline  
264 position are not necessarily representative of changes in the nearshore sediment budget if the subtidal  
265 region is considered as well (*Harley et al., 2022*). In addition, different shoreline contours respond at  
266 different dominant time scales (*Montaño et al., 2021*), for example, compared to the MSL contour, the  
267 dune foot responds in a less seasonal and more multi-annual fashion with significant set-back only  
268 occurring during a handful of winters (*Castelle et al., 2017a; Flor-Blanco et al., 2021; Masselink et*  
269 *al., 2022; Burvingt and Castelle, 2023*).

270 Winter values for climate indices (December–March) are generally used because they tend to have the  
271 strongest relation to wave climate and it is the climate hazards during winter (e.g., dune erosion,  
272 coastal flooding, overtopping) that are usually of most interest. So, here we demonstrate that shoreline  
273 response during winter is significantly correlated to winter WEPA, and, for example, *Jalón-Rojas and*  
274 *Castelle (2021)* show that precipitation and river flows over the winter period across most of Europe

275 are also positively correlated with winter WEPA. From a coastal management point of view, it is of  
276 interest to determine the longevity of the winter storm impacts; therefore, the annual shoreline  
277 response (from December to December) was correlated with winter WEPA (from December to  
278 March) for Perranporth and Truc Vert. Compared to correlating winter WEPA with the winter  
279 shoreline response, Pearson  $r$  dropped from -0.54 ( $p=0.03$ ) to -0.40 ( $p=0.14$ ) for Perranporth, and  
280 from -0.52 ( $p=0.02$ ) to -0.46 ( $p=0.06$ ) for Truc Vert. The reduction in explanatory power of WEPA is  
281 due to the significant beach recovery that takes place over subsequent summers (*Burvingt et al., 2018*;  
282 *Dodet et al., 2019*; *Konstantinou et al., 2021*). Shoreline advance during summer is particularly  
283 pronounced after an extreme winter (Fig. **1h** and **3h**) and it is perhaps not surprising that winter  
284 WEPA is not correlated to the shoreline response when 1-year periods are considered.

285 Global studies of shoreline change based on satellite-derived shorelines (SDS) are becoming  
286 increasing common (*Luijendijk et al., 2018*; *Mentaschi et al., 2018*; *Vousdoukas et al., 2020*; *Almar et*  
287 *al., 2023*; *Ghanavati et al., 2023*); however, concerns have been raised regarding satellite-derived  
288 global applications (*Cooper et al., 2020*; *Zăinescu et al., 2023*; *Warrick, 2024*). To explore links  
289 between shoreline response and modes of climate variability, robust methodologies for deriving  
290 shorelines involving wave and/or tide corrections (*Castelle et al., 2021*; *Vos et al., 2023*) or time- and  
291 spatial-averaging techniques (*Castelle et al., 2022*; *Warrick et al., 2023*) must be applied. However,  
292 the typical time- and space-averaging windows and type of water-level correction are essentially site-  
293 specific (*Konstantinou et al., 2023*), which challenges such global application. Based on SDS, *Almar*  
294 *et al. (2023)* recently claimed that interannual shoreline changes at the global scale are largely driven  
295 by different ENSO regimes and their complex inter-basin teleconnections, including along the  
296 Atlantic coast of Europe. Noteworthy, the authors used uncorrected SDS data at 0.5° spaced transects.  
297 Critically, our contribution shows that, at three intensely monitored sites, which use conventional  
298 survey techniques from which accurate shoreline position can be derived, shoreline change is  
299 essentially uncorrelated with ENSO. This is perhaps not surprising, as there is no clear consensus as  
300 to whether a robust ENSO signal can be detected in the north Atlantic and West Europe region  
301 (*Toniazzo and Scaife, 2006*). We advocate that future, regional to global, SDS assessment must use  
302 carefully ground-truth validated, high-resolution data accounting for the diversity of coastal settings to  
303 provide robust conclusions on the link between climate modes of variability and coastal response.

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314 the survey data at the three studied beaches.

## 315 **Methods**

### 316 **Field sites**

317 Perranporth and Slapton Sands are situated on the macrotidal coast of SW England (Fig. **S1** and  
318 **S2a,b**). The coastline is largely embayed with more than 150 separate beaches and 21 estuaries and is  
319 highly variable in terms of static (shoreline orientation, geology, sediment size and abundance) and  
320 dynamic (waves, tides) boundary conditions; therefore, the resulting beach morphology is also very  
321 diverse (*Scott et al., 2011*). Both Perranporth and Slapton Sands have been widely studied over the  
322 past 15 years and the reader is referred to *Valiente et al. (2019)* and *Wiggins et al. (2019)*,  
323 respectively, for detailed descriptions of the setting and characteristics of both beaches. Here, only a  
324 summary is provided. Perranporth is a 3.5-km long and 400-m wide (at low tide) sandy and  
325 dissipative beach (gradient  $\approx 0.015$ ) with subtidal and intertidal bar morphology and an extensive

326 dune system (Fig. S2a). The mean summer and winter significant wave height  $H_s$  at this location is  
 327 1.2 and 2.2 m, respectively, and maximum  $H_s$  during winter storms can attain 8 m. Waves along the  
 328 north coast of SW England are almost exclusively from the west and the mean wave direction is 280°. Slapton Sands is a 4-km long and 100-m (at low tide) gravel and reflective beach (gradient  $\approx 0.1$ ) with  
 329 a maximum elevation of 6 m above MSL and is backed by a fresh water lagoon (Fig. 2b). Here, the  
 331 mean summer and winter  $H_s$  is 0.5 and 0.9 m, respectively, and maximum  $H_s$  during winter storms can  
 332 attain 5 m. Waves along the south coast of SW England are bi-directional and characterised by swell  
 333 waves from the south and wind waves from the east. The mean spring tide range at Perranporth and  
 334 Slapton Sands is 6.3 m and 4.3 m, respectively.

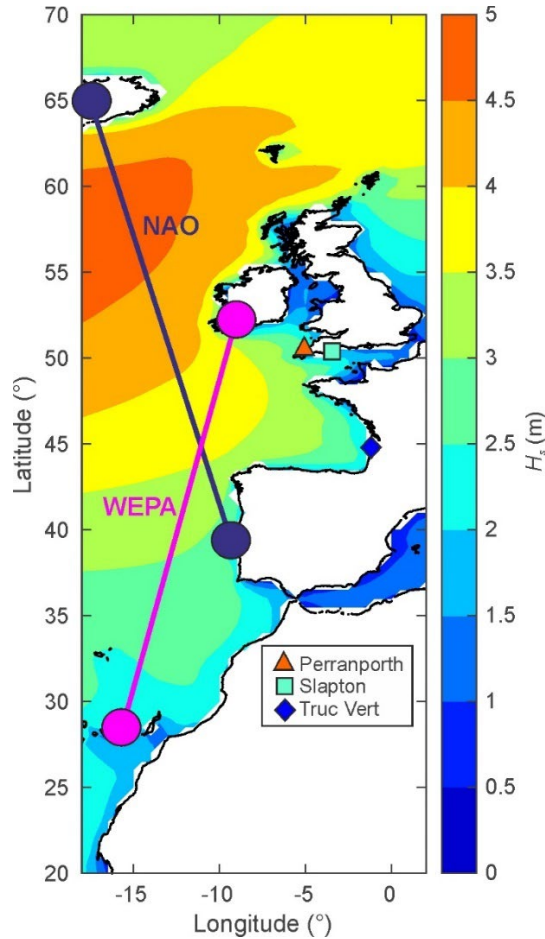


Fig S1. Atlantic coast of Europe with winter-mean (2006–2023) significant wave height  $H_s$ , locations used for determining NAO and WEPA based on sea-level pressure (SLP), and location of the three studied beaches. In the present paper, WEPA was based on SLP, but NAO was obtained using an PCA-based approach as explained below.

335 Truc Vert is located along a relative straight sector of the meso-macrotidal coast of SW France (Fig.  
 336 S1 and S2c). It is an open, intermediate double-barred sandy beach, backed by a high (~20 m) and  
 337 wide (~200 m) coastal dune system (Robin *et al.*, 2021). The wave climate is similar to that of  
 338 Perranporth, with mean  $H_s$  ranging from 1.1 m in July to 2.4 m in January (Castelle *et al.*, 2020).  
 339 Waves come predominantly from the W-NW quadrant, with more waves from the W (NW) in winter  
 340 (summer). The mean spring tide range is approximately 3.7 m.

341 Time series of wave conditions at all three sites are shown in Figs. S4, S5 and S6. All sites are  
 342 characterised by a pronounced seasonality with energetic winters and relatively calm summers, and  
 343 Truc Vert represents the most energetic site, while Slapton Sands is the least exposed site (Table S1).

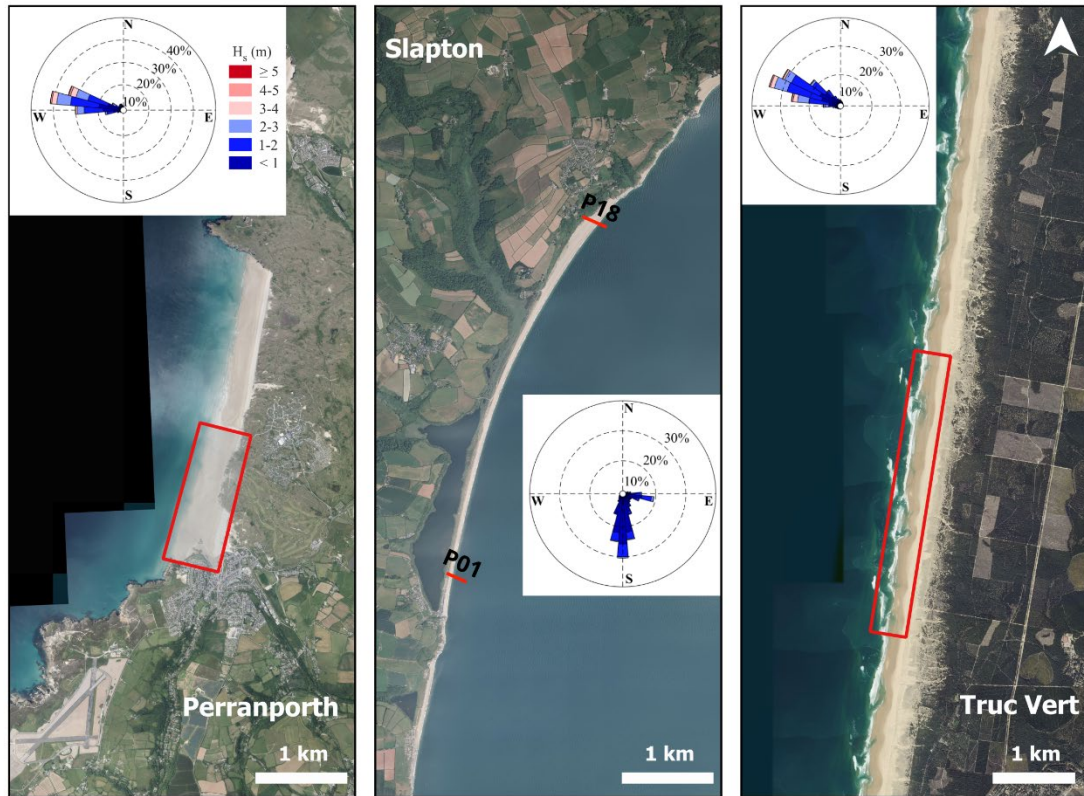


Fig. S2. Aerial photographs of the three studied beaches with wave rose: (a) Perranporth in north Cornwall, UK, with the survey area indicated by red box; (b) Slapton Sands in South Devon, UK, with the southern (P01) and northern (P18) survey transects; and (c) Truc Vert on the Aquitaine coast, France, with the survey area indicated by red box.

### 344 Data collection and analysis

345 Monthly NAO and ENSO (3-month running mean of Southern Oscillation index) were downloaded  
 346 from <https://www.cpc.ncep.noaa.gov/> and the monthly values were used to obtain winter-averaged  
 347 values, where winter represents the period December–March. These NAO values are not based on  
 348 sea-level pressure (SLP), but are obtained using the PCA-based approach described in *Barnston and*  
 349 *Livezey (1987)*. Monthly WEPA values were directly computed from the SLP records Santa Cruz de  
 350 Tenerife (Canary Islands) and Valentia (Ireland), obtained from the European Climate Assessment &  
 351 Dataset (ECA&D; <http://www.ecad.eu>) and the Irish Meteorological Service (Met Eireann;  
 352 <https://www.met.ie>), and used to determine winter-averaged values considering December–March.  
 353 Time series of the winter values for the climate indices reveal significant variability with alternating  
 354 positive and negative phases (Fig. S3a,b,c). There appears to be a trend towards increasingly positive  
 355 values in the NAO time series (Fig. S3a), which previously has been linked to increased extreme  
 356 wave conditions over the period (1948–2017) along the European Atlantic seaboard (*Castelle et al.,*  
 357 *2018*). There is no significant correlation between the different climate indices (Fig. S3d,e).



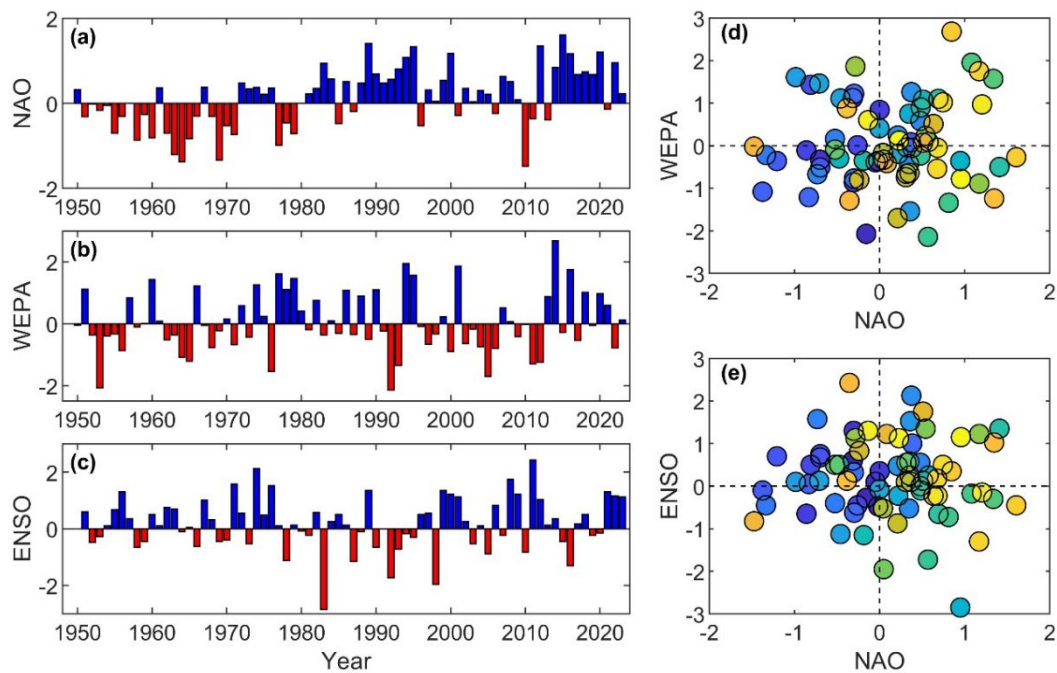


Fig. S3. Annual time series of: (a) North Atlantic Oscillation (NAO); (b) Western Europe Pressure Anomaly (WEPA); (c) El Niño – Southern Oscillation (ENSO); and scatter plot of (d) NAO versus WEPA, and (e) NAO versus ENSO. The color gradient associated with the symbols in the scatter plots represent 1950 (blue) to 2023 (yellow).

358 Both Perranporth and Slapton Sands have been surveyed monthly since 2006 by the Coastal Processes  
 359 Research Group, University of Plymouth, using quad bike and walking surveys. For Perranporth, an  
 360 area of 1 km x 0.5 km at the southern end of the beach is surveyed using a GPS/GNSS-mounted quad  
 361 bike; on Slapton Sands several pre-defined survey lines (10–20 each month; only P01 and P18 are  
 362 used here), spaced 250 m apart, are surveyed on foot using GPS/GNSS. The surveyed data represents  
 363 the supra- and intertidal beach, generally down to the mean spring low tide level. The beach survey  
 364 data are converted into time series of beach volume above mean low water level, nominally -2 m  
 365 ODN, to a fixed backshore position that is seaward of the shortest profile, with units  $\text{m}^3$  per unit meter  
 366 of beach, thus  $\text{m}^3\text{m}^{-1}$ , or  $\text{m}^2$ . Shoreline positions, representing elevations of 0, 1, 2, 3, 4 and 5 m, are  
 367 interpolated from the beach profile data. The shoreline position associated with 0 m ODN  
 368 (representing c. 0.2 m above MSL) was found to best represent the beach volume (Fig. S4a,b,c)  
 369 (Konstantinou *et al.*, 2023). The shoreline data were linearly interpolated onto a monthly time-axis  
 370 which was necessary to enable extraction of the shoreline position at the start and end of winter (1  
 371 December and 1 March, respectively), and to enable computing the auto-correlation function.  
 372 Directional wave buoys are installed c. 1 km off Perranporth and Slapton Sands in c. 15 and 12 m  
 373 water depth, respectively, and have been recording wave conditions since 2007. These data are  
 374 collected continuously at 3.84 Hz, with standard statistics reported every 30 min, and the significant  
 375 wave height  $H_s$ , peak wave period  $T_p$  and the average water depth  $h$  were used to compute the ‘local’  
 376 wave energy flux  $P$  (i.e., without de-shoaling to obtain the deep-water wave energy flux). This paper  
 377 reports on data collected over the period 2007–2023, but complete data sets for the two beaches  
 378 covering the period 2007–2018, and including bathymetric and dune surveys, are reported in  
 379 McCarroll *et al.* (2023).



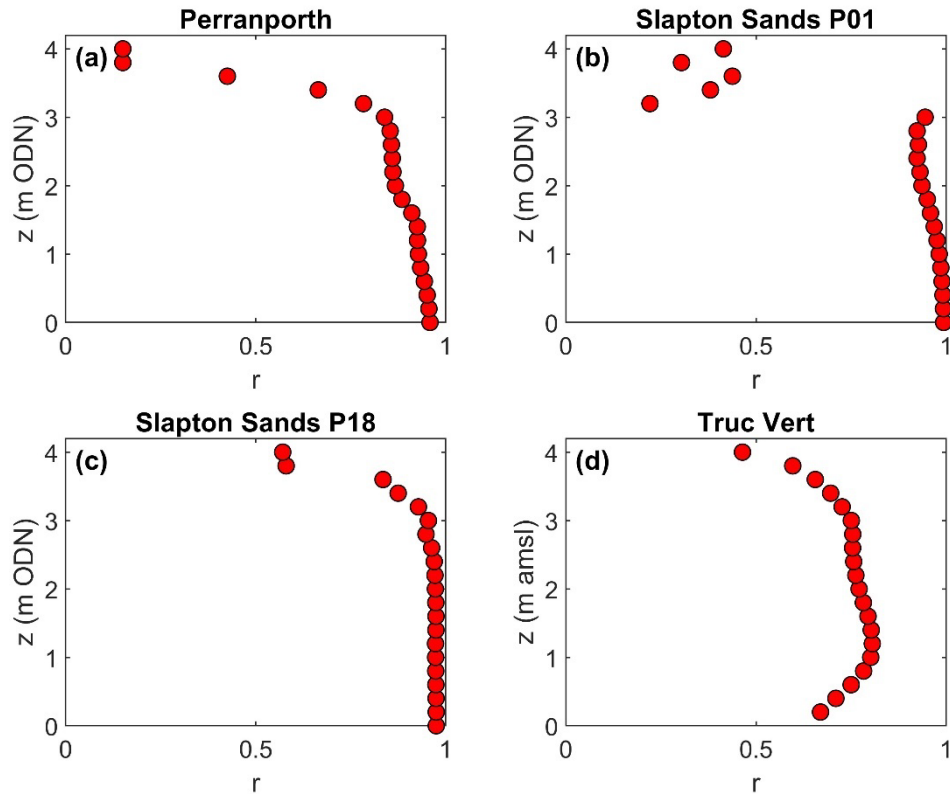


Fig. S4. Correlation  $r$  between beach volume and shoreline position defined by different contour line elevations  $z$  on the beach: (a) Perranporth; (b) Slapton Sands P01; (c) Slapton Sands P18; and (d) Truc Vert. For Perranporth and Slapton Sands, beach volume was computed above  $z=-2$  m ODN up to a fixed backshore position, and the  $z=0$  m ODN shoreline position was selected to best represent the beach volume. For Truc Vert, beach volume was computed between  $z=0$  and 6 m amsl, and the  $z=1.4$  m amsl shoreline position was selected to best represent the beach volume.

380 Truc Vert has been surveyed at monthly to bi-monthly since 2003 using walking and quad bike  
 381 GPS/GNSS surveys. Surveys are performed at spring low tide, with an average transect spacing of  
 382 around 50 m. The alongshore coverage progressively extended from 300 m in 2003 to over 2000 m  
 383 after 2016, to both describe the alongshore-variable changes and provide robust alongshore-averaged  
 384 proxies (shoreline position, volume) by smoothing out the effect of ubiquitous and prominent mega-  
 385 cusp embayments. Like for Perranporth and Slapton, the surveys were converted into time series of  
 386 beach volume computed between 0 m and 6 m amsl (amsl represents MSL in France) and shoreline  
 387 positions were determined for different elevation proxies. Consistent with earlier work (Robinet *et al.*,  
 388 2016), the shoreline position associated with 1.4 m amsl was found to represent the beach volume best  
 389 (Fig. S4d). The survey data collected over 2008 had issues and were removed from the analysis. As  
 390 for the shoreline data from SW England, the Truc Vert shoreline data were also linearly interpolated  
 391 onto a monthly time-axis. Because there are no continuous wave buoy measurements nearby Truc  
 392 Vert covering the entire monitoring period, we resorted to 20 years of continuous hourly numerical  
 393 wave hindcast (ERA5; Hersbach *et al.*, 2023) to estimate incident wave conditions. We used the grid  
 394 point closely located with the CANDHIS directional wave buoy ( $1^{\circ} 26.8'W$ ,  $44^{\circ} 39.15'N$  in Fig. 1a)  
 395 moored in approximately 54-m depth c. 20 km SW of Truc Vert. The model wave data were  
 396 compared with the measured wave data for the period July 2013 to July 2014, representing the most  
 397 energetic period. Over this period, the measured and modelled  $H_s$  and  $P$  are highly correlated, with  
 398 Pearson  $r=0.98$  and  $0.95$ , respectively. For most of the storms that occurred over the 2013/14 winter  
 399 period, the ERA5 model under-predicts  $H_s$  during the storm peaks, sometimes by several meters, but  
 400 the summed wave power  $\Sigma P$  over the 2013/14 winter period based on the ERA5 data is 96.4% of  $\Sigma P$   
 401 based on the measured wave data. The complete Truc Vert dataset up to 2019 is described in Castelle  
 402 *et al.* (2020).

403 Perranporth and Truc Vert are characterised by a unidirectional wave climate (Fig. S2a,c) and the  
 404 shoreline response is mainly a function of the total wave power; therefore,  $P$  was summed over the  
 405 months December–March to yield the total amount of winter wave power  $\Sigma P$  (in kWhr m<sup>-1</sup>). Slapton  
 406 Sands, on the other hand, is characterized by a bi-directional wave climate (Fig. S2b) and  $P$  was divided  
 407 into a southerly and easterly component,  $P_{south}$  and  $P_{east}$ , using a directional threshold of 135°, and was  
 408 summed integrated over the winter periods, yielding  $\Sigma P_{south}$  and  $\Sigma P_{east}$ . Wiggins *et al.* (2019) showed  
 409 that that  $\Sigma P_{east}$  and  $\Sigma P_{west}$  should be considered collectively when attempting to understand the rotational  
 410 beach response at Slapton Sands. They combined both wave power components in the annual  
 411 directional power index  $WDI$  defined as:

$$412 \quad WDI = \frac{(\Sigma P_{south} - \Sigma P_{east}) - \langle \Sigma P_{south} - \Sigma P_{east} \rangle}{\sigma(\Sigma P_{south} - \Sigma P_{east})}$$

413 where  $(\Sigma P_{south} - \Sigma P_{east})$  is the difference between the southerly and easterly wave power,  $\langle \Sigma P_{south} -$   
 414  $\Sigma P_{east} \rangle$  is the long-term average of those differences (averaged over the complete survey period), and  
 415  $\sigma(\Sigma P_{south} - \Sigma P_{east})$  is the standard deviation associated with the long-term average. Wiggins *et al.* (2020)  
 416 further showed that the process of beach rotation, where opposing ends of the beach show anti-phase  
 417 behaviour, can be quantified using a Rotation Index  $RI$ . To compute  $RI$ , the shoreline time series  $x$  for  
 418 P01 and P18 were first normalized each by setting the minimum and maximum  $x$  to 0 and 1,  
 419 respectively. The normalized shoreline time series  $x_{norm}$  is then used to obtain the change in the  
 420 normalized volume  $\Delta x_{norm}$ . The beach rotation index  $RI$  is then computed by subtracting  $\Delta x_{norm}$  for P01  
 421 from that of P18. Positive values for  $RI$  denote clockwise rotation and negative values represent anti-  
 422 clockwise rotation.

423

Table S1. Mean seasonal wave statistics\* for Perranporth and Slapton Sands computed for the period 2007–2023.

|                               | <b>Significant wave height</b><br>$H_s$ (m) | <b>Peak wave period</b><br>$T_p$ (m) | <b>Wave power</b><br>$P$ (kW $s^{-1}m^{-1}$ ) |
|-------------------------------|---|--------------------------------------|---|
| <b>Perranporth - summer</b>   | 1.33  | 9.5                                  | 13.4  |
| <b>Perranporth – winter</b>   | 2.08  | 11.8                                 | 34.2  |
| <b>Slapton Sands – summer</b> | 0.59  | 7.7                                  | 2.2   |
| <b>Slapton Sands – winter</b> | 0.92  | 9.4                                  | 5.5   |
| <b>Truc Vert – summer</b>     | 1.49  | 10.1                                 | 15.0  |
| <b>Truc Vert – winter</b>     | 2.30  | 12.2                                 | 41.4  |

\* Winter and summer represent December–March and April–November, respectively.

424

425

Table S2. Pearson correlation coefficient  $r$  and associated p-values for correlations between climate indices, and wave forcing and shoreline response. Underlined and bold  $r$  values are significant at the 0.05 level.

|                                       | <b>NAO</b>                  | <b>WEPA</b>                  | <b>ENSO</b>    |
|---------------------------------------|-----------------------------|------------------------------|----------------|
| <b>Perranporth</b>                    |                             |                              |                |
| $\Sigma P - \langle \Sigma P \rangle$ | <u><b>0.62</b></u> (p=0.01) | <u><b>0.71</b></u> (p=0.00)  | -0.23 (p=0.36) |
| $\Delta x$                            | -0.22 (p=0.40)              | <u><b>-0.54</b></u> (p=0.03) | 0.32 (p=0.23)  |
| <b>Slapton Sands</b>                  |                             |                              |                |
| WDI                                   | 0.41 (p=0.12)               | <u><b>0.68</b></u> (p=0.00)  | -0.30 (p=0.26) |
| RI                                    | 0.09 (p=0.73)               | 0.47 (p=0.07)                | -0.30 (p=0.25) |
| <b>Truc Vert</b>                      |                             |                              |                |
| $\Sigma P - \langle \Sigma P \rangle$ | <u><b>0.43</b></u> (0.05)   | <u><b>0.88</b></u> (0.00)    | -0.09 (0.71)   |
| $\Delta x$                            | -0.20 (0.42)                | <u><b>-0.52</b></u> (0.02)   | 0.03 (0.90)    |

426

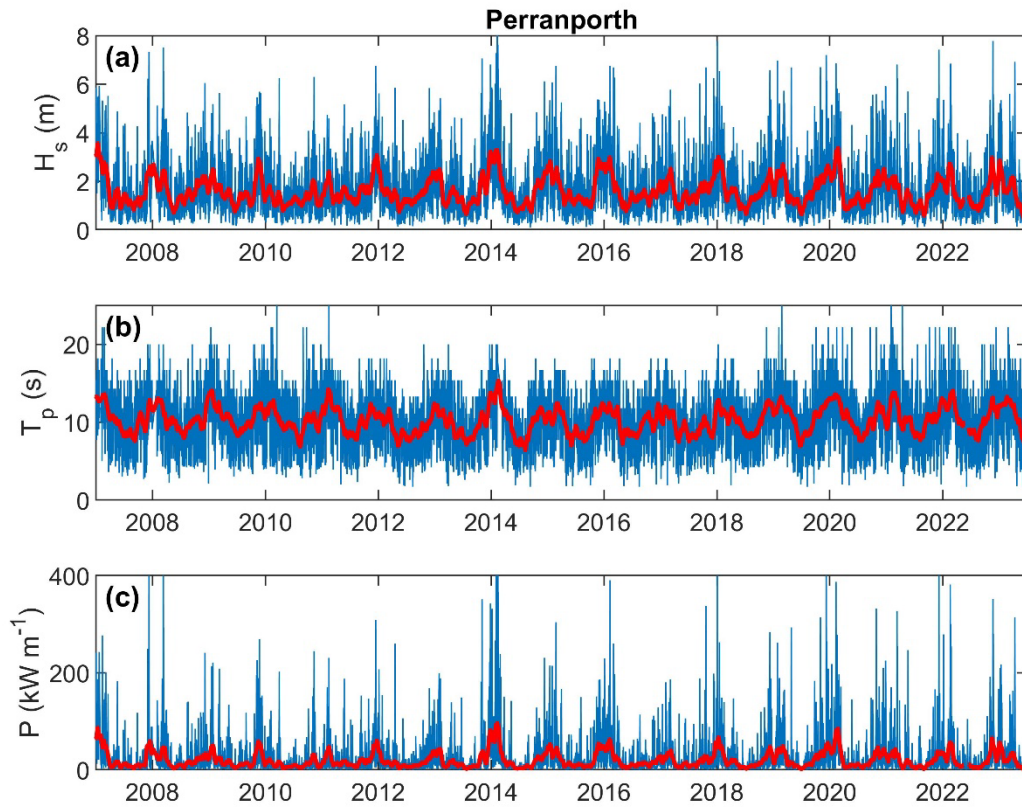


Fig. S5. Time series of wave conditions at Perranporth: (a) significant wave height  $H_s$ ; (b) peak wave period  $T_p$ ; and (c) wave power  $P$  for the period 2007–2023. Thick red line represents 30-day moving average.

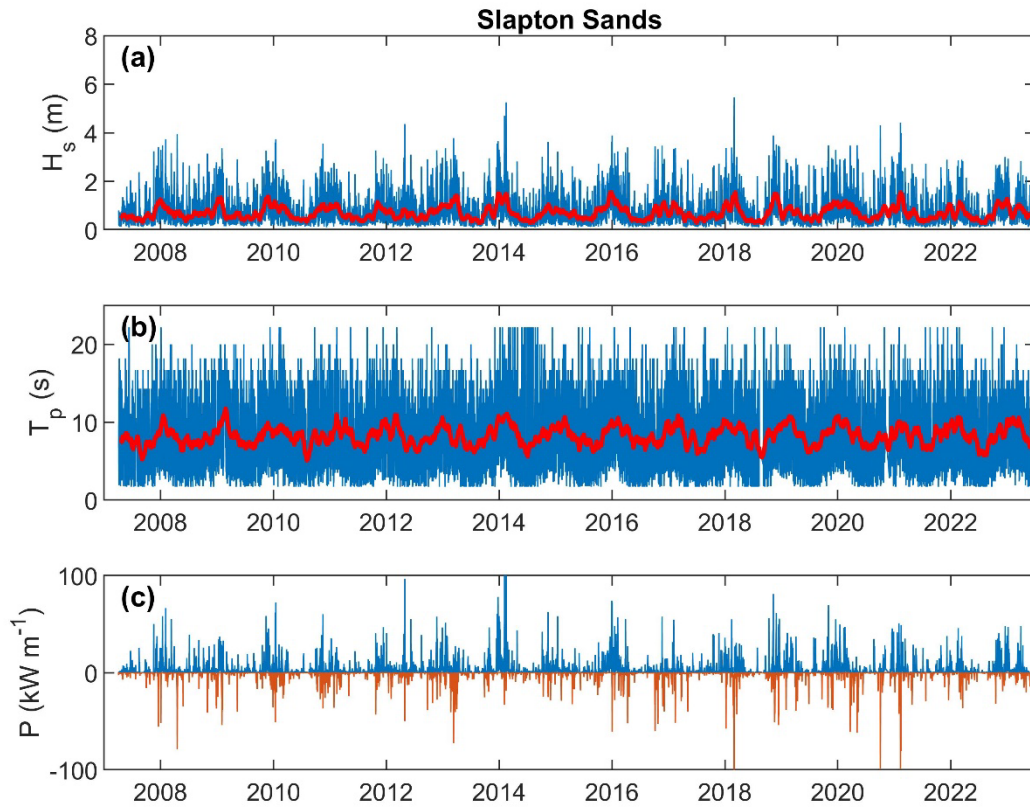


Fig. S6. Time series of wave conditions at Slapton Sands: (a) significant wave height  $H_s$ ; (b) peak wave period  $T_p$ ; and (c) wave power  $P$  for the period 2007–2023. Positive (blue) and negative (orange) values for  $P$  represents southerly ( $> 135^\circ$ ) and easterly waves ( $< 135^\circ$ ), respectively. Thick red line represents 30-day moving average.

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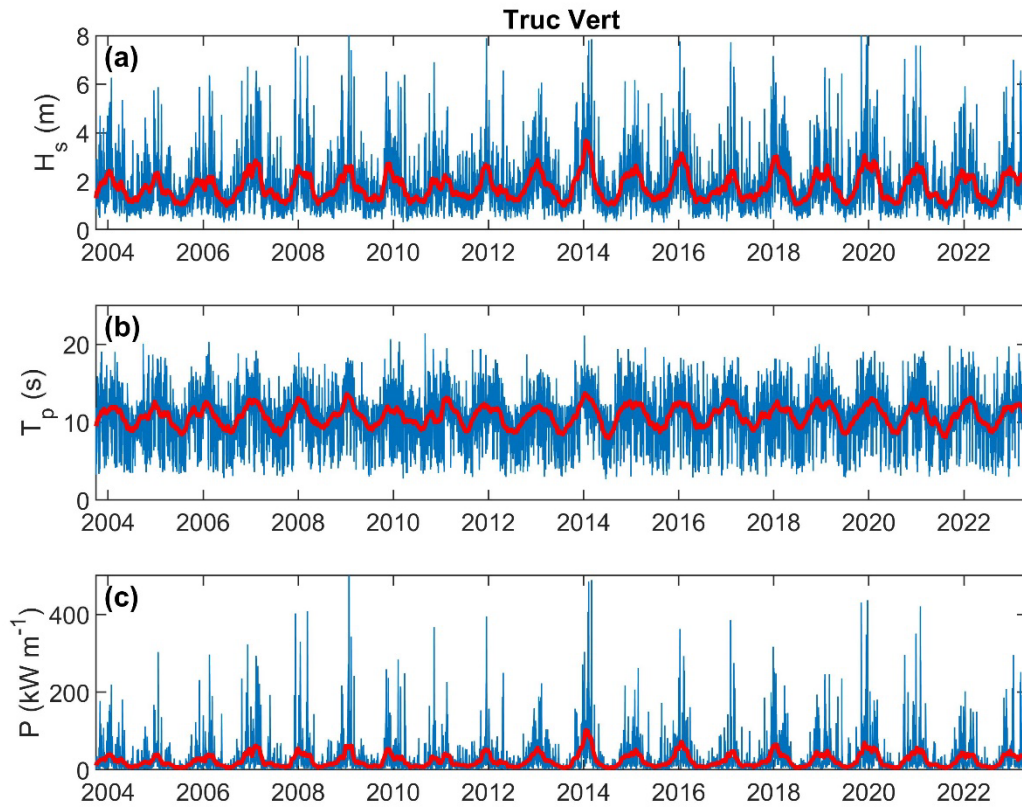


Fig. S7. Time series of modelled deep-water wave conditions at Truc Vert: (a) significant wave height  $H_s$ ; (b) peak wave period  $T_p$ ; and (c) wave power  $P$  for the period 2004–2023. Thick red line represents 30-day moving average.

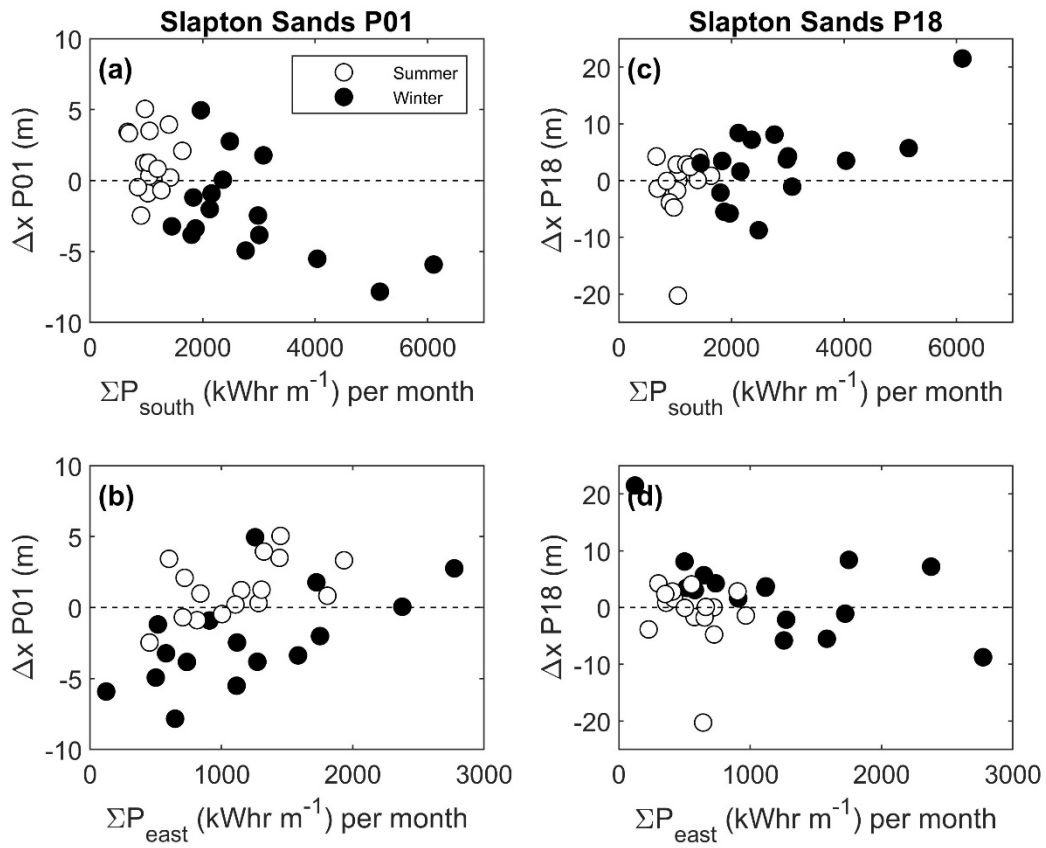


Fig. S8. Shoreline change  $\Delta x$  over winter (black circles) and summer (white circles) as a function of southerly and easterly wave power,  $\Sigma P_{south}$  and  $\Sigma P_{east}$ , summed over the respective seasons for profiles P01 and P18 on Slapton Sands: (a)  $\Delta x$  P01 versus  $\Sigma P_{south}$ ; (b)  $\Delta x$  P18 versus  $\Sigma P_{south}$ ; (c)  $\Delta x$  P01 versus  $\Sigma P_{east}$ ; (d)  $\Delta x$  P18 versus  $\Sigma P_{east}$ .

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