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

1. Introduction

Multi-annual and decadal time-series of shoreline and/or beach volume change are becoming increasingly available from around the world (Pye and Blott, 2008; Senechal et al., 2009; Corbella and Stretch, 2012; Barnard et al., 2015; Masselink et al., 2016; Scott et al., 2016; Turner et al., 2016; Castelle et al., 2017a; Phillips et al., 2017). In regions with a seasonal wave climate, these time-series generally show regularly alternating periods of beach erosion and accretion in response to annual variations in incident wave height and period (Wright et al., 1984; Dubois, 1988; Komar, 1999; Ruggiero et al., 2005). More commonly, however, the temporal coastal behaviour is less regular and governed by processes operating across multiple time scales. Although long-term (100+ years) beach evolution is mainly affected by variations in sea level and sediment supply (Zhang et al., 2002), beach and shoreline behaviour at short- (hours/months) to medium- (months/years) timescales are more impacted by storm events (Ruggiero et al., 2005; Pye and Blott, 2016; Coco et al., 2014; Castelle et al., 2015; Masselink et al., 2015; Scott et al., 2016; Barnard et al., 2017; Harley et al., 2017). Storminess in the North Atlantic, which is characterized by considerable inter-annual and inter-decadal variability was previously shown to be strongly linked to the North Atlantic Oscillation (NAO, Bromirski and Cayan, 2015). However, the NAO index was not correlated to the 2013/14 winter, when a series of extreme storms (H_s > 5.2 m) in the North Atlantic provided the most energetic winter waves since at least 1948 (Masselink et al., 2016). On the other hand, the West Europe Pressure Anomaly (WEPA), recently proposed by Castelle et al. (2017b), was strongly linked to the 2013/14 winter and therefore serves as a useful proxy for winter wave conditions in this study.

Many beaches along the southwest of England were highly affected by the 2013/14 sequence of storms and the morphological impact has been well documented (Masselink et al., 2015; Scott et al., 2016). Using pre- and post-storm airborne LiDAR datasets over that winter, Burvingt et al. (2017) demonstrated the existence of coherent storm response at beaches showing similar exposure to storm waves. This coherent storm response was characterized by medium to large alongshore uniform sediment losses. Short et al. (2014) also showed that synchronous oscillation and rotation were observed over six years at three beaches with the same orientation and length, and exposed to a similar deep water wave climate and tidal regime. This 'regionally representative' behaviour in response to varying and/or changing wave and other climatic forcing, could guide the extent and scope of the ongoing beach monitoring effort required (Bracs et al., 2016). In this paper, a 10-year dataset of RTK-GPS topographic surveys collected at a regional scale from 10 beaches with similar morphodynamic characteristics (Scott et al., 2011), orientation and wave/tide exposure, but contrasting geomorphological boundaries, will be analysed and discussed. This dataset thus gives an opportunity to address the hypothesis of coherent beach behaviour at a regional scale within a context of extreme storms.

Extreme storms, and the recovery period following these events, are of particular relevance in urbanized coastal areas, since beaches naturally act as a coastal buffer (Stive et al., 2002). Beach recovery processes occur over a wide range of timescales: days (Poate et al., 2015); months (Birkemeier, 1979; Wang et al., 2006; Splinter et al., 2011; Yu et al., 2013; Senechal et al., 2015; Phillips et al., 2017); years (Ruggiero et al., 2005; Choowong et al., 2009; Corbella and Stretch, 2012; Suanez et al., 2012; Castelle et al., 2017a); decades (McLean and Shen, 2006; Thom and Hall, 1991; Houser et al., 2015); or may never fully recover if longshore transport dominated the beach response with permanent sediment losses. Although beach recovery is often associated with small wave conditions (Komar, 1999; Ruggiero et al., 2005; Bramato et al., 2012; Roberts et al., 2013), relatively energetic waves can be essential for mobilisation/recovery of deep offshore storm bar deposits (Scott et al., 2016). Beach morpho-dynamics, including surf zone, beach and foredune interactions, also control beach recovery. Studies showed the importance of the relationship between the beach and the intertidal/subtidal bar (Houser et al., 2015; Scott et al., 2016; Brooks et al., 2017; Phillips et al., 2017; Ge et al., 2017) and/or subaerial dune systems (Suanez et al., 2012; Houser et al., 2015) in beach recovery. The 10 study sites in this paper were surveyed over 10 years including a period of three years following an extremely energetic winter season, and represent a valuable resource for a better understanding of recovery processes at a regional scale.

Predicting coastline response to storms and longer-term seasonal to inter-annual variability in regional wave climate is an ongoing challenge for coastal zone managers, scientists and engineers. A relatively simple equilibrium shoreline model, ShoreFor, was shown to provide skilful hindcasts of coastal change on coastlines dominated by cross-shore sediment transport (Davidson and Turner, 2009; Davidson et al., 2010; Splinter et al., 2014). This model primarily encapsulates beach behaviour forced by wave-driven cross-shore sediment transport, including antecedent hydro-/morphodynamic conditions. Based on these skills, the ShoreFor model is one of the best tools to provide a better understanding and interpretation of beach behaviour time series along the exposed and cross-shore dominated 10 beaches presented here.

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

2. Study area, datasets and methodology

2.1. Study area

The 10 study sites, located along the north coast of southwest England (Fig. 1), are all high-energy macrotidal sandy beaches that are exposed to swells and wind-waves from the North Atlantic. The wave climate is seasonal with larger waves (mean H_s = 2.2 m, mean T_p = 11 s) in winter from October to March, and smaller waves (mean H_s = 1.4 m, mean T_p = 9 s) in summer from April to September (Fig. 1, Table 3 and 4). The largest waves are generated by extra-tropical storms originating in the mid-latitude westerly wind belt (Lozano et al., 2004), although, occasionally, the coast is also affected by the remnants of tropical cyclones. On average, 17 storm events (peak H_s > 4 m) and 5 severe storm events (peak H_s > 6 m) occur annually (Scott, 2009). The extra-tropical storminess is strongly linked to the North Atlantic Oscillation (NAO; Bromirski and Cayan, 2015) and the West Europe Pressure Anomaly (WEPA; Castelle et al., 2017b), which are both characterized by considerable inter-annual and inter-decadal variability (Table 3 and 4).

A diverse set of beach systems is represented by the 10 study sites (Fig. 2 and Table 1) with the median size of the beach sediment ranging from 0.25 to 0.61 mm. Several beaches are backed by dune systems that vary in size and height (Widemouth #1, Constantine #2, Porthcothan #3, Gwithian #9 and Sennen #10) and front high cliffs (Trenance #4 and Watergate #5). Relatively large rocky platforms can be found at Widemouth #1, Constantine #2 and Fistral #7 beaches (Fig. 2). All beaches in the data set are constrained by rocky headlands (Fig. 2) and can either be considered as very embayed (Porthcothan #3 and Porth #6), semi-embayed (Constantine #3, Trenance #4, Fistral #7 and Porthtowan #8) or relatively open (Widemouth #1, Watergate #5, Gwithian #9 and Sennen #10). A beach being considered here as very embayed (relatively open) is when its cross-shore length, from the backshore to mean low water spring level, is more (less) than twice its longshore length, from one headland to the other. Although the studied beaches are characterized by diverse geological settings, Scott et al. (2011) found them to be similar with respect to beach type and all beaches are considered Low-Tide Bar Rip (LTBR) beaches. The similarity in beach state is explained by the similar hydrodynamic conditions. All beaches are macrotidal, with the mean spring tidal range decreasing from north (6.7 m at Widemouth #1) to south (5.8 m at Sennen #10) (Table 1). The beaches also all have a similar SSW-NNE orientation (Fig. 2 and Table 1) and are, therefore, exposed to similar shore-normal wave conditions. The resulting cross-shore exchange of sediment in response to changing wave conditions is more significant than sediment redistribution alongshore (Buscombe and Scott, 2008), as demonstrated by an analysis of the 2013/14 storm response of all beaches in the southwest of England by Burvingt et al. (2017).

Fig. 1 here

Fig. 2 here

Table 1 here

2.2. Topographic data

As part as the South West Coastal Monitoring Program, many beaches along the coastline of SW England are surveyed every 6/12 months, and RTK-GPS data sets are provided by the Plymouth Coastal Observatory (http://southwest.coastalmonitoring.org/). The study sites were surveyed twice a year from 2007 to 2017 in spring season (February-March-April) and autumn season (September-October-November), except for Watergate #5 and Gwithian #9 beaches, which were surveyed once a year during spring season (Table 2). All beaches are generally surveyed at the same time of the year within a period of 2-3 months (Table 2) and because they are fairly dynamic, a difference of 3 months can make the inter-site comparison between beach changes potentially problematic. However, beach behaviour at these 10 study sites is also very seasonal, and the seasonal variations observed at the beach are more significant than the variations that occur over 2-3 months within the same season. The lag between surveys therefore accounts only for relatively small variations in beach changes and these are discussed later in sections 4.1 and 6.

Table 2 here

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

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

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

where z corresponds to the topographic values interpolated every metre, and z_{min} and z_{max} are the lowest and the fixed backshore topographic points, respectively (Fig. 3). These volumes are computed for every survey to create a beach volume time series, *V* in $m^3 m^{-1}$, relative to the first survey (*V (Autumn 2007) = 0*). Beaches are also represented by either one or several cross-shore profiles (*N*) that are approximatively equally-spaced and spread over the entire beach (Figure 2). As these beaches are cross-shore dominated, the profile volume time series can be averaged to obtain longshore-averaged beach volume time series *V* (Equation 2).

$$V = {}^{1}/_{N} \sum_{1}^{N} V_{profile} \tag{2}$$

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

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

$$Recovery = 100 * \frac{V_{last} - V_{post}}{V_{pre} - V_{post}} \tag{3}$$

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

Fig. 3 here

2.3. Wave, tidal and climate index data

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

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

Fig.4 here

2.4. ShoreFor model

To test whether any coherent responses between the study sites are coherently related to the offshore wave forcing, and importantly whether this variability is potentially predictable, observations are compared with a subtle variant of the equilibrium shoreline ShoreFor model proposed by Davidson et al. (2013). This variant predicts beach volume variability rather than shoreline change, the results proposed in this study are thus comparable with other recent studies using beach volume changes to describe the 2013/14 storm response (Castelle et al., 2015; Masselink et al., 2016; Scott et al., 2016) and no significant differences should be observed in terms of model predictions. This equilibrium model is based upon the principle that cross-shore-dominated shorelines migrate toward a time-varying equilibrium position (Wright et al., 1985). Here we give a very brief description of the model and the reader is referred to Davidson et al., (2013) for a more detailed description of the model.

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

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

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

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

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

3. Wave forcing

3.1. Multi-annual wave conditions time-series

The time series of modelled significant wave height H_s, peak energy period T_p and winter WEPA index from 1980 to 2016 are presented in Fig. 5. The 8-week block-averaged H_s and T_p time series clearly highlight the seasonal variability in wave conditions between winter and summer. Over the last 36 years, six very energetic winters can be observed from the H_s time series (Fig. 5a and 5b). The ‘Great Storm’ of 1987 and the ‘Burn’s Day Storm’ in 1990 were reported (McCallum, 1990) for the strength of wind gusts recorded, and caused widespread damage and the dramatic loss of 18 and 47 lives in the UK, respectively. Three years later, the ‘Braer Storm’ of 1993 had one of the lowest-ever recorded central pressures (914 mb) in the North Atlantic (McCallum and Grahame, 1993; Burt, 1993) and the 1994/95 winter was reported as ‘very cyclonic’ (Hulme, 1997). More recently, the 2013/14 winter wave conditions associated with storms were the most energetic since at least 1948 along the southwest coast of England (Masselink et al., 2015), followed by the 2015/16 winter that was as energetic as 1993 and 1994/95 mentioned previously (Fig. 5a).

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

Fig. 5 here

Fig. 6 here

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

Tables 3 and 4 here

3.2. *Multi-annual storminess*

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

Fig. 7 here

4. Regionally coherent beach behaviour, storm response and recovery

4.1. Influence of wave forcing in beach behaviour

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

When considering the average of the 10 beach volume time-series, V_{avg}, and its bounded standard deviation, representing inter-site variability, four different phases can be identified (Fig. 10a). During the first phase, from autumn 2007 to autumn 2010, the 10 beaches accreted with an average rate of volume change of 3.6 m^3 m^{-1} per month (Fig. 10a). During this phase, winter periods were ranked as 5th, 7th and 9th most energetic and corresponded to the recovery phase following the energetic 2006/07 winter ranked as the 3rd most energetic over the last 10 years (Table 3). Accordingly, the yearly WEPA index gradually decreased from 0.5 to -1.25 during this 3-year phase (Fig. 10c). The second phase, spanning the three years between autumn 2010 and autumn 2013, was characterized by an equilibrium in beach volume change (- 7 m^3 m^{-1}) where seasonal sediment exchange was dominant over inter-annual exchange (Fig. 9). This suggests that the beaches reached an equilibrium as recovery from the 2006/07 winter was complete. This phase was associated with a relatively stable WEPA index from 2010 to 2012 followed by a rapid increase from -1.20 to 1 during 2013 which did not seem to influence the volume changes (Fig. 10c). Phase 3, corresponding to the 2013/14 winter, was the strongest erosive event over the last 10 years as previously observed along the three cross-shore profiles in Fig. 8. Between autumn 2013 and spring 2014, the 10 beaches lost from 80 to 384 m^3 m^{-1} (Fig. 9), resulting in an average erosion rate of 34 m^3 m^{-1} per month. These large losses of sand occurred during the most energetic winter of the study period (Fig. 10b), where 17 storms were recorded (Fig. 7a and Table 3), associated to the WEPA index 10-year maximum value of 2.7 (Fig. 10c). Although the increase in WEPA values between 2013 and 2014 is similar to the increase observed between 2012 and 2013, the wave conditions and associated beach responses were much stronger, suggesting a threshold effect in the WEPA control on wave climate. Phase 4, which corresponded to the following three years from spring 2014 to spring 2017, was related to the recovery period from the extreme storms of phase 3. From spring 2014 to autumn 2015, the beaches slowly recovered with an average accretion rate of 3.5 $m^3\ m^{-1}$ per month (Fig. 10a). The smaller wave conditions during the 2014/15 winter compared to the 2013/14 winter (Fig. 7a and 7b) were associated with a decrease of the WEPA index through 2015 (Fig. 10b and 10c). However, that winter was still relatively energetic (ranked 4th, Table 3) and resulted in variable response among the 10 study sites with both erosion or accretion depending on the beach (Fig. 9). Most of the sand recovered over this 1.5 years was lost during the energetic 2015/16 winter (Fig. 7c), which ranked as the second most energetic period over the last 10 years (Table 3) and paired with the second highest value of WEPA index (Fig. 10c), adding to the hypothesis of a threshold effect observed in phase 3. These losses were quickly recovered the next summer in 2016 (Fig. 10a), and accretion (36 $m^3\ m^{-1}$) even occurred during the 2016/17 winter when calm wave conditions prevailed and no storms occurred (Fig. 7c and 10b). This winter also had a reduced WEPA index (Fig. 10c). When considering the volumes lost between spring 2013 and spring 2014, these losses were recovered on average by 77% in spring 2017. However, recovery percentages were highly variable between the 10 study sites (from 5 to 200%), as testified by the increase in standard deviation along the average volume time-series during phase 4 (Fig. 10a).

Fig. 10 here

The volume changes observed during the 3-year recovery period (phase 4) suggested that summer conditions contribute to beach recovery but, above all, the recovery trajectory is largely and mainly forced by winter waves. The mean of the 6-monthly volume changes, dV_{mean}, over winter and summer months, and the associated 6-monthly significant wave height, H_s, were therefore computed and compared. Results showed that both volume changes and wave conditions during summer months represent rather small inter-annual variability compared to winter months (Fig. 11). For example, the 58 m^3 m^{-1} gained during the 2015 summer was rapidly lost during the subsequent energetic winter (-97 m^3 m^{-1}) while the 96 m^3 m^{-1} gained during the 2016 summer were supplemented by the subsequent calm winter (+36 m^3 m^{-1}). Results also showed that inter-site variability in volume change, represented by the error bars, was larger during winter months than summer months over the study period, especially when wave conditions were energetic (Fig. 11). The 10 beaches average standard deviation of 6-monthly volume changes from 2007 to 2017, dV_{std}, which represents the inter-site variability in volume change, was therefore computed and plotted against the corresponding 6-monthly significant wave height mean values (Fig. 12). Over winter months, the increase of deviation in volume changes between the 10 study sites was strongly correlated with the increase of significant wave height (r = 0.83), while no significant correlation was found between these two variables over summer months (Fig. 12).

Fig. 11 here

Fig. 12 here

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

4.2. Influence of geomorphological and geological boundaries in beach behaviour

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

In the present study, five sites have dune systems that vary in alongshore extent (from 160 to 2400 m) and height (from 11 to 22 m). The role of storm surge is limited along the open coast of North Cornwall, and rarely exceeds 1 m (Masselink et al., 2015); however, the coincidence of events of energetic and long-period waves with spring high tides can induce strong dune erosion. The influence of coastal dune systems on beach volumetric changes over the last 10 years was investigated by quantifying the longshore-averaged dune volume time series, as mentioned in section 2. The volume time series associated with the dunes, V_{dunes}, at Widemouth #1, Constantine #2, Porthcothan #3, Gwithian #9 and Sennen #10, show that dunes were 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 $m^3 m^{-1}$, respectively), while very little volume change was observed at Widemouth #1 (-9 $m^3 m^{-1}$). The 2015/16 winter was also responsible for strong and significant dune erosion at Porthcothan #3 and Sennen #10 (-41 and -16 $m^3 m^{-1}$, 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).

Fig. 13 here

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

5. Modelling of multi-annual beach behaviour

In the previous section, the longshore-averaged beach volume time series was strongly controlled by seasonal and inter-annual wave forcing. The 6-monthly volume changes, dV, for each study site were plotted against the corresponding 6-monthly significant wave height mean values $H_{s\ mean}$, and the 6-monthly cumulative storm duration (Fig. 14). Trends of decrease in beach sand volumes with increase in wave height (Fig. 14a) and storm duration (Fig. 14b) can be observed. Despite the presence of some inter-site variability, a threshold between accretion and erosion can be observed within a range of mean significant wave height from 1.6 to 1.7 m, while most of the study sites were subject to erosion when cumulative storm wave conditions exceeded 13 hours. These threshold values correspond roughly to an energetic summer and a calm winter, when considering the seasonal wave conditions of the last 10 years. Furthermore, erosion was systematically observed when waves exceed 2.5 m and the cumulative storm duration exceeds 100 hours (Fig. 14).

Fig. 14 here

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

Fig. 15 here

Pearson's correlation coefficient, R, and the Brier Skill Score, BSS (Sutherland et al., 2004) calculations suggested that the model provides a good hindcast of the average of the 10 beach volume time-series (r = 0.85 and BSS = 0.71, respectively). In general, the model predicts quite well both the seasonal and inter-annual variability in volume change. While apparent overestimations of the eroded volumes can be observed in phase 1 and 2 (e.g. 2007/08 winter, 2009/10 winter, 2011/12 winter), the erosive impact of the extreme 2013/14 storms (phase 3) is slightly under-estimated, and the recovery during the following 6 months (Summer 2014) is largely over-estimated if the previous underestimation is not considered (Fig. 15). The increase of inter-site variability in the magnitude of volume change over that period partially dilutes the skill of the model. Indeed, less accretion occurred during the 2014 summer at most of the study sites than the model suggests. Because most of the beaches were still in a very-much depleted state by the end of the 2014 summer, the 2014/15 winter was accretionary. The ShoreFor model predicts erosion during the 2014/15 winter because of the over-prediction for the accretion during the preceding summer. However, the energetic 2015/16 winter storm response and its subsequent recovery was very well captured by the model. The good ShoreFor model results demonstrate that the observed coherent regional variability in sand volume is linked to incident wave forcing. Consideration of antecedent conditions through their inclusion in the model also demonstrates the importance of antecedent conditions on future volume change in comparison to the simple correlations with significant wave height (Fig. 14).

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

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

Fig. 16 here

6. Discussion

From 2007 to 2017, the north coast of Cornwall experienced highly variable wave conditions on seasonal and inter-annual temporal scales. This variability in wave conditions, which was fairly well correlated to a new climate index proposed for the Atlantic coast of Europe (WEPA; Castelle et al., 2017b), drove a synchronous and coherent beach response, dominated by cross-shore sediment transport, for the 10 studied beaches along this coastline. Such regionally-coherent coastal response has also been demonstrated for the east coast of Australia, where it was found that beaches of similar orientation had synchronous oscillation and rotation over a 6-year period (Short et al., 2014; Bracs et al., 2016). However, the three beaches along the east coast of Australia have similar size while, here, the 10 study sites represent a wide variety of beach size and length. As also observed for Perranporth beach (Poate et al., 2014; Masselink et al., 2016 ; Scott et al., 2016), a well-studied beach located along the north coast of Cornwall not included in the present data set, beach volume time series of all 10 studied beaches showed seasonal variations superimposed on inter-annual variations coupled to winter wave activity. Such multi-scale variation in wave conditions is generally observed on storm-dominated coastlines with a seasonal wave climate (Ruggiero et al., 2005; Pye and Blott, 2008; Castelle et al., 2015; Barnard et al., 2017; Harley et al., 2017a).

The 10-year study period includes the 2013/14 winter, which was the most energetic winter since, at least, 1948 and caused significant morphological changes all along the west coast of Europe (Masselink et al., 2016). Results showed that these extreme wave conditions to which our 10 study sites were fully exposed (Burvingt et al., 2017), were responsible of the most erosive event over, at least, the last decade. The antecedent morphological beach state being a controlling factor of beach response to storm (Voudoskas et al., 2012; Harley et al., 2016), the dramatic response of the beaches to the 2013/14 winter is partly attributed to the fact that the beaches were in their most accreted state after the 2013 summer, enhancing the disequilibrium between beach state and wave forcing during the 2013/14 winter. Furthermore, these extreme events drove an increase of variability in the magnitude of volume change between the 10 study sites. Many factors can account for this increase of spatial variability. First, as shown in Table 2, the dates for which the cross-shore profiles were surveyed vary from one beach to another. A late winter survey could possibly not include one or several storms, while a late spring survey would and could even capture some of the recovery processes. This issue has, however, only minor consequences on the results since seasonal variations in beach volume change are much larger than the changes measured by 2-month-spaced surveys carried out within the same season. Second, the 10 study sites present different geological settings. Beach morphological response to storms was demonstrated to be strongly controlled by local coastline orientation relative to storm wave direction (Burvingt et al., 2017; Harley et al., 2017a). The small differences in coastline orientation among our study sites, resulting in differences in inshore storm wave conditions, not accounted for here, could have been enhanced during storm conditions and may explain the increase of variability in volume change magnitude among the 10 beaches following the 2013/14 winter. Moreover, this study also showed that, after being relatively stable from 2007 to 2013, dunes shifted from swash to collision regime (Sallenger, 2000) during the 2013/14 winter, highlighting the episodic and irregular nature of beach-dune interactions (Pye and Blott, 2008; Castelle et al., 2015). The spatial variability of dune response to storm waves can be accounted for by the increased variability in volume change magnitude among the 10 beaches; likewise, other intrinsic beach characteristics could also have played a role, such as sediment size and availability (Prodger et al., 2016), headland by-passing (Burvingt et al., 2017; Valiente et al., in prep.; Wiggins et al., in prep.) or the presence of large rocky platforms.

Three years after the 2013/14 extreme storms, beach recovery is variable (from 5 to 200%) between study sites covering the four beach recovery stages defined by Morton et al. (1994). Recent studies have also shown that substantial beach recovery following storm events can occur after days (Angnuureng et al., 2017) or between one and two years (Castelle et al., 2017a; Harley et al., 2017b). In our 10-beach dataset, only six beaches showed a percentage of recovery close or superior to 100% after 3 years, while four beaches are still recovering (between 5 and 70%). The belated post-storm beach recovery along the north coast of Cornwall appears to be mainly controlled by the winter wave conditions over the years following extreme storms, with the wave height variability in summer only playing a minor role. Indeed, only one energetic winter, such as the 2015/16 winter, nullified the total recovery that occurred over the previous 18 months. Summer conditions consistently contribute to modest beach recovery, but substantial recovery over a year only takes place when a mild and therefore accretionary winter occurs. Over the 10-year study period, the 2008/09, 2014/15 and 2016/17 winters were all accretionary and they also followed intense erosive periods during the 2006/07, 2013/14 and 2015/16 winters that left the beaches in a depleted state. These results re-emphasise the importance of the antecedent wave conditions, as well as the actual wave forcing in driving beach response. It should be noted that this conclusion concerning beach recovery is valid only for beaches with prevailing cross-shore sediment transport; recovery of beaches dominated by longshore sediment transport processes (Scott et al., 2016; Burvingt et al., 2017) is not simply dictated by the difference between antecedent and actual wave steepness, and requires a consideration of the wave direction.

Building on the coherent and synchronous beach behaviour at all study sites and the strong correlation between wave forcing and beach response, the ShoreFor equilibrium model (Davidson et al., 2013) was used to hindcast the average beach volume time series taking into account all 10 beaches. The good skill of the model indicates that the observed regionally-coherent variability in sand volume is linked to incident wave forcing and is, importantly, potentially predictable. Consideration of antecedent conditions through their inclusion in the model improves the skill of predictions, highlighting the importance of antecedent conditions on future beach volume/shoreline change, as demonstrated in previous field studies (Wright et al., 1985; Plant et al., 1999; Miller and Dean, 2004) and applications of the model to other exposed sites (Splinter et al., 2014). In agreement with the results of Splinter et al. (2014), application of the ShoreFor model to the average beach volume time series for the 10 Cornish beaches yields a response factor ϕ ≈1000 days. This illustrates the strong seasonal signal with larger-winter (small-summer) waves driving beach erosion (accretion) superimposed on inter-annual variability in winter wave height driving extreme storm-erosion during energetic winters and stability, or even recovery, during mild winters. These results also show that the ShoreFor model explains most of the variability in 10 beaches when only modelled wave data were provided to force the model; this reinforces the conclusion that coherent behaviour is mainly controlled by offshore wave climate and is highly sensitive to the antecedent conditions, while beach intrinsic factors only act as secondary control factors. These findings illustrate that in regions with coherent coastal response, a relatively simple shoreline model based on the difference between actual wave conditions and the equilibrium conditions can be successfully applied for the whole region. This has further implications for the management of beaches in terms of both predicting the impact of storms and assessing potential rates of beach recovery following severe erosion (Davidson et al., 2017). Moreover, the significant correlations between the climate index controlling winter wave activity along the Atlantic coast of Europe (WEPA) especially during very energetic winters, and observed/modelled beach annual volume changes is a promising result for the development of weather regime-driven beach/shoreline models, as suggested by Robinet et al. (2016). The recent skilful predictability of the winter North Atlantic Oscillation (Dunstone et al., 2016), which is the primary mode of atmospheric variability in the North Atlantic region, and its implication on coastline change along the western coast of Europe is worthwhile exploring.

7. Conclusions

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

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

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

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

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

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

Acknowledgments

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

References

Almeida, L.P., Vousdoukas, M.V., Ferreira, O., Rodrigues, B.A., Matias, A., 2012. Thresholds for storm impacts on an exposed sandy coastal area in southern Portugal. Geomorphology 143-144, 3–12.

Angnuureng, D.B., Almar, R., Senechal, N., Castelle, B., Addo, K.A., Marieu, V., Ranasinghe, R., 2017. Shoreline resilience to individual storms and storm clusters on a meso-macrotidal barred beach. Geomorphology 290, 265–276.

Barnard, P.L., Short, A.D., Harley, M.D., Splinter, K.D., Vitousek, S., Turner, I.L., Allan, J., Banno, M., Bryan, K.R., Doria, A., Hansen, J.E., Kato, S., Kuriyama, Y., Randall-Goodwin, E., Ruggiero, P., Walker, I.J., Heathfield, D.K., 2015. Coastal vulnerability across the Pacific dominated by El Nino/Southern Oscillation. Nat. Commun. 8, 801-808.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Choowong, M., Phantuwongraj, S., Charoentitirat, T., Chutakositkanon, V., Yumuang, S., Charusiri, P., 2009. Beach recovery after 2004 Indian Ocean tsunami from Phang-nga, Thailand. Geomorphology 104, 134–142.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

McCallum, E., 1990. The Burn's day storm, 25 January 1990. Weather 45 (5), 166–173.

McCallum, E., Grahame, N.S., 1993. The Braer storm – 10 January 1993. Weather 48 (4), 103–107.

McLean, R., Shen, J.S., 2006. From foreshore to foredune: foredune development over the last 30 years at Moruya Beach, New South Wales, Australia. J. Coast. Res. 22, 28–36.

Miller, J.K., Dean, R.G., 2004. A simple new shoreline model. Coast. Eng. 51, 531–556.

Morton, R.A., Paine, J.G., Gibeaut, J.C., 1994. Stages and Durations of post-Storm Beach Recovery, Southeastern Texas Coast, U.S.A. J. Coast. Res. 10 (4), 884–908.

Phillips, M.S., Harley, M.D., Turner, I.L., Splinter, K.D., Cox, R.J., 2017. Shoreline recovery on wave-dominated sandy coastlines: the role of sandbar morphodynamics and nearshore wave parameters. Mar. Geol. 385, 146–159.

Plant, N.G., Holman, R.A., Freilich, M.H., Birkemeier, W.A., 1999. A simple model for interannual sandbar behavior. J. Geoph. Res. 104 (C7), 15,755–15,776.

Poate, T., Masselink, Russell, P., Austin, M., 2014. Morphodynamic variability of high-energy macrotidal beaches, Cornwall, UK. Mar. Geol. 350, 97–111.

Poate, T., Masselink, G., McCall, R., Russell, P., Davidson, M., 2015. UK storms 2014: gravel beach response. Proceedings Coastal Sediments, ASCE, San Diego, USA.

Prodger, S., Russell, P., Davidson, M., Miles, J., Scott, T., 2016. Understanding and predicting the temporal variability in sediment grain size characteristics on high energy beaches. Mar. Geol. 376, 109-117.

Pye, K., Blott, S.J., 2008. Decadal-scale variation in dune erosion and accretion rates: An investigation of the significance of changing storm tide frequency and magnitude on the Sefton coast, UK. Geomorphology 102, 652–666.

Pye, K., Blott, S.J., 2016. Assessment of beach and dune erosion and accretion using LiDAR: Impact of the stormy 2013–14 winter and longer term trends on the Sefton Coast, UK. Geomorphology 266, 146-167.

Roberts, T.M., Wang, P., Puleo, J.A., 2013. Storm-driven cyclic beach morphodynamics of a mixed sand and gravel beach along the Mid-Atlantic Coast, USA. Mar. Geol. 346, 403–421.

Robinet, A., Castelle, B., Idier, I., Le Cozannet, G., Deque, M., Charles, E., 2016. Statistical modelling of interannual shoreline change driven by North Atlantic climate variability spanning 2000–2014 in the Bay of Biscay. Geo. Mar. Lett. 36, 479–490.

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

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

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

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

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

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

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

Scott, T., Masselink, G., O’Hare, T., Saulter, A., Poate, T., Russell, P., Davidson, M., Conley, D., 2016. The extreme 2013/2014 winter storms: Beach recovery along the southwest coast of England. Mar. Geol. 382, 224–241.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Figure and table captions

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

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

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

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

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

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

Figure 6. Scatter plots of the winter-mean (DJFM) modelled significant wave height, $H_{s\,mean}$, and the winter WEPA index (a) from the 1980/81 to the 2016/17 winter; and (b) from the 2007/08 to the 2016/17 winter.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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