2018-07-01

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

Burvingt, Olivier

<http://hdl.handle.net/10026.1/11476>

10.1016/j.margeo.2018.04.004

Marine Geology

Elsevier BV

All content in PEARL is protected by copyright law. Author manuscripts are made available in accordance with publisher policies. Please cite only the published version using the details provided on the item record or document. In the absence of an open licence (e.g. Creative Commons), permissions for further reuse of content should be sought from the publisher or author.

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

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

Abstract

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

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

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 Ω 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 Ω_{ϕ} , which is based on a weighted
 315 average of the antecedent dimensionless fall velocity over a time-
 316 scale ϕ , describes the “memory” of a beach to antecedent conditions.
 317 The second model free parameter, ϕ , 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 0.41ϕ , thus seasonal variation have ϕ -values of order 10^3 days, whilst
 321 more storm dominated site are characterised by ϕ -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, ϕ . Thus, here we use the
326 parameterisation proposed by Splinter et al. (2014), to compute an
327 appropriate value of ϕ , 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

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

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

Fig. 8 here

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

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 5th,
 474 7th and 9th most energetic and corresponded to the recovery phase
 475 following the energetic 2006/07 winter ranked as the 3rd 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 ¹ 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 4th, 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

dune volume changes over intertidal beach volume changes was highly variable between the different study sites, being either insignificant at Widemouth #1, small at Constantine #2, Gwithian #9 and Sennen #10, or significant at Porthcothan #3. Being relatively stable during phases 1 and 2, larger dune volume changes are observed during the third and fourth phases (Fig. 13). The largest losses of dune sand were observed during the 2013/14 winter at Constantine #2, Porthcothan #3, Gwithian #9 and Sennen #10 (-48, -40, -35, and -23 m³ m⁻¹, respectively), while very little volume change was observed at Widemouth #1 (-9 m³ m⁻¹). The 2015/16 winter was also responsible for strong and significant dune erosion at Porthcothan #3 and Sennen #10 (-41 and -16 m³ m⁻¹, respectively). Moreover, the cross-shore RTK-GPS profiles showed that the way dunes eroded was also variable between study sites. At Constantine #2, and Sennen #10, which have relatively steep and high dunes, sand was mostly eroded from the fore dunes or/and the toe of the dunes during the 2013/14 winter, while much larger dune scarping and steepening was observed at Porthcothan #3 (Fig. 13). Cross-shore RTK-GPS profiles of the dunes at Widemouth #1 and Gwithian #9 was not presented here because no significant dune erosion was observed at Widemouth and only yearly beach profiles are available at Gwithian. The rate of dune recovery between these study sites was also site-specific; between their pre-storm state in spring 2013 and spring 2017, dunes completely recovered (Constantine #2), partly recovered (Gwithian #9 and Sennen #10) or remained in an erosive 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

878 **Acknowledgments**

879 This research was funded by NERC grants NE/M004996/1 (Urgency
880 Grant) and NE/N015525/1 (Strategic Highlights Topic grant). The
881 authors would like to thank Bruno Castelle, the Plymouth Coastal
882 Observatory team and the UK Met Office (Dr Andy Saulter), for kindly
883 providing the supporting WEPA index values, RTK-GPS data and the
884 modelled wave data, respectively. Marine Geology Editor Edward
885 Anthony, and anonymous reviewers are gratefully acknowledged for
886 their constructive comments that improved the manuscript.

887 **References**

- 888 Almeida, L.P., Voudoukas, M.V., Ferreira, O., Rodrigues, B.A.,
889 Matias, A., 2012. Thresholds for storm impacts on an exposed sandy
890 coastal area in southern Portugal. *Geomorphology* 143-144, 3–12.
- 891 Angnuureng, D.B., Almar, R., Senechal, N., Castelle, B., Addo, K.A.,
892 Marieu, V., Ranasinghe, R., 2017. Shoreline resilience to individual
893 storms and storm clusters on a meso-macrotidal barred beach.
894 *Geomorphology* 290, 265–276.
- 895 Barnard, P.L., Short, A.D., Harley, M.D., Splinter, K.D., Vitousek, S.,
896 Turner, I.L., Allan, J., Banno, M., Bryan, K.R., Doria, A., Hansen, J.E.,
897 Kato, S., Kuriyama, Y., Randall-Goodwin, E., Ruggiero, P., Walker, I.J.,

898 Heathfield, D.K., 2015. Coastal vulnerability across the Pacific
 899 dominated by El Nino/Southern Oscillation. *Nat. Commun.* 8, 801-
 900 808.

901 Barnard, P.L., Hoover, D., Hubbard, D.M., Snyder, A., Ludka, B.C.,
 902 Allan, J., Kaminsky, G.M., Ruggiero, P., Gallien, T.W., Gabel, L.,
 903 McCandless, D., Weiner, H.M., Cohn, N., Anderson, D.L., Serafin,
 904 K.A., 2017. Extreme oceanographic forcing and coastal response due
 905 to the 2015–2016 El Nino. *Nat. Commun.* 8, 14365.

906 Birkemeier, W.A., 1979. The effects of the 19 December 1977
 907 coastal storm on beaches in North Carolina and New Jersey. *Shore*
 908 *Beach* 47, 7–15.

909 Bracs, M.A., Turner, I.L., Splinter, K.D., Short, A.D., Mortlock, T.R.,
 910 2016. Synchronised patterns of erosion and deposition observed at
 911 two beaches. *Mar. Geol.* 380, 196–204.

912 Bramato, S., Ortega-Sanchez, M., Mans, C., Losada, M.A., 2012.
 913 Natural Recovery of a Mixed Sand and Gravel Beach after a
 914 Sequence of a Short Duration Storm and Moderate Sea States. *J.*
 915 *Coast. Res.* 28 (1), 89–101.

916 Bromirski, P.D., Cayan, D.R., 2015. Wave power variability and
 917 trends across the North Atlantic influenced by decadal climate
 918 patterns. *J. Geophys. Res. Oceans* 120, 3419–3443.

919 Brooks, S.M., Spencer, T., Christie, E.K., 2017. Storm impacts and
 920 shoreline recovery: Mechanisms and controls in the southern North
 921 Sea. *Geomorphology* 283, 48–60.

922 Burt, S., 1993. Another new North Atlantic low pressure record.
 923 Weather 48 (4), 98–103.

924 Burvingt, O., Masselink, G., Russell, P., Scott, T., 2017. Classification
 925 of beach response to extreme storms. Geomorphology 295, 722–
 926 737.

927 Buscombe, D.D., Scott, T.M., 2008. The Coastal Geomorphology of
 928 North Cornwall: St. Ives Head to Trevoise Head. Wave Hub Impact on
 929 Seabed and Shoreline Processes (WHISSP). University of Plymouth.

930 Castelle, B., Marieu, V., Bujan, S., Splinter, K.D., Robinet, A.,
 931 Sénéchal, N., Ferreira, S., 2015. Impact of the winter 2013-2014
 932 series of severe Western Europe storms on a double-barred sandy
 933 coast: beach and dune erosion and megacusp embayments.
 934 Geomorphology 238, 135-148.

935 Castelle, B., Bujan, S., Ferreira, S., Dodet, G., 2017a. Foredune
 936 morphological changes and beach recovery from the extreme
 937 2013/2014 winter at a high-energy sandy coast. Mar. Geol. 385, 41–
 938 55.

939 Castelle, B., Dodet, G., Masselink, G., Scott, T., 2017b. A new climate
 940 index controlling winter wave activity along the Atlantic coast of
 941 Europe: the West Europe Pressure Anomaly. Geophys. Res. Lett. 44.

942 Castelle, B., Dodet, G., Masselink, G., Scott, T., in prep. Increased
 943 winter-mean wave height, variability and periodicity in the North-
 944 east Atlantic over 1949-2017. Geophys. Res. Lett.

945 Ciavola, P., Coco, G., 2017. Coastal Storms: Processes and Impacts.
 946 Wiley, 1–22.

947 Choowong, M., Phantu Wongraj, S., Charoentitirat, T.,
 948 Chutakositkanon, V., Yumuang, S., Charusiri, P., 2009. Beach
 949 recovery after 2004 Indian Ocean tsunami from Phang-nga,
 950 Thailand. *Geomorphology* 104, 134–142.

951 Coco, G., Senechal, N., Rejas, A., Bryan, K.R., Capo, S., Parisot, J.P.,
 952 Brown, J.A, MacMahan, J.H.M., 2014. Beach response to a sequence
 953 of extreme storms. *Geomorphology* 204, 493–501.

954 Corbella, S., Stretch, D.D., 2012. Shoreline recovery from storms on
 955 the east coast of Southern Africa. *Nat. Hazards Earth Syst. Sci.* 12,
 956 11–22.

957 Davidson, M.A., Turner, I.L., 2009. A behavioral template beach
 958 profile model for predicting seasonal to interannual shoreline
 959 evolution. *J. Geol. Res.* 114, F01020.

960 Davidson, M.A., Lewis, R.P., Turner, I.L., 2010. Forecasting seasonal
 961 to multi-year shoreline change. *Coast. Eng.* 57, 620–629.

962 Davidson, M.A., Splinter, K.D., Turner, I.L., 2013. A simple
 963 equilibrium model for predicting shoreline change. *Coast. Eng.* 73,
 964 191–202.

965 Davidson, M.A., Turner, I.A., Splinter, K.D., Harley, M.D., 2017.
 966 Annual prediction of shoreline erosion and subsequent recovery.
 967 *Coast. Eng.* 130, 14–25.

968 Dubois, R.N, 1988. Seasonal changes in beach topography and beach
 969 volume in Delaware. *Mar. Geol.* 81 (1), 79–96.

970 Dunstone, N., Smith, D., Scaife, A., Hermanson, L., Eade, R.,
 971 Robinson, N., Andrews, M., Knight, J., 2016. Skilful predictions of the
 972 winter North Atlantic Oscillation one year ahead. *Nat. Geosci.* 9,
 973 809–814.

974 Ge, Z., Dai, Z., Pang, W., Li, S., Wei, W., Mei, X., Huang, H., Gu, J.,
 975 2017. LiDAR-based detection of the post-typhoon recovery of a
 976 meso-macro-tidal beach in the Beibu Gulf, China. *Mar. Geol.* 391,
 977 127–143.

978 Harley, M.D., Turner, I.L., Splinter, K.D., Phillips, M.S., Simmons, J.A.,
 979 2016. Beach response to Australian East Coast Lows: a comparison
 980 between the 2007 and 2015 events, Narrabeen-Collaroy Beach. *J.*
 981 *Coast. Res.* 75 (SI), 388-392.

982 Harley, M.D., Turner, I.L., Kinsela, M.A., Middleton, J.H., Mumford,
 983 P.J., Splinter, K.D., Phillips, M.S., Simmons, J.A., Hanslow, D.J., Short,
 984 A.D., 2017a. Extreme coastal erosion enhanced by anomalous
 985 extratropical storm wave direction. *Scientific Reports* 7, 6033.

986 Harley, M.D., Turner, I.L., Middleton, J.H., Kinsela, M.A., Hanslow, D.,
 987 Splinter, K.D., Mumford, P., 2017b. Observations of beach recovery
 988 in SE Australia following the June 2016 east coast low. *Coasts &*
 989 *Ports 2017 Conference – Cairns, Australia.*

990 Houser, C., Greenwood, B., 2005. Profile response of a lacustrine
 991 multiple barred nearshore to a sequence of storm events.
 992 *Geomorphology* 69, 118–137.

993 Houser, C., Wernette, P., Rentschlar, E., Jones, H., Hammond, B.,
 994 Trimble, S., 2015. Post-storm beach and dune recovery: Implications
 995 for barrier island resilience. *Geomorphology* 234, 54–63.

996 Hulme, M., 1997. The climate in the UK from November 1994 to
 997 October 1995. *Weather* 52 (8), 242–257.

998 Komar, P.D., 1999. Beach processes and sedimentation. Prentice-
 999 Hall, New Jersey, p. 544.

1000 Lozano, I., Devoy, R.J.N., May, W., Andersen, U., 2004. Storminess
 1001 and vulnerability along the Atlantic coastlines of Europe: analysis of
 1002 storm records and of a greenhouse gases induced climate scenario.
 1003 *Mar. Geol.* 210, 205–225.

1004 Masselink, G., Scott, T., Davidson, M., Russell, P., Conley, D., 2015.
 1005 The extreme 2013/2014 winter storms: hydrodynamic forcing and
 1006 coastal response along the southwest coast of England. *Earth Surf.*
 1007 *Process. Landf.* 41, 378–391.

1008 Masselink, G., Castelle, B., Scott, T., Dodet, G., Suanez, S., Jackson,
 1009 D., Floc’h, F., 2016. Extreme wave activity during 2013/2014 winter
 1010 and morphological impacts along the Atlantic coast of Europe,
 1011 *Geophys. Res. Lett.* 43, 2135–2143.

- 1012 McCallum, E., 1990. The Burn's day storm, 25 January 1990.
1013 Weather 45 (5), 166–173.
- 1014 McCallum, E., Grahame, N.S., 1993. The Braer storm – 10 January
1015 1993. Weather 48 (4), 103–107.
- 1016 McLean, R., Shen, J.S., 2006. From foreshore to foredune: foredune
1017 development over the last 30 years at Moruya Beach, New South
1018 Wales, Australia. J. Coast. Res. 22, 28–36.
- 1019 Miller, J.K., Dean, R.G., 2004. A simple new shoreline model. Coast.
1020 Eng. 51, 531–556.
- 1021 Morton, R.A., Paine, J.G., Gibeaut, J.C., 1994. Stages and Durations
1022 of post-Storm Beach Recovery, Southeastern Texas Coast, U.S.A. J.
1023 Coast. Res. 10 (4), 884–908.
- 1024 Phillips, M.S., Harley, M.D., Turner, I.L., Splinter, K.D., Cox, R.J., 2017.
1025 Shoreline recovery on wave-dominated sandy coastlines: the role of
1026 sandbar morphodynamics and nearshore wave parameters. Mar.
1027 Geol. 385, 146–159.
- 1028 Plant, N.G., Holman, R.A., Freilich, M.H., Birkemeier, W.A., 1999. A
1029 simple model for interannual sandbar behavior. J. Geoph. Res. 104
1030 (C7), 15,755–15,776.
- 1031 Poate, T., Masselink, Russell, P., Austin, M., 2014. Morphodynamic
1032 variability of high-energy macrotidal beaches, Cornwall, UK. Mar.
1033 Geol. 350, 97–111.

- 1034 Poate, T., Masselink, G., McCall, R., Russell, P., Davidson, M., 2015.
- 1035 UK storms 2014: gravel beach response. Proceedings Coastal
- 1036 Sediments, ASCE, San Diego, USA.
- 1037 Prodger, S., Russell, P., Davidson, M., Miles, J., Scott, T., 2016.
- 1038 Understanding and predicting the temporal variability in sediment
- 1039 grain size characteristics on high energy beaches. Mar. Geol. 376,
- 1040 109-117.
- 1041 Pye, K., Blott, S.J., 2008. Decadal-scale variation in dune erosion and
- 1042 accretion rates: An investigation of the significance of changing
- 1043 storm tide frequency and magnitude on the Sefton coast, UK.
- 1044 Geomorphology 102, 652–666.
- 1045 Pye, K., Blott, S.J., 2016. Assessment of beach and dune erosion and
- 1046 accretion using LiDAR: Impact of the stormy 2013–14 winter and
- 1047 longer term trends on the Sefton Coast, UK. Geomorphology 266,
- 1048 146-167.
- 1049 Roberts, T.M., Wang, P., Puleo, J.A., 2013. Storm-driven cyclic beach
- 1050 morphodynamics of a mixed sand and gravel beach along the Mid-
- 1051 Atlantic Coast, USA. Mar. Geol. 346, 403–421.
- 1052 Robinet, A., Castelle, B., Idier, I., Le Cozannet, G., Deque, M.,
- 1053 Charles, E., 2016. Statistical modelling of interannual shoreline
- 1054 change driven by North Atlantic climate variability spanning 2000–
- 1055 2014 in the Bay of Biscay. Geo. Mar. Lett. 36, 479–490.

1056 Ruggiero, P., Kaminsky, G.M., Gelfenbaum, G., Voigt, B., 2005.
1057 Seasonal to Interannual Morphodynamics along a High-Energy
1058 Dissipative Littoral Cell. *J. Coast. Res.* 21 (3), 553–578.

1059 Sallenger, A.H., 2000. Storm Impact Scale for Barrier Islands. *J.*
1060 *Coast. Res.* 16 (3), 890–895.

1061 Saulter, A., 2017. North West European Shelf Production Centre
1062 NORTHWESTSHELF_ANALYSIS_FORECAST_WAV_004_012 Quality
1063 Information Document. Copernicus Marine Environment Monitoring
1064 service.

1065 Senechal, N., Gouriou, T., Castelle, B., Parisot, J.-P., Capo, S., Bujan,
1066 S., Howa, H., 2009. Morphodynamic response of a meso- to macro-
1067 tidal intermediate beach based on a long-term data set.
1068 *Geomorphology* 107, 263–274.

1069 Senechal, N., Coco, G., Castelle, B., Marieu, V., 2015. Storm impact
1070 on the seasonal shoreline dynamics of a meso- to macrotidal open
1071 sandy beach (Biscarrosse, France). *Geomorphology* 228, 448–461.

1072 Scott, T.M., 2009. Beach Morphodynamics and Associated Hazards
1073 in the UK. (Ph.D. thesis). University of Plymouth.

1074 Scott, T., Masselink G., Russell P., 2011. Morphodynamic
1075 characteristics and classification of beaches in England and Wales.
1076 *Mar. Geol.* 286, 1-20.

1077 Scott, T., Masselink, G., O'Hare, T., Saulter, A., Poate, T., Russell, P.,
1078 Davidson, M., Conley, D., 2016. The extreme 2013/2014 winter

1079 storms: Beach recovery along the southwest coast of England. *Mar.*
 1080 *Geol.* 382, 224–241.

1081 Short, A.D., Bracs, M.A., Turner, I.L., 2014. Beach oscillation and
 1082 rotation: local and regional response at three beaches in southeast
 1083 Australia. *J. Coast. Res.* 70 (SI), 712–717.

1084 Splinter, K.D., Strauss, D.R., Tomlinson, R.B., 2011. Assessment of
 1085 post-storm recovery of beaches using video imaging techniques: a
 1086 case study at Gold Coast, Australia. *IEEE Trans. Geosci. Remote Sens.*
 1087 49 (12), 4704–4716.

1088 Splinter, K.D., Turner, I.L., Davidson, M.A., 2013. How much data is
 1089 enough? The importance of morphological sampling interval and
 1090 duration for calibration of empirical shoreline models. *Coast. Eng.*
 1091 77, 14–27.

1092 Splinter, K.D., Turner, I.L., Davidson, M.A., Barnard, P., Castelle, B.,
 1093 Oltman-Shay, J., 2014. A generalized equilibrium model for
 1094 predicting daily to interannual shoreline response. *J. Geophys. Res.*
 1095 *Earth Surf.* 119, 1936–1958.

1096 Stive, M.J.F., Aarninkhof, S.G.J., Hamm, L., Hanson, H., Larson,
 1097 M., Wijnberg, K.M., Nicholls, R.J., Capobianco, M., 2002. Variability of
 1098 shore and shoreline evolution. *Coast. Eng.* 47, 211–235.

1099 Stockdon, H.F., Holman, R.A., Howd, P.A., Sallenger, A.H., 2006.
 1100 Empirical parameterization of setup, swash, and runup. *Coast. Eng.*
 1101 53, 573–588.

1102 Suanez, S., Cariolet, J.M., Cancouët, R., Ardhuin, F., Delacourt, C.,
 1103 2012. Dune recovery after storm erosion on a high-energy beach:
 1104 Vougot Beach, Brittany (France). *Geomorphology* 139-140, 16–33.

 1105 Sutherland, J., Peet, A.H., Soulsby, R.L., 2004. Evaluating the
 1106 performance of morphological models. *Coast. Eng.* 51, 917– 939.

 1107 Thom, B.H., Hall, W., 1991. Behaviour of beach profiles during
 1108 accretion and erosion dominated period. *Earth Surf. Process. Landf.*
 1109 16, 113–127.

 1110 Turner, I.L., Harley, M.D., Short, A.D., Simmons, J.A., Bracs, M.A.,
 1111 Phillips, M.S., Splinter, K.D., 2016. A multi-decade dataset of
 1112 monthly beach profile surveys and inshore wave forcing at
 1113 Narrabeen, Australia. *Scientific Data* 3, 160024.

 1114 Valiente, N.G., Masselink, G., Scott, T., Conley, D., McCarroll, R.J., in
 1115 prep. Depth of closure: a multi-criteria approach for a macrotidal,
 1116 embayed and exposed coast. *J. Geophy. Res.*

 1117 Voudoukas, M.I., Almeida, L.P.M., Ferreira, Ó., 2012. Beach erosion
 1118 and recovery during consecutive storms at a steep-sloping, meso-
 1119 tidal beach. *Earth Surf. Process. Landf.* 37 (6), 583–593.

 1120 Wang, P., Kirby, J.H., Haber, J.D., Horwitz, M.H., Knorr, P.O., Krock,
 1121 J.R., 2006. Morphological and sedimentological impacts of hurricane
 1122 Ivan and immediate post-storm beach recovery along the
 1123 Northwestern Florida barrier-island coasts. *J. Coast. Res.* 6, 1382–
 1124 1402.

1125 Wiggins, M., Scott, T., Masselink, G., Russell, P., in prep. Controls on
 1126 full embayment sediment dynamics: a decade of multi-method
 1127 surveys.

1128 Wright, L.D., Short, A.D., 1984. Morphodynamic variability of surf
 1129 zones and beaches: a synthesis. *Mar. Geol.* 56, 93–118.

1130 Wright, L.D., Short, A.D., Green, M.O., 1985. Short-term changes in
 1131 the morphodynamic states of beaches and surf zones; an empirical
 1132 predictive model. *Mar. Geol.* 62, 339–364.

1133 Yu, F., Switzer, A.D., Lau, A.Y.A, Yeung, H.Y.E, Chik, S.W., Chiu, H.C.,
 1134 Huang, Z., Pile, J., 2013. A comparison of the post-storm recovery of
 1135 two sandy beaches on Hong Kong Island, southern China.
 1136 *Quaternary International* 304, 163–175.

1137 Zhang, K., Douglas, B., Leatherman, S., 2002. Do Storms Cause Long-
 1138 Term Beach Erosion along the U.S. East Barrier Coast? *J. Geol.* 110
 1139 (4), 493–502.

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, Fistril #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 ($H_{s\ 1\% \text{ exceedance}}$)
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 Fistril #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 α : 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.