

2023-08-19

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

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15 Submitted to Geophysical Research Letters
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 ΣP 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 Δx 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**; $r=-0.42$, $p=0.10$).

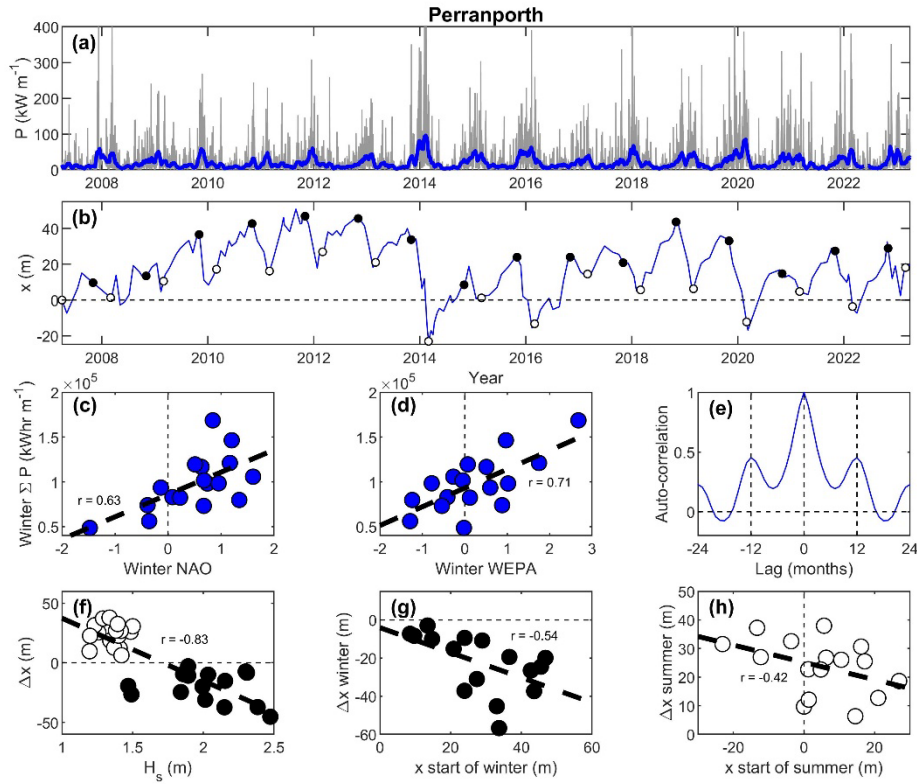


Fig. 1. Wave conditions and shoreline response for Perranporth: (a) time series of wave power P (grey line) and 30-day moving average of the wave power (blue line); (b) time series of monthly shoreline position x (0 m ODN) relative to start of the survey period with start of winter (1 December) and summer (1 April) marked by black and white circles, respectively; (c,d) scatter plot of winter wave power ΣP versus winter NAO and WEPA; (e) auto-correlation function of the monthly survey data; (f) shoreline change Δx versus season-averaged significant wave height H_s with black and white circles representing winter and summer, respectively; (g) Δx over winter season versus x at the start of winter; and (h) Δx 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 ΣP_{south} is positively correlated with winter
 150 WEPA (Fig. 2d; $r=0.89$, $p=0.00$), whereas easterly wave power ΣP_{east} , is correlated with winter NAO
 151 (Fig. 2c; $r=0.53$, $p=0.03$) indicating that large ΣP_{east} values are associated with negative NAO). No
 152 significant correlations were found with ENSO (with ΣP_{south} : $r=-0.1$, $p=0.70$; with ΣP_{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).

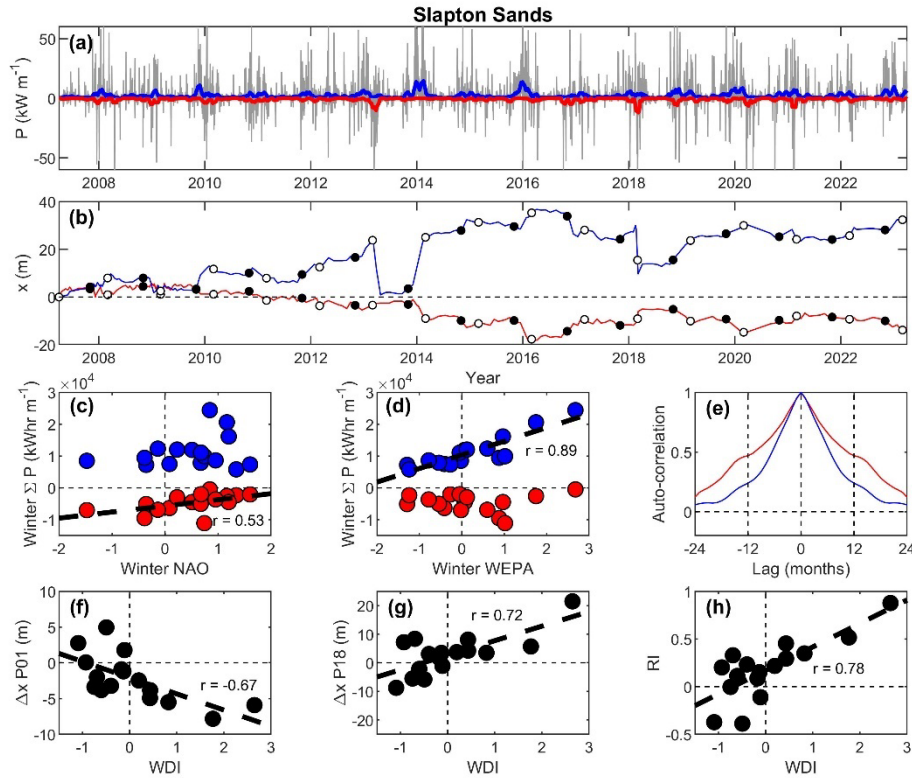


Fig. 2. Wave conditions and shoreline response for Slapton Sands: (a) time series of wave power P (grey line) and 30-day moving average of the southerly ($> 135^\circ$; blue line) and easterly ($< 135^\circ$; red line) wave power; (b) time series of monthly shoreline position x (0 m ODN) for P01 (red) 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 ΣP_{south} (blue) and the east ΣP_{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 Δx 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 ΣP_{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 ΣP_{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 Δx 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 ΣP 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, and
 185 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 Δx 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).

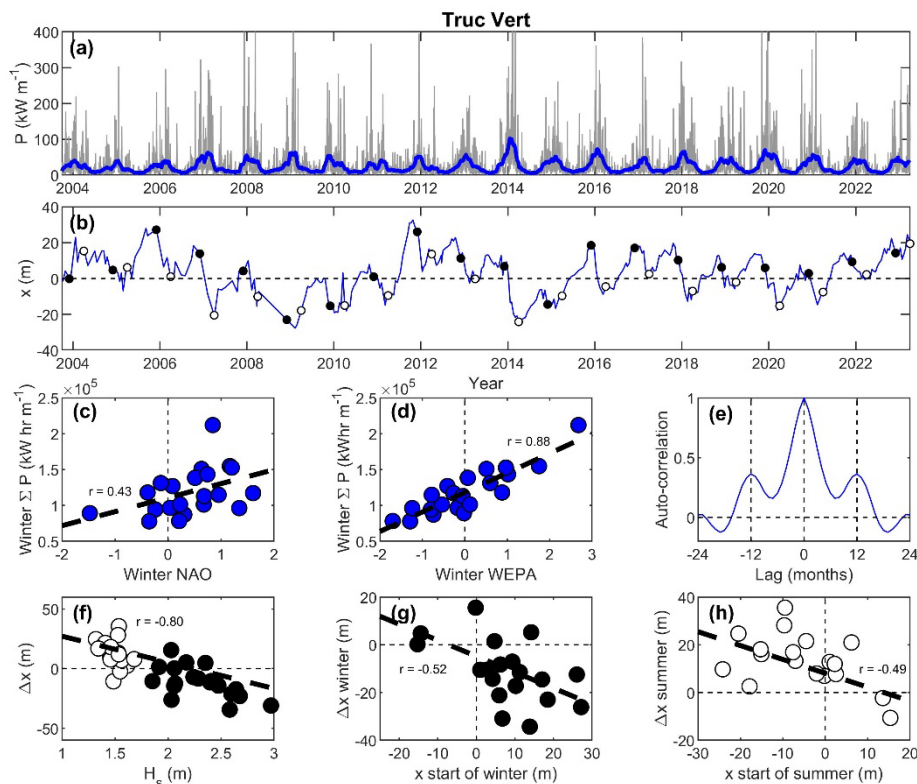


Fig. 3. Wave conditions and shoreline response for Truc Vert (for caption, cf. Fig. 1).

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 Δx 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.

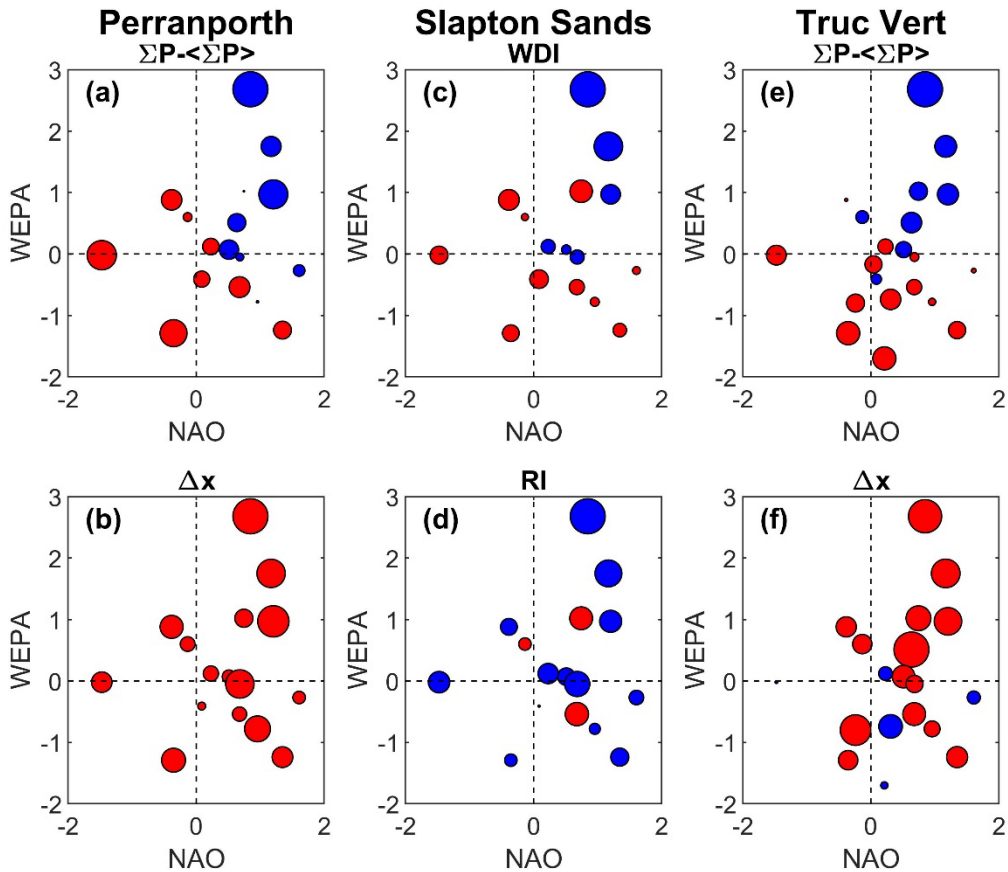


Fig. 4. Wave and morphological response parameters representing the winter season plotted in NAO-WEPA parameter space: (a) winter wave power ΣP minus winter-averaged wave power $\langle \Sigma P \rangle$ for Perranporth; (b) shoreline change Δx for Perranporth; (c) Directional Power index WDI for Slapton Sands; (d) Rotation Index RI for Slapton Sands; (e) winter wave power ΣP minus winter-averaged wave power $\langle \Sigma P \rangle$ for Truc Vert; and (f) shoreline change Δx 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 (Δx 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 Δx 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.

304 **Acknowledgements**

305 GM and TS were supported by the UK Natural Environment Research Council (Grant
306 NE/M004996/1; BLUE-coast project) and AK was supported by a PhD studentship awarded by
307 CMAR. The University of Plymouth and the Making Space for Sand Project (part of Defra's
308 Innovative Resilience Programme and managed by Cornwall Council) provided additional financial
309 support for the surveys. BC was supported by Agence Nationale de la Recherche (ANR-21-CE01-
310 0015). Truc Vert beach is a coastal monitoring site labelled by the Service National d'Observation
311 (SNO) Dynalit (<https://www.dynalit.fr>). The Observatoire de la Côte Aquitaine (OCA) and
312 Observatoire Aquitain des Sciences de l'Univers (OASU) provide additional financial support for the
313 surveys. The authors would like to acknowledge all participants that contributed to the collection of
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 ≈ 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 ≈ 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.

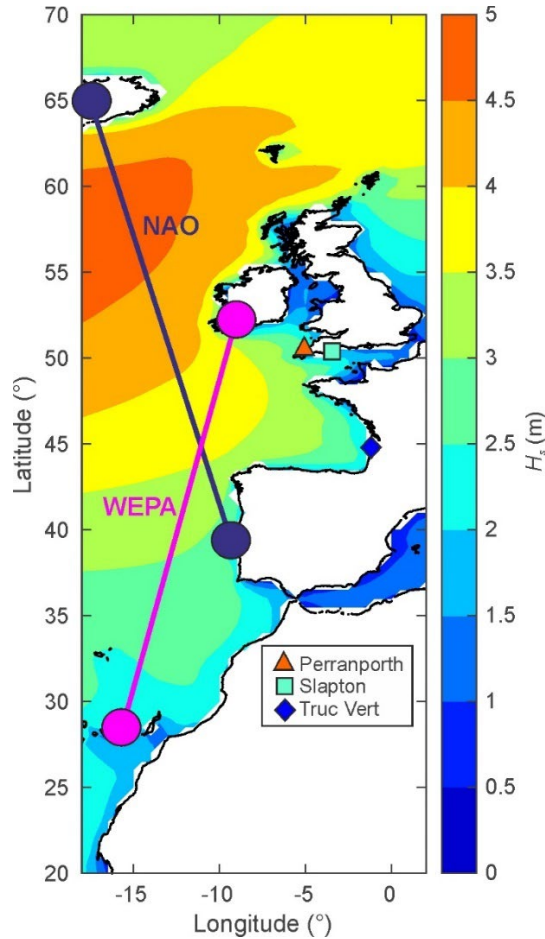


Fig S1. Atlantic coast of Europe with winter-mean (2006–2023) significant wave height H_s , locations used for determining NAO and WEPA based on sea-level pressure (SLP), and location of the three studied beaches. In the present paper, WEPA was based on SLP, but NAO was obtained using an PCA-based approach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

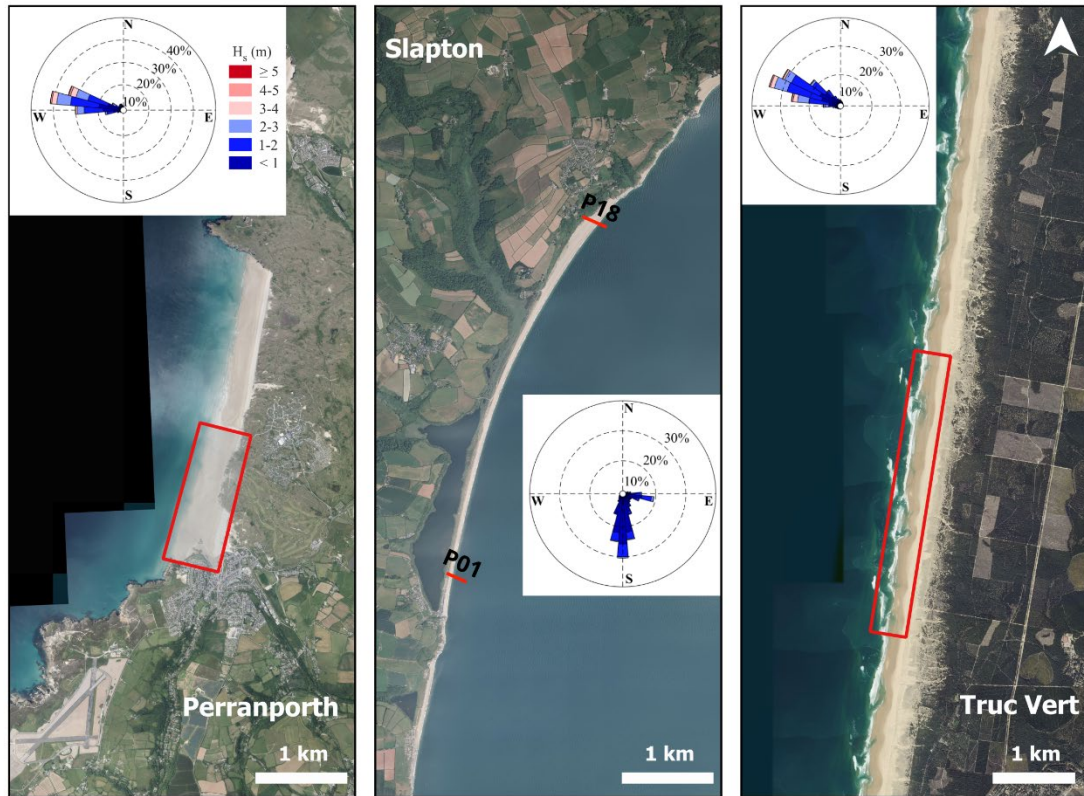


Fig. S2. Aerial photographs of the three studied beaches with wave rose: (a) Perranporth in north Cornwall, UK, with the survey area indicated by red box; (b) Slapton Sands in South Devon, UK, with the southern (P01) and northern (P18) survey transects; and (c) Truc Vert on the Aquitaine coast, France,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

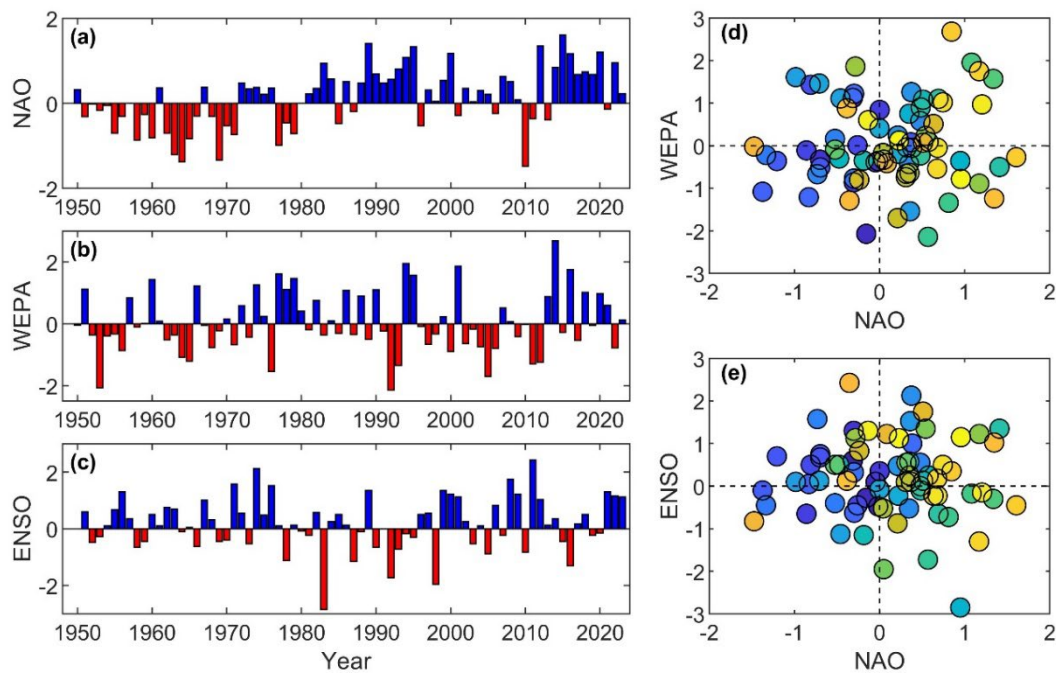


Fig. S3. Annual time series of: (a) North Atlantic Oscillation (NAO); (b) Western Europe Pressure Anomaly (WEPA); (c) El Niño – Southern Oscillation (ENSO); and scatter plot of (d) NAO versus WEPA, and (e) NAO versus ENSO. The color gradient associated with the symbols in the scatter plots represent 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 m^3 per unit meter
 366 of beach, thus m^3m^{-1} , or 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).

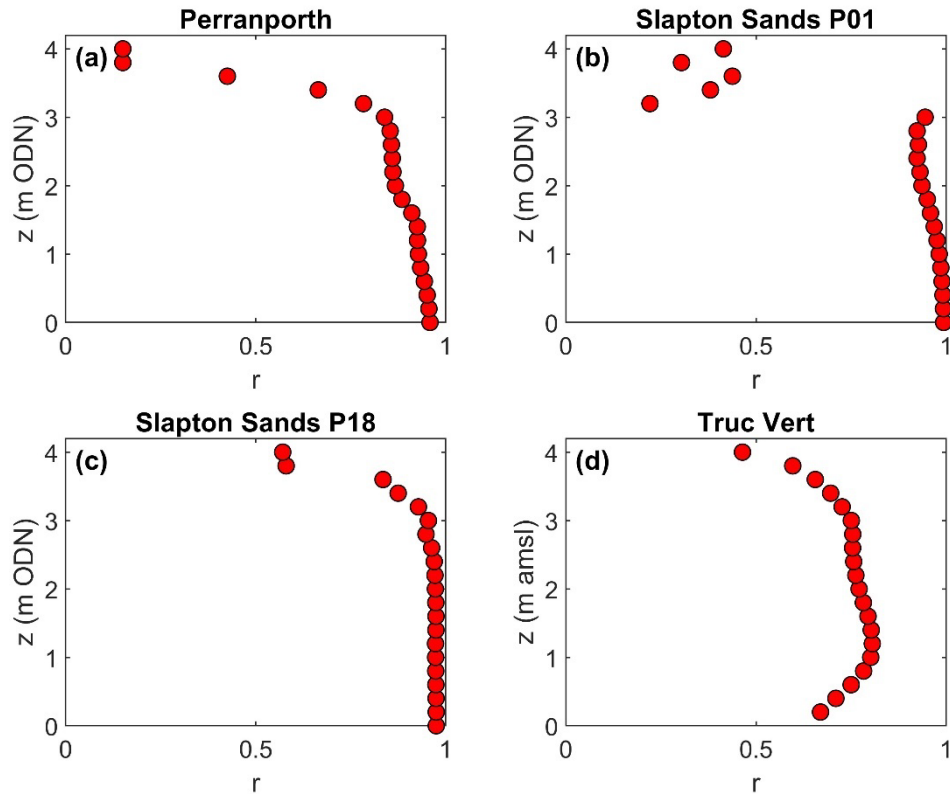


Fig. S4. Correlation r between beach volume and shoreline position defined by different contour line elevations z on the beach: (a) Perranporth; (b) Slapton Sands P01; (c) Slapton Sands P18; and (d) Truc Vert. For Perranporth and Slapton Sands, beach volume was computed above $z=-2$ m ODN up to a fixed 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 ΣP over the 2013/14 winter period based on the ERA5 data is 96.4% of ΣP
 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 ΣP (in kWhr m⁻¹). 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 ΣP_{south} and ΣP_{east} . Wiggins *et al.* (2019) showed
 409 that that ΣP_{east} and ΣP_{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 Δx_{norm} . The beach rotation index RI is then computed by subtracting Δx_{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.

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

	NAO	WEPA	ENSO
Perranporth			
$\Sigma P - \langle \Sigma P \rangle$	<u>0.62</u> (p=0.01)	<u>0.71</u> (p=0.00)	-0.23 (p=0.36)
Δx	-0.22 (p=0.40)	<u>-0.54</u> (p=0.03)	0.32 (p=0.23)
Slapton Sands			
WDI	0.41 (p=0.12)	<u>0.68</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)
Truc Vert			
$\Sigma P - \langle \Sigma P \rangle$	<u>0.43</u> (0.05)	<u>0.88</u> (0.00)	-0.09 (0.71)
Δx	-0.20 (0.42)	<u>-0.52</u> (0.02)	0.03 (0.90)

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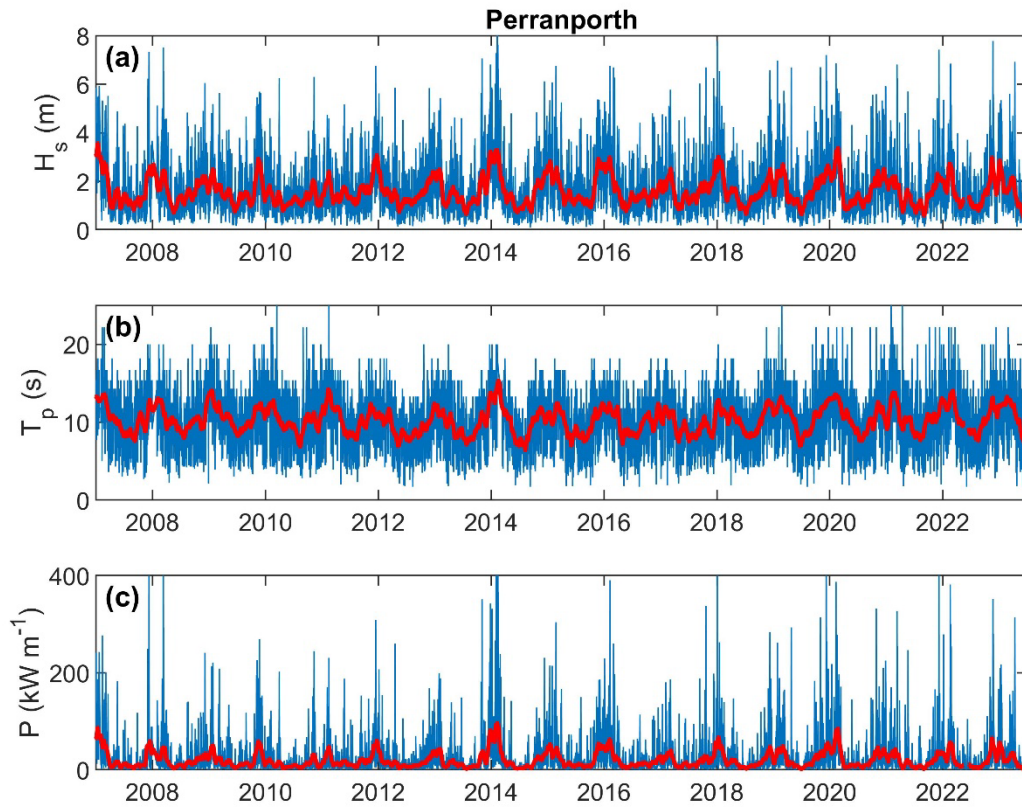


Fig. S5. Time series of wave conditions at Perranporth: (a) significant wave height H_s ; (b) peak wave period T_p ; and (c) wave power P for the period 2007–2023. Thick red line represents 30-day moving average.

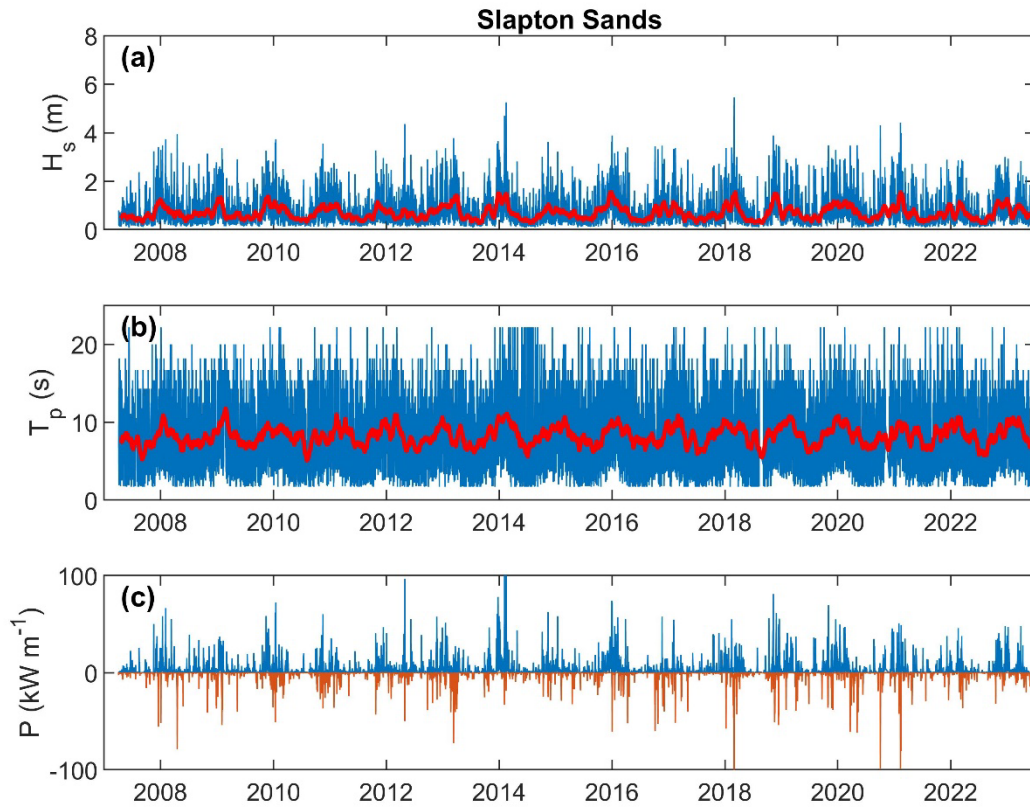


Fig. S6. Time series of wave conditions at Slapton Sands: (a) significant wave height H_s ; (b) peak wave period T_p ; and (c) wave power P for the period 2007–2023. Positive (blue) and negative (orange) values for P represents southerly ($> 135^\circ$) and easterly waves ($< 135^\circ$), respectively.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

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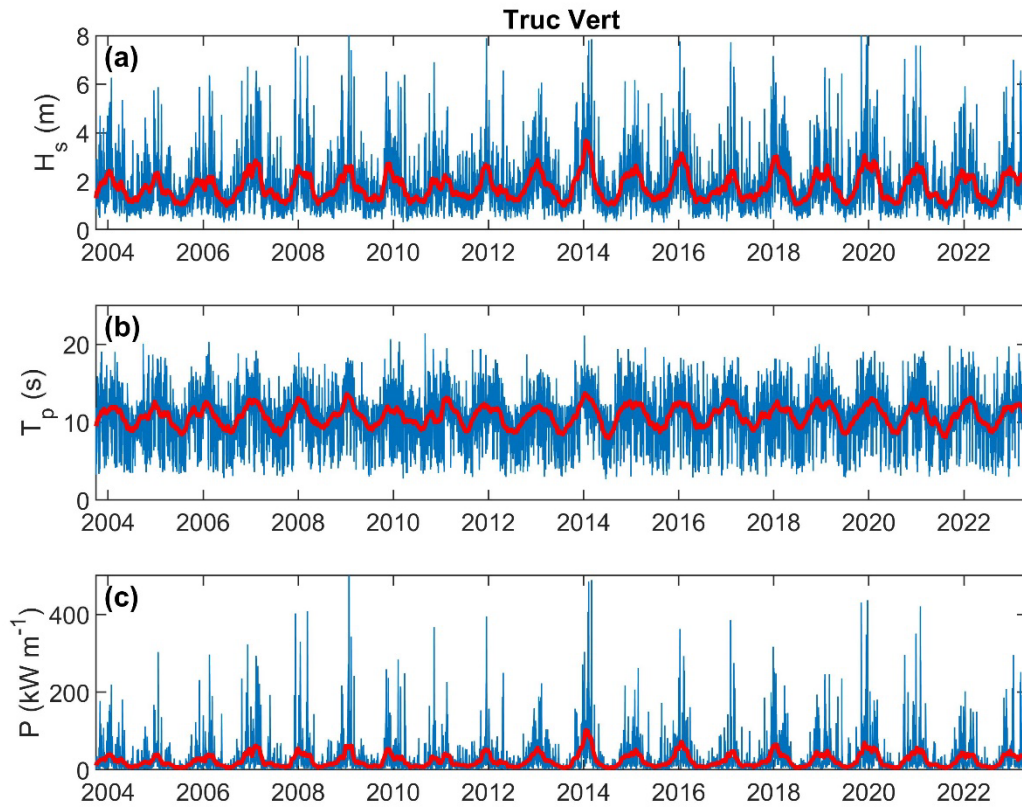


Fig. S7. Time series of modelled deep-water wave conditions at Truc Vert: (a) significant wave height H_s ; (b) peak wave period T_p ; and (c) wave power P for the period 2004–2023. Thick red line represents 30-day moving average.

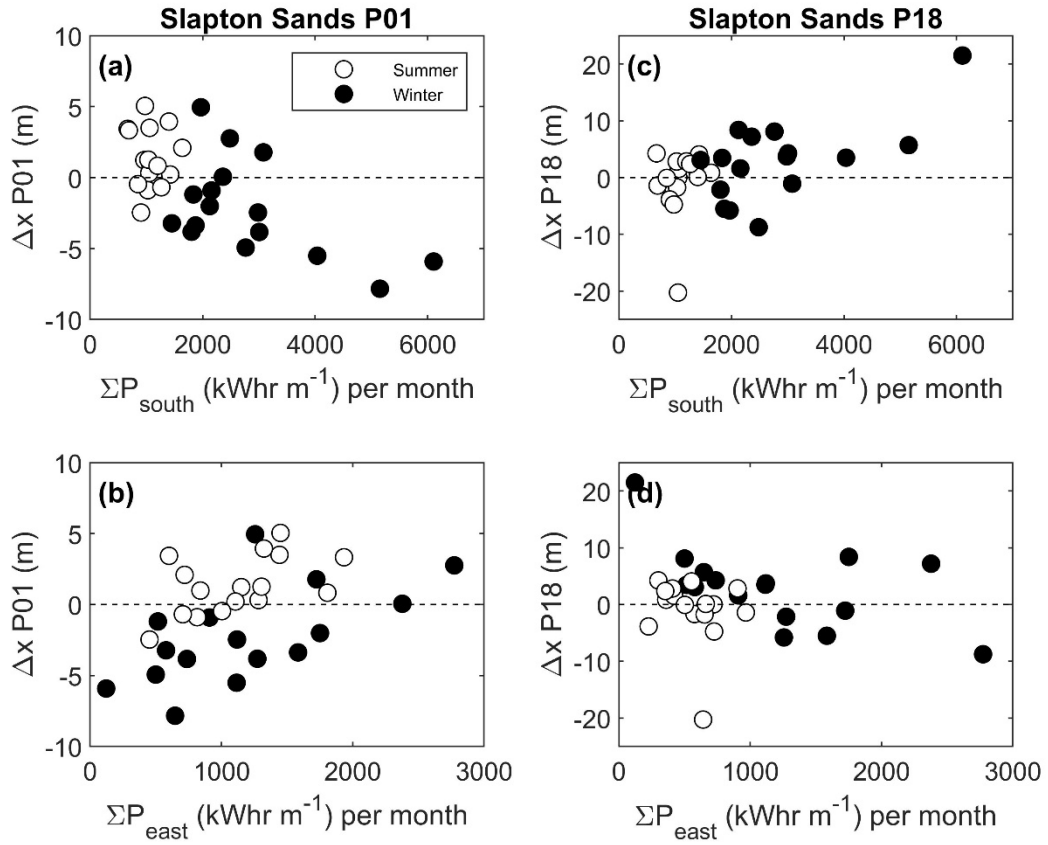


Fig. S8. Shoreline change Δx over winter (black circles) and summer (white circles) as a function of southerly and easterly wave power, ΣP_{south} and ΣP_{east} , summed over the respective seasons for profiles P01 and P18 on Slapton Sands: (a) Δx P01 versus ΣP_{south} ; (b) Δx P18 versus ΣP_{south}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

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