

2015-08-15

Observation and prediction of three-dimensional morphology at a high-energy macrotidal beach

Stokes, C

<http://hdl.handle.net/10026.1/3668>

10.1016/j.geomorph.2015.04.024

GEOMORPHOLOGY

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.

1 **Observation and Prediction of Three-Dimensional**

2 **Morphology at a High Energy Macrotidal Beach**

3 **Christopher Stokes***, Mark Davidson, Paul Russell

School of Marine Science and Engineering, Christopher.Stokes@plymouth.ac.uk

University of Plymouth, Drake Circus, M.Davidson@plymouth.ac.uk

Plymouth, PL4 8AA, UK.

P.Russell@plymouth.ac.uk

4

5 *Corresponding author, tel.: +44 (0)1752 586102, email: Christopher.Stokes@plymouth.ac.uk, post:

6 School of Marine Science and Engineering, University of Plymouth, Plymouth, PL4 8AA, UK.

7

8 **Abstract**

9 Three-dimensional beach features such as crescentic sandbars and rip channels influence beach
10 response to, and recovery from, storm waves, as well as significantly affecting the safety and
11 amenity provided by the surf-zone for beach water-users. In this contribution temporal variations in
12 subtidal and intertidal beach three-dimensionality are observed at a high-energy macrotidal beach,
13 and a simple equilibrium model is developed to predict the changes over multi-year timescales. A
14 dataset of 5.5 years of quasi-weekly bar measurements, and quasi-monthly intertidal surveys from
15 Perranporth beach (Cornwall, UK) were used to quantify seasonal to inter-annual changes in three-
16 dimensionality. The three-dimensionality of the outer bar displayed significant annual periodicity,
17 with annual minima and maxima occurring in winter and spring, respectively. The lower intertidal
18 beach displayed a similar periodicity, but developed three-dimensionality 1-4 months before the

19 outer bar. The model predicts increases or decreases in the scale of three-dimensional features by
20 examining the disparity between instantaneous wave conditions and a temporally varying
21 equilibrium wave condition. A tidally-modulated wave power term determines the rate of
22 morphological change. Negative feedback was found to be an important process governing the
23 changes in three-dimensionality; while free morphological behaviour may drive three-dimensional
24 growth, negative feedback exerts stability in the system, making it inherently predictable using a
25 temporally varying equilibrium value. The model explained 42% and 61% of the overall variability in
26 outer bar and lower beach three-dimensionality, respectively. It skilfully predicted changes outside
27 the training data range, during the most energetic 8-week period of waves measured in the last 65
28 years off SW England, in winter 2013/14. The model outperformed a simple baseline model (a linear
29 fit), as well as a comparable linearized feedback model from the literature, providing the first long-
30 term (multi-year) predictions of seasonal to inter-annual beach three-dimensionality for a macrotidal
31 beach.

32 **Keywords:** Three-dimensional, sandbar, morphology, equilibrium, behavioural, macrotidal

33 **1. Introduction**

34 **1.1 Background and rationale**

35 Much of our conceptual understanding about the variability of beach morphology comes from
36 sequential models developed for single-barred microtidal beaches in Australia (Short, 1979; Wright
37 and Short, 1984; Wright *et al.*, 1985). Through extensive field observations made over a number of
38 years, Wright and Short (1984) reduced the natural continuum of beach forms into a sequence of 6
39 discrete states. The end-members of the model have a shallow gradient in the Dissipative (D)
40 extreme, or a steep gradient in the Reflective (R) extreme, both of which consist of a planar beach
41 face with little alongshore variability. The intermediate stages (Longshore Bar and Trough - LBT,
42 Rhythmic Bar and Beach - RBB, Transverse Bar and Rip - TBR, Low Tide Terrace - LTT) are typified by

43 greatly increased alongshore variability in the form of rip channels, and crescentic bar formations.
44 The general applicability of this sequence has subsequently been verified at other sites and
45 extended to include beaches with meso- and macro-tidal range (Short, 1991; Masselink and Short,
46 1993; Masselink and Hegge, 1995; Scott *et al.*, 2011; Masselink *et al.*, 2014), double or multi-bar
47 systems (Short, 1992; Short and Aagaard, 1993; Castelle *et al.*, 2007; Scott *et al.*, 2011), and beaches
48 with dominant headlands or geological features (Short, 1996; Castelle and Coco, 2012; Loureiro *et*
49 *al.*, 2012). Although the intermediate beach forms observed in the different studies vary slightly,
50 they all feature alongshore non-uniformities such as rip channels and crescentic bars, collectively
51 referred to as three-dimensional (3D) morphology (see Fig. 1 for example images).

52 Beach morphology often becomes 3D during the recovery period following energetic waves, when
53 the straightened, offshore bar(s) migrates back toward shore unevenly under the action of accretive,
54 low-steepness waves (Short, 1979; Wright and Short, 1984; Lippmann and Holman, 1990; Poate *et*
55 *al.*, 2014). The result is a sinuous, crescentic bar which can either be rhythmic in form, or a range of
56 wavelengths (from 150 m – 2 km) and cross-shore amplitudes (from 5 – 80 m) can occur (Van
57 Enckevort *et al.*, 2004). Under sustained accretive conditions the shoreward bar horns will eventually
58 weld to the shore, resulting in the highly 3D TBR beach state. The final states in the ‘downstate’
59 sequence feature diminishing three-dimensionality, and a bar that is close to shore (LTT and R). The
60 landward return of sediment during this downstate sequence forms an important mechanism for
61 beach recovery following erosive, ‘upstate’ conditions. Conversely the presence of 3D features such
62 as cusps and rip channels during a storm can potentially allow erosive swashes to reach further
63 landward and undercut the dune foot (Thornton *et al.*, 2007). 3D morphology therefore heavily
64 influences a beach’s response to, and recovery from, storm waves.

65 3D features also significantly affect the safety and amenity provided by the surf-zone for beach
66 water-users. The alongshore varying morphology causes localised refraction and breaking; while
67 these factors improve the amenity provided by waves for popular recreational activities such as

68 surfing (Mead and Black, 2001a; Mead and Black, 2001b; Scarfe et al., 2009), they also influence the
69 type and strength of surf-zone currents (Bowen, 1969; Ranasinghe *et al.*, 2004). Rip channels allow
70 water set-up by wave breaking to funnel back out to sea in concentrated offshore flows (Fig. 1)
71 which can take water-users from the shallows out into deeper water (MacMahan *et al.*, 2006; Austin
72 *et al.*, 2010). As a result rip currents are the largest cause of surf-zone rescues and fatalities globally
73 (Scott *et al.*, 2008; MacMahan *et al.*, 2011; Scott *et al.*, 2011; Brighton *et al.*, 2013). In the UK 90% of
74 rip incidents occur during the highly 3D intermediate Low Tide Bar-Rip (LTBR) and LTT with rip
75 (LTT+R) beach states (Scott *et al.*, 2008), which are analogous to the TBR and LTT states.

76 **1.2 Approaches to modelling three-dimensional morphology**

77 Process-based models have shown that horizontal wave-driven circulation in the nearshore
78 contributes to the growth of 3D morphology through positive feedback between the developing
79 morphology and local hydrodynamics, termed bed-surf coupling (Falqués *et al.*, 2000; Caballeria *et al.*
80 *et al.*, 2002; Caballeria *et al.*, 2003a; Caballeria *et al.*, 2003b; Ranasinghe *et al.*, 2004). In the case of
81 subtidal bars, this process starts with waves breaking preferentially over the shallowest bar sections.
82 The dispersion of energy and gradient of the beach decelerates the shoreward flowing water,
83 promoting a decreasing sediment flux and sand deposition directly shoreward of the bar, further
84 reducing the water depth and enhancing wave breaking in that region (Falqués *et al.*, 2000; Falqués
85 *et al.*, 2008). The water set-up by the breakers locally increases hydrostatic pressure and forces an
86 alongshore flow away from the region of breaking. These flows converge at points between the
87 shallow regions of wave breaking, and return seaward over the deeper portions of the sandbar crest,
88 creating horizontal circulation (Fig. 1) (Falqués *et al.*, 2000; Ranasinghe *et al.*, 2004). The offshore-
89 directed return flows are coupled with increasing sediment fluxes and sand erosion, enhancing the
90 depth of the channels between the horns. Eventually the developing morphology begins to hinder
91 the sediment transport and the initial positive feedback diminishes as equilibrium is approached
92 (Smit *et al.*, 2008). This 'negative feedback' has been shown to play an important role in controlling
93 free morphological behaviour, making the system inherently predictable (Plant *et al.*, 2006).

94 Behavioural models provide an alternative approach to process-based modelling of 3D morphology.
95 Although sometimes criticized for consisting of incomplete physical representations (Splinter *et al.*,
96 2011; Van de Lageweg *et al.*, 2013) or being overly dependent on tuning parameters (Ruessink *et al.*,
97 2013), behavioural models are often capable of explaining substantial amounts of data variance and
98 accurately forecasting large-scale beach changes over multiyear timescales (e.g. Plant *et al.*, 1999;
99 Yates *et al.*, 2009; Davidson *et al.*, 2010; Splinter *et al.*, 2011; Davidson *et al.*, 2013a), which is
100 presently unachievable using process-based models. Wright *et al.* (1985) proposed a behavioural
101 beach state model based on the assumption that state changes occur when instantaneous wave
102 conditions differ from the conditions associated with zero change for each state, termed the
103 disequilibrium stress, $\Delta\Omega$:

$$104 \quad \Delta\Omega = \Omega - \Omega_{eq} \quad (1)$$

105 where Ω and Ω_{eq} are the instantaneous and equilibrium dimensionless fall velocity respectively
106 (Gourlay, 1968; Dean, 1973):

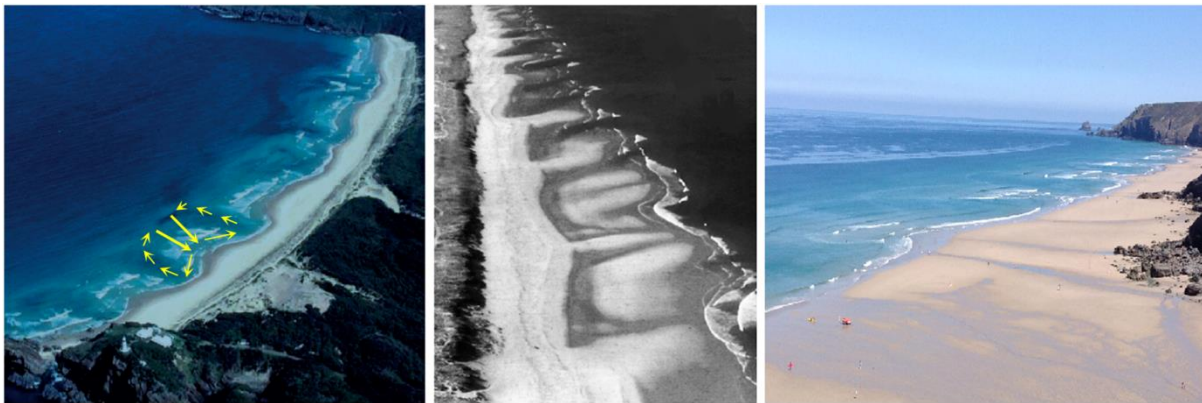
$$107 \quad \Omega = H_b / \bar{W}_s T_p \quad (2)$$

108 H_b is significant wave height (H_s) at breaking, \bar{W}_s is the mean sediment fall velocity, and T_p is the
109 peak wave period. Large departures from equilibrium (large $\Delta\Omega$) represent an increased potential for
110 change, and upstate and downstate changes occur under positive and negative disequilibrium,
111 respectively. As instantaneous conditions approach the equilibrium condition ($\Omega \rightarrow \Omega_{eq}$) the
112 morphological change appropriately reduces to zero. Although successful predictions of beach state
113 were not achieved by Wright *et al.* (1985), their approach recognizes the importance of negative
114 feedback in maintaining system stability, and the concept may therefore be suited to predicting
115 beach three-dimensionality. Disequilibrium stress has since been used in adapted forms to predict
116 cross-shore shoreline (Yates *et al.*, 2009; Davidson *et al.*, 2010; Yates *et al.*, 2011; Davidson *et al.*,
117 2013a; Castelle *et al.*, 2014; Splinter *et al.*, 2014) and barline (Plant *et al.*, 1999; Masselink *et al.*,

118 2014) migration under varying waves, but is yet to be applied to the prediction of alongshore non-
119 uniform changes. Other attempts to behaviourally model three-dimensionality have either been
120 restricted to single storm cycles (Plant *et al.*, 2006) or have included relatively complex sediment
121 transport parameterisations, with limited predictive improvement (Splinter *et al.*, 2011).

122 1.3 Aims

123 This study aims to investigate the temporal variability of seasonal to inter-annual, subtidal and
124 intertidal beach three-dimensionality at a high energy, macrotidal beach (Perranporth, Cornwall,
125 UK). A morphological data set consisting of 5.5 years of monthly intertidal surveys and quasi-daily
126 Argus barline observations presents an opportunity to apply disequilibrium stress to the prediction
127 of subtidal and intertidal three-dimensionality for the first time. Furthermore this will be the first
128 attempt to model multi-year changes in three-dimensionality at a macrotidal beach.



129

130 **Figure 1.** Examples of three-dimensional beach morphology from the microtidal New South Wales coast, Australia (Price
131 *et al.*, 2014), meso-macrotidal Aquatanian coast, France (Castelle *et al.*, 2007), and macrotidal North Cornwall coast,
132 England (left to right panels respectively). Yellow arrows demonstrate typical wave-driven horizontal cell circulation
133 with seaward directed rip current component.

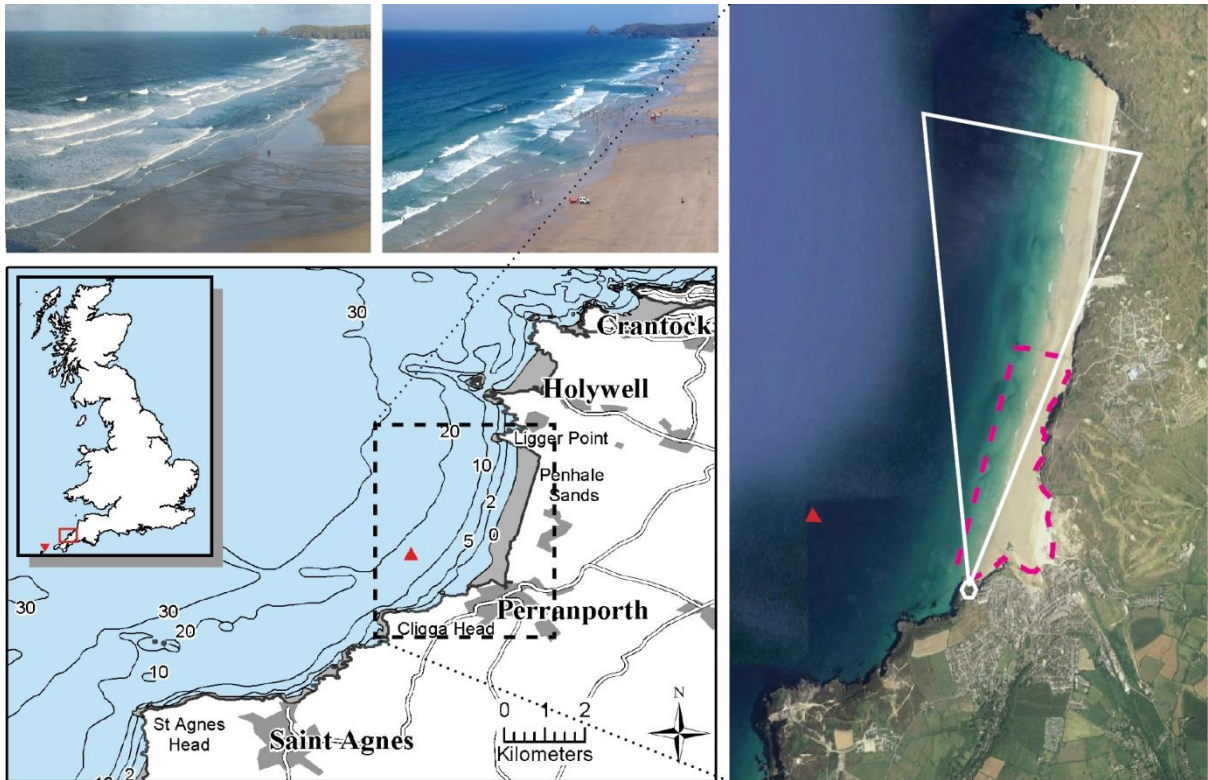
134

135 2. Methods

136 2.1 Study area

137 Perranporth (PPT) beach on the North West coast of Cornwall, UK (Fig. 2) is fully exposed to the
138 dominant westerly wave approach, receiving an energetic wave climate of Atlantic swell and locally
139 generated wind seas (Davidson *et al.*, 1997). The directional wave rider buoy located just offshore in
140 approximately 15 m water depth (upwards triangle, Fig. 2) measured mean and maximum significant
141 wave heights, H_s , of 1.6 m and 7.2 m, respectively, and a mean peak period, T_p , and direction, θ_p ,
142 of 10.6 s and 283°, respectively, between January 2007 and May 2014. The region is macrotidal, with
143 mean neap and spring tide ranges of 3.1 m and 6.1 m, respectively. The beach is 3.4 km long with a
144 cross-shore extent of approximately 500 m at spring low tide. Devonian hard rock cliffs and steep
145 vegetated dunes surround the beach. The sediment is composed of medium quartz sand with a
146 median grain size D_{50} (mean fall velocity $\overline{W_s}$) of 0.35 mm (0.04 m s^{-1}) (Poate *et al.*, 2014). The lower
147 beach gradient is shallow ($\tan\beta \approx 0.012$), but compared to the subdued (<1 m vertical range) and
148 alongshore-uniform morphology that characterise the upper beach, the region below mean-low-
149 water-neap (MLWN) is highly dynamic (2 m vertical range), and the double bar system regularly
150 exhibits pronounced crescentic bar and rip features (see example in Fig. 3) (Poate, 2011; Austin *et*
151 *al.*, 2013; Masselink *et al.*, 2014).

152



153

154 Figure 2. Map of study site and example morphology. The bottom left panel shows the geographic location and
 155 bathymetry of Perranporth beach. The right panel shows the location (white octagon) and field of view (large white
 156 triangle) of the Argus camera, and the typical intertidal survey extents (dashed magenta region). The position of the
 157 nearshore wave buoy is shown in the bottom left and right panels as an upwards pointing triangle, while the deep-water
 158 wave buoy is shown in the inset map as a downwards pointing triangle. The top left and top middle panels show
 159 examples of 2D (without rips) and 3D (with rips) morphology, taken from the Argus station vantage point in August and
 160 November 2008, respectively.

161 **2.2 Observation of beach three-dimensionality**

162 **2.2.1 Video data**

163 An elevated Argus video camera located at the southern end of the beach (Fig. 2) collected time
 164 exposure (timex) images of the lower intertidal and subtidal regions between September 2008 and
 165 April 2014. As a result of the preferential breaking of waves over the shallow bar crests, foam is
 166 often visible on the water surface at the position of the sandbars, creating conspicuous bands of
 167 high pixel intensity that reveal the position of the underlying bars (Lippmann and Holman, 1989). A
 168 barline intensity mapping tool (Pape *et al.*, 2007) was used to detect the inner and outer bar crest

169 positions by the alongshore tracking of the intensity maxima within the surf zone (Fig. 3). The
170 barlines were measured at 1 m intervals, between -1700 m and -200 m alongshore. The detected
171 barline positions can be artificially shifted due to tide and wave conditions (Kingston *et al.*, 2000; Van
172 Enckevort and Ruessink, 2001). To minimize tidal shifting, a single low tide image was selected for
173 each day (Van Enckevort and Ruessink, 2001), and to minimize the combined effects of a large tide
174 range and large waves, or a small tide range with small waves, images were also constrained by the
175 Hydrodynamic Forcing Index (Almar *et al.*, 2010):

$$176 \quad \text{HFI} = \frac{H_s}{d_{\min}} \quad (3)$$

177 where H_s is averaged over a tidal cycle and d_{\min} is the lowest water level above the lowest
178 astronomical tide experienced during a tidal cycle. To maximise clear breaking over the bars, only
179 images collected within the following hydrodynamic constraints were used:

$$180 \quad 0.5 \text{ m} < H_s < 2 \text{ m}$$

$$181 \quad 0.9 < \text{HFI} < 2$$

182 Images were also unavailable during poor light and weather conditions, or occasionally due to
183 technical issues with the camera system. Of the 2067 days of the study period 254 usable images
184 were obtained, with a minimum, mean and maximum interval of 1, 8 and 74 days, respectively.

185 *2.2.2 Topographic surveys*

186 Topographic surveys were conducted using an RTK-GPS system mounted on an all-terrain vehicle
187 (ATV) each month between October 2008 and April 2014. The surveys were conducted around low
188 tide during the largest spring tide of each month, to maximise beach coverage. Typical survey
189 extents are shown in Fig. 2. A total of 64 monthly surveys were conducted, with a minimum, mean
190 and maximum interval of 16, 32 and 73 days respectively. The collected topographic data were used
191 to generate digital elevation maps (DEM's), which were converted from OSGB36 coordinates by

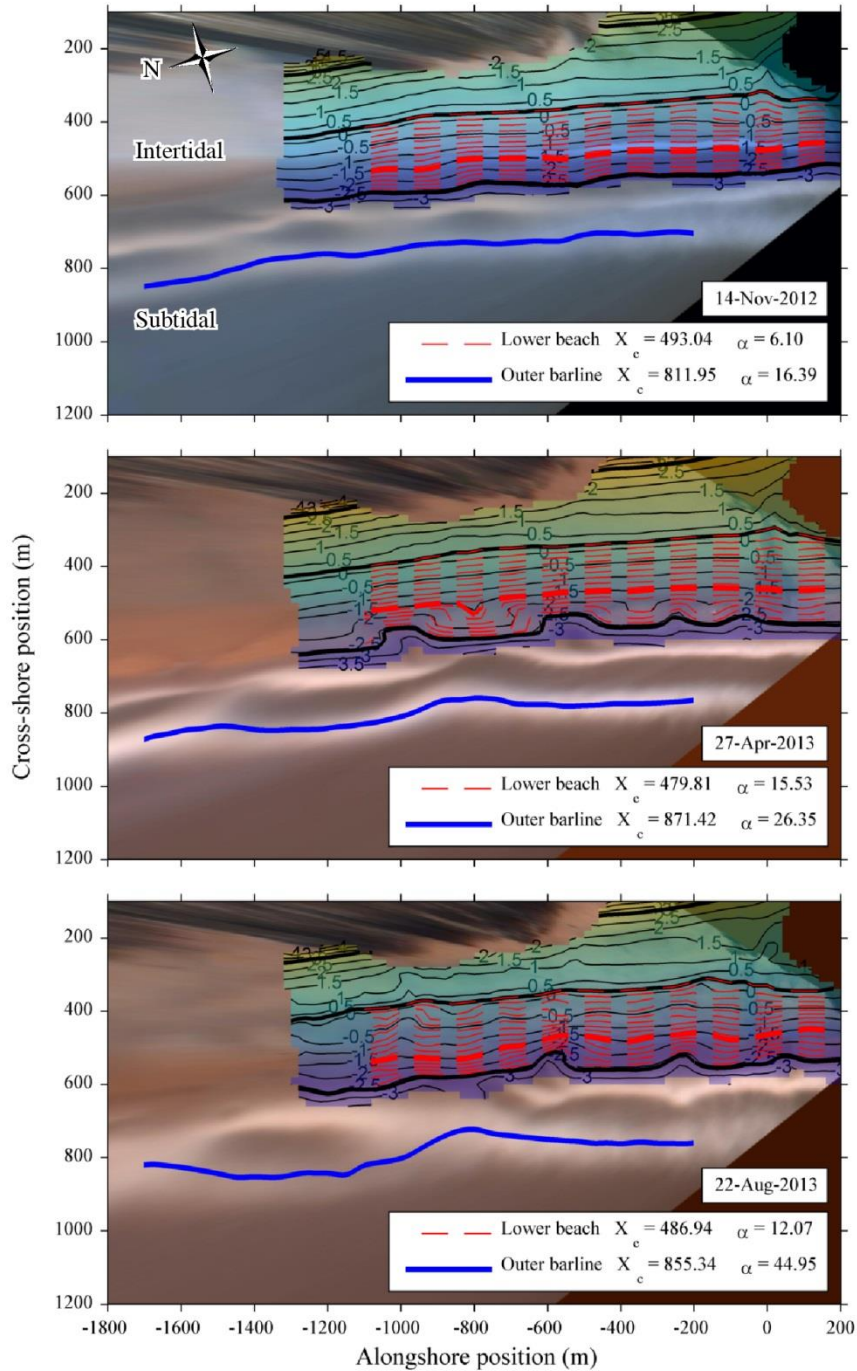
192 rotation and translation to the same local grid as used by the Argus camera system (Fig. 3). The data
193 were gridded at 20 m resolution in both the alongshore and cross-shore directions with a quadratic
194 loess interpolation scheme (Plant *et al.*, 2002).

195 2.2.3 Parameterisation of three-dimensionality

196 To objectively quantify the three-dimensionality of the subtidal bars, the standard deviation, α ,
197 about the alongshore averaged cross-shore position, X_c , of the barlines was measured in keeping
198 with previous studies of barline variability (Plant *et al.*, 2006; Splinter *et al.*, 2011). To obtain a single
199 representative measure of α at the lower beach, contours were extracted from each DEM every 0.2
200 m between +0.2 m Ordnance Datum Newlyn (ODN) and -2.4 m ODN (between -1100 m and 200 m
201 alongshore, thin dashed lines in Fig. 3), and the mean of the highest 1/3rd of α values was used.
202 Short contours covering less than 2/3rd of the alongshore length of the survey area were omitted to
203 avoid erroneous α values. It is recognised that across flat, non-sloping sections this parameter could
204 incorrectly yield large values of α . As the lower beach region at Perranporth was either planar and
205 gently sloping, or exhibited 3D features in this data set, this was not deemed to be an issue and α
206 was used in the form described above for consistency with the barline measurements. At sites which
207 exhibit flat profile sections, other computations of α should be considered however. The MLWN
208 contour (thick dashed line in Fig. 3) was chosen to represent the cross-shore position (X_c) of the
209 lower beach. Before calculating α the barlines and contours were linearly de-trended, then band-
210 pass filtered between 25 and 1000 m. For reference, 0 m ODN is approximately Mean Sea Level
211 (MSL) at this beach.

212 To estimate measurement errors Argus detected barlines were compared to residual barlines
213 (Masselink *et al.*, 2014) from 10 bathymetric surveys. The root-mean-square measurement errors,
214 ΔX_c and $\Delta \alpha$, were 13.82 m and 4.78 m, respectively, at the outer bar. The inner bar data were
215 deemed to have excessively large $\Delta \alpha$ (16.55 m), which is thought to be due to saturation of the inner
216 surf-zone at low tide when the Argus images were collected. As such the inner bar data are not

217 included in this study. The measurement error from the intertidal contours was conservatively
218 estimated by summing the accuracy of the RTK-GPS equipment (± 0.03 m) and maximum
219 interpolation error (± 0.05 m), resulting in ΔX_c and $\Delta\alpha$ of 0.08 m and 0.16 m, respectively. As
220 seasonal and inter-annual changes are of primary interest, the α and X_c time series were low-pass
221 filtered using a frequency domain Fourier filter with 1/42 days cut off, chosen to be sufficiently
222 longer than the timescale of individual storms yet shorter than an individual season. Examples of α
223 and X_c measured at the lower beach, and outer bar are shown in Fig. 3. The data time series are
224 plotted in Fig. 5, where vertical dotted lines indicate the data measured in Fig. 3.



225

226

Figure 3. Combined topographic survey data (semi-transparent contour plots) and rectified timex images from

227

Perranporth beach, demonstrating seasonal changes in three-dimensionality. The thin dashed lines and thick subtidal

228

line in each plot show the lower beach contours and outer barline respectively, used to determine the three-

229

dimensionality, α , of the intertidal and subtidal regions respectively. The thick dashed line shows the MLWN contour

230

used to represent the cross-shore position of the lower beach. The solid contour lines show elevation (m) above ODN,

231

and the thick lines indicate (top to bottom) Mean-High-Water-Spring, Mean-Sea-Level and Mean-Low-Water-Spring,

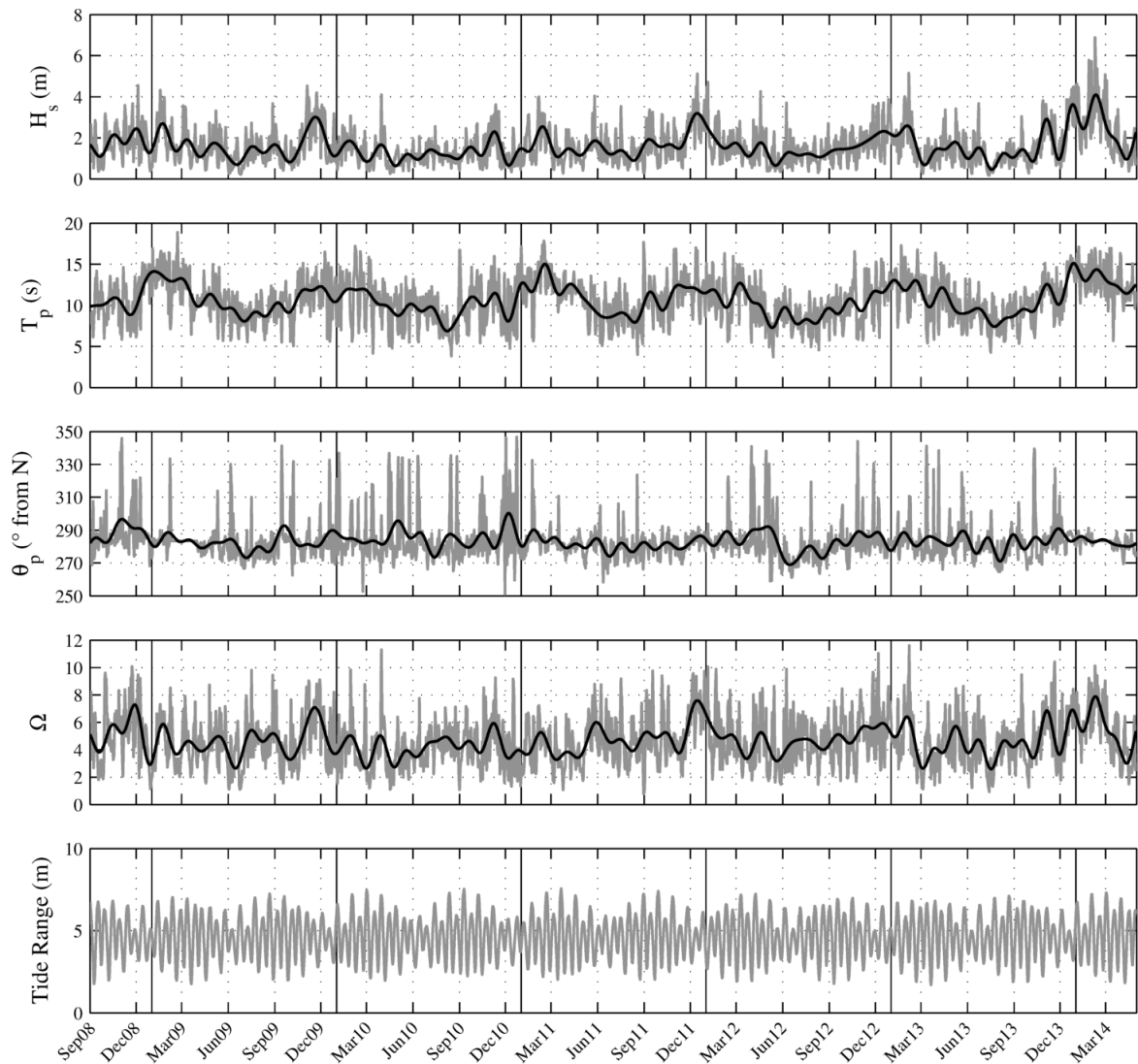
232

respectively.

233

234 **2.3 Wave and tide data**

235 Wave data were provided by a nearshore Datawell Waverider III buoy (Fig. 2), moored at a water
236 depth of approximately 15 m. The half hourly wave statistics were used to calculate daily mean
237 values of significant wave height, H_s , peak wave period, T_p , and peak wave direction, θ_p . Occasional
238 gaps exist in the wave series; daily mean parameters were calculated for days with at least 75% of
239 measurements present, leaving 203 days (7.6 %) over the period of interest (2007 – 2014) with
240 missing measurements. These gaps were filled using adjusted wave data from the Sevenstones
241 lightship, located in deep water approximately 70 km south-west of PPT (Fig. 2). A linear fit between
242 the PPT and Sevenstones data was used to adjust the deep water data to approximate nearshore
243 conditions. Correlation between the available PPT measurements and the concurrent adjusted
244 Sevenstones measurements was high ($r = 0.92$ and 0.81 , $RMSE = 0.36$ m and 1.68 s, for H_s and T_p ,
245 respectively). Remaining H_s and T_p data gaps (16 days, 0.6 %) and all gaps in θ_p (203 days, 7.6 %)
246 were filled using time-series mean values. H_b was calculated from linear theory using the formula of
247 Larson *et al.* (2010), and depth-limited breaking was imposed using a commonly applied depth
248 breaker ratio of 0.78 (Sverdrup and Munk, 1946). A continuous prediction of tidal elevation over the
249 period of interest was generated from pressure transducer data from a 3 month deployment (Poate,
250 2011). Example wave and tide data are shown in Fig. 4.



251

252 **Figure 4. Wave and tide measurements over the study period. H_s , T_p and θ_p are plotted as measured by the PPT wave**
 253 **buoy in ~15 m depth. Thin lines are daily average values, thick lines show the seasonal signal, after low-pass filtering**
 254 **with a 1/42 day cut-off. Vertical lines indicate the start of each year.**

255

256 **2.4 Modelling beach three-dimensionality**

257 *2.4.1 DST13 model.*

258 Davidson *et al.* (2010; 2013a; 2013b) applied the concept of disequilibrium stress to the prediction of
 259 cross-shore shoreline position at two Australian beaches; their formula are developed here to better
 260 suit the prediction of three-dimensionality (α). The adapted model predicts the rate of change in α ,
 261 taking the following form (herein referred to as DST13):

262 $\frac{d\alpha}{dt} = b + c(F^+ + rF^-)$ (4)

263 The forcing term F is defined as the product of the incident wave power raised to the 0.5 exponent,
 264 $P^{0.5}$, and the normalised disequilibrium ($\Delta\Omega$):

265 $F = P^{0.5} \frac{\Delta\Omega}{\sigma_{\Delta\Omega}}$ (5)

266 $\Delta\Omega$ controls the direction of beach change (2D to 3D or 3D to 2D) and for convenience positive
 267 values are associated with increasing three-dimensionality by changing the sign of Eq. (1) (therefore
 268 $\Delta\Omega = \Omega_{\text{eq}} - \Omega$). Following Splinter *et al.* (2014) $\Delta\Omega$ is normalised by its standard deviation (denoted
 269 $\sigma_{\Delta\Omega}$ in Eq. 5), so that the rate of change in α is predominantly controlled by the rate parameter, c ,
 270 and the wave power ($P^{0.5}$), rather than the magnitude of $\Delta\Omega$. Ω_{eq} is determined from weighted
 271 antecedent values of Ω , and is highly dependent on a memory decay parameter ϕ , which
 272 determines the number of days, i , prior to the present time at which the weighting function has
 273 dropped to 10%:

274 $\Omega_{\text{eq}} = \left[\sum_{i=1}^{2\phi} 10^{-i/\phi} \right]^{-1} \sum_{i=1}^{2\phi} \Omega_i 10^{-i/\phi}$ (6)

275 Low ϕ values (<30 days) indicate a short, storm dominated response time, whereas large values
 276 (>100 days) indicate that variations from the long-term mean conditions cause changes in α
 277 (Davidson *et al.*, 2013a). Example weightings are discussed in section 4.2.

278 Water depth over the bar crest, and by association tidal range, have been recognised as important
 279 modulators of wave driven horizontal circulation and therefore the development of 3D morphology
 280 (Caballeria *et al.*, 2003a; Caballeria *et al.*, 2003b; Almar *et al.*, 2010; Austin *et al.*, 2013). Austin *et al.*
 281 (2013) for example found that rip currents at Perranporth reached maximum velocities around
 282 spring low tide, which is likely to enhance the sediment transport potential. The forcing term F is
 283 therefore modified to include the combined effects of a large tidal range and high wave power by

284 adapting a previously used parameter, the normalised wave power, $P\eta_o$ (Morris *et al.*, 2001;
 285 Loureiro *et al.*, 2012):

$$286 \quad P\eta_o = P^{0.5}(\eta_{dtr}/\eta_{str}) \quad (7)$$

287 where η_{dtr} and η_{str} are the maximum daily and spring tide ranges respectively. When the tide range
 288 approaches its overall (spring tide) maximum, the ratio on the right-hand side approaches unity and
 289 the normalised wave power is maximised. Conversely during neap tides the ratio drops to around $\frac{1}{2}$,
 290 reducing the normalised wave power by half. In initial tests, inclusion of this tidally modulated
 291 power term made little difference to the lower beach predictions (R^2 was 0.61 in both cases), but
 292 significantly improved model skill at the outer bar, increasing R^2 from 0.32 to 0.42. The Relative Tide
 293 Range parameter (Masselink and Short, 1993) and HFI parameter (Almar *et al.*, 2010) were also
 294 tested but did not yield comparable model improvements.

295 Recognising that increasing and decreasing three-dimensionality are caused by different physical
 296 processes, the forcing term F is broken into positive and negative elements in Eq. (4):

$$297 \quad F = P\eta_o \frac{\Delta\Omega}{\sigma\Delta\Omega} \quad (8)$$

$$298 \quad F^+ = P\eta_o \frac{\Delta\Omega}{\sigma\Delta\Omega} \quad (\text{when } \Omega < \Omega_{eq}) \quad (8a)$$

$$299 \quad F^- = P\eta_o \frac{\Delta\Omega}{\sigma\Delta\Omega} \quad (\text{when } \Omega > \Omega_{eq}) \quad (8b)$$

300 The relative weighting of F^+ and F^- are determined by the ratio term r in Eq. (4); this is calculated
 301 from the wave data and is therefore not considered a ‘model free’ parameter. r describes the
 302 relative efficiency of positive and negative disequilibria in altering the beach three-dimensionality,
 303 and long-term equilibrium is maintained if:

$$304 \quad r = \left| \frac{\sum_{i=0}^N \hat{F}_i^+}{\sum_{i=0}^N \hat{F}_i^-} \right| \quad (9)$$

305 N is the length of the time series, and the triangular over-bar represents a numerical operation that
 306 removes any linear trend in F, but retains the time-series mean. As negative disequilibrium (e.g.
 307 storms) often has higher associated wave power, a strong tendency towards beach straightening
 308 would be predicted if only F was considered. Instead r is determined such that zero trend in the
 309 forcing results in zero trend in α , and therefore the term $(F^+ + rF^-)$ only contributes to a predicted
 310 trend if one exists in the wave forcing series. Any trend in α not explained by trends in the wave
 311 series is handled (albeit crudely) by the trend term b in Eq. (4).

312 To predict values of α at times t , F and r are computed from the wave data and Eq. (4) is numerically
 313 integrated with respect to time, yielding the final model equation:

$$314 \quad \alpha(t) = a + bt + c \int_0^t (F^+ + rF^-) dt \quad (10)$$

315 where a is an offset that deals with non-zero mean values of α . Eq. (10) is regressed against
 316 observed values of $\alpha(t)$ using a least squares method to optimize the coefficients b , c and offset a .
 317 The optimal ϕ value is determined iteratively by changing ϕ from 1 to 1000 days, each time
 318 regressing the model against calibration data, and finally using the ϕ that yields the greatest R^2 .

319 2.4.2 PHH06 model

320 The predictions of the DST13 model will be compared to an existing behavioural model. Recognising
 321 the coupling between X_c and α , Plant *et al.* (2006) proposed a linearized feedback model that
 322 assumes that rates of change in X_c and α are dependent on their instantaneous values as well as the
 323 squared instantaneous wave height, H_b^2 . The model involves two coupled differential equations and
 324 by necessity simultaneously estimates both X_c and α , taking the following combined form (herein
 325 referred to as PHH06):

$$326 \quad \begin{bmatrix} \dot{X}_c \\ \dot{\alpha} \end{bmatrix} = A \begin{bmatrix} X_c \\ \alpha \end{bmatrix} + B \begin{bmatrix} 1 \\ H_b^2 \end{bmatrix} \quad (11)$$

327 where, for brevity, \dot{X}_c and $\dot{\alpha}$ denote rates of change. X_c or α are predicted by integrating all terms in
 328 Eq. (11) with respect to time, then separately optimising the [2 x 2] coefficient matrices (A and B)
 329 through least squares regression against observations. Full details are given in the original text (Plant
 330 *et al.*, 2006).

331 2.4.3 Assessment of model skill

332 Four objective measures of the models' predictive ability are assessed, namely:

- 333 1. The squared correlation, R^2 , between the model predictions, x_m , and measured data, x .
- 334 2. The root-mean-squared error (RMSE) between x_m and x .
- 335 3. The Brier Skill Score, BSS, which quantifies the improvement that the model predictions
 336 provide over that of a pre-defined benchmark model, x_b (in this case a linear fit to the data).
 337 BSS also considers the estimated measurement error in the data, Δx (m), and is therefore
 338 deemed highly suited to assessment of morphological models (Sutherland *et al.*, 2004):

$$339 \quad BSS = 1 - \left[\frac{\langle (|x - x_m| - \Delta x)^2 \rangle}{\langle (x - x_b)^2 \rangle} \right] \quad (12)$$

340 Angular brackets denote a time-series average value. Brier skill scores exceeding 0.0, 0.3,
 341 0.6, and 0.8 are respectively classed as 'poor', 'fair', 'good' and 'excellent'.

- 342 4. The Akaike's information criterion (Akaike, 1974; Kuriyama, 2012; Davidson *et al.*, 2013a),
 343 AIC , provides an additional comparative assessment of model skill, where a penalty is
 344 incurred for the number of free parameter used, m .

$$345 \quad AIC = n[\log 2\pi + 1] + n \log \sigma^2 + 2m \quad (13)$$

346 n is the sample size, and σ^2 is the variance of the residuals (between validation data and the
 347 baseline or model predictions). Differences in AIC score (ΔAIC) are used to compare the
 348 models; if a model's AIC score is smaller than another model's AIC score by at least 1, it is
 349 considered more appropriate (Kuriyama, 2012).

350 **3. Results**

351 **3.1 Description of the temporal evolution of beach three-dimensionality**

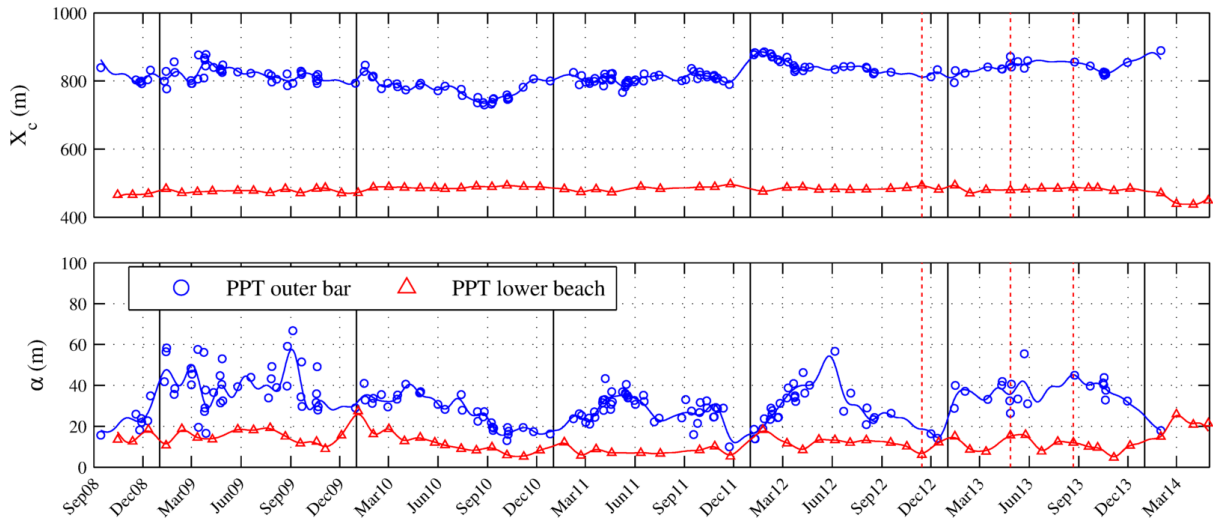
352 Time series of α (Fig. 5) show that the lower beach contours and outer barline range in alongshore
353 standard deviation from 5 – 30 m and 10 – 70 m, respectively. The seasonal signals (solid lines)
354 reveal some complex annual periodicity in beach three-dimensionality. Outer bar α displays
355 pronounced minima in winter each year (December), after which α begins to increase in the new
356 year and usually displays a local maximum ($\alpha > 40$ m) in spring between March and June. Summer is
357 characterised by slightly lower outer bar α ($20 \text{ m} < \alpha < 30 \text{ m}$), although 2009 and 2013 are notable
358 exceptions, when high α ($> 35 \text{ m}$) was maintained between March and September. The last third of
359 each year sees a reduction in outer bar α back to its annual minimum in winter. The lower beach
360 similarly displays reduced α in winter (annual minima in December), after which α rapidly increases
361 (annual maxima in January/February).

362 Between December 2013 and February 2014 an unprecedented series of long period, high energy
363 swell events occurred, making it the most energetic 8-week period of waves in the last 65 years
364 (Masselink *et al.*, In press). One storm swell ‘Hercules’ featured wave heights and periods of 9.6 m
365 and 22 s, respectively (Castelle *et al.*, 2015). During that stormy winter the lower beach retreated
366 landward, and became highly three-dimensional in spring 2014. The outer bar became increasingly
367 linear and moved offshore, but due to a subsequent lack of wave breaking over the stranded
368 offshore bar after the storms, there are no measurements after February 2014 to indicate its
369 recovery behaviour.

370 Autocorrelation of the low-pass filtered and weekly resampled α time series (Fig. 6, upper panel)
371 reveals an annual signal at the outer bar, with significant positive and negative correlations at lags of
372 1 and 1.5 years, respectively. The lower beach has a sub-annual periodicity, revealed by the peaks in
373 autocorrelation at 15 and 30 weeks lag. Cross-correlation between α at the lower beach and outer
374 bar (Fig. 6, lower panel) reveals significant positive correlation ($r \approx 0.5$) at negative lags up to 15

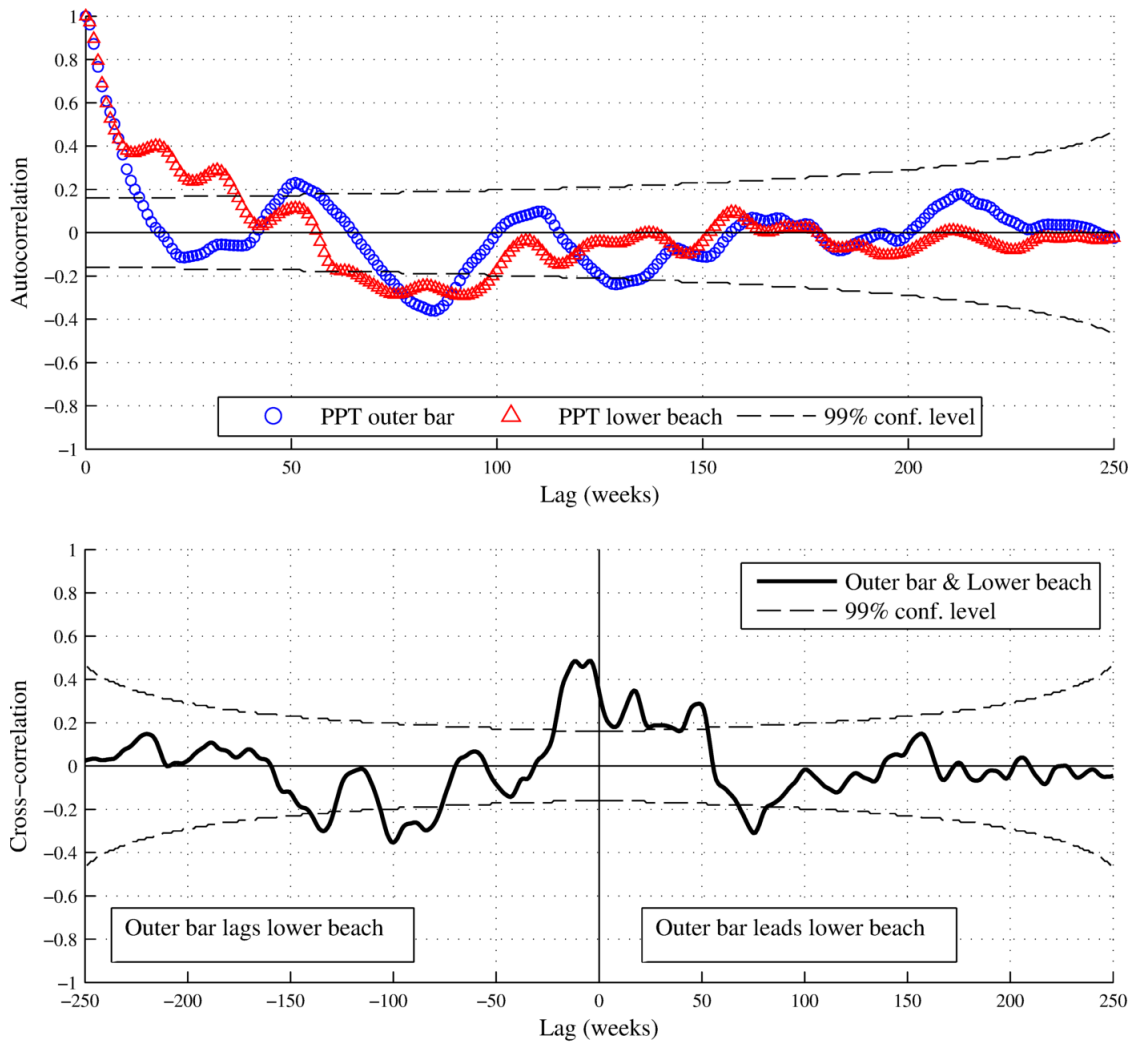
375 weeks, indicating that the lower beach becomes three-dimensional 1 – 4 months before the outer
376 bar.

377



378

379 **Figure 5. Time series of alongshore averaged cross-shore position, X_c , (upper) and standard deviation, α , (lower) of the**
380 **outer barline and lower beach contours at Perranporth beach. The scattered points are the measured data and the**
381 **associated lines are the low-pass filtered (1/42 days cut off) seasonal signal. Solid and dotted vertical lines indicate the**
382 **start of each year and the measurement dates of the example data from fig. 3, respectively.**



384

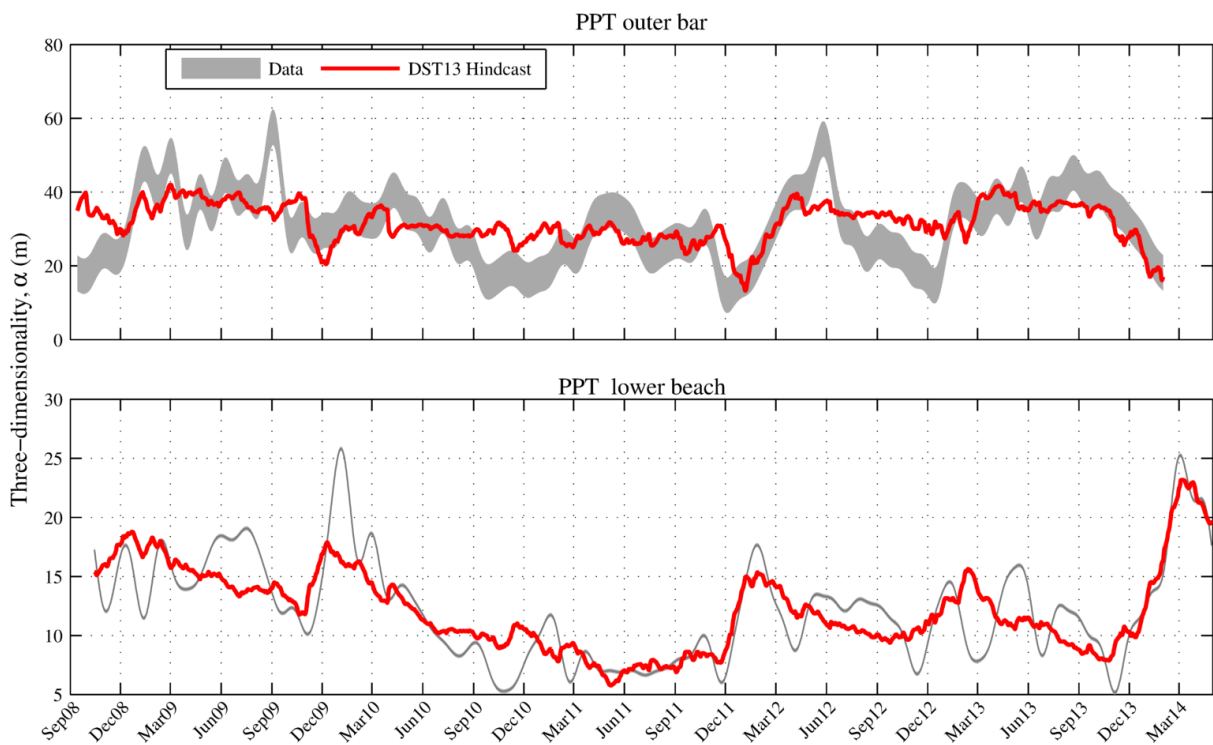
385 **Figure 6. Upper panel: Autocorrelation function of three-dimensionality (α) at the outer bar and lower beach, at lags up**
386 **to 250 weeks. Lower panel: Cross-correlation function between α at the outer bar and lower beach, at lags up to 250**
387 **weeks.**

388

389 **3.2 Modelling Results**

390 *3.2.1 Model Hindcast*

391 Fig. 7 shows DST13 model hindcasts. Summary statistics (Table 1) indicate that the model performed
392 well, explaining 42% of the variance in α at the outer bar, (RMSE = 6.55 m) and 61% of the variance
393 in α at the lower beach (RMSE = 2.84 m). Brier Skill Scores were ‘good’ for both the outer bar and
394 lower beach (0.77 and 0.63. respectively). The outer bar predictions achieved higher BSS than those
395 at the lower beach despite the other statistics suggesting that the model performed better for the
396 lower beach. This is due to BSS scoring sympathetically towards data with larger estimated errors
397 (the data lines in Fig. 7 demonstrate the greater measurement error, $\Delta\alpha$, at the outer bar).



398
399 **Figure 7. DST13 Model hindcasts plotted alongside the seasonal (low pass-filtered) α data at Perranporth’s outer bar**
400 **(upper panel) and lower beach (lower panel). The thickness of the data lines indicates the measurement error ($\Delta\alpha$).**

401
402 *3.2.2 Model validation*

403 The predictive skill of the DST13 model was more rigorously tested by validating its predictions
404 against an unseen portion of the data, as well as comparing the predictions to those made by the

405 PHH06 model. Both models were calibrated using the first 60% of available data, and validation was
406 performed using the remaining unseen 40% of the data (Fig. 8). As with the hindcast, the DST13
407 model predicted α well at the outer bar and lower beach, explaining 57% - 59% of the variance in
408 the validation data (RMSE = 5.9 m and 3.2 m) and achieving 'good' and 'fair' Brier Skill Scores (BSS =
409 0.71 and 0.53), respectively. The frequency and timing of the annual fluctuations in the lower beach
410 data were well predicted by the model, although sub-annual signals were not well reproduced.
411 Although the magnitude and timing of some changes at the outer bar were not accurately predicted,
412 DST13 did predict the large increase in α between January and April 2012, and decrease in α
413 between October 2013 and February 2014. The PHH06 model also performed well for the lower
414 beach contour data (Fig. 8 and Table 1), explaining 61% of the variance in the data (RMSE = 3.46 m)
415 and achieving a 'fair' Brier Skill Score (BSS = 0.46). For the outer bar the PHH06 model predicted
416 some annual variability but the phase and amplitude of the data were not reproduced. The positive
417 ΔAIC scores (Table 2) achieved by the DST13 model (4 free parameters) indicate that the model out-
418 performed a linear fit to the data (2 free parameters) and the PHH06 model (8 free parameters),
419 when the complexity of each model is taken into consideration.

420

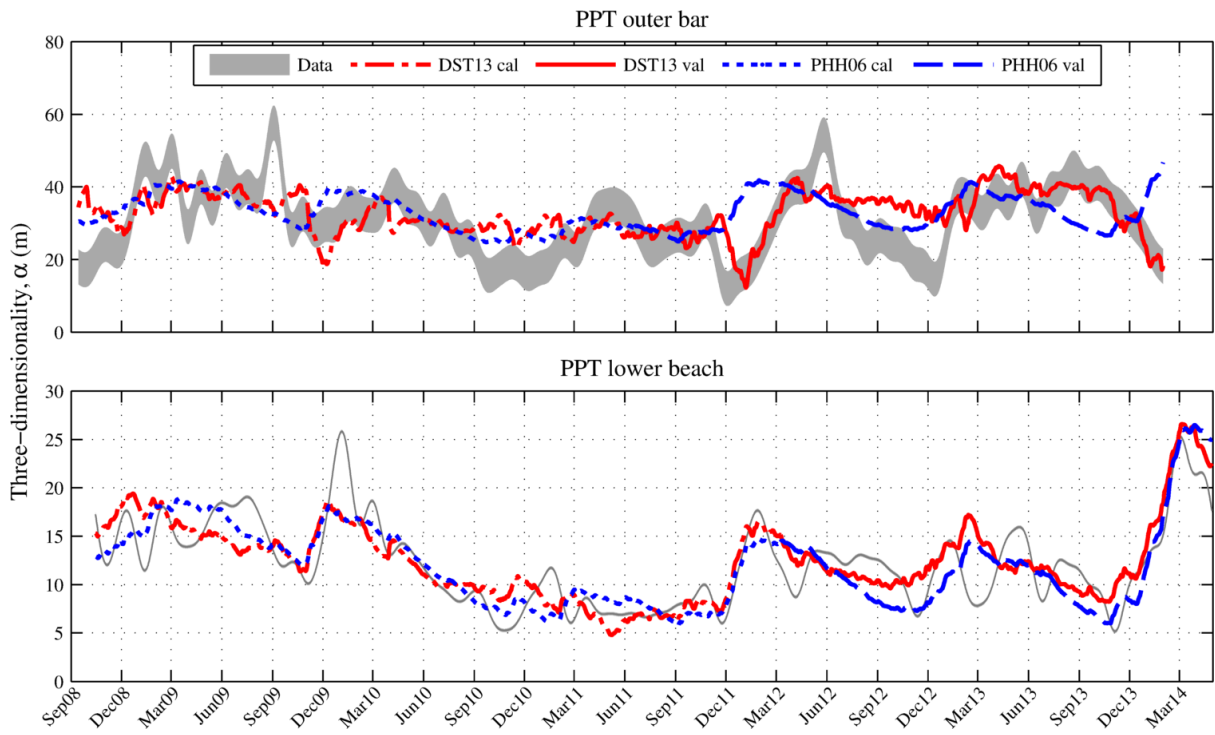
<i>DST13</i> <i>model</i>	Free Parameters					Model Skill			
						R ²	RMSE (m)	BSS	AIC
	a	b	c	φ	r'				
PPT OB	47.5 ±3.16 (48.6 ±4.75)	-0.00718 ± 0.00212 [-0.00587 ± 0.00491]	0.00632 ± 0.00117 (0.00725 ± 0.00275)	69 (67)	0.350 (0.351)	0.417 (0.332) [0.565]	6.55 (7.21) [5.90]	0.766 'good' [0.709 'good']	1150 [440]
	PPT LC	13.3 ± 1.40 (12.9 ± 2.32)	0.00300 ± 0.00148 (0.00459 ± 0.00521)	-0.00202 ± 0.000424 (-0.00240 ± 0.000877)	1000 (1000)	0.279 (0.279)	0.606 (0.634) [0.585]	2.84 (2.82) [3.22]	0.628 'good' [0.533 'fair']
<i>PHH06</i> <i>model</i>	Free Parameters					Model Skill			
						R ²	RMSE (m)	BSS	AIC
PPT OB	A	[-0.0000664 ± 0.000237 -0.000135 ± 0.0000942] [-0.0145 ± 0.00385 -0.00157 ± 0.00153]				(0.316)	(7.23)	[0.155	[527]
	B	[803 ± 11.9 30.5 ± 4.73] [0.109 ± 0.0371 0.0344 ± 0.0148]				[0.00270]	[10.3]	'poor']	
PPT LC	A	[-0.0000392 ± 0.000127 -0.000162 ± 0.0000616] [0.00448 ± 0.00259 -0.00106 ± 0.00125]				(0.692)	(2.58)	[0.463 'fair']	[150]
	B	[470 ± 5.47 12.9 ± 2.65] [-0.00481 ± 0.0132 0.0191 ± 0.00640]				[0.614]	[3.46]		

Table 1. Model coefficients and skill assessment results for the DST13 model and PHH06 model, for the outer bar (OB) and lower beach contours (LC). Model skill values are given for hindcast, (calibration) and [validation] data; note that a hindcast was only performed with the DST13 model. Ratio *r* is grouped here as a parameter, but was not counted as one in the calculation of AIC. Values are given to 3 significant figures.

	ΔAIC (Linear fit – PHH06)	ΔAIC (Linear fit – DST13)	ΔAIC (PHH06 – DST13)
PPT OB	-22	57	87
PPT LC	13	18	14

Table 2. Difference in AIC scores between a linear fit to the data, the PHH06 model, and the DST13 model. Values greater than 1 (shown as bold values) indicate that the second model in parentheses is significantly better than the first.

425



426

427 **Figure 8.** Calibration (cal) and validation (val) model predictions for the alongshore variability of the outer bar (upper
428 panel) and lower beach (lower panel) at Perranporth. The thickness of the data lines indicates the measurement error.

429

430 **4. Discussion**

431 The model results indicate that disequilibrium stress is suited to modelling changes in beach three-
432 dimensionality. It is particularly encouraging that the DST13 model performed well between
433 December 2013 and February 2014 when an unprecedented series of long period, high energy swell
434 events occurred. Throughout this period the model skilfully predicted three-dimensionality at the
435 lower beach and outer bar, under wave conditions well outside the calibration data set. The time-
436 varying equilibrium value (Ω_{eq}) in the DST13 model is a weighted function of the antecedent
437 dimensionless fall velocity and therefore accounts for antecedent waves, but also estimates the
438 likely state that the beach is approaching, due to the relationship between Ω and beach state
439 (Wright and Short, 1984). As process models have shown that alongshore non-uniformities do not
440 grow indefinitely under constant wave forcing (e.g. Smit *et al.*, 2008), the negative feedback
441 implicitly represented in this temporally varying term maintains the stability of the system,
442 appropriately constraining 3D growth. Allowing Ω_{eq} to vary also permits for hysteresis to occur,
443 which is often observed as beaches change state (Lippmann and Holman, 1990; Ranasinghe *et al.*,
444 2004).

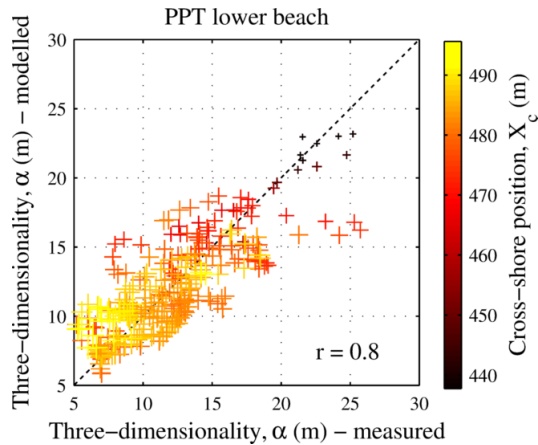
445 **4.1 Comparison of the PHH06 and DST13 models**

446 Both models predicted three-dimensionality better at the lower beach than at the outer bar,
447 suggesting that the barline measurement error may be masking the relationship with incident
448 waves. Despite poorly predicting outer bar α , the PHH06 model made accurate predictions of lower
449 beach α . Unlike DST13, the PHH06 coefficients can describe positive or negative feedback depending
450 on the results of the least squares regression. The self-interaction terms (left to right diagonal) in
451 matrix A (Table 1) for the lower beach are both negative, showing that increases in α reduce the rate
452 of further changes in α , suggesting a stable and deterministic system (Plant *et al.*, 2006). The fact
453 that these terms are negative adds credence to the negative feedback approach used in the DST13

454 model and explains the remarkably similar predictions of lower beach α made by the two models,
455 despite the differences in driving parameters.

456 The inclusion of a tidally modulated power term in DST13 may explain why it performed better than
457 PHH06 at the outer bar, which is often inactive during small tides. While DST13 is forced by wave
458 and tide parameters, PHH06 requires knowledge of wave height and X_c in order to predict changes
459 in α . Plant *et al.* (2006) argue that knowledge of both X_c and α is necessary to predict either
460 parameter, but as the DST13 model was able to predict α with significant skill, and without
461 knowledge of X_c , this may not necessarily be the case. Fig. 9 reveals that seaward and landward
462 lower beach contour positions that occur as the beach flattens (erodes) and steepens (accretes), are
463 often associated with low and high three-dimensionality, respectively. This dependency may allow
464 DST13 to predict α without explicit knowledge of X_c .

465



466

467 **Figure 9. Measured vs modelled lower intertidal three-dimensionality, α .** The measured data were low-pass filtered and
468 resampled at weekly intervals, and the DST13 model predictions were resampled at the same instances. The size and
469 colour of the markers represents the alongshore averaged cross-shore position of the MLWN contour, X_c , with larger
470 markers and lighter colours showing more seaward positions. The dotted line shows a 1:1 relationship for reference.

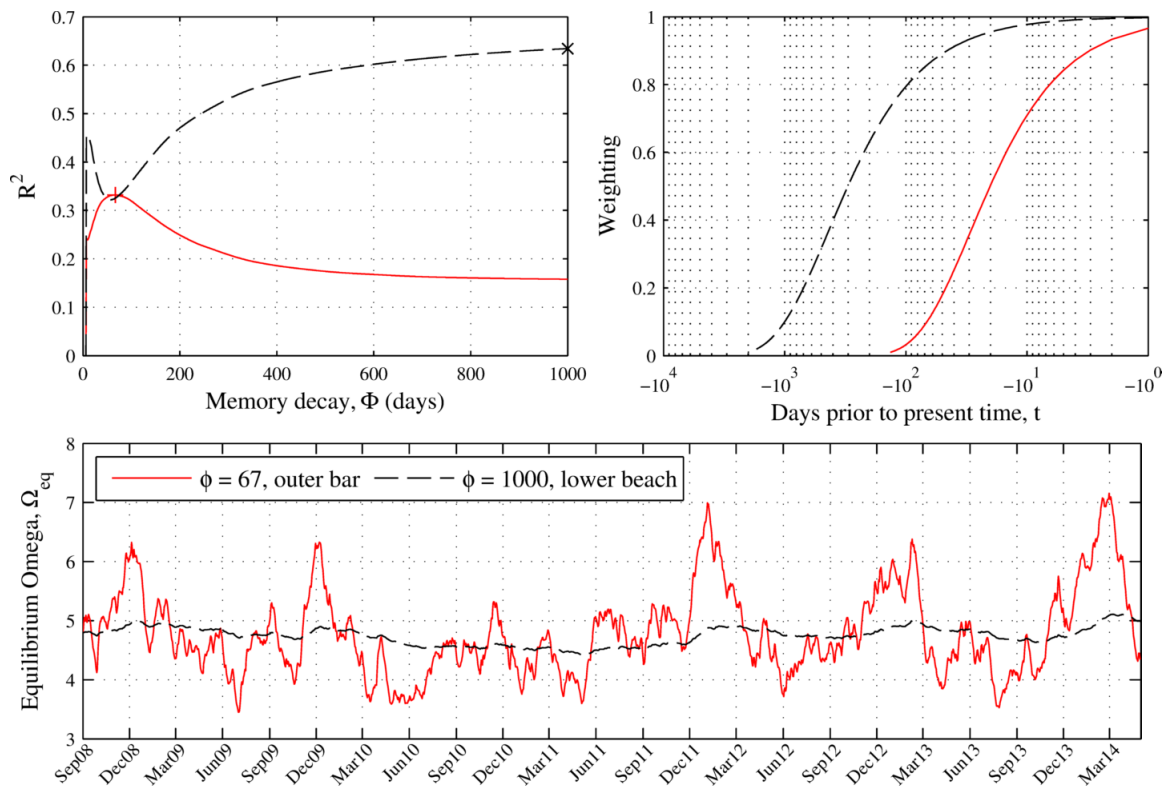
471

472 4.2 Effect of varying memory decay length (ϕ)

473 Fig. 10 (upper panels) shows the effect of varying the value of ϕ on the performance and memory
474 decay of the DST13 model. The peaks at $\phi = 67$ days and $\phi \geq 1000$ days reveal that the memory
475 decay for the outer bar and lower beach are more than an order of magnitude different. Fig. 10
476 (lower panel) further demonstrates that equilibrium conditions vary greatly over a single year at the
477 outer bar (storm-dominated timescale), but very little at the lower beach (seasonal response). The
478 slight peak in model performance for the lower beach at $\phi = 10$ days indicates that a shorter
479 response may also occur there, but data with a higher temporal resolution would be needed to
480 investigate this further. Interestingly, the peak ϕ value for the outer bar is associated with a drop in
481 model skill at the lower beach (Fig. 10, upper left panel). This is likely to be due to the lagged
482 behaviour of the outer bar, which was previously shown to reach peak values of α up to 15 weeks
483 after the lower beach (Fig. 6). Because high α at the lower beach can occur alongside low α at the
484 outer bar (Fig. 5), a model suited to predicting one (i.e. with $\phi = 67$ days) is likely to perform poorly
485 for the other.

486 This lag also results in rate coefficients (c) with opposing signs at the outer bar and lower beach. As
487 the outer bar becomes 3D weeks to months after annual peak wave conditions, the increase in α
488 coincides with positive $\Delta\Omega$, yielding a positive c term. Conversely at the lower beach three-
489 dimensionality begins to increase immediately following the annual peak wave conditions while $\Delta\Omega$
490 is decreasing but still negative, and therefore yields a negative c term. The lagged increase in α at
491 the outer bar relative to the lower beach raises questions about whether 3D features formed at the
492 lower beach influence or initiate the bed-surf coupling required to develop 3D features at the bars,
493 but this question cannot be answered with the present data alone.

494



495

496 **Figure 10. Upper left panel: Model sensitivity to the value of ϕ for the outer bar (solid line) and lower beach (dashed**
 497 **line). The ϕ associated with the largest calibration R^2 was chosen as the optimal value for each data set, denoted as a**
 498 **cross ($\phi = 67$) and an x ($\phi = 1000$). Upper right panel: example of memory decay used to determine the weighted-**
 499 **average antecedent wave conditions for $\phi = 67$ (solid line) and $\phi = 1000$ (dashed line). Note the x axis is logarithmic.**
 500 **Lower panel: Time series of Ω_{eq} over the period of interest for the outer bar (solid line) and lower beach (dashed line).**

501

502 4.3 Model limitations and improvements

503 Although processes are not explicitly modelled, DST13 assumes changes in three-dimensionality
 504 occur as a result of normal, open beach circulation. For example the model presently ignores the
 505 effects of alongshore oriented wave power, which idealised modelling (Ranasinghe *et al.*, 2004;
 506 Splinter *et al.*, 2011; Garnier *et al.*, 2013; Price *et al.*, 2013) and field studies (Holman *et al.*, 2006;
 507 Thornton *et al.*, 2007; Price *et al.*, 2011; Price *et al.*, 2013) have shown to be an important cause of
 508 sandbar straightening at some sites. It is proposed that this could be accounted for simply in the
 509 model by incorporating the absolute value of the alongshore component of wave power $|P_y|$, either

510 as an additional model parameter at the cost of one extra regression term, or by incorporating it into
511 forcing term F . When tested, this altered the model results very little due to the small contribution
512 of obliquely incident waves at Perranporth, where alongshore-oriented power is typically an order of
513 magnitude smaller than the total wave power. This modification was therefore not included in the
514 present model, but provides a basis for further model development at sites with significant
515 alongshore wave power.

516 As the degree of three-dimensionality at dissipative-intermediate sites (such as Perranporth) is
517 inversely related to Ω (Wright and Short, 1984), Ω_{eq} provides a suitable equilibrium value for three-
518 dimensionality. However, beaches that transition from the TBR to LTT states and eventually to the R
519 end state, feature decreasing three-dimensionality as Ω decreases. Therefore in order to generalise
520 the model to sites that feature intermediate-reflective beach states the model would need to be
521 adapted, such that when Ω_{eq} exceeds an appropriate threshold the sign of the disequilibrium is
522 inverted. At that point increases in Ω would change from driving an increase in α to driving a
523 decrease in α .

524 The improvements achieved at the outer bar by moderating the wave power based on the tidal
525 range reflect the fact that significant sediment transport can only occur under sufficient wave
526 breaking (Splinter *et al.*, 2011). A large tide range reduces the water depth over the outer bar at low
527 tide, and therefore increases breaking and sediment transport which enhances the rate of change in
528 the bar. Conversely under neap tides, when water depth over the bar is large relative to the wave
529 height, sediment transport (and therefore changes in the bar) can significantly reduce due to the
530 lack of breaking. These processes may also explain the storm-dominated timescale of the outer bar
531 response, as a previously inactive bar can rapidly change when larger storm waves break. Although
532 the tidally modulated wave power term reduces the rate of morphological change under small tides
533 and waves, completely reducing bar change to zero when the subtidal bar is inactive may yield
534 further improvements.

535 **5. Conclusions**

536 A dataset of 5.5 years of quasi-daily bar measurements, and quasi-monthly intertidal beach surveys
537 from Perranporth beach (Cornwall, UK) were used to quantify seasonal to inter-annual changes in
538 beach three-dimensionality (α). α at the outer bar displayed significant annual periodicity, with
539 annual minima and maxima occurring in winter and spring respectively. The lower intertidal beach
540 displayed a similar periodicity, but developed three-dimensionality 1-4 months before the outer bar.
541 A simple equilibrium model (DST13) was developed, which made skilful hindcast and calibration-
542 validation predictions of α , explaining 42% and 61% of the variability in outer bar and lower beach
543 three-dimensionality, respectively. The model was able to make skilful predictions during an
544 unprecedented series of long period, high energy swell events, including the most energetic 8-week
545 period of waves measured in the last 65 years (December 2013 to February 2014), which were
546 outside the training data range.

547 At present the model assumes that open beach, cross-shore processes, such as horizontal wave-
548 driven circulation control the morphodynamics, but alongshore-oriented wave power should be
549 considered at sites where it is significant relative to the normally oriented power. Negative feedback
550 was found to be an important process governing the changes in beach three-dimensionality. While
551 free morphological behaviour may drive three-dimensional growth, negative feedback processes
552 exert stability in the system, making it inherently predictable using a temporally varying equilibrium
553 value, as used here. In its present form the model out-performed a simple baseline model (a linear
554 fit) as well as a comparable linearized feedback model from the literature (Plant *et al.*, 2006),
555 providing the first long-term (multi-year) predictions of seasonal to inter-annual beach three-
556 dimensionality for a macrotidal beach.

557

558 **Acknowledgements**

559 We would like to thank Martin Austin, Tim Poate, Tim Scott, Erwin Bergsma and Sam Prodger for
560 their hard work in collecting much of the survey data. Thanks also go to Peter Ganderton and Megan
561 Sheridan for technical support. We would also like to thank the NERC DRIBS project (code:
562 NE/HOO4262/1), the EU SOWFIA project, and the Plymouth University Marine Institute for funding
563 the beach surveys.

564

References

- 566 Akaike, H., 1974. A new look at the statistical model identification. *Automatic Control, IEEE*
567 *Transactions on*, 19(6), 716-723.
- 568 Almar, R., Castelle, B., Ruessink, B., Sénéchal, N., Bonneton, P., Marieu, V., 2010. Two-and three-
569 dimensional double-sandbar system behaviour under intense wave forcing and a meso-
570 macro tidal range. *Continental Shelf Research*, 30(7), 781-792.
- 571 Austin, M., Scott, T., Brown, J., MacMahan, J., Masselink, G., Russell, P., 2010. Temporal observations
572 of rip current circulation on a macrotidal beach. *Continental Shelf Research*, 30(9), 1149-
573 1165.
- 574 Austin, M.J., Scott, T.M., Russell, P.E., Masselink, G., 2013. Rip current prediction: Development,
575 validation, and evaluation of an operational tool. *Journal of Coastal Research*, 29(2), 283-
576 300.
- 577 Bowen, A.J., 1969. Rip currents: 1. Theoretical investigations. *Journal of Geophysical research*,
578 74(23), 5467-5478.
- 579 Brighton, B., Sherker, S., Brander, R., Thompson, M., Bradstreet, A., 2013. Rip current related
580 drowning deaths and rescues in Australia 2004–2011. *Natural Hazards and Earth System*
581 *Science*, 13(4), 1069-1075.
- 582 Caballeria, M., Calvete, D., Coco, G., Dodd, N., Falques, A., 2003a. Formation and alongshore spacing
583 of crescentic bars, The 3rd Symposium on River, Coastal and Estuarine Morphodynamics. Int.
584 Assoc. for Hydraul. Res., Delft.
- 585 Caballeria, M., Coco, G., Falques, A., 2003b. Crescentic patterns and self-organization processes on
586 barred beaches, *Coastal Sediments*. Am. Soc. of Civ. Eng., New York.
- 587 Caballeria, M., Coco, G., Falqués, A., Huntley, D., 2002. Self-organization mechanisms for the
588 formation of nearshore crescentic and transverse sand bars. *Journal of Fluid Mechanics*, 465,
589 379-410.
- 590 Castelle, B., Bonneton, P., Dupuis, H., Sénéchal, N., 2007. Double bar beach dynamics on the high-
591 energy meso-macrotidal French Aquitanian Coast: A review. *Marine Geology*, 245(1–4), 141-
592 159.
- 593 Castelle, B., Coco, G., 2012. The morphodynamics of rip channels on embayed beaches. *Continental*
594 *Shelf Research*, 43, 10-23.
- 595 Castelle, B., Marieu, V., Bujan, S., Ferreira, S., Parisot, J.-P., Capo, S., Sénéchal, N., Chouzenoux, T.,
596 2014. Equilibrium shoreline modelling of a high-energy meso-macrotidal multiple-barred
597 beach. *Marine Geology*, 347, 85-94.
- 598 Castelle, B., Marieu, V., Bujan, S., Splinter, K.D., Robinet, A., Sénéchal, N., Ferreira, S., 2015. Impact
599 of the winter 2013–2014 series of severe Western Europe storms on a double-barred sandy
600 coast: Beach and dune erosion and megacusp embayments. *Geomorphology*, 238, 135-148.
- 601 Davidson, M., Huntley, D., Holman, R., George, K., 1997. The evaluation of large scale (km) intertidal
602 beach morphology on a macrotidal beach using video images, *Coastal Dynamics*. ASCE, pp.
603 385-394.
- 604 Davidson, M., Lewis, R., Turner, I., 2010. Forecasting seasonal to multi-year shoreline change.
605 *Coastal Engineering*, 57(6), 620-629.
- 606 Davidson, M., Splinter, K., Turner, I., 2013a. A simple equilibrium model for predicting shoreline
607 change. *Coastal Engineering*, 73, 191-202.
- 608 Davidson, M.A., Turner, I.L., Splinter, K.D., 2013b. Predicting Shoreline Response to Cross-Shore
609 Processes in a Changing Wave Climate, *Coastal Dynamics*, Arcachon, France.
- 610 Dean, R.G., 1973. Heuristic models of sand transport in the surf zone, *First Australian Conference on*
611 *Coastal Engineering: Engineering Dynamics of the Coastal Zone*. Institution of Engineers,
612 Australia, pp. 215.

613 Falqués, A., Coco, G., Huntley, D., 2000. A mechanism for the generation of wave-driven rhythmic
614 patterns in the surf zone. *Journal of Geophysical Research: Oceans (1978–2012)*, 105(C10),
615 24071-24087.

616 Falqués, A., Dodd, N., Garnier, R., Ribas, F., MacHardy, L.C., Larroudé, P., Calvete, D., Sancho, F.,
617 2008. Rhythmic surf zone bars and morphodynamic self-organization. *Coastal Engineering*,
618 55(7–8), 622-641.

619 Garnier, R., Falqués, A., Calvete, D., Thiebot, J., Ribas, F., 2013. A mechanism for sandbar
620 straightening by oblique wave incidence. *Geophysical Research Letters*, 40(11), 2726-2730.

621 Gourlay, M., 1968. Beach and dune erosion tests. Delft Hydraulics Laboratory, Report M, 935.

622 Holman, R.A., Symonds, G., Thornton, E.B., Ranasinghe, R., 2006. Rip spacing and persistence on an
623 embayed beach. *Journal of Geophysical Research: Oceans (1978–2012)*, 111(C1).

624 Kingston, K., Ruessink, B., Van Enckevort, I., Davidson, M., 2000. Artificial neural network correction
625 of remotely sensed sandbar location. *Marine Geology*, 169(1), 137-160.

626 Kuriyama, Y., 2012. Process-based one-dimensional model for cyclic longshore bar evolution. *Coastal*
627 *Engineering*, 62, 48-61.

628 Larson, M., Hoan, L.X., Hanson, H., 2010. Direct formula to compute wave height and angle at
629 incipient breaking. *Journal of waterway, port, coastal, and ocean engineering*, 136(2), 119-
630 122.

631 Lippmann, T., Holman, R., 1990. The spatial and temporal variability of sand bar morphology. *Journal*
632 *of Geophysical Research*, 95, 11575-11590.

633 Lippmann, T., Holman, R.A., 1989. Quantification of sand bar morphology: A video technique based
634 on wave dissipation. *Journal of Geophysical Research: Oceans (1978–2012)*, 94(C1), 995-
635 1011.

636 Loureiro, C., Ferreira, Ó., Cooper, J.A.G., 2012. Geologically constrained morphological variability and
637 boundary effects on embayed beaches. *Marine Geology*, 329–331, 1-15.

638 MacMahan, J., Reniers, A., Brown, J., Brander, R., Thornton, E., Stanton, T., Brown, J., Carey, W.,
639 2011. An introduction to rip currents based on field observations. *Journal of Coastal*
640 *Research*, 27(4), 3-6.

641 MacMahan, J.H., Thornton, E.B., Reniers, A.J., 2006. Rip current review. *Coastal Engineering*, 53(2),
642 191-208.

643 Masselink, G., Austin, M., Scott, T., Poate, T., Russell, P., 2014. Role of wave forcing, storms and NAO
644 in outer bar dynamics on a high-energy, macro-tidal beach. *Geomorphology*, 226, 76-93.

645 Masselink, G., Hegge, B., 1995. Morphodynamics of meso-and macrotidal beaches: examples from
646 central Queensland, Australia. *Marine Geology*, 129(1), 1-23.

647 Masselink, G., Scott, T., Conley, D.C., Davidson, M., Russell, P., In press. Regional Variability in
648 Atlantic Storm Response Along the SouthWest Coast of England, *Coastal Sediments 2015*,
649 San Diego, CA, USA.

650 Masselink, G., Short, A.D., 1993. The effect of tide range on beach morphodynamics and
651 morphology: a conceptual beach model. *Journal of Coastal Research*, 9(3), 785-800.

652 Mead, S., Black, K., 2001a. Field studies leading to the bathymetric classification of world-class
653 surfing breaks. *Journal of Coastal Research(SI 29)*, 5-20.

654 Mead, S., Black, K., 2001b. Functional component combinations controlling surfing wave quality at
655 world-class surfing breaks. *Journal of Coastal Research(SI 29)*, 21-32.

656 Morris, B.D., Davidson, M.A., Huntley, D.A., 2001. Measurements of the response of a coastal inlet
657 using video monitoring techniques. *Marine Geology*, 175(1), 251-272.

658 Pape, L., Ruessink, B.G., Wiering, M.A., Turner, I.L., 2007. Recurrent neural network modeling of
659 nearshore sandbar behavior. *Neural Networks*, 20(4), 509-518.

660 Plant, N.G., Holland, K.T., Puleo, J.A., 2002. Analysis of the scale of errors in nearshore bathymetric
661 data. *Marine Geology*, 191(1-2), 71-86.

662 Plant, N.G., Holman, R.A., Freilich, M.H., Birkemeier, W., 1999. A simple model for interannual
663 sandbar behavior. *Journal of Geophysical Research: Oceans* (1978–2012), 104(C7), 15755-
664 15776.

665 Plant, N.G., Todd Holland, K., Holman, R.A., 2006. A dynamical attractor governs beach response to
666 storms. *Geophysical Research Letters*, 33(17).

667 Poate, T., Masselink, G., Russell, P., Austin, M., 2014. Morphodynamic variability of high-energy
668 macrotidal beaches, Cornwall, UK. *Marine Geology*, 350, 97-111.

669 Poate, T.G., 2011. Morphological Response of High Energy Macrotidal Beaches. Doctor of Philosophy
670 Ph.D. thesis, Plymouth University, Plymouth, 255 pp.

671 Price, T., Ruessink, B., Castelle, B., 2014. Morphological coupling in multiple sandbar systems—a
672 review. *Earth Surface Dynamics*, 2, 309-321.

673 Price, T., Rutten, J., Ruessink, B., 2011. Coupled behaviour within a double sandbar system. *Journal*
674 *of Coastal Research*(SI 64), 125-129.

675 Price, T.D., Ruessink, B., Castelle, B., 2013. Morphological coupling in a double sandbar system Ph.D.
676 thesis, Utrecht University.

677 Ranasinghe, R., Symonds, G., Black, K., Holman, R., 2004. Morphodynamics of intermediate beaches:
678 a video imaging and numerical modelling study. *Coastal Engineering*, 51(7), 629-655.

679 Ruessink, G., Price, T., Castelle, B., 2013. Finite-Amplitude Behaviour of alongshore variability in
680 nearshore sandbars: observations and modelling, *Coastal Dynamics*, pp. 1-15.

681 Scarfe, B.E., Healy, T.R., Rennie, H.G., 2009. Research-based surfing literature for coastal
682 management and the science of surfing—a review. *Journal of Coastal Research*, 25(3), 539-
683 557.

684 Scott, T., Masselink, G., Russell, P., 2011. Morphodynamic characteristics and classification of
685 beaches in England and Wales. *Marine Geology*, 286(1-4), 1-20.

686 Scott, T., Russell, P., Masselink, G., Wooler, A., Short, A., 2008. High volume sediment transport and
687 its implications for recreational beach risk, *Proceedings 31st International Conference on*
688 *Coastal Engineering*. ASCE, Hamburg, Germany, pp. 4250-4262.

689 Short, A., 1991. Macro-meso tidal beach morphodynamics: An overview. *Journal of Coastal*
690 *Research*, 7, 417-436.

691 Short, A.D., 1979. Wave power and beach-stages: a global model, *Proc. 16th Int. Conf. Coastal*
692 *Engineering*, Hamburg, pp. 1145-1162.

693 Short, A.D., 1992. Beach systems of the central Netherlands coast: processes, morphology and
694 structural impacts in a storm driven multi-bar system. *Marine Geology*, 107(1), 103-137.

695 Short, A.D., 1996. The role of wave height, period, slope, tide range and embaymentisation in beach
696 classifications: a review. *Revista Chilena de Historia Natural*, 69(4), 589-604.

697 Short, A.D., Aagaard, T., 1993. Single and multi-bar beach change models. *Journal of Coastal*
698 *Research*, 141-157.

699 Smit, M., Reniers, A., Ruessink, B., Roelvink, J., 2008. The morphological response of a nearshore
700 double sandbar system to constant wave forcing. *Coastal Engineering*, 55(10), 761-770.

701 Splinter, K.D., Holman, R.A., Plant, N.G., 2011. A behavior-oriented dynamic model for sandbar
702 migration and 2DH evolution. *Journal of Geophysical Research: Oceans* (1978–2012),
703 116(C1).

704 Splinter, K.D., Turner, I.L., Davidson, M.A., Barnard, P., Castelle, B., Oltman-Shay, J., 2014. A
705 generalized equilibrium model for predicting daily to interannual shoreline response. *Journal*
706 *of Geophysical Research: Earth Surface*, 119(9), 1936-1958.

707 Sutherland, J., Peet, A., Soulsby, R., 2004. Evaluating the performance of morphological models.
708 *Coastal Engineering*, 51(8), 917-939.

709 Sverdrup, H.U., Munk, W.H., 1946. Theoretical and empirical relations in forecasting breakers and
710 surf. *Transactions, American Geophysical Union*, 27, 828-836.

711 Thornton, E.B., MacMahan, J., Sallenger Jr, A., 2007. Rip currents, mega-cusps, and eroding dunes.
712 *Marine Geology*, 240(1), 151-167.

713 Van de Lageweg, W., Bryan, K.R., Coco, G., Ruessink, B., 2013. Observations of shoreline–sandbar
714 coupling on an embayed beach. *Marine Geology*, 344, 101-114.

715 Van Enckevort, I., Ruessink, B., 2001. Effect of hydrodynamics and bathymetry on video estimates of
716 nearshore sandbar position. *Journal of Geophysical Research: Oceans (1978–2012)*, 106(C8),
717 16969-16979.

718 Van Enckevort, I., Ruessink, B., Coco, G., Suzuki, K., Turner, I., Plant, N.G., Holman, R.A., 2004.
719 Observations of nearshore crescentic sandbars. *Journal of Geophysical Research: Oceans*
720 (1978–2012), 109(C6).

721 Wright, L., Short, A., Green, M., 1985. Short-term changes in the morphodynamic states of beaches
722 and surf zones: an empirical predictive model. *Marine Geology*, 62(3), 339-364.

723 Wright, L.D., Short, A.D., 1984. Morphodynamic variability of surf zones and beaches: A synthesis.
724 *Marine Geology*, 56(1–4), 93-118.

725 Yates, M., Guza, R., O'Reilly, W., 2009. Equilibrium shoreline response: Observations and modeling.
726 *Journal of Geophysical Research: Oceans (1978–2012)*, 114(C9).

727 Yates, M., Guza, R., O'Reilly, W., Hansen, J., Barnard, P., 2011. Equilibrium shoreline response of a
728 high wave energy beach. *Journal of Geophysical Research: Oceans (1978–2012)*, 116(C4).

729

730