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# Climate forcing of regionally-coherent extreme storm impact and recovery on embayed beaches

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1           Climate forcing of regionally-  
2           coherent extreme storm impact and  
3           recovery on embayed beaches

4

5   Olivier Burvingt, Gerd Masselink, Tim Scott, Mark Davidson and Paul  
6   Russell.

7   **Abstract**

8   The effective management of sedimentary coastlines demands a  
9   good understanding of the seasonal and inter-annual cycles in beach  
10  volumes, as well as the potential impact of extreme events. This  
11  paper uses a 10-year time series (2007–2017) of supra- and intertidal  
12  beach volume from exposed and cross-shore transport-dominated  
13  sites to examine the extent to which beach behaviour is coherent  
14  over a relatively large region (100-km stretch of coast) and  
15  predictably coupled to incident wave forcing. Over the study period,  
16  10 beaches, exposed to similar wave/tide conditions, but having  
17  different sediment characteristics, beach lengths and degrees of  
18  embaymentisation, showed coherent and synchronous variations in  
19  sediment volumes, albeit at different magnitudes. The sequence of  
20  extreme storms of the 2013/14 winter, which represents the most  
21  erosive event over at least a decade along most of the Atlantic coast  
22  of Europe, is included in the data set, and three years after this winter,

23 beach recovery is still on-going for some of the 10 beaches. Post-  
24 storm beach recovery was shown to be mainly controlled by post-  
25 storm winter wave conditions, while summer conditions consistently  
26 contributed to modest beach recovery. Skilful hindcasts of regional  
27 changes in beach volume were obtained using an equilibrium-type  
28 shoreline model (ShoreFor; Davidson et al., 2013), demonstrating  
29 that beach changes are coherently linked to changes in the offshore  
30 wave climate and are sensitive to the antecedent conditions. The  
31 ShoreFor model can successfully be applied to exposed coastal areas  
32 dominated by cross-shore sediment transport, and can also be used  
33 as a relatively simple and regional tool for the future management of  
34 beaches where coherence in coastal response is observed.  
35 Furthermore, a good correlation was found between the beach  
36 volume changes and the new climate index WEPA (West Europe  
37 Pressure Anomaly; Castelle et al., 2017b), which offers new  
38 perspectives for the role and the use of climatic variations proxies to  
39 forecast coastline evolution.

## 40 **1. Introduction**

41 Multi-annual and decadal time-series of shoreline and/or beach  
42 volume change are becoming increasingly available from around the  
43 world (Pye and Blott, 2008; Senechal et al., 2009; Corbella and Stretch,  
44 2012; Barnard et al., 2015; Masselink et al., 2016; Scott et al., 2016;  
45 Turner et al., 2016; Castelle et al., 2017a; Phillips et al., 2017). In  
46 regions with a seasonal wave climate, these time-series generally  
47 show regularly alternating periods of beach erosion and accretion in

48 response to annual variations in incident wave height and period  
49 (Wright et al., 1984; Dubois, 1988; Komar, 1999; Ruggiero et al., 2005).  
50 More commonly, however, the temporal coastal behaviour is less  
51 regular and governed by processes operating across multiple time  
52 scales. Although long-term (100+ years) beach evolution is mainly  
53 affected by variations in sea level and sediment supply (Zhang et al.,  
54 2002), beach and shoreline behaviour at short- (hours/months) to  
55 medium- (months/years) timescales are more impacted by storm  
56 events (Ruggiero et al., 2005; Pye and Blott, 2016; Coco et al., 2014;  
57 Castelle et al., 2015; Masselink et al., 2015; Scott et al., 2016; Barnard  
58 et al., 2017; Harley et al., 2017). Storminess in the North Atlantic,  
59 which is characterized by considerable inter-annual and inter-decadal  
60 variability was previously shown to be strongly linked to the North  
61 Atlantic Oscillation (NAO, Bromirski and Cayan, 2015). However, the  
62 NAO index was not correlated to the 2013/14 winter, when a series  
63 of extreme storms ( $H_s > 5.2$  m) in the North Atlantic provided the  
64 most energetic winter waves since at least 1948 (Masselink et al.,  
65 2016). On the other hand, the West Europe Pressure Anomaly (WEPA),  
66 recently proposed by Castelle et al. (2017b), was strongly linked to  
67 the 2013/14 winter and therefore serves as a useful proxy for winter  
68 wave conditions in this study.

69 Many beaches along the southwest of England were highly affected  
70 by the 2013/14 sequence of storms and the morphological impact has  
71 been well documented (Masselink et al., 2015; Scott et al., 2016).  
72 Using pre- and post-storm airborne LiDAR datasets over that winter,  
73 Burvingt et al. (2017) demonstrated the existence of coherent storm

74 response at beaches showing similar exposure to storm waves. This  
75 coherent storm response was characterized by medium to large  
76 alongshore uniform sediment losses. Short et al. (2014) also showed  
77 that synchronous oscillation and rotation were observed over six  
78 years at three beaches with the same orientation and length, and  
79 exposed to a similar deep water wave climate and tidal regime. This  
80 'regionally representative' behaviour in response to varying and/or  
81 changing wave and other climatic forcing, could guide the extent and  
82 scope of the ongoing beach monitoring effort required (Bracs et al.,  
83 2016). In this paper, a 10-year dataset of RTK-GPS topographic  
84 surveys collected at a regional scale from 10 beaches with similar  
85 morphodynamic characteristics (Scott et al., 2011), orientation and  
86 wave/tide exposure, but contrasting geomorphological boundaries,  
87 will be analysed and discussed. This dataset thus gives an opportunity  
88 to address the hypothesis of coherent beach behaviour at a regional  
89 scale within a context of extreme storms.

90 Extreme storms, and the recovery period following these events, are  
91 of particular relevance in urbanized coastal areas, since beaches  
92 naturally act as a coastal buffer (Stive et al., 2002). Beach recovery  
93 processes occur over a wide range of timescales: days (Poate et al.,  
94 2015); months (Birkemeier, 1979; Wang et al., 2006; Splinter et al.,  
95 2011; Yu et al., 2013; Senechal et al., 2015; Phillips et al., 2017); years  
96 (Ruggiero et al., 2005; Choowong et al., 2009; Corbella and Stretch,  
97 2012; Suarez et al., 2012; Castelle et al., 2017a); decades (McLean  
98 and Shen, 2006; Thom and Hall, 1991; Houser et al., 2015); or may  
99 never fully recover if longshore transport dominated the beach

100 response with permanent sediment losses. Although beach recovery  
101 is often associated with small wave conditions (Komar, 1999;  
102 Ruggiero et al., 2005; Bramato et al., 2012; Roberts et al., 2013),  
103 relatively energetic waves can be essential for mobilisation/recovery  
104 of deep offshore storm bar deposits (Scott et al., 2016). Beach  
105 morpho-dynamics, including surf zone, beach and foredune  
106 interactions, also control beach recovery. Studies showed the  
107 importance of the relationship between the beach and the  
108 intertidal/subtidal bar (Houser et al., 2015; Scott et al., 2016; Brooks  
109 et al., 2017; Phillips et al., 2017; Ge et al., 2017) and/or subaerial dune  
110 systems (Suarez et al., 2012; Houser et al., 2015) in beach recovery.  
111 The 10 study sites in this paper were surveyed over 10 years including  
112 a period of three years following an extremely energetic winter  
113 season, and represent a valuable resource for a better understanding  
114 of recovery processes at a regional scale.

115 Predicting coastline response to storms and longer-term seasonal to  
116 inter-annual variability in regional wave climate is an ongoing  
117 challenge for coastal zone managers, scientists and engineers. A  
118 relatively simple equilibrium shoreline model, ShoreFor, was shown  
119 to provide skilful hindcasts of coastal change on coastlines dominated  
120 by cross-shore sediment transport (Davidson and Turner, 2009;  
121 Davidson et al., 2010; Splinter et al., 2014). This model primarily  
122 encapsulates beach behaviour forced by wave-driven cross-shore  
123 sediment transport, including antecedent hydro-/morphodynamic  
124 conditions. Based on these skills, the ShoreFor model is one of the  
125 best tools to provide a better understanding and interpretation of

126 beach behaviour time series along the exposed and cross-shore  
127 dominated 10 beaches presented here.

128 The aim of this paper is to study, over a 10-year period, the regional  
129 behaviour of 10 beaches in a context of extreme storms. The first  
130 objective is to investigate the hypothesis of multi-annual and  
131 regionally coherent beach behaviour at beaches exposed to similar  
132 wave forcing. The second objective is to contextualize beach  
133 response and volume change to a sequence of extreme storms within  
134 a 10-year time frame, and to explore the key factors that controlled  
135 beach recovery during the 3 years following these extreme storms.  
136 The third objective is to use an equilibrium model to provide a better  
137 understanding and interpretation of the link between beach  
138 behaviour and wave forcing. The fourth objective is to study the link  
139 between North Atlantic climate variability and beach volume change  
140 using a climate index controlling winter wave activity along the  
141 Atlantic coast of Europe.

## 142 **2. Study area, datasets and methodology**

### 143 *2.1. Study area*

144 The 10 study sites, located along the north coast of southwest  
145 England (Fig. 1), are all high-energy macrotidal sandy beaches that are  
146 exposed to swells and wind-waves from the North Atlantic. The wave  
147 climate is seasonal with larger waves (mean  $H_s = 2.2$  m, mean  $T_p = 11$   
148 s) in winter from October to March, and smaller waves (mean  $H_s = 1.4$   
149 m, mean  $T_p = 9$  s) in summer from April to September (Fig. 1, Table 3

150 and 4). The largest waves are generated by extra-tropical storms  
151 originating in the mid-latitude westerly wind belt (Lozano et al., 2004),  
152 although, occasionally, the coast is also affected by the remnants of  
153 tropical cyclones. On average, 17 storm events (peak  $H_s > 4$  m) and 5  
154 severe storm events (peak  $H_s > 6$  m) occur annually (Scott, 2009). The  
155 extra-tropical storminess is strongly linked to the North Atlantic  
156 Oscillation (NAO; Bromirski and Cayan, 2015) and the West Europe  
157 Pressure Anomaly (WEPA; Castle et al., 2017b), which are both  
158 characterized by considerable inter-annual and inter-decadal  
159 variability (Table 3 and 4).

160 A diverse set of beach systems is represented by the 10 study sites  
161 (Fig. 2 and Table 1) with the median size of the beach sediment  
162 ranging from 0.25 to 0.61 mm. Several beaches are backed by dune  
163 systems that vary in size and height (Widemouth #1, Constantine #2,  
164 Porthcothan #3, Gwithian #9 and Sennen #10) and front high cliffs  
165 (Trenance #4 and Watergate #5). Relatively large rocky platforms can  
166 be found at Widemouth #1, Constantine #2 and Fistral #7 beaches  
167 (Fig. 2). All beaches in the data set are constrained by rocky headlands  
168 (Fig. 2) and can either be considered as very embayed (Porthcothan  
169 #3 and Porth #6), semi-embayed (Constantine #3, Trenance #4, Fistral  
170 #7 and Porthtowan #8) or relatively open (Widemouth #1, Watergate  
171 #5, Gwithian #9 and Sennen #10). A beach being considered here as  
172 very embayed (relatively open) is when its cross-shore length, from  
173 the backshore to mean low water spring level, is more (less) than  
174 twice its longshore length, from one headland to the other. Although  
175 the studied beaches are characterized by diverse geological settings,



176 Scott et al. (2011) found them to be similar with respect to beach type  
177 and all beaches are considered Low-Tide Bar Rip (LTBR) beaches. The  
178 similarity in beach state is explained by the similar hydrodynamic  
179 conditions. All beaches are macrotidal, with the mean spring tidal  
180 range decreasing from north (6.7 m at Widemouth #1) to south (5.8  
181 m at Sennen #10) (Table 1). The beaches also all have a similar SSW-  
182 NNE orientation (Fig. 2 and Table 1) and are, therefore, exposed to  
183 similar shore-normal wave conditions. The resulting cross-shore  
184 exchange of sediment in response to changing wave conditions is  
185 more significant than sediment redistribution alongshore (Buscombe  
186 and Scott, 2008), as demonstrated by an analysis of the 2013/14  
187 storm response of all beaches in the southwest of England by Burvingt  
188 et al. (2017).

189 **Fig. 1 here**

190 **Fig. 2 here**

191 **Table 1 here**

## 192 *2.2. Topographic data*

193 As part as the South West Coastal Monitoring Program, many  
194 beaches along the coastline of SW England are surveyed every 6/12  
195 months, and RTK-GPS data sets are provided by the Plymouth Coastal  
196 Observatory (<http://southwest.coastalmonitoring.org/>). The study  
197 sites were surveyed twice a year from 2007 to 2017 in spring season  
198 (February-March-April) and autumn season (September-October-  
199 November), except for Watergate #5 and Gwithian #9 beaches, which

200 were surveyed once a year during spring season (Table 2). All beaches  
201 are generally surveyed at the same time of the year within a period  
202 of 2-3 months (Table 2) and because they are fairly dynamic, a  
203 difference of 3 months can make the inter-site comparison between  
204 beach changes potentially problematic. However, beach behaviour at  
205 these 10 study sites is also very seasonal, and the seasonal variations  
206 observed at the beach are more significant than the variations that  
207 occur over 2-3 months within the same season. The lag between  
208 surveys therefore accounts only for relatively small variations in  
209 beach changes and these are discussed later in sections 4.1 and 6.

210 Table 2 here

211 Individual datasets consist of a site-specific number of 2D cross-shore  
212 profiles that were surveyed at the exact same location throughout  
213 the 10 years and that often stretch along the entire longshore length  
214 of the beach (Fig.2 and Table 1). The surveys are carried out during  
215 spring tides to maximise beach coverage and extend vertically from  
216 around mean low water spring level (MLWS) to the top of the  
217 backshore, or dunes when present.

218 Beach sand volume per unit metre width,  $V_{profile}$  in  $m^3 m^{-1}$ , is  
219 integrated for every cross-shore profile based on the shortest profile  
220 over the 10-year period (Equation 1).

$$221 \quad V_{profile} = \int_{z_{min}}^{z_{max}} z dz \quad (1)$$

222 where  $z$  corresponds to the topographic values interpolated every  
223 metre, and  $z_{min}$  and  $z_{max}$  are the lowest and the fixed backshore

224 topographic points, respectively (Fig. 3). These volumes are  
225 computed for every survey to create a beach volume time series,  $V$  in  
226  $\text{m}^3 \text{m}^{-1}$ , relative to the first survey ( $V(\text{Autumn } 2007) = 0$ ). Beaches are  
227 also represented by either one or several cross-shore profiles ( $N$ ) that  
228 are approximatively equally-spaced and spread over the entire beach  
229 (Figure 2). As these beaches are cross-shore dominated, the profile  
230 volume time series can be averaged to obtain longshore-averaged  
231 beach volume time series  $V$  (Equation 2).

$$232 \quad V = 1/N \sum_1^N V_{profile} \quad (2)$$

233 The cross-shore profiles stretching from  $z_{min}$  to  $z_{max}$  (fixed backshore  
234 topographic) point were also vertically divided in two zones if dunes  
235 are present, with the dunes area extending from the dune foot to the  
236  $z_{max}$  (Fig. 3). For the sediment volume computations, the distinction  
237 between the elevation of the top of the beach and the base of the  
238 dunes (the dune foot) was estimated by adding the vertical storm  
239 runup computed using Stockdon et al. (2006), for a typical beach  
240 gradient of 0.02 and average storm wave conditions characterised by  
241  $H_s = 5.2 \text{ m}$  and  $T_p = 11 \text{ s}$ , to the MHWS level. This storm runup  
242 elevation is 1.2 m and is representative of a storm event and was  
243 coherent with the few dune foot measurements present in the  
244 dataset.

245 In the following sections, beach volume changes,  $dV$  in  $\text{m}^3 \text{m}^{-1}$ , are  
246 used to express the longshore-averaged beach volume changes  
247 between surveys. Beach recovery from erosion, expressed as a %, is  
248 defined as:

249  $Recovery = 100 * \frac{V_{last} - V_{post}}{V_{pre} - V_{post}}$  (3)

250 where  $V_{last}$  is the profile for which the recovery is being computed,  
251 and  $V_{pre}$  and  $V_{post}$  represent the beach volumes associated with pre-  
252 and post-storm surveys, respectively.

253 **Fig. 3 here**

### 254 *2.3. Wave, tidal and climate index data*

255 Modelled wave data were obtained from the Met Office 8-km  
256 WAVEWATCH III model; data were validated by Saulter (2017). Three-  
257 hourly values of significant wave height  $H_s$  and peak wave period  $T_p$   
258 were extracted from 1 January 1980 to 31 December 2016 at a 50-m  
259 deep grid point located half-way along the study region (Fig. 1). This  
260 time-series was extended to 30 June 2017 using  $H_s$  and  $T_p$  values  
261 measured at a nearshore directional wave buoy located 1.4 km  
262 offshore of Perranporth beach in 16-m water depth deep  
263 (50.35379°N, 5.17497°W, Fig. 1), deployed since December 2006 by  
264 the Channel Coastal Observatory. Least-squares regression between  
265 the measured (averaged every 3 hours) and modelled datasets for the  
266 period 2006–2016 reveals that the  $H_s$  time-series are significantly  
267 correlated ( $r = 0.93$ ,  $p = 0.000$ ), despite the fact that the model node  
268 is located further offshore. There is more scatter in the  $T_p$  time series  
269 ( $r = 0.84$ ,  $p = 0.000$ ) (Fig. 4). The linear regression models obtained  
270 (refer to Fig. 4) were used to extend the modelled  $H_s$  and  $T_p$  time  
271 series to 30 June 2017 to maximise the overlap between wave forcing  
272 and beach profile observations. Wave directions measured at the

273 Perranporth wave buoy were also used to produce the wave rose in  
274 Fig. 1. Measured tidal water levels, from an Etrometa step gauge  
275 deployed in July 2010 at Port Isaac (Fig. 1), were also provided by the  
276 Channel Coastal Observatory. The WEPA winter index values from  
277 1980 to 2017 were provided by Bruno Castelle (University of  
278 Bordeaux, France). This index was computed using the variations of  
279 the sea level pressure gradient between the stations Valentia (Ireland)  
280 and Santa Cruz de Tenerife (Canary Islands) located in the North  
281 Atlantic Ocean (Castelle et al., 2017b). These variations were  
282 averaged and normalized each year over the months of December,  
283 January, February and March (Boreal winter) to obtain the time-  
284 series presented in Figure 5c.

285

286 **Fig.4 here**

#### 287 *2.4. ShoreFor model*

288 To test whether any coherent responses between the study sites are  
289 coherently related to the offshore wave forcing, and importantly  
290 whether this variability is potentially predictable, observations are  
291 compared with a subtle variant of the equilibrium shoreline ShoreFor  
292 model proposed by Davidson et al. (2013). This variant predicts beach  
293 volume variability rather than shoreline change, the results proposed  
294 in this study are thus comparable with other recent studies using  
295 beach volume changes to describe the 2013/14 storm response  
296 (Castelle et al., 2015; Masselink et al., 2016; Scott et al., 2016) and no  
297 significant differences should be observed in terms of model

298 predictions. This equilibrium model is based upon the principle that  
299 cross-shore-dominated shorelines migrate toward a time-varying  
300 equilibrium position (Wright et al., 1985). Here we give a very brief  
301 description of the model and the reader is referred to Davidson et al.,  
302 (2013) for a more detailed description of the model.

303 The change in beach volume per metre coastline,  $dV$ , with time is  
304 computed using Equation 4 where  $P$  is the incident wave power  
305 expressed in  $W$ ,  $c$  is a rate parameter expressed in  $m^{2.5} s^{-1} W^{-0.5}$ , and  
306  $\Omega$  is the dimensionless fall velocity which is a simple function of local  
307 wave conditions and sediment grain size ( $\Omega = H_b/wT_p$  where  $H_b$  is the  
308 significant breaking wave height,  $w$  is the settling velocity, and  $T_p$  is  
309 the spectral peak wave period).

$$310 \quad \frac{dV}{dt} = cP^{0.5} \left( \Omega_{\phi} - \Omega \right) \quad (4)$$

311 The first model free parameter,  $c$ , controls the magnitude of the  
312 volume change and is optimized by direct comparison between the  
313 model prediction and observations, while the use of a temporally  
314 varying equilibrium condition  $\Omega_{\phi}$ , which is based on a weighted  
315 average of the antecedent dimensionless fall velocity over a time-  
316 scale  $\phi$ , describes the “memory” of a beach to antecedent conditions.  
317 The second model free parameter,  $\phi$ , is called the response factor  
318 and it controls the window-width (in days) of the weighted  
319 antecedent average. This weighting function has a centre of mass at  
320  $0.41 \phi$ , thus seasonal variation have  $\phi$ -values of order  $10^3$  days, whilst  
321 more storm dominated site are characterised by  $\phi$ -values  $<10^2$  days.

322 The numerical tests on ShoreFor by Splinter et al. (2013) suggested  
323 that bi-annual measurements of coastal change utilised in the present  
324 paper would not be of sufficient temporal resolution to adequately  
325 optimise the second model free parameter,  $\phi$ . Thus, here we use the  
326 parameterisation proposed by Splinter et al. (2014), to compute an  
327 appropriate value of  $\phi$ , based only on the knowledge of the observed  
328 sediment characteristics and wave climate. Based on an average grain  
329 size value of 0.37 mm, the Splinter et al., (2014) parameterisation  
330 yielded a value for  $\phi \approx 1000$  days, which typifies environments with a  
331 strong seasonal variability.

332 The ShoreFor model has been shown to have high skill at forecasting  
333 coastal recession and progradation on exposed energetic coastlines  
334 dominated by cross-shore sediment transport (Davidson et. al, 2013;  
335 Splinter et al., 2014; Davidson et al., 2017); however, it takes no  
336 account of the longshore sediment transport process. For the current  
337 study sites, this model restriction is not thought to be particularly  
338 severe since sediment transport at the 10 beaches is dominated by  
339 cross-shore processes (Buscombe and Scott, 2008; Burvingt et al.,  
340 2017).

### 341 **3. Wave forcing**

#### 342 *3.1. Multi-annual wave conditions time-series*

343 The time series of modelled significant wave height  $H_s$ , peak energy  
344 period  $T_p$  and winter WEPA index from 1980 to 2016 are presented in  
345 Fig. 5. The 8-week block-averaged  $H_s$  and  $T_p$  time series clearly

346 highlight the seasonal variability in wave conditions between winter  
347 and summer. Over the last 36 years, six very energetic winters can be  
348 observed from the  $H_s$  time series (Fig. 5a and 5b). The ‘Great Storm’  
349 of 1987 and the ‘Burn’s Day Storm’ in 1990 were reported (McCallum,  
350 1990) for the strength of wind gusts recorded, and caused  
351 widespread damage and the dramatic loss of 18 and 47 lives in the  
352 UK, respectively. Three years later, the ‘Braer Storm’ of 1993 had one  
353 of the lowest-ever recorded central pressures (914 mb) in the North  
354 Atlantic (McCallum and Grahame, 1993; Burt, 1993) and the 1994/95  
355 winter was reported as ‘very cyclonic’ (Hulme, 1997). More recently,  
356 the 2013/14 winter wave conditions associated with storms were the  
357 most energetic since at least 1948 along the southwest coast of  
358 England (Masselink et al., 2015), followed by the 2015/16 winter that  
359 was as energetic as 1993 and 1994/95 mentioned previously (Fig. 5a).

360 The winter WEPA time-series show that the high  $H_s$  values during the  
361 1993/94, 1994/95, 2013/2014 and 2015/2016 winters are all  
362 synchronous with positive peaks along the winter WEPA index time-  
363 series (Fig. 5c). However, only average wave conditions occurred  
364 during the 2001 winter when WEPA was strongly positive. The  
365 relationship between the winter-mean significant wave height  $H_s$  and  
366 the winter WEPA index was analysed and showed that the two time-  
367 series were strongly correlated over the 1980–2017 and the 10-year  
368 study period ( $r = 0.76$ ,  $p = 0.000$  and  $r = 0.80$ ,  $p = 0.006$ , respectively)  
369 (Fig. 6).

370 **Fig. 5 here**



371 **Fig. 6 here**

372 Based on the 6-monthly topographic surveys carried out around  
373 spring and autumn months, and the monthly-averaged wave  
374 conditions ( $H_s$  and  $T_p$ ) presented in Fig. 1, each year is divided into a  
375 winter and summer season spanning the 6 months between October-  
376 March (ONDJFM), and April-September (AMJJAS), respectively. The  
377 addition of October and November to the Boreal winter (December,  
378 January, February, March), used to calculate winter WEPA index  
379 values, did not alter the relationship between winter WEPA index and  
380 winter-mean significant wave height over the study period, which  
381 show an even better correlation coefficient ( $r = 0.84$ ,  $p = 0.000$ ). Over  
382 the 2007–2017 period, for which RTK-GPS survey data are available,  
383  $H_s$  and  $T_p$  winter-mean values ranged from 1.80 m to 2.73 m, and 10.6  
384 s to 11.9 s, respectively (Table 3), with the highest winter-mean  
385 values exceeding 2.5 m and 11 s during the 2013/14 and 2015/16  
386 winters. Summers are characterized by lower  $H_s$  and  $T_p$  mean values,  
387 ranging from 1.30 to 1.54 m and 8.6 to 9.1 s (Table 4), respectively,  
388 with the least energetic months corresponding to the 2014 summer  
389 (1.18 m and 8.8 s). As observed in Fig. 5,  $H_s$  and  $T_p$  values also show a  
390 strong seasonal signal, in addition to inter-annual variability.

391 **Tables 3 and 4 here**

### 392 *3.2. Multi-annual storminess*

393 The peaks-over-threshold (POT) method is commonly used to identify  
394 coastal storms from significant wave height time series (Houser and

395 Greenwood, 2005; Almeida et al., 2012; Corbella and Stretch, 2012;  
396 Castelle et al., 2015; Masselink et al., 2015). Ciavola and Coco (2017)  
397 identified three parameters to specify when using the POT method:  
398 (1) the storm threshold; (2) the minimum storm duration; and (3) the  
399 meteorological independence criterion. Based on the time series of  
400 modelled significant wave height  $H_s$  and similarly to Masselink et al.  
401 (2015), a storm is defined here as a wave event during which the  
402 maximum  $H_s$  exceeds the 1% exceedance offshore wave height (5.2  
403 m), and where the start and the end of the storm event is when  $H_s$   
404 exceeds or falls below the 5% exceedance wave height (3.8 m). These  
405 wave exceedance values were calculated using the modelled  $H_s$  wave  
406 time-series over the last 10 years only, to avoid the influence of long-  
407 term trends in winter-mean wave height (Castelle et al., in prep).  
408 Given that the southwest coast of England is mostly exposed to extra-  
409 tropical storms, a meteorological independence criterion of 24 hours  
410 is used to distinguish storm events, as suggested by Ciavola and Coco  
411 (2017). The numbers of storm events during winter and summer  
412 months from 2006 to 2016 are reported in Table 3 and 4. The number  
413 of storms shows a high seasonal variability and only three of the 76  
414 storm events identified between October 2006 and June 2017  
415 occurred during summer months (Table 3 and 4). The highest number  
416 of storm events are associated with the 2013/14 and 2015/16 winters  
417 (17 and 12 storms, respectively) while only one storm occurred during  
418 the 2016/17 winter, representing the lowest number among the last  
419 10 years (Table 3 and Fig. 7). The number of winter storms varies from  
420 one year to another, ranging from 1 to 17 over the 10-year study

421 period. Mean storm durations are also highly variable from one  
422 winter to another, ranging from 5 to 18 hours (Table 3), justifying the  
423 use of an independence meteorological criterion of 24 hours.  
424 Although the role of storm surge is limited and rarely exceeds 1 m  
425 along this open coast (Masselink et al., 2015), the coincidence of the  
426 peak storm with spring tides has a particular importance since 5 of  
427 the macro-tidal study sites have a supra-tidal dune system (Table 1).  
428 During the 2013/14 winter, for the 17 storms recorded, 7 storms  
429 occurred at approximatively the highest stage of the spring tides,  
430 while 6 of the 12 storms occurred at that stage during the 2015/16  
431 winter (Fig. 7).

432 **Fig. 7 here**

## 433 **4. Regionally coherent beach behaviour, storm** 434 **response and recovery**

### 435 *4.1. Influence of wave forcing in beach behaviour*

436 In the previous section, results showed that the 10 study sites were  
437 exposed to temporally-varying seasonal wave conditions over the last  
438 10 years. The 6-monthly or yearly topographic changes in response to  
439 this variability in wave forcing can be observed along individual RTK-  
440 GPS beach profiles (Fig. 8). Observations at Constantine #2, Trenance  
441 #4 and Fistral #7, used as three representative examples for all study  
442 sites, showed that beach response is temporally and spatially  
443 coherent. Overall, few morphological changes were observed at the  
444 three representative study sites over the 2011/12 winter while beach

445 erosion and accretion were observed over the 2013/14 winter and  
446 the 2016 summer, respectively (Fig. 8). However, the magnitude of  
447 the morphological changes differs from one site to another. All beach  
448 profiles surveyed over the last 10 years are bounded by the Autumn  
449 2013 and Spring 2014 profiles, suggesting that the 2013/14 winter  
450 corresponds to the most erosive event for at least 10 years, and the  
451 three beach profiles corresponding to Autumn 2016 suggest that  
452 beach recovery from that winter was not complete 2.5 years later (Fig.  
453 8).

454 **Fig. 8 here**

455 To capture and study the temporal volume changes observed along  
456 these cross-shore profiles, the longshore-averaged beach volume  
457 time-series,  $V$ , were computed from 2007 to 2017, using the  
458 methodology presented in section 2.2 (Equation 2). All the 10  
459 longshore-averaged beach volume time-series over the last 10 years,  
460 presented in Fig. 9, showed that: (1) beaches presented a seasonal  
461 behaviour with most winters characterised by erosion while most  
462 summers were associated with accretion; and (2) beaches showed a  
463 coherent behaviour, although volume change magnitude can differ  
464 (Fig. 9). These differences in magnitude can be partly explained by the  
465 differences in beach characteristics, and also by the different dates at  
466 which beaches were surveyed, as mentioned in section 2.2.

467 **Fig. 9 here**

468 When considering the average of the 10 beach volume time-series,  
469  $V_{avg}$ , and its bounded standard deviation, representing inter-site  
470 variability, four different phases can be identified (Fig. 10a). During  
471 the first phase, from autumn 2007 to autumn 2010, the 10 beaches  
472 accreted with an average rate of volume change of  $3.6 \text{ m}^3 \text{ m}^{-1}$  per  
473 month (Fig. 10a). During this phase, winter periods were ranked as 5<sup>th</sup>,  
474 7<sup>th</sup> and 9<sup>th</sup> most energetic and corresponded to the recovery phase  
475 following the energetic 2006/07 winter ranked as the 3<sup>rd</sup> most  
476 energetic over the last 10 years (Table 3). Accordingly, the yearly  
477 WEPA index gradually decreased from 0.5 to -1.25 during this 3-year  
478 phase (Fig. 10c). The second phase, spanning the three years between  
479 autumn 2010 and autumn 2013, was characterized by an equilibrium  
480 in beach volume change ( $-7 \text{ m}^3 \text{ m}^{-1}$ ) where seasonal sediment  
481 exchange was dominant over inter-annual exchange (Fig. 9). This  
482 suggests that the beaches reached an equilibrium as recovery from  
483 the 2006/07 winter was complete. This phase was associated with a  
484 relatively stable WEPA index from 2010 to 2012 followed by a rapid  
485 increase from -1.20 to 1 during 2013 which did not seem to influence  
486 the volume changes (Fig. 10c). Phase 3, corresponding to the 2013/14  
487 winter, was the strongest erosive event over the last 10 years as  
488 previously observed along the three cross-shore profiles in Fig. 8.  
489 Between autumn 2013 and spring 2014, the 10 beaches lost from 80  
490 to  $384 \text{ m}^3 \text{ m}^{-1}$  (Fig. 9), resulting in an average erosion rate of  $34 \text{ m}^3 \text{ m}^{-1}$   
491 per month. These large losses of sand occurred during the most  
492 energetic winter of the study period (Fig. 10b), where 17 storms were  
493 recorded (Fig. 7a and Table 3), associated to the WEPA index 10-year

494 maximum value of 2.7 (Fig. 10c). Although the increase in WEPA  
495 values between 2013 and 2014 is similar to the increase observed  
496 between 2012 and 2013, the wave conditions and associated beach  
497 responses were much stronger, suggesting a threshold effect in the  
498 WEPA control on wave climate. Phase 4, which corresponded to the  
499 following three years from spring 2014 to spring 2017, was related to  
500 the recovery period from the extreme storms of phase 3. From spring  
501 2014 to autumn 2015, the beaches slowly recovered with an average  
502 accretion rate of  $3.5 \text{ m}^3 \text{ m}^{-1}$  per month (Fig. 10a). The smaller wave  
503 conditions during the 2014/15 winter compared to the 2013/14  
504 winter (Fig. 7a and 7b) were associated with a decrease of the WEPA  
505 index through 2015 (Fig. 10b and 10c). However, that winter was still  
506 relatively energetic (ranked 4<sup>th</sup>, Table 3) and resulted in variable  
507 response among the 10 study sites with both erosion or accretion  
508 depending on the beach (Fig. 9). Most of the sand recovered over this  
509 1.5 years was lost during the energetic 2015/16 winter (Fig. 7c), which  
510 ranked as the second most energetic period over the last 10 years  
511 (Table 3) and paired with the second highest value of WEPA index (Fig.  
512 10c), adding to the hypothesis of a threshold effect observed in phase  
513 3. These losses were quickly recovered the next summer in 2016 (Fig.  
514 10a), and accretion ( $36 \text{ m}^3 \text{ m}^{-1}$ ) even occurred during the 2016/17  
515 winter when calm wave conditions prevailed and no storms occurred  
516 (Fig. 7c and 10b). This winter also had a reduced WEPA index (Fig. 10c).  
517 When considering the volumes lost between spring 2013 and spring  
518 2014, these losses were recovered on average by 77% in spring 2017.  
519 However, recovery percentages were highly variable between the 10

520 study sites (from 5 to 200%), as testified by the increase in standard  
521 deviation along the average volume time-series during phase 4 (Fig.  
522 10a).

523 **Fig. 10 here**

524 The volume changes observed during the 3-year recovery period  
525 (phase 4) suggested that summer conditions contribute to beach  
526 recovery but, above all, the recovery trajectory is largely and mainly  
527 forced by winter waves. The mean of the 6-monthly volume changes,  
528  $dV_{mean}$ , over winter and summer months, and the associated 6-  
529 monthly significant wave height,  $H_s$ , were therefore computed and  
530 compared. Results showed that both volume changes and wave  
531 conditions during summer months represent rather small inter-  
532 annual variability compared to winter months (Fig. 11). For example,  
533 the  $58 \text{ m}^3 \text{ m}^{-1}$  gained during the 2015 summer was rapidly lost during  
534 the subsequent energetic winter ( $-97 \text{ m}^3 \text{ m}^{-1}$ ) while the  $96 \text{ m}^3 \text{ m}^{-1}$   
535 gained during the 2016 summer were supplemented by the  
536 subsequent calm winter ( $+36 \text{ m}^3 \text{ m}^{-1}$ ). Results also showed that inter-  
537 site variability in volume change, represented by the error bars, was  
538 larger during winter months than summer months over the study  
539 period, especially when wave conditions were energetic (Fig. 11). The  
540 10 beaches average standard deviation of 6-monthly volume changes  
541 from 2007 to 2017,  $dV_{std}$ , which represents the inter-site variability in  
542 volume change, was therefore computed and plotted against the  
543 corresponding 6-monthly significant wave height mean values (Fig.  
544 12). Over winter months, the increase of deviation in volume changes

545 between the 10 study sites was strongly correlated with the increase  
546 of significant wave height ( $r = 0.83$ ), while no significant correlation  
547 was found between these two variables over summer months (Fig.  
548 12).

549 **Fig. 11 here**

550 **Fig. 12 here**

551 The longshore-averaged beach volume time-series showed that the  
552 10 study sites located along the north coast of Cornwall presented a  
553 coherent and synchronous behaviour from 2007 to 2017. For each  
554 beach, the volume changes were partly controlled by intra-annual  
555 variability due to the strongly seasonal wave climate, but largely  
556 controlled by the inter-annual variability in wave forcing during  
557 winter months, especially when sequences of extreme storms were  
558 recorded. This variability in winter wave forcing was also shown to  
559 create some variability in volume change between study sites and to  
560 have a large influence on recovery processes. Furthermore, the  
561 average of the 10 beach volume time-series was shown to be fairly  
562 well correlated with North Atlantic climate variations illustrated by  
563 the yearly WEPA index, although similar variations in WEPA index  
564 values were not associated with the same beach response, suggesting  
565 the existence of a threshold in WEPA control or the influence of other  
566 processes.

567 *4.2. Influence of geomorphological and geological boundaries*  
568 *in beach behaviour*



569 In the previous section, the 10 beaches showed a coherent and  
570 synchronous behaviour over the last 10 years. However, some  
571 variability in the magnitude of volume change was observed between  
572 the 10 study sites, which increased when waves become more  
573 energetic. Accordingly, the percentages of sand volume recovered  
574 following the extreme events of the 2013/14 winter highly varied  
575 between the 10 beaches. This variability could be partly explained by  
576 small differences in coastline orientation that influence inshore wave  
577 conditions, which were not addressed here because a generalised  
578 offshore wave forcing was used for all study sites, rather than a  
579 beach-specific inshore wave forcing. It could also be explained by  
580 other intrinsic beach characteristics that vary between the 10 study  
581 sites (Table 1). The influence of dune systems on multi-annual beach  
582 behaviour is investigated here.

583 In the present study, five sites have dune systems that vary in  
584 alongshore extent (from 160 to 2400 m) and height (from 11 to 22 m).  
585 The role of storm surge is limited along the open coast of North  
586 Cornwall, and rarely exceeds 1 m (Masselink et al., 2015); however,  
587 the coincidence of events of energetic and long-period waves with  
588 spring high tides can induce strong dune erosion. The influence of  
589 coastal dune systems on beach volumetric changes over the last 10  
590 years was investigated by quantifying the longshore-averaged dune  
591 volume time series, as mentioned in section 2. The volume time series  
592 associated with the dunes,  $V_{dunes}$ , at Widemouth #1, Constantine #2,  
593 Porthcothan #3, Gwithian #9 and Sennen #10, show that dunes were  
594 variably active over the last 10 years (Fig. 13). The contribution of

595 dune volume changes over intertidal beach volume changes was  
596 highly variable between the different study sites, being either  
597 insignificant at Widemouth #1, small at Constantine #2, Gwithian #9  
598 and Sennen #10, or significant at Porthcothan #3. Being relatively  
599 stable during phases 1 and 2, larger dune volume changes are  
600 observed during the third and fourth phases (Fig. 13). The largest  
601 losses of dune sand were observed during the 2013/14 winter at  
602 Constantine #2, Porthcothan #3, Gwithian #9 and Sennen #10 (-48, -  
603 40, -35, and -23 m<sup>3</sup> m<sup>-1</sup>, respectively), while very little volume change  
604 was observed at Widemouth #1 (-9 m<sup>3</sup> m<sup>-1</sup>). The 2015/16 winter was  
605 also responsible for strong and significant dune erosion at  
606 Porthcothan #3 and Sennen #10 (-41 and -16 m<sup>3</sup> m<sup>-1</sup>, respectively).  
607 Moreover, the cross-shore RTK-GPS profiles showed that the way  
608 dunes eroded was also variable between study sites. At Constantine  
609 #2, and Sennen #10, which have relatively steep and high dunes, sand  
610 was mostly eroded from the fore dunes or/and the toe of the dunes  
611 during the 2013/14 winter, while much larger dune scarping and  
612 steepening was observed at Porthcothan #3 (Fig. 13). Cross-shore  
613 RTK-GPS profiles of the dunes at Widemouth #1 and Gwithian #9 was  
614 not presented here because no significant dune erosion was observed  
615 at Widemouth and only yearly beach profiles are available at  
616 Gwithian. The rate of dune recovery between these study sites was  
617 also site-specific; between their pre-storm state in spring 2013 and  
618 spring 2017, dunes completely recovered (Constantine #2), partly  
619 recovered (Gwithian #9 and Sennen #10) or remained in an erosive  
620 state (Porthcothan #3).

621 **Fig. 13 here**

622 Dune systems can therefore represent a source of temporal and  
623 spatial variability when comparing the magnitude of volume change  
624 from one site to another. Over the last 10 years, dunes along the  
625 north coast of Cornwall were only significantly impacted during the  
626 2013/14 winter, and were likely to be one of the factors that  
627 contributed to the increase of inter-site variability in volume change  
628 during that period. Furthermore, some variability in the way dunes  
629 responded to the 2013/14 extreme storms was also observed  
630 between the 5 sites that have dunes, which consequently influenced  
631 storm response and beach recovery over the whole beach system.

## 632 **5. Modelling of multi-annual beach behaviour**

633 In the previous section, the longshore-averaged beach volume time  
634 series was strongly controlled by seasonal and inter-annual wave  
635 forcing. The 6-monthly volume changes,  $dV$ , for each study site were  
636 plotted against the corresponding 6-monthly significant wave height  
637 mean values  $H_{s, mean}$ , and the 6-monthly cumulative storm duration  
638 (Fig. 14). Trends of decrease in beach sand volumes with increase in  
639 wave height (Fig. 14a) and storm duration (Fig. 14b) can be observed.  
640 Despite the presence of some inter-site variability, a threshold  
641 between accretion and erosion can be observed within a range of  
642 mean significant wave height from 1.6 to 1.7 m, while most of the  
643 study sites were subject to erosion when cumulative storm wave  
644 conditions exceeded 13 hours. These threshold values correspond  
645 roughly to an energetic summer and a calm winter, when considering

646 the seasonal wave conditions of the last 10 years. Furthermore,  
647 erosion was systematically observed when waves exceed 2.5 m and  
648 the cumulative storm duration exceeds 100 hours (Fig. 14).

649 **Fig. 14 here**

650 The trends between volume changes and wave forcing storms  
651 depicted in Figure 14 do not take into account antecedent wave  
652 conditions, while previous results suggested that they have a  
653 significant role in beach behaviour. For this purpose, the ShoreFor  
654 model was used to explore in more detail the relationship between  
655 wave forcing and beach response. Considering the largely coherent  
656 beach behaviour dominated by cross-shore sediment transport  
657 across the study region, the time series representing the average  
658 beach volume time series for the 10 beaches was used (Fig. 15).

659 **Fig. 15 here**

660 Pearson's correlation coefficient,  $R$ , and the Brier Skill Score, BSS  
661 (Sutherland et al., 2004) calculations suggested that the model  
662 provides a good hindcast of the average of the 10 beach volume time-  
663 series ( $r = 0.85$  and  $BSS = 0.71$ , respectively). In general, the model  
664 predicts quite well both the seasonal and inter-annual variability in  
665 volume change. While apparent overestimations of the eroded  
666 volumes can be observed in phase 1 and 2 (e.g. 2007/08 winter,  
667 2009/10 winter, 2011/12 winter), the erosive impact of the extreme  
668 2013/14 storms (phase 3) is slightly under-estimated, and the  
669 recovery during the following 6 months (Summer 2014) is largely

670 over-estimated if the previous underestimation is not considered (Fig.  
671 15). The increase of inter-site variability in the magnitude of volume  
672 change over that period partially dilutes the skill of the model. Indeed,  
673 less accretion occurred during the 2014 summer at most of the study  
674 sites than the model suggests. Because most of the beaches were still  
675 in a very-much depleted state by the end of the 2014 summer, the  
676 2014/15 winter was accretionary. The ShoreFor model predicts  
677 erosion during the 2014/15 winter because of the over-prediction for  
678 the accretion during the preceding summer. However, the energetic  
679 2015/16 winter storm response and its subsequent recovery was very  
680 well captured by the model. The good ShoreFor model results  
681 demonstrate that the observed coherent regional variability in sand  
682 volume is linked to incident wave forcing. Consideration of  
683 antecedent conditions through their inclusion in the model also  
684 demonstrates the importance of antecedent conditions on future  
685 volume change in comparison to the simple correlations with  
686 significant wave height (Fig. 14).

687 In the previous section, the average of the 10 beach volume time-  
688 series was shown to be fairly well correlated with North Atlantic  
689 climate variations illustrated by the WEPA index (Fig. 10). Based on  
690 these results, winter volume changes,  $dV$ , for each study site were  
691 plotted against values of the winter WEPA index (Fig. 16a). Results  
692 showed that these two variables were well and negatively correlated  
693 ( $r = -0.78$ ) over the last 10 years. Similarly, modelled winter volume  
694 changes obtained using ShoreFor were plotted against values of the  
695 winter WEPA index (Fig. 16b), and also showed a good correlation ( $r$

696 = -0.80). Although the thin line between an accretive and an erosive  
697 winter was difficult to observe within the variability in WEPA index  
698 values, these negative correlations were particularly verified for the  
699 extreme values of the datasets (e.g. 2013/14 and 2015/16 winters),  
700 implying the use of strong positive WEPA index values as extremely  
701 energetic winters and a possible threshold effect as mentioned in  
702 section 4. Since our volume time series were shown to be mainly  
703 shaped by the temporal occurrence of these extreme events, these  
704 results suggest that the WEPA index values and the ShoreFor model  
705 predictions could be used as proxies for wave conditions and  
706 measured beach volume changes, respectively, in studies focusing on  
707 beach dynamics over multi-annual timescales.

708 **Fig. 16 here**

## 709 **6. Discussion**

710 From 2007 to 2017, the north coast of Cornwall experienced highly  
711 variable wave conditions on seasonal and inter-annual temporal  
712 scales. This variability in wave conditions, which was fairly well  
713 correlated to a new climate index proposed for the Atlantic coast of  
714 Europe (WEPA; Castelle et al., 2017b), drove a synchronous and  
715 coherent beach response, dominated by cross-shore sediment  
716 transport, for the 10 studied beaches along this coastline. Such  
717 regionally-coherent coastal response has also been demonstrated for  
718 the east coast of Australia, where it was found that beaches of similar  
719 orientation had synchronous oscillation and rotation over a 6-year  
720 period (Short et al., 2014; Bracs et al., 2016). However, the three

721 beaches along the east coast of Australia have similar size while, here,  
722 the 10 study sites represent a wide variety of beach size and length.  
723 As also observed for Perranporth beach (Poate et al., 2014; Masselink  
724 et al., 2016 ; Scott et al., 2016), a well-studied beach located along  
725 the north coast of Cornwall not included in the present data set,  
726 beach volume time series of all 10 studied beaches showed seasonal  
727 variations superimposed on inter-annual variations coupled to winter  
728 wave activity. Such multi-scale variation in wave conditions is  
729 generally observed on storm-dominated coastlines with a seasonal  
730 wave climate (Ruggiero et al., 2005; Pye and Blott, 2008; Castelle et  
731 al., 2015; Barnard et al., 2017; Harley et al., 2017a).

732 The 10-year study period includes the 2013/14 winter, which was the  
733 most energetic winter since, at least, 1948 and caused significant  
734 morphological changes all along the west coast of Europe (Masselink  
735 et al., 2016). Results showed that these extreme wave conditions to  
736 which our 10 study sites were fully exposed (Burvingt et al., 2017),  
737 were responsible of the most erosive event over, at least, the last  
738 decade. The antecedent morphological beach state being a  
739 controlling factor of beach response to storm (Voudoskas et al., 2012;  
740 Harley et al., 2016), the dramatic response of the beaches to the  
741 2013/14 winter is partly attributed to the fact that the beaches were  
742 in their most accreted state after the 2013 summer, enhancing the  
743 disequilibrium between beach state and wave forcing during the  
744 2013/14 winter. Furthermore, these extreme events drove an  
745 increase of variability in the magnitude of volume change between  
746 the 10 study sites. Many factors can account for this increase of

747 spatial variability. First, as shown in Table 2, the dates for which the  
748 cross-shore profiles were surveyed vary from one beach to another.  
749 A late winter survey could possibly not include one or several storms,  
750 while a late spring survey would and could even capture some of the  
751 recovery processes. This issue has, however, only minor  
752 consequences on the results since seasonal variations in beach  
753 volume change are much larger than the changes measured by 2-  
754 month-spaced surveys carried out within the same season. Second,  
755 the 10 study sites present different geological settings. Beach  
756 morphological response to storms was demonstrated to be strongly  
757 controlled by local coastline orientation relative to storm wave  
758 direction (Burvingt et al., 2017; Harley et al., 2017a). The small  
759 differences in coastline orientation among our study sites, resulting  
760 in differences in inshore storm wave conditions, not accounted for  
761 here, could have been enhanced during storm conditions and may  
762 explain the increase of variability in volume change magnitude among  
763 the 10 beaches following the 2013/14 winter. Moreover, this study  
764 also showed that, after being relatively stable from 2007 to 2013,  
765 dunes shifted from swash to collision regime (Sallenger, 2000) during  
766 the 2013/14 winter, highlighting the episodic and irregular nature of  
767 beach-dune interactions (Pye and Blott, 2008; Castelle et al., 2015).  
768 The spatial variability of dune response to storm waves can be  
769 accounted for by the increased variability in volume change  
770 magnitude among the 10 beaches; likewise, other intrinsic beach  
771 characteristics could also have played a role, such as sediment size  
772 and availability (Prodger et al., 2016), headland by-passing (Burvingt



773 et al., 2017; Valiente et al., in prep.; Wiggins et al., in prep.) or the  
774 presence of large rocky platforms.

775 Three years after the 2013/14 extreme storms, beach recovery is  
776 variable (from 5 to 200%) between study sites covering the four  
777 beach recovery stages defined by Morton et al. (1994). Recent studies  
778 have also shown that substantial beach recovery following storm  
779 events can occur after days (Angnuureng et al., 2017) or between one  
780 and two years (Castelle et al., 2017a; Harley et al., 2017b). In our 10-  
781 beach dataset, only six beaches showed a percentage of recovery  
782 close or superior to 100% after 3 years, while four beaches are still  
783 recovering (between 5 and 70%). The belated post-storm beach  
784 recovery along the north coast of Cornwall appears to be mainly  
785 controlled by the winter wave conditions over the years following  
786 extreme storms, with the wave height variability in summer only  
787 playing a minor role. Indeed, only one energetic winter, such as the  
788 2015/16 winter, nullified the total recovery that occurred over the  
789 previous 18 months. Summer conditions consistently contribute to  
790 modest beach recovery, but substantial recovery over a year only  
791 takes place when a mild and therefore accretionary winter occurs.  
792 Over the 10-year study period, the 2008/09, 2014/15 and 2016/17  
793 winters were all accretionary and they also followed intense erosive  
794 periods during the 2006/07, 2013/14 and 2015/16 winters that left  
795 the beaches in a depleted state. These results re-emphasise the  
796 importance of the antecedent wave conditions, as well as the actual  
797 wave forcing in driving beach response. It should be noted that this  
798 conclusion concerning beach recovery is valid only for beaches with

799 prevailing cross-shore sediment transport; recovery of beaches  
800 dominated by longshore sediment transport processes (Scott et al.,  
801 2016; Burvingt et al., 2017) is not simply dictated by the difference  
802 between antecedent and actual wave steepness, and requires a  
803 consideration of the wave direction.

804 Building on the coherent and synchronous beach behaviour at all  
805 study sites and the strong correlation between wave forcing and  
806 beach response, the ShoreFor equilibrium model (Davidson et al.,  
807 2013) was used to hindcast the average beach volume time series  
808 taking into account all 10 beaches. The good skill of the model  
809 indicates that the observed regionally-coherent variability in sand  
810 volume is linked to incident wave forcing and is, importantly,  
811 potentially predictable. Consideration of antecedent conditions  
812 through their inclusion in the model improves the skill of predictions,  
813 highlighting the importance of antecedent conditions on future beach  
814 volume/shoreline change, as demonstrated in previous field studies  
815 (Wright et al., 1985; Plant et al., 1999; Miller and Dean, 2004) and  
816 applications of the model to other exposed sites (Splinter et al., 2014).  
817 In agreement with the results of Splinter et al. (2014), application of  
818 the ShoreFor model to the average beach volume time series for the  
819 10 Cornish beaches yields a response factor  $\phi \approx 1000$  days. This  
820 illustrates the strong seasonal signal with larger-winter (small-  
821 summer) waves driving beach erosion (accretion) superimposed on  
822 inter-annual variability in winter wave height driving extreme storm-  
823 erosion during energetic winters and stability, or even recovery,  
824 during mild winters. These results also show that the ShoreFor model

825 explains most of the variability in 10 beaches when only modelled  
826 wave data were provided to force the model; this reinforces the  
827 conclusion that coherent behaviour is mainly controlled by offshore  
828 wave climate and is highly sensitive to the antecedent conditions,  
829 while beach intrinsic factors only act as secondary control factors.  
830 These findings illustrate that in regions with coherent coastal  
831 response, a relatively simple shoreline model based on the difference  
832 between actual wave conditions and the equilibrium conditions can  
833 be successfully applied for the whole region. This has further  
834 implications for the management of beaches in terms of both  
835 predicting the impact of storms and assessing potential rates of beach  
836 recovery following severe erosion (Davidson et al., 2017). Moreover,  
837 the significant correlations between the climate index controlling  
838 winter wave activity along the Atlantic coast of Europe (WEPA)  
839 especially during very energetic winters, and observed/modelled  
840 beach annual volume changes is a promising result for the  
841 development of weather regime-driven beach/shoreline models, as  
842 suggested by Robinet et al. (2016). The recent skilful predictability of  
843 the winter North Atlantic Oscillation (Dunstone et al., 2016), which is  
844 the primary mode of atmospheric variability in the North Atlantic  
845 region, and its implication on coastline change along the western  
846 coast of Europe is worthwhile exploring.

## 847 **7. Conclusions**

848 1. Regionally-coherent and synchronous behaviour over the decadal  
849 time scale was observed at 10 cross-shore dominated and energetic

850 beaches exposed to similar wave conditions, but having different  
851 sediment characteristics, beach lengths and degrees of  
852 embaymentisation. Some inter-site variability in the magnitude of  
853 volume change was observed and was shown to increase with winter  
854 significant wave height.

855 2. The sequence of extreme storms during the 2013/14 winter  
856 corresponded to the most erosive event over, at least, the last 10  
857 years along the southwest coast of England. Three years later, 60% of  
858 the beaches fully or over-recovered, while the remaining 40% only  
859 showed partial or almost non-existent recovery. Many factors  
860 accounted for this inter-site variability, such as the variability in dune  
861 erosion and recovery. Despite this spatial variability, beach recovery  
862 was shown to be mainly controlled by winter wave conditions over  
863 the years following extreme storms, in comparison to summer wave  
864 conditions that consistently contribute to modest beach recovery.

865 3. Skilful hindcasts of regional changes in beach volumes were  
866 obtained using an equilibrium-type shoreline model (ShoreFor),  
867 demonstrating that beach changes are coherently linked to changes  
868 in the offshore wave climate and highly sensitive to the antecedent  
869 conditions. This finding also illustrates that, in regions with cross-  
870 shore dominated beaches and coherent coastal response, the  
871 ShoreFor model can successfully be applied for the whole region.

872 4. Over the last 10 years, good correlations were also found between  
873 winter beach volume changes and climate index values controlling  
874 winter wave activity along the Atlantic coast of Europe (WEPA),

875 opening up the opportunity for the development of weather regime-  
876 driven beach/shoreline models.

877

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## 1140 **Figure and table captions**

1141 **Figure 1.** Bathymetric map of southwest England with the location of  
1142 the 10 study sites, Perranporth (PPT) wave buoy, Port Isaac (PI) tidal  
1143 gauge, the 8-km WWIII modelled wave node and the depth contour  
1144 representing the 30-m line (left panel). The bar graphs and wave roses  
1145 represent, respectively, monthly-averaged wave conditions ( $H_s$  and  $T_p$ )  
1146 and winter/summer wave direction recorded by the Perranporth  
1147 wave buoy from 2007 to 2017.



1148 **Figure 2.** Mosaic of Google Earth images showing the  
1149 geomorphological diversity of the 10 study sites (Widemouth #1,  
1150 Constantine #2, Porthcothan #3, Trenance #4, Watergate #5, Porth  
1151 #6, Fistral #7, Porthtowan #8, Gwithian #9 and Sennen #10 beaches).  
1152 All pictures are oriented according to north-south axis and the beach  
1153 profile surveyed by the Plymouth Coastal Observatory are located  
1154 with dashed white lines.

1155 **Figure 3.** RTK-GPS cross-shore profiles of Porthcothan #3 (left panel)  
1156 and Trenance #4 (right panel) beaches, where vertical beach and  
1157 dune areas are highlighted according to the different topographic and  
1158 water levels ( $z_{max}$ : fixed backshore topographic point;  $z_{min}$ : lowest  
1159 topographic point; *MHWS*: mean high water spring; *MSL*: mean sea  
1160 level; *MLWS*: mean low water spring).

1161 **Figure 4.** Scatter plots of measured and modelled (a) significant wave  
1162 height,  $H_s$ , and (b) peak wave period,  $T_p$ , from 2007 to 2017.  
1163 Measured wave data were obtained from the Perranporth wave buoy  
1164 (16 m deep) managed by the Channel Coastal Observatory, and 8-km  
1165 WaveWatch III modelled wave data (50 m deep) were provided by the  
1166 MetOffice.

1167 **Figure 5.** Time series from 1980 to 2017 of: (a) 3-hourly modelled  
1168 significant wave height  $H_s$  (grey) and 8-weeks block-averaged wave  
1169 significant wave height (black); (b) 3-hourly modelled peak wave  
1170 period  $T_p$  (grey) and 8-week averaged peak wave period (black) at  
1171 modelled grid point; and (c) winter WEPA index (DJFM). The red  
1172 dashed-square represent the 10-year study period for which beach

1173 topographic surveys are available and for which mean values are  
1174 provided in Tables 3 and 4.

1175 **Figure 6.** Scatter plots of the winter-mean (DJFM) modelled  
1176 significant wave height,  $H_s$  mean, and the winter WEPA index (a) from  
1177 the 1980/81 to the 2016/17 winter; and (b) from the 2007/08 to the  
1178 2016/17 winter.

1179 **Figure 7.** Time series of significant wave height  $H_s$  (m), water level (m  
1180 above Ordnance Datum, OD) and storm threshold ( $H_s$  1% exceedance)  
1181 during the winter of: (a) 2013/14; (b) 2015/16; and (c) 2016/2017.  
1182 Storms that occurred during spring tides are highlighted by red dots.

1183 **Figure 8.** Three representative examples of RTK-GPS cross-shore  
1184 profiles showing the 2011/12 winter (top panels), 2013/14 winter  
1185 (middle panels) and the 2016 summer (bottom panels) beach  
1186 responses at Constantine #2, Trenance #4 and Fistral #7 beaches.  
1187 Antecedent and subsequent profiles are, respectively, coloured in  
1188 blue and red, while all other profiles from Autumn 2007 to Spring  
1189 2017 are coloured in grey. Beach profiles are also presented on a  
1190 variable vertical scale to give a better visualization of the  
1191 morphological changes at beaches where dunes are not present.

1192 **Figure 9.** Time series from 2007 to 2017 of the longshore-averaged  
1193 beach volume time-series  $V$  ( $\text{m}^3 \text{m}^{-1}$ ) for the 10 study sites.

1194 **Figure 10.** Time series from 2007 to 2017 of: (a) the average of the 10  
1195 beach volume time-series,  $V_{avg}$  ( $\text{m}^3 \cdot \text{m}^{-1}$ ) in black bounded by its  
1196 standard deviation in grey; (b) 3-hourly modelled significant wave

1197 height  $H_s$  (grey) and 8-week block-averaged significant wave height  
1198 (black); and (c) winter WEPA index. Surveys in spring (end of winter)  
1199 each year are indicated with black dots to highlight seasonal  
1200 variations in the beach volume time-series.

1201 **Figure 11.** Time series of 6-monthly average of longshore averaged  
1202 beach volumes changes  $dV_{mean}$  ( $m^3 m^{-1}$ ) and 6-monthly average  
1203 significant wave height  $H_s_{mean}$  during winter (upper panel) and  
1204 summer (lower panel) months, from 2007 to 2017. The error bars  
1205 represent the standard deviation in volume change. Watergate #5  
1206 and Gwithian #9 were not incorporated because they were only  
1207 yearly surveyed.

1208 **Figure 12.** Scatter plots of the 10 beaches average standard deviation  
1209 of 6-monthly volume changes,  $dV_{std}$ , and the corresponding 6-  
1210 monthly significant wave height mean values,  $H_s_{mean}$ , over (a) winter  
1211 months, and (b) summer months from 2007 to 2017.

1212 **Figure 13.** Longshore-averaged dunes and intertidal beach volume  
1213 time series ( $V_{dunes}$ ,  $V_{beach}$ ) from 2007 to 2017 at Widemouth #1,  
1214 Constantine #2, Porthcothan #3, Gwithian #9 and Sennen #10  
1215 beaches (left panel). The vertical scale between each tick mark  
1216 represents a  $100 m^{-3} m^{-1}$  volume change. Pre-storm (Autumn 2013),  
1217 post-storm (Spring 2013) and last (Spring 2017) RTK-GPS cross-shore  
1218 profiles showing dune erosion and recovery at three representative  
1219 beaches: Constantine #2, Porthcothan #3, and Sennen #10 (right  
1220 panel). Autumn 2013, Spring 2014 and Spring 2017 profiles are  
1221 respectively coloured in blue, red and black and the beach profiles

1222 have been vertically cropped for a better visualization of the area of  
1223 interest (dunes).

1224 **Figure 14.** Scatter plot of 6-monthly beach volumes changes,  $dV$ , with  
1225 (a) the corresponding 6-monthly significant wave height mean values  
1226  $H_{s\ mean}$ , and (b) the 6-monthly cumulative storm duration, at the 10  
1227 study sites represented by different colours (same code of colours  
1228 relative to Fig. 9). Interpreted threshold of  $H_{s\ mean}$  is indicated by the  
1229 grey band. For every beach, each 6-monthly volume change  $dV$  value  
1230 is attributed to a 6-monthly wave height mean  $H_s$  or storm duration  
1231 value, a same value of wave height/storm duration can therefore  
1232 correspond to several summer or winter periods. Watergate #5 and  
1233 Gwithian #9 were not incorporated because they were only yearly  
1234 surveyed.

1235 **Figure 15.** Time series from 2007 to 2017 of: (a) 3-hourly modelled  
1236 significant wave height  $H_s$  (grey) and 8-week block-averaged  
1237 significant wave height (black); and (b) the average of the 10  
1238 longshore-averaged beach volume time-series,  $V_{avg}$  ( $m^3.m^{-1}$ ), in thin  
1239 black line bounded by its standard deviation in grey and ShoreFor  
1240 model results represented by the thick black line.

1241 **Figure 16.** Scatter plots of the winter WEPA index with (a) the average  
1242 of the 10 beach observed winter volumes changes, and (b) the  
1243 average of the 10 beach modelled winter volumes changes from the  
1244 2007/08 to the 2016/17 winter.

1245 **Table 1.** Key beach characteristics and RTK-GPS profile surveyed at  
1246 the 10 study sites.  $L$ : longshore beach length in m;  $d50$ : beach grain  
1247 size in mm along the upper/lower part of the beach (Scott et al., 2008);  
1248  $\alpha$ : clockwise beach angle orientation compare to the north-south axis;  
1249 number of beach RTK-GPS profiles surveyed; percentage of beach  
1250 profiles surveyed going through dune system;  $MSR$ : mean spring tidal  
1251 range (in m).

1252 **Table 2.** Survey dates of the RTK-GPS beach profiles from 2007 to  
1253 2017 at the 10 study sites. Surveys were carried out by the Plymouth  
1254 Coastal Observatory.

1255 **Table 3.** Winter-mean values (from October to March) of significant  
1256 wave height  $H_s$  (m), wave peak period  $T_p$  (s), number of storms, mean  
1257 duration of storms (h), cumulative storm duration (h) and energetic  
1258 rank based on wave energy level, from the 2006/07 to the 2016/17  
1259 winter.

1260 **Table 4.** Summer-mean (from April to September) values of  
1261 significant wave height  $H_s$  (m), wave peak period  $T_p$  (s), number of  
1262 storms, mean duration of storms (h), cumulative storm duration (h)  
1263 and energetic rank based on wave energy level, during summer  
1264 months from 2007 to 2016.