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The extreme 2013/2014 winter storms: Beach recovery along the southwest coast of England

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ABSTRACT

Sand and gravel beaches naturally act as a coastal buffer, absorbing wave energy and dynamically adapting to the seasonal and long-term wave climate. Significant shifts in nearshore morphology can occur during extreme wave events, which can have a significant impact on coastal vulnerability. During the winter of 2013/14, the Atlantic coast of Europe received an unprecedented sequence of very energetic wave conditions (8-week mean offshore $H_s = 4.4$ m). These events caused extensive physical (beach and dune erosion) and socio-economic (flooding, damage to infrastructure) impacts throughout the west coast of Europe. Many monitored sites in the UK and France were in their most eroded state since morphological records began (5–10 years). We consider the geomorphological significance of the storm response at 38 natural beaches in the southwest of England, ranging from semi-sheltered reflective gravel barriers to ultra-dissipative exposed sand beaches with dunes. The extent and patterns of post-storm recovery are examined in detail at three beaches with characteristic storm response behaviours. Exposed sandy beaches were dominated by cross-shore transport processes leading to significant loss of sediment offshore from the intertidal zone (>200 m^3/m); exposed gravel beaches were dominated by overwash with significant loss landward; and semi-sheltered sites exposed to more oblique wave forcing were dominated by a rotational response due to alongshore sediment redistribution. Due to these contrasting responses, mechanisms and timescales for beach recovery displayed strong inter-site and intra-site variations. In offshore and rotational cases, the recovery processes were multi-annual, comprising seasonal to decadal signals and were intrinsically linked to the storm response mechanisms, while permanent losses occurred when overwash dominated. We show that post-storm recovery does not necessarily occur during calm periods and that in many cases high-energy wave events appear to be essential for recovery of sediment (offshore and counter-rotation). Our results highlight the significance of dominant climatic oscillations, multi-annual storm sequencing, storm tracks and resultant variations in wave angle, in controlling the impact that extreme wave events have on contrasting sand/gravel beaches in exposed/sheltered locations.

1. Introduction

Sand and gravel beaches naturally act as a coastal buffer (Stive et al., 2002), absorbing wave energy and dynamically adapting to the seasonal and long-term wave climate. In the short- to medium-term (seasons to years), significant shifts in nearshore morphology can occur during extreme events (single large storms or storm clusters), causing lowering of intertidal beaches and scarping of dune systems (Splinter and Palmsten, 2012), reducing the protection offered to subsequent storm events and elevating risks of coastal inundation (Elko et al., 2014). High-energy wave events will also mobilise offshore sediments at depth, advected by storm driven nearshore currents, like bed return flow (e.g., Roelvink and Stive, 1989; Özkan-Haller, 2013) and rip currents (e.g., Loureiro et al., 2012), modifying the position of offshore bars and shoals, and hence nearshore wave transformation (Senechal et al., 2011; Coco et al., 2014; Lewis et al., 2014). These erosional responses can result in reduced or modified beach levels, which have short- to medium-term impacts for coastal vulnerability (Masselink et al., 2015). Therefore, understanding post-storm recovery mechanisms and timescales, throughout a range of coastal environments, is critical for future coastal hazard prediction, as well as long-term coastal evolution modelling (Ranasinghe et al., 2013).

Shorelines can recover from storm-induced erosion, but beach recovery rates are highly variable. Significant recovery can occur within days (Birkemeier, 1979; Poate et al., 2015), but more typically takes several months. In some cases, full recovery from severe storms can take up to a decade (Thom and Hall, 1991), if at all, especially where sediment

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has been lost to the system, either offshore, alongshore or landward. It is the balance between storm response, storm frequency and recovery rates that controls the long-term coastal evolution and vulnerability, but our understanding of coastal storm response is limited by the quality and appropriateness of the datasets available (Coco et al., 2014), particularly for quantitative measurements throughout a full sequence of beach recovery.

During winter, the coasts of western Europe are exposed to strong easterly-tracking extratropical cyclones, which can arrive explosively in high-frequency (order days) storm sequences during particularly high-energy seasons, often associated with positive North Atlantic Oscillation (NAO) index (Donat, 2010; Bromirski and Cayan, 2015). Recent studies have shown that the NAO and extreme storm clustering can be dynamically linked to atmospheric Rossby wave breaking (Woollings et al., 2008; Hanley and Caballero, 2012) and quasi-annual stratospheric east-west wind reversals associated with the Quasi-Biennial Oscillation (QBO; Baldwin et al., 2001). The QBO influences the stratospheric polar vortex and hence the winter NAO and Atlantic-European climate, especially in winter (Marshall and Scaife, 2009). These mechanisms collectively contribute to climate variability, which has been shown over recent decades to modify the wave climate (Dodet et al., 2010; Bromirski and Cayan, 2015) and subsequently beach morphological state (Masselink et al., 2014).

While there is currently little consensus on long-term changes in Atlantic storminess, an analysis of satellite observations over NW Europe by Young et al. (2011) showed a significant increase in extreme wave heights ($H_{s\ 1\%}$) over the past 20 years (1985–2008), greater than anywhere throughout the global oceans. Donat et al. (2011) showed upward trends in European storminess and demonstrated strong decadal variability in extreme wind storms over the last century in NW Europe, with some climate research suggesting that the northeast Atlantic is predicted to experience significant increases in winter and autumn extreme values of significant wave height (H_s) by the end of the this century (Wang et al., 2012). Most importantly, large amounts of interannual and decadal variability in the climate-ocean system leads to the potential for significant coastal morphological changes that can expose coastal communities to sequences of higher levels of flood risk than the long-term background.

The storm events described by Masselink et al. (2015) that took place during the winter of 2013/14 along the Atlantic coast of Europe represented an unprecedented sequence of very energetic wave conditions occurring over a 3-month period. The peak value of the 8-week averaged significant wave height (8-week mean offshore $H_s = 4.4$ m) measured offshore of southwest England during the winter of 2013/14 was extremely rare.

Analysis of a 60-year hindcast wave model record (validated by offshore wave buoy measurements) by Masselink et al. (2016) suggests that with the exception of the far north region (Ireland), the 2013/2014 winter was the most energetic since 1948. In this study, a Generalized Extreme Value (GEV) analysis of annual maxima (Coles, 2001) in peak 8-week average wave heights suggest the 2013/2014 storm sequence had a minimum return period of 1 in 50 years and a best fit estimate of order 1 in 250 years. Measured offshore wave data from the southwest of England (wave platform 30 km offshore in 60 m water depth; refer to Fig. 1 for wave platform location) showed that H_s during the largest recorded storm exceeded 9 m with a peak wave period (T_p) of 23 s. These storms caused extensive physical (beach and dune erosion) and socio-economic (flooding, damage to infrastructure) impacts throughout the west coast of Europe (Ireland, UK, France, Spain and Portugal). Throughout monitored sites in the UK and France, most were in their most eroded state since morphological records began (5–10 years; Poate et al., 2014; Castelle et al., 2015; Masselink et al., 2015), highlighting the vulnerability of the Atlantic coast of Europe to such coastal hazards (Castelle et al., 2015).

To assess and mitigate coastal impacts of future extreme storm events, consideration of forcing mechanisms operating over short- (weeks-months; individual storms), medium- (months-years; storm clusters/patterns) as well as long-term (years-decades; climatic variability) time scales is required. Recent work by Masselink et al. (2015) reported on a preliminary analysis of the beach response in southwest England during the extreme winter of 2013/14 in Europe. In addition to highlighting the important roles played by storm characteristics

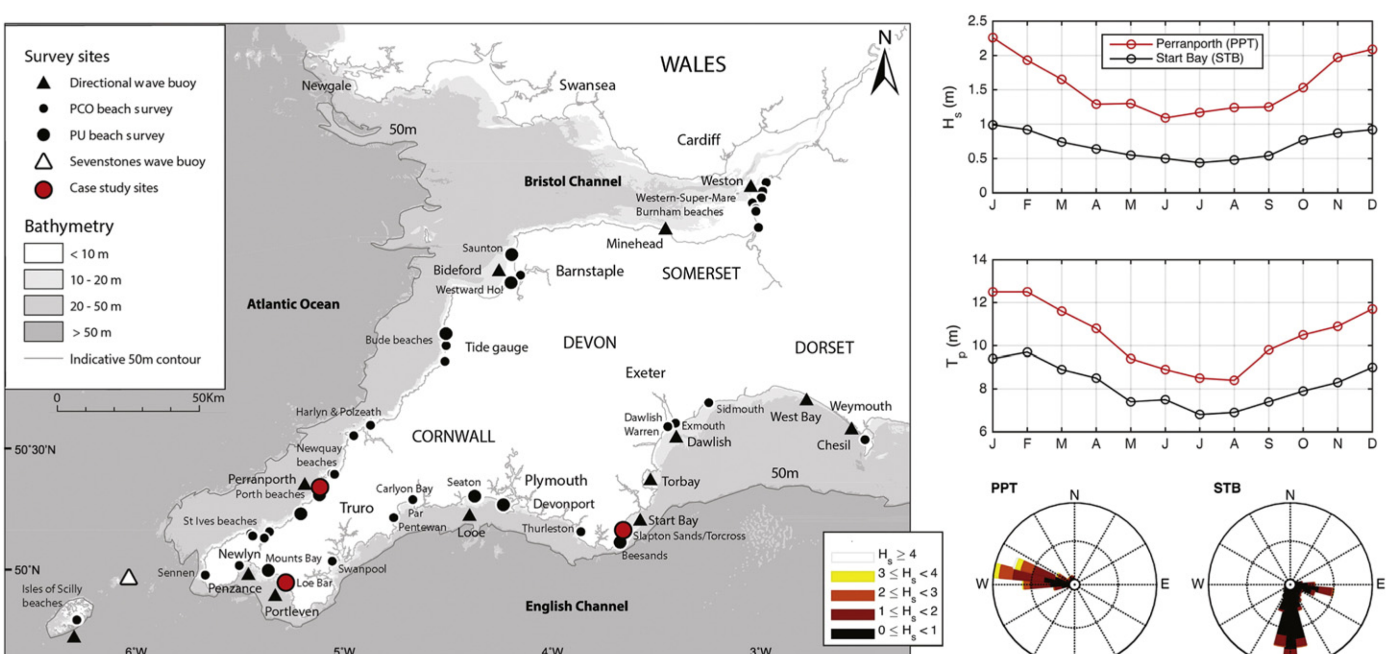

Fig. 1. Location of data sources. Left panel: map of the southwest of England showing location of offshore and nearshore directional wave buoys, beaches regularly monitored by the Plymouth Coastal Observatory (PCO), sites that are part of the Plymouth University (PU) coastal monitoring programme and specific case study sites discussed further in this study (red circles). The 50-m depth is indicated. Upper right panels: nearshore mean monthly significant waves height (H_s) and peak wave period (T_p) measured at Perranporth (exposed west coast; red) and Start Bay (semi-exposed; black) south coast in 16 m and 10 m depth, respectively. Bottom right panel: directional wave rose for both sites indicating distribution of H_s. Wave data represents a 9-year record from 2006 to 2015.

(track, intensity and frequency) and water level (tide and surge heights), this study also observed considerable spatial variability in the geomorphic storm response due to the embayed nature of the coastline and the associated variability in coastal orientation. On west-facing beaches, typical of the west coast, the westerly Atlantic storm waves approach the coastline shore-parallel, and the prevailing storm response was offshore sediment transport and widespread beach/dune erosion. On south- and east-facing beaches, typical of the south coast, the storm waves were associated with oblique wave approach, resulting in strong littoral drift and beach rotation. The type of storm response is expected to have a significant impact on the rate of post-storm recovery.

In this paper, we aim to quantify the significance of the winter 2013/14 storms within a medium-term (multi-annual to decadal) context. Specifically, the study extends the work presented in Masselink et al. (2015) to: (1) identify the dominant storm impact mechanisms throughout 38 natural beaches in the southwest of England; (2) assess the relative morphological impacts of the 2013/14 winter within a longer term morphological time series at three sand and gravel beach sites representative of the dominant regional response mechanisms; and (3) quantify extents and timescales of multi-annual beach recovery processes utilising >5 year morphological records at each site.

2. Methodology and study area

The embayed coastline of the southwest of England is extremely diverse incorporating a broad range of geomorphic and hydrodynamic settings. Fig. 1 illustrates the regional coastal physiography, which can be broken down into three main sections: the north coast (Bristol Channel), west coast (Atlantic Ocean) and south coast (English Channel). These regions span the counties of Devon, Cornwall, Dorset and Somerset. The beaches of the region cover the full morphological spectrum from reflective to dissipative, non-barred to multi-barred, including dunes, sand and gravel beaches, barriers and spits, as well as various types of estuaries, tidal flats and rocky coasts (e.g., Steers, 1946; May and Hansom, 2003; Scott et al., 2011).

The west and north coasts have a macro- to mega-tidal range (mean spring tide range (MSR) from 4 to 12 m) and are typically exposed medium- to high-energy open-coasts dominated by high hard rock cliffs and embayed sandy beaches. Along the meso- to macrotidal south coast (MSR = 3–5 m), the eastward reduction in Atlantic exposure results in a more complicated bimodal wave frequency-direction spectrum, as attenuated Atlantic swell waves are complimented by local wind seas generated in the English Channel. Fig. 1 illustrates this geographic variation by showing monthly average H_s and T_p values for nearshore wave buoys at Perranporth (exposed west coast; 16 m depth) and Start bay (semi-sheltered south coast; 10 m depth). H_s and T_p values for Perranporth range from 1.17 m and 8.5 s in July, to 2.26 m and 12.5 s in January. Likewise, H_s and T_p values for Start Bay range from 0.44 m and 6.8 s in July to 0.99 m and 8.5 s in January. The nearshore wave record highlights the strong seasonal variability in wave climate in the southwest region, which is the most energetic in England. The 10% exceedance wave heights ($H_{S\ 10\%}$) at Sevenstones light vessel (60 m depth; Fig. 1) during winter and summer from 2003 to present were 4.2 m and 2.5 m, respectively, and the analysis of the joint wave distributions indicate that a significant portion of the increase in energy during the winter months is due to storms with relatively long-period waves. It is interesting to note that even though water levels are critical when assessing storm impacts (Masselink et al., 2015), positive residuals related to storm surge rarely exceed 0.5 m and 1 m along the west and south coasts, respectively. This is in stark contrast to observations along the east coast of England during the 2013/14 winter (Spencer et al., 2015).

The supra and inter-tidal beach morphological data used in this study were collected both via the Plymouth Coastal Observatory (38-beach storm response dataset, see Masselink et al. (2015) for more details) and Plymouth University (long-term monthly monitoring at Perranporth (Masselink et al., 2014), Loe Bar (Poate et al., 2014) and Slapton Sands (Ruiz de Alegria-Arzaburu and Masselink (2010) using RTK-GPS. Computed changes in the beach sediment volume for the 38-beach response dataset represent changes to the dune, backshore and intertidal beach area, but do not include the subtidal zone. In contrast, the long-term intertidal beach morphological data collected by Plymouth University are supplemented by quasi-bimonthly RTK-GPS aided single-beam echo-sounder bathymetric surveys at Perranporth beach during the period 2010–2012 and 2014–2015. These bathymetric data were collected using an Arancia inshore rescue boat (IRB) to extend profiles (25-m alongshore line spacing) to incorporate the full active morphological envelope (depth of c. 16 m Ordnance Datum Newlyn (ODN)). Fig. 1 provides an overview of data sources and beach locations used in the study.

To examine the long-term wave climate and assess the significance of recent storm activity, a combination of available wave (measured/modelled) and wind (measured) datasets were used to represent forcing at each of the beach monitoring sites. The southwest coast of England has a network of 12 nearshore directional wave buoys (at c. 10 m depth from mean sea level) that record 30-min inshore wave statistics and are managed by the South West Regional Coastal Monitoring Programme. Buoys at Perranporth, Porthleven and Start Bay are used in this study, and all have relatively unbroken records since 2006. Unfortunately, due to their shallow water location, data can be poor under extreme storm conditions. Therefore, short-term wave conditions for west coast locations are represented by the UK Met Office European (8-km) wave model, and long-term wave conditions were represented regionally by a combination of the Sevenstones wave record (2003–2015; available from http://www.previmer.org/), combined with a co-located 57-year hindcast (1953–2009) obtained with a spectral wave model (version 3.14 of WAVEWATCH III) forced with reanalysis wind fields (Dodet et al., 2010). Finally, hourly wind records from UK Met Office Mountbatten weather station (1949–present) were used to infer wind seas states for the period 1960–present at Start Bay (south coast) due to a lack of local long-term wave records.

3. Wave forcing

Based on Sevenstones offshore wave data, the winter of 2013/14, between December and February, was a rare (>1:50-year) event due to the unprecedented frequency, or clustering, of high-energy storms within a 3-month period. There were 18 individual storms (with a further 4 occurring during March 2014) with an offshore $H_s > 5.9$ m (1% exceedence wave height) that were bounded by periods when $H_s < 4.5$ m (5% exceedence wave height), resulting in an average $H_s > 4$ m for the period (Fig. 2; upper panel). According to the UK Met Office, the joint H_s-T_p probability of the storm named *Hercules* ($H_s = 9$ m; $T_p = 23$ s) on 6 January 2014 identified it as a 1:5 to 1:10 year wave event (Met Office, 2014), whereas the combined wave and water level characteristics of the storm named *Petra* ($H_s = 8$ m; $T_p = 15$ s) on 5 February 2014 meant it was the most damaging storm in terms of coastal impact (physical and socio-economic) on the south coast of Devon and Cornwall for the last 50 years (Devon Maritime Forum, 2014; Masselink et al., 2015). Fig. 2 (lower panel) illustrates the 8-week running mean of offshore H_s since 1950, demonstrating significance of 2013/14 winter.

One of the key features of the storm events during this period was the regional variability of inshore H_s around the southwest coast. Fig. 2 (middle panel) shows H_s throughout all of the monitored beach sites (see Fig. 1) through assessment of their co-located inshore wave model nodes (Met Office 8-km WAVEWATCH III model). As explored in detail by Masselink et al. (2015), all recorded storms approached from the WNW–SW direction, invariably impacting the higher-energy exposed west coast beaches, but it is evident that several of these storms also generated extreme wave heights ($H_s > 5$ m) on the more sheltered

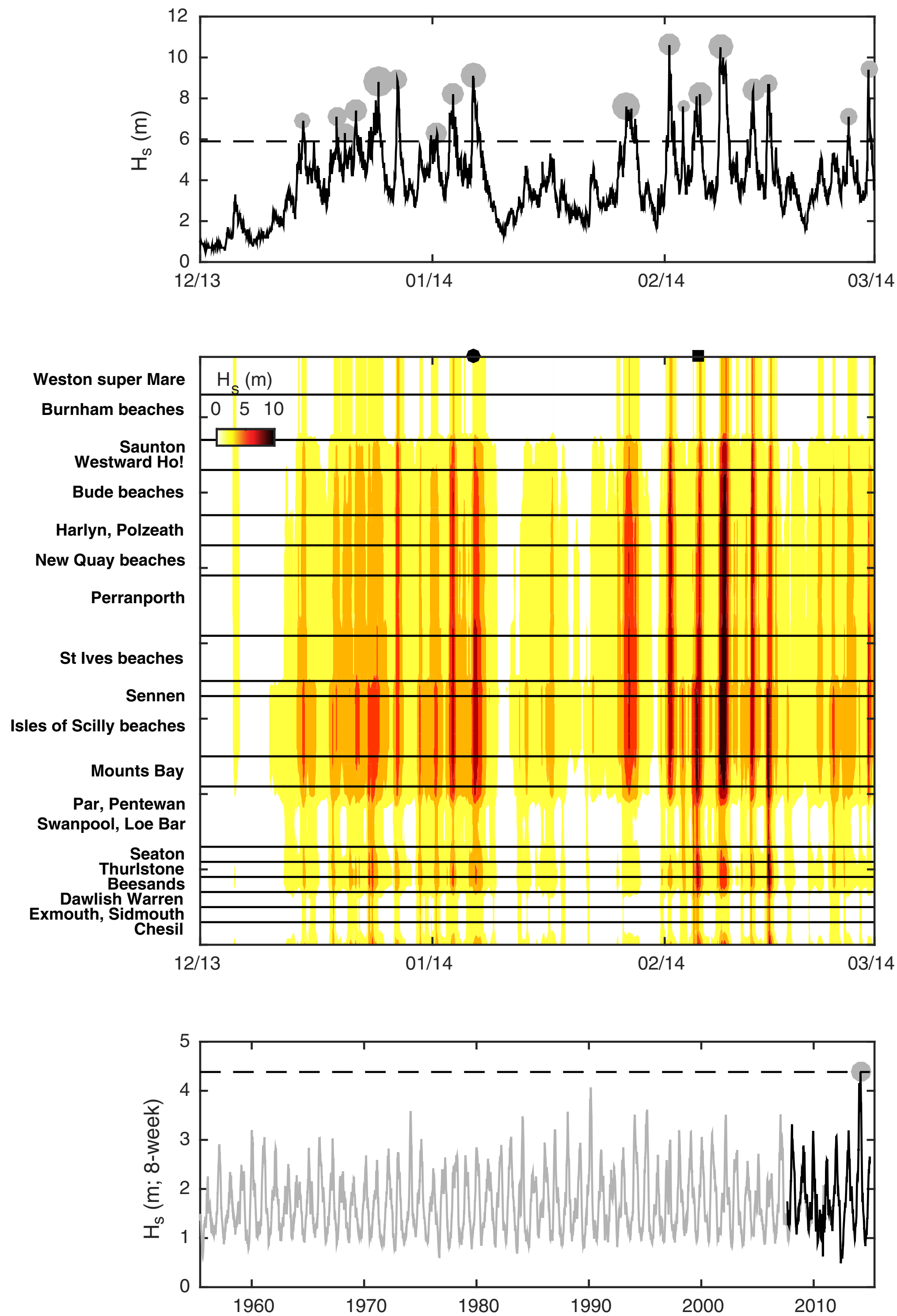

Fig. 2. Regional distribution of wave heights during the winter of 2013/14 and long-term context. Top panel: 3-month measured offshore hourly wave record from Sevenstones covering the winter 2013/14 period. Dashed line indicates 1% exceedence significant wave height and grey circles indicate major storm events and their duration (circle size). Middle panel: time-series of the round-coast distribution of wave height during the winter 2013/14 period. Locations relate to monitored beach sites shown in Fig. 1. Data are modelled outputs from Met Office 8-km WAVEWATCH III model. Storms Hercules (6/1) and Petra (5/2) are indicated by a filled black circle and square, respectively. Bottom panel: long-term 8-week averaged wave record from WAVEWATCH III modelled (1953–2011) and measured (2008–2014) significant wave height at Sevenstones. Modelled wave data were obtained from Dodet et al. (2010), and measured data were collected and made freely available by the CDOCO in the framework of Previmer project and programs that contribute to it (http://www.previmer.org).

south coast beaches, especially at Mounts Bay, Seaton, Thurlstone, Beesands and Chesil (Fig. 2; middle panel).

When considering the difference in the significant storm wave height between the west and south coast, referred to as the residual wave height ΔH_s, it is evident that for 15 of the 18 storm events north coast H_s is 1–5 m larger than the south coast H_s (Fig. 3; upper panel). However, the west coast is generally more exposed that the south coast, and it is more insightful from the perspective of coastal storm impacts to consider the nearshore wave conditions impacts in relation to the long-term (5-year) mean winter wave condition (December–

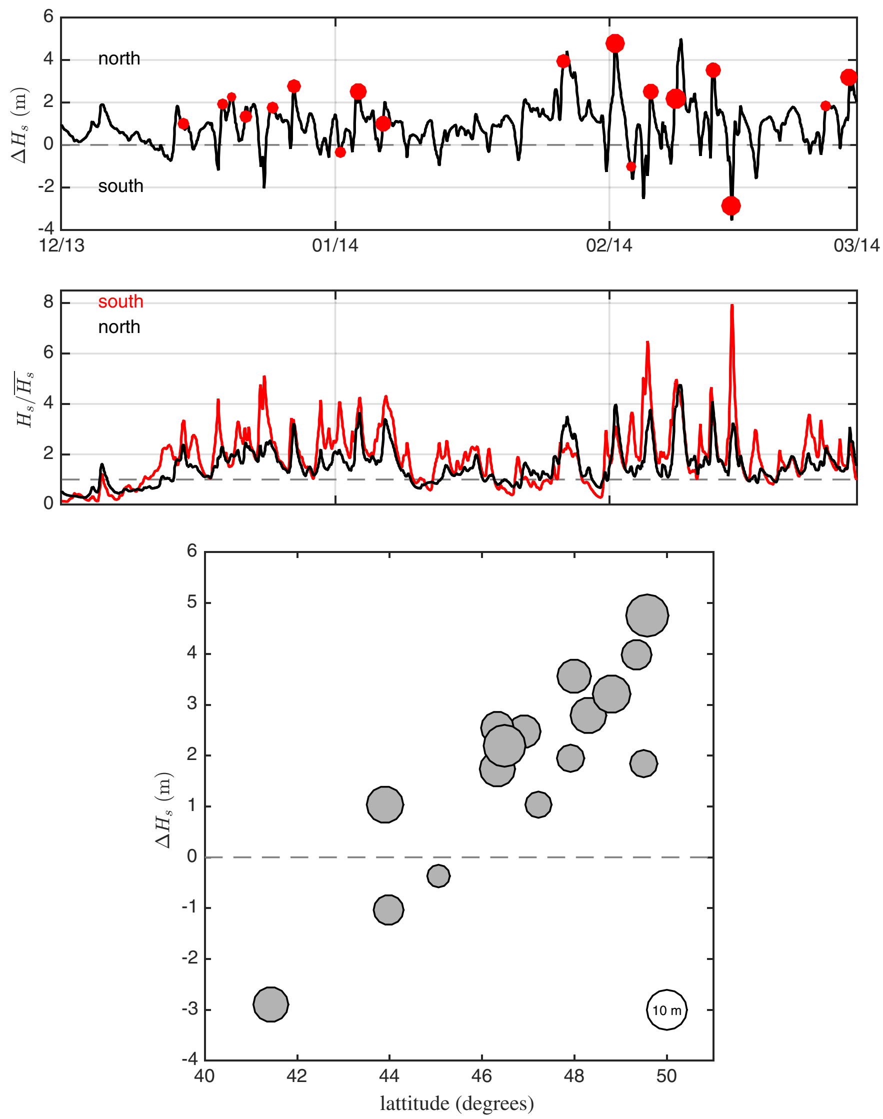

Fig. 3. Wave data illustrating the importance of considering storm track on geographical distribution of wave impacts. Top panel shows the wave height residual H_s (Perranporth)-H_s (Looe) ΔH_s, indicating the relative geographic impact of individual storms (storm peaks highlighted in red). Middle panel shows disequilibrium parameter $Hs/\overline{Hs}$ for Looe (red) located on the south coast and Perranporth (black) located on the west coast (see Fig. 1 for buoy locations). Bottom panel shows the storm wave residual ΔH_s as a function of the mean storm latitude (centre of westerly focussed wave generation) 12–24 h prior to peak wave height at Sevenstones Lightvessel (SW approaches). Circle size scaled by H_s.

January–February (DJF)), referred to as the disequilibrium parameter $Hs/\overline{Hs}$. Fig. 3 (middle panel) shows $Hs/\overline{Hs}$ for the winter 2013/14 at two coastal locations, representing west and south coast conditions. Measured nearshore wave data are used here, but several gaps in these data due to storm damage were filled using model data. Despite the consistently larger H_s values on the west coast compared to the south coast, the disequilibrium parameter was significantly and consistently larger for the south coast (Fig. 3; middle panel). During 10 (2) of the 18 storm events, the significant wave height on the south (north) coast was >4 times the long time average wave height ($Hs/\overline{Hs}>4$), suggesting, perhaps, that the coastal impacts of these storms are likely to have been more significant on the south coast.

The difference in wave conditions between the west and north coast for specific storms, quantified by ΔH_s, was found to be strongly related to the latitude associated with the specific storm tracks, identified here as the peak of westerly-focussed wave-generating winds from Met Office model outputs 12–24 h prior to peak wave height at Sevenstones (Fig. 3; lower panel). A very strong positive correlation was obtained between these two parameters (r = 0.88) indicating that the storms with larger wave heights on the south coast ($\Delta H_s < 0$) were characterised by storm track latitudes of <45°N and vice versa. The more southerly storm tracks enable storm waves to propagate into the Channel relatively unimpeded, causing larger nearshore wave conditions along the south coast. Storm track latitude does not appear to be related to the storm wave conditions at the tip of southwest England (size of bubbles in Fig. 3; lower panel).

4. 2013/14 storm response

The beach survey data from 38 beaches collected by the Plymouth Coastal Observatory were used to assess the storm response characteristics during the 2013/14 winter along the southwest coast of England (see Masselink et al. (2015) for more details). A variety of significant storm responses (change >5 m^3/m) were observed throughout the 38 monitored beaches; 53% eroded (mean = −77 m^3/m, max = −215 m^3/m, σ = 69), 24% accreted (mean = +17 m^3/m, max = 47 m^3/m, σ = 17), and 24% displayed insignificant change. Fig. 4 illustrates the wide variety of beach responses that occurred

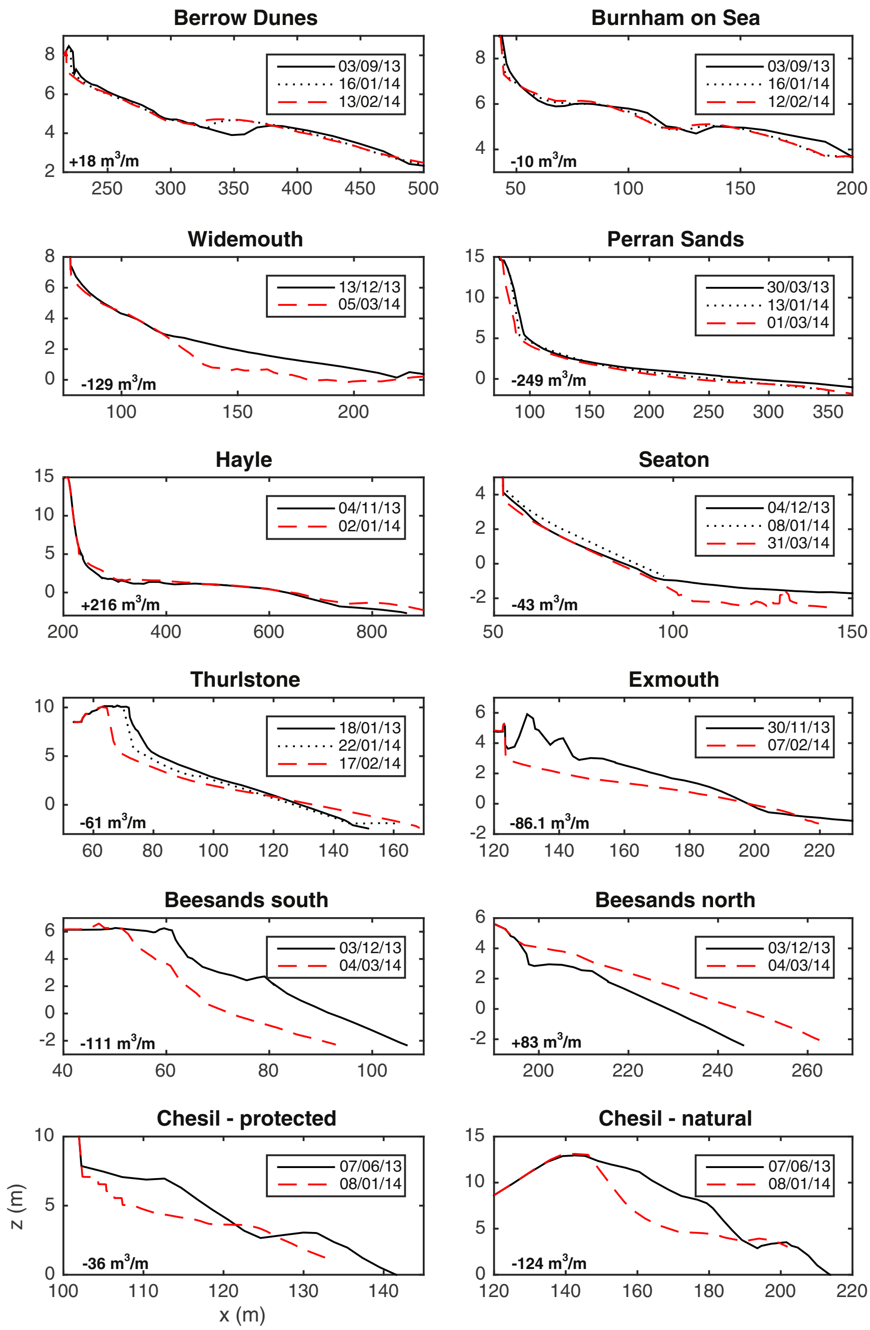

Fig. 4. Examples of morphological change during the 2013/2014 winter season for selected locations along the coast of SW England. The values in the lower left corners of the panels represent the volumetric change in m^3 per unit meter beach width (m^3/m) for the profile in question. Locations can be found on the regional map in Fig. 1 and proceed clockwise around the coast from the mega-tidal Bristol Channel (top panels) to the exposed west coast beaches (second row), sheltered west coast (third row left), semi-sheltered sand, gravel and mixed sand/gravel south coast (third row right downwards). Although Chesil pre storm profiles were measured 6-months prior to storm events, beach change observed is significantly greater than interim variability expected.

during this winter period and a summary of these coastal responses is provided first. This will be followed by more detailed consideration of the three most significant response mechanisms using additional beach monitoring data collected by Plymouth University. Pre- and post storm survey dates were selected that best represent the morphological changes over the 2013/14 winter period.

4.1. Dune erosion

All beaches characterised by coastal dunes experienced dune erosion to varying degrees. On most beaches, significant dune scarping of several meters (c. 10 m) occurred (Fig. 4; Berrow Dunes, Perran Sands, Thurlestone) and at some locations the entire foredune was removed (Fig. 4; Exmouth). Inspection of morphological data for locations for which more than one post-storm survey was available (Fig. 4; Berrow Dunes, Thurlestone) further revealed that dune erosion was not limited to a single storm event. Dune erosion does not automatically imply a loss in beach sediment volume; in fact, in many cases (e.g., Berrow Dunes) modest changes in volume, often moderate gains (<20 m^3/m) occurred mostly across the lower part of the intertidal zone, despite erosion of the coastal dunes. This response was typical for all megatidal (MSR > 9 m) Bristol Channel beaches with dune systems.

4.2. Intertidal bar dynamics

Along the most sheltered sections of the study area along the Somerset (Bristol Channel) coast, the intertidal zone (MSR > 9 m) is characterised by an extremely (ultra) dissipative profile and multiple subdued intertidal bars (Scott et al., 2011). Generally, these beaches displayed a modest influx of sediment from the offshore (<20 m^3/m), as evidenced by onshore migration of the intertidal bars (Fig. 4; Burnham on Sea, Berrow Dunes). This onshore bar migration took place, despite significant erosion of the upper beach and coastal dunes (see above). Significant onshore bar migration and associated significant increases in sediment volume (>200 m^3/m) was also experienced at several partly-exposed sandy estuary and river mouth beaches (Fig. 4; Hayle).

4.3. Exposure of rocky shore platform and coastal defence structures

On two beaches (Widemouth, Seaton), observed profile change revealed the presence of relatively thin veneers of sand *O* (1–2 m) overlying rocky shore platforms. On these sites, storm erosion removed this sand cover, exposing the underlying platforms. Although the presence of this underlying geology would have limited the actual erosion losses, the dramatic transformation of a sandy beach into a rocky platform greatly affected the amenity value of the affected beaches and increases beach hazard severity to bathers. On beaches protected by hard engineering structures (Fig. 4; Beesands south and Chesil - protected) a similar process was observed, with lowering of the upper beach level revealing the underlying structure, sometimes even exposing its foundations. Dramatic beach lowering occurred at reflective gravel beaches with vertical erosion of 2–4 m on some profiles (Fig. 4; Chesil - natural).

4.4. Erosion of entire profile

On all exposed intermediate/dissipative sandy beaches, considerable erosion occurred across the upper part of the beach, more or less above mean sea level (MSL), with some deposition occurring over the lower intertidal zone. However, on the beaches with the largest sediment losses, generally the most exposed west coast beaches, erosion occurred across the entire beach profile (Fig. 4; Perran Sands). These are the types of beaches for which erosion losses exceeded 100 m^3/m and the fate of these sediments will be addressed in more detail in Section 5.1.

4.5. Alongshore distribution of sediment

On several beaches, both erosive and accretionary responses were observed, although the beach-average response was generally erosive. Such contrasting responses were most frequently observed along the south coast where Atlantic storm waves typically approach the coast at an oblique angle. This is exemplified in Fig. 4 at Beesands, where significant erosion occurred along the south (upwave) section of the reflective gravel beach, while accretion occurred along the north (downwave) end of the beach. Such response is suggestive of an alongshore redistribution of sediment and will be addressed in more detail in Section 5.2. In many cases, net intertidal sediment loss within the embayment still occurred, suggesting either sediment losses to the offshore, between embayment through headland bypassing, or through overwash of sediment.

4.6. Barrier overwash

The sandy beaches in Fig. 4 are all backed by coastal cliffs, dunes or engineering structures; however, most gravel beaches form part of coastal barriers and are backed by a coastal lagoon and/or low-lying coastal plain. During extreme storm activity these gravel barrier systems were overtopped and overwashed, resulting in sediment deposition on or landward of the barrier crest (Fig. 4; Chesil - natural). Barrier overwash was also observed at Westward Ho!, Loe Bar, Slapton Sands and Chesil (see Fig. 1 for locations; see Fig. 5 for photographic example from Slapton Sands) and this process is further explored in more detail in Section 5.3.

4.7. Accretion

Although the dominant morphological response to the extreme storms has been erosion, a significant number of beaches (24%) experienced overall gains (>5 m^3/m) in intertidal sediment volume. Small sediment gains occurred on the most locally sheltered sites, where shelter from the westerly and southwesterly storm waves was provided by offshore islands, protruding headlands, hard engineering structures, and/or due to the beach orientation. This included relatively significant gains (approx. 50 m^3/m) in sediment volume at small north facing beaches (11%) in St Ives embayment (see Figs. 1 and 4).

5. Dominant storm-driven sediment pathways

The observed geographic variability in storm response along the SW coast of England unveiled three important sediment transport response pathways: offshore, alongshore and overwash. These processes had significant impacts on coastal cell morphology, long-term beach volumes and therefore coastal vulnerability. These responses were typically site-specific, associated with beach type and hydrodynamic setting. The overall loss of sediment volume at many of the monitored sites raises questions regarding the fate of removed sediment outside of the coverage of this intertidal dataset, even in the case of beaches that were dominated by alongshore redistribution of sediments. Here, more comprehensive data collected by Plymouth University at three sites (Perranporth in north Cornwall, Loe Bar in south Cornwall and Slapton Sands in south Devon coast; Fig. 1) are used to provide additional insight into these dominant storm-driven sediment pathways and the fate of lost sediment, vital for the assessment of post-storm beach recovery mechanisms and timescales.

5.1. Offshore sediment transport and nearshore bar dynamics

The most significant inter-tidal sediment losses were observed on exposed sandy west coast beaches (Fig. 4). These macro-tidal beaches, epitomised by Perranporth beach (Figs. 1, 4 and 6: Perran Sands), are typically of a single-double barred intermediate/dissipative beach type and commonly have a morphologically subdued, wide (200–300 m), intertidal beach (Scott et al., 2011; Poate et al., 2014; Stokes et al., 2015).

Under shore-normal storm conditions, bed return flow currents, aided by (mega-) rip currents are the dominant mechanism that drives offshore sediment transport at these exposed beaches types (Aagaard et al., 2013), advecting sediment from the intertidal mid-upper beach and depositing it in sub-tidal sand bars located around the seaward limit of the surf zone (Fig. 6). Some insight into the fate of the eroded sediment at exposed west facing beaches during the 2013/14 storms is provided by inter- and sub-tidal morphological data collected at Perranporth during pre and post 2013/14 winter surveys in July 2012 and April 2014 (Fig. 6). While there is a significant temporal gap between these datasets, examining them within a context of a multi-annual morphological record provides evidence of a quasi-seasonal cross-shore migration of sediment between the inter-to sub-tidal zones (for more detail see Section 6.1).

Fig. 6 shows an intertidal beach lowering of 0.5–1 m accompanied by significant sediment accumulation of c. 1 m within the sub-tidal zone. The subtidal deposition occurred offshore of the summer 2012 outer bar location (in depths between −6.5 and −13.5 mODN), representing an offshore bar crest translation of approximately 100 m and mean accretion of 185 m^3/m during that period. Comparing the total cross-shore beach volume changes within the entire beach area surveyed (Fig. 6 left panel), the mean difference was −20 m^3/m. The imbalance of which could be explained by the alongshore variability in subtidal

Fig. 5. Example of overwash at Slapton Sands. The road that runs along the gravel barrier of Slapton Sands, south Devon, became covered with gravel due to overwash occurring during the significant storm 'Petra' on 5 February 2014, but also the 'Valentine's Day' storm on 14 February 2014 (http://www.bbc.co.uk/news/uk-26064424).

bar/rip morphology (only 1.5 rip channel morphological wavelengths in survey region), the component of alongshore sediment transport, and the lack of sufficient data regarding the contribution of dune erosion/accretion to the total sediment budget. The extent in both offshore distance and depth of the offshore sediment transport during storms has significant implications for post-storm recovery processes (subsequent onshore sediment transport).

5.2. Longshore sediment transport and beach rotation

Along the semi-sheltered north (Bristol Channel) and south (English Channel) coasts, the dominant Atlantic storm wave approach is oblique to the regional coastline orientation. Beaches in these locations experienced a significant proportion of alongshore sediment redistribution within the embayment (Fig. 4; Beesands, and Fig. 7; Slapton Sands).

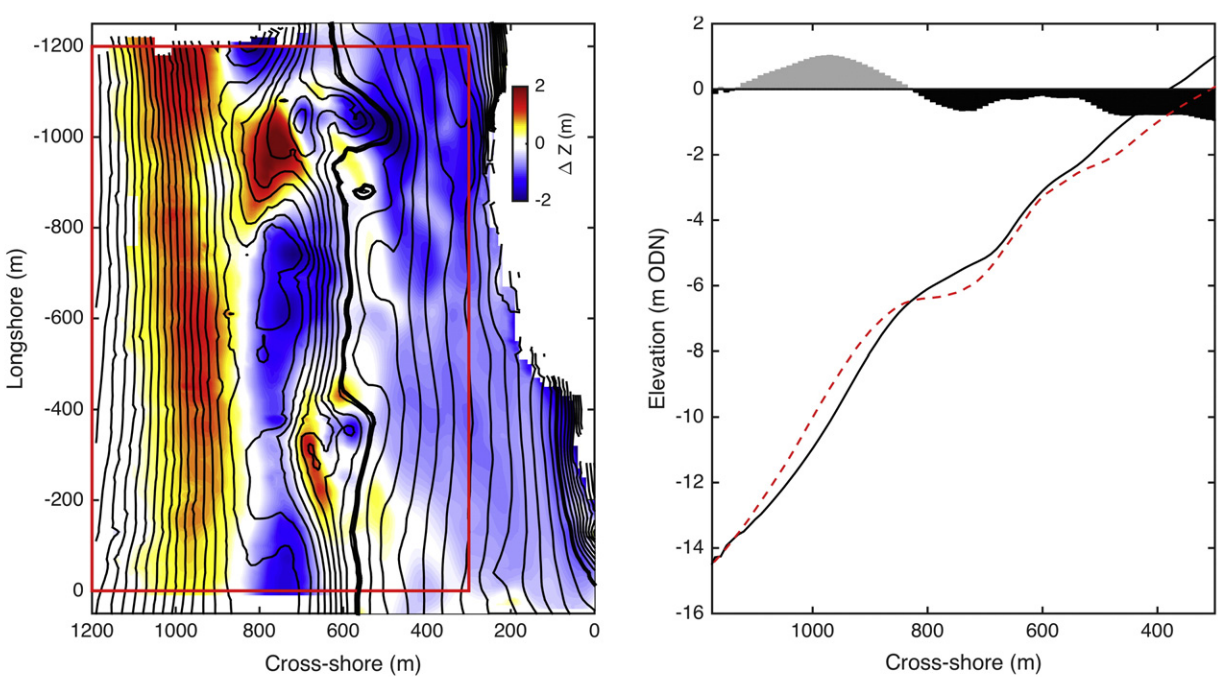

Fig. 6. Morphological change at Perranporth, located on the north Cornwall coast, between July 2012 and April 2014. The change recorded is mainly attributed to the 2013/14 storm period and consists of extensive intertidal erosion (beach lowering c. 1 m), development of a very pronounced large-scale rip current system and growth of a subtidal (storm) bar system. Left panel shows difference bathymetry between the results of two combined sub-tidal single-beam echo-sounder and intertidal RTK-GPS beach surveys (July 2012–April 2014). July 2012 was the most recent pre-storm subtidal survey. Bold black contours represent mean high/low tide levels and the depth contours are plotted with 0.5-m separation. Right panel shows the alongshore-average cross-shore profile from within red box in the left panel. Red dashed line is post-2013/14 winter profile. Levels of erosion (black) and accretion (grey) throughout the profile are indicated.

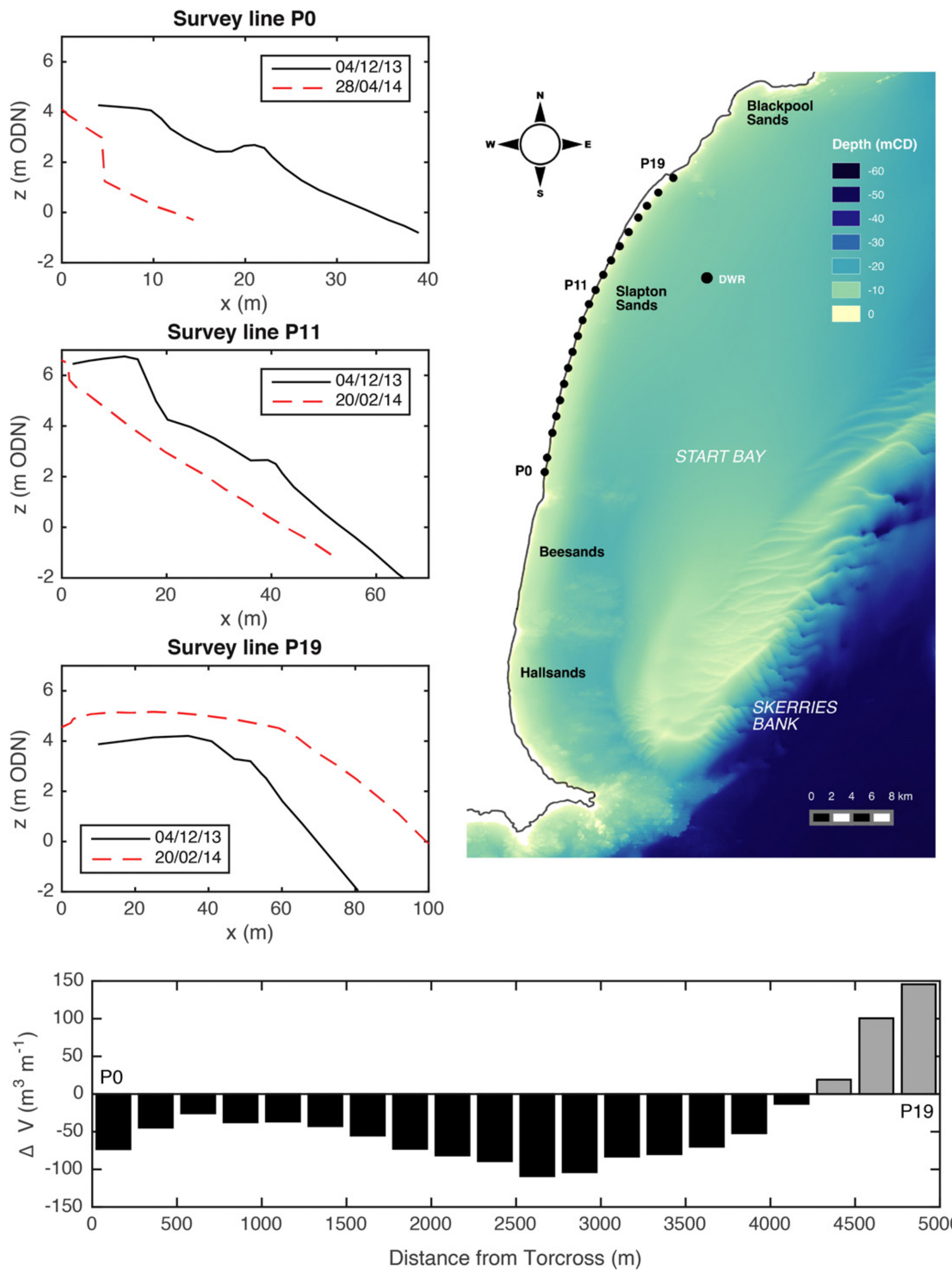

Fig. 7. Storm impacts on the gravel beach of Slapton Sands, located on the south Devon coast, during the 2013/2014 winter season. Upper left panels show the cross-shore morphological response for selected locations along the beach. Every month, up to 20 cross-shore profiles are surveyed using RTK-GPS and transects run from south (P0) to north (P19) at 250-m intervals, as shown in the map in the top right panel. Lower panel shows bar graph representing the alongshore distribution of the intertidal beach volumetric change ΔV (above the −2 mODN level). Transects P0–P16 all show erosion, but the northernmost transects P17–P19 display an increase in the beach sediment volume.

Within the Start Bay embayment, Slapton Sands, a reflective gravel beach, provides a good example of the observed rotational behaviour (Fig. 7). Erosion occurred throughout the southern and middle beach (0–4250 m from Torcross) with hotspots occurring in the south at the sub-embayment boundary and mid-bay profiles (P0 & P11): up to 3 m of beach lowering occurred at P0, exposing the foundations of the coastal protection structure and at P11 the beach retreated by over 10 m. In contrast, the northern end of the embayment (4250–5000 m from Torcross) experienced very high levels of accretion throughout the intertidal tidal to the berm crest and also into the back barrier region (−2 and 5 mODN).

Integrating the storm-induced sediment budget along the entire beach indicate that significant losses occurred during the 2013/14 winter. Qualitative evidence indicates that barrier overwash provides an important mechanism for losses of sediment from the beach, although not of the barrier system as a whole (Fig. 5). Other mechanisms that are currently under investigation are sediment exchange between adjacent embayments through headland bypassing, as well as offshore transport beyond the low tide level. On reflective gravel beaches like Slapton Sands offshore sediment exchange during storms is expected to be in the form of backwash/step material deposited as slumped deposits under extreme swash events below the mean spring low water level; such response is supported by preliminary bathymetric surveys offshore of Chesil beach indicating slumped gravel deposits just below low tide level (Poate et al., 2015). In mixed sand/gravel and sandy beaches with wider surf zones, a greater component of offshore transport via bed return flow is expected to contribute to sediment losses and potentially nearshore bar formation.

5.3. Onshore sediment transport and barrier overwash

There are limited quantitative records of barrier overwash during the 2013/14 storms. This is partially due to overwash deposits being distributed as thin veneers of material, often landward of the measured profiles, but also because the overwashed material often covered backshore infrastructure (roads and urban areas) in vulnerable locations, material is rapidly rapidly removed and redistributed by coastal engineers post-storm. Nonetheless, photographic evidence exists (Fig. 5) confirming overwash occurrence. An example of a recorded overwash event is shown in Fig. 8, collected by Plymouth University at Loe Bar, a natural fine gravel barrier in Cornwall (Poate et al., 2015). During the peak storm conditions of early 2014, the crest of the barrier, which was 6.1 m above the mean high water level, was overwashed leading to back barrier accretion (~0.3 m) and 17 m landward migration of the barrier crest (Fig. 8). Extensive (~1.5 m) lowering of the upper profile was observed, although regions of accretion can also be seen across the lower beach related to the complex cuspate morphodynamics at this site (Poate et al., 2014). The net loss of material transported from the seaward profile of the barrier through overwashing was 17 m^3/m (Fig. 8). Overwashing also occurred at Chesil with 14 m^3/m removed from the seaward slope across an unconstrained natural profile. This removal resulted in a landward migration of the crest position and steepening of the crest slope, increasing vulnerability to further storm events (McCall et al., 2014). Although the sediment losses due to overwash were relatively modest compared to some of the losses on the west coast, material transported landward of the barrier crest cannot be returned to the front of the beach during recovery and thus such response represents an irreversible landward transfer of sediment.

6. Multi-annual storm recovery

A number of recent studies (e.g., Cooper et al., 2004; Castelle et al., 2007; Coco et al., 2014; Splinter et al., 2014) have highlighted the importance of antecedent morphological state in controlling subsequent morphological response to storms. It also has a significant bearing on the vulnerability of coastal communities and infrastructure to further storm impacts. Therefore, understanding the rate at which a beach recovers from storm-induced erosion is of broad interest to scientists and coastal managers. The rate at which beach volumes and elevations return to pre-storm levels (if at all) is intrinsically linked to the dominant mechanisms driving sediment transport at each beach site (as discussed in previous section), as well as a function of the post-storm wave conditions. Here we investigate the long-term impacts of the

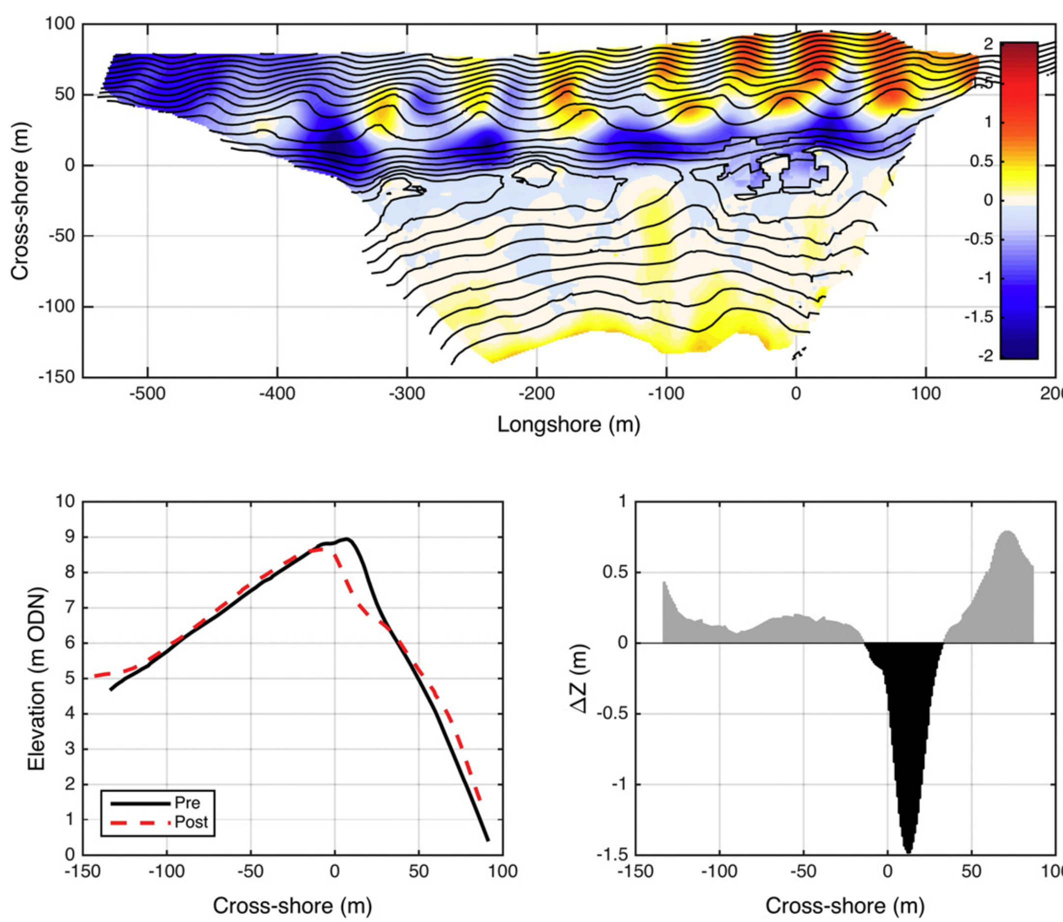

Fig. 8. Overwash observations at Loe Bar, a high-energy natural gravel barrier located on the south Cornwall coast, showing pre- and post-storm survey (winter 2013/14) of the intertidal shoreface and back barrier regions. Top panel shows surface difference in colour and post-storm contoured morphology. Bottom panels show an example cross-shore profile (bottom-left panel) with associated levels of erosion and accretion across the profile (bottom-right panel).

erosional response to extreme storm sequences at the three contrasting sites utilising extended multi-annual timeseries. These sites represent the three dominant morphological response types outlined above: offshore, overwash and rotation.

6.1. Perranporth

Located on the west coast of Cornwall, Perranporth is a double-barred exposed sandy beach (mean spring range of 6.3 m; 3.5-km long) backed by an eroding sand dune system (Fig. 1). It is a low-tide bar/rip beach type and, similar to other beaches in the region, exhibits pronounced low-tide bar/rip morphology which varies on a seasonal timescale (Scott et al., 2014). The intertidal beach is relatively flat ($\tan\beta = 0.015–0.025$) and composed of medium quartz sand ($D_{50} = 0.28–0.34$ mm). The beach faces west-northwest and is predominantly exposed to Atlantic storm and swell waves; it has an annual average significant wave height and peak period of $H_s = 1.6$ m and $T_p = 10.6$ s, respectively. Perranporth is regarded as a representative example of both the exposed sandy beaches of Devon and Cornwall, as well as high-energy macrotidal beaches globally.

Analysis of multi-annual intertidal and sub-tidal morphological records indicate that the beach system is dominated by cross-shore surf zone driven sediment transport and shore-normal waves (Masselink et al., 2014). The time series shown in Fig. 9 captures a single 7-year morphological cycle, which starts with a fully accreted state in mid-2006 (reference beach volume) followed by a significant period of erosion during the 2006/7 winter (where sparse data unfortunately conceal full story), leading to a severely depleted beach volume of -165 m^3/m throughout the analysed beach section (250 m section in the alongshore, and intertidal beach above mean low water in the cross-shore; red box Fig. 9). After the 2006/7 winter a dramatic increase in alongshore standard deviation in profile volume occurred throughout the beach section (reaching $\sigma = 54$ m^3/m during spring 2008) associated with the development of large-scale three-dimensional sandbar morphology within the low- and sub-tidal regions (grey shading Fig. 9; middle left panel). Subsequently, between spring 2008 and autumn 2012 an extended multi-annual period of beach recovery/accretion was observed. Intertidal beach volumes recovered to 2006 reference level by late 2010 (3-year sequence) and reached a volume maximum of 12 m^3/m by autumn 2012. Superimposed on this recovery phase were annual seasonal fluctuations of erosion in winter and accretion in spring/summer. Fig. 9 (lower left panel) reveals that the lower intertidal beach took a year longer (autumn 2011; 4 years) to recover to the reference state than the upper beach (autumn 2010; 3 years).

The second major erosional event observed is during the extreme 2013/14 winter, resulting in a severely depleted beach by spring 2014 (-243 m^3/m), representing intertidal erosion of 223 m^3/m (a 0.5 m beach lowering throughout the 400 m wide intertidal profile) during a 4-month period, associated with a 73-m landward migration of the mean low water shoreline. Following this event, observed annual recovery behaviour ($+112$ m^3/m) is similar to mean recovery volumes during previous years (mean = 94.8 m^3/m and $\sigma = 17.8$ m^3/m). Due

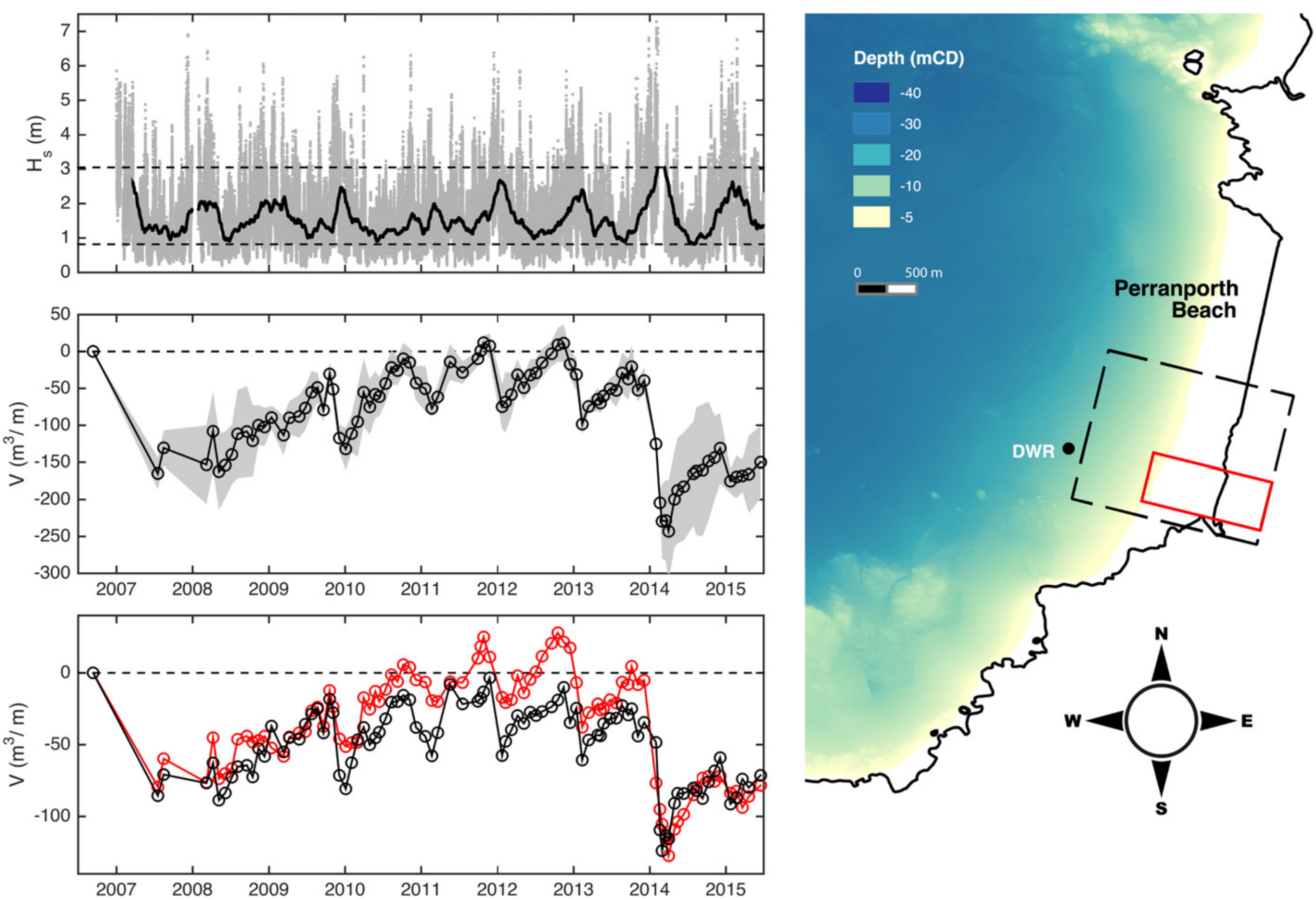

Fig. 9. Intertidal morphological change at Perranporth beach. Right panel shows multi-beam bathymetric survey of Perranporth with location of directional wave buoy (DWR), region of the beach covered by single-beam bathymetric surveys in Fig. 6 (black dashed box) and region of intertidal beach volume calculation (red box). Left upper panel shows 8-year time series of wave height H_s (30-min and 8-week running mean). Left middle panel shows mean intertidal beach sediment volume (m^3/m alongshore) with bounded region representing alongshore standard deviation. Left lower panel shows the upper (red) and lower (black) intertidal sediment volume above and below mean sea level.

to the extreme level of erosion, by the onset of the 2014/15 winter season only 50% of the pre-storm intertidal volume was recovered.

Previous work at Perranporth by Masselink et al. (2014) examined the cross-shore displacement of the offshore bar crest as a function of wave forcing parameters, and found that the 4-month and 12-month (primary and secondary) averaged wave forcing terms best explained the sub-tidal bar dynamics. While there are individual storms where $H_s > 6$ m in each year of the record (Fig. 9), the offshore 8-week average wave conditions (black line; Fig. 9) has greatest correlation with the monthly intertidal erosion and accretion sequences (r = 0.42). This highlights the importance of considering sequences of storms (number and density) in generating significant erosion events throughout the intertidal zone on an exposed macro-tidal sandy beach like Perranporth.

The morphological timeseries indicates, as one would expect, that the impact of high energy winter periods have a greater erosive impact on a fully accreted beach. This is observed at Perranporth during the erosive events of the 2006/7 and 2013/14 winters, while the opposite effect occurs during 2008/9 and 2014/15 where initial pre-winter beaches are in a more erosive state. By extension, one might expect greater recovery rates from more erosive states, but this assumes that eroded sediment (sub-tidal) can be mobilised under accretionary conditions. This can be further explored through analysis of available sub-tidal bathymetric records.

Combined sub-tidal bathymetric and intertidal topographic survey data (Fig. 10) from 2014 confirms the significant development (+112 m^3/m since July 2012) and offshore translation (c.100 m) of an offshore sub-tidal bar, with associated bar crest lowering to −7.4 mODN (from −6.4 mODN in July 2012). This extreme winter led induced morphological change to a depth of −14 mODN. While a significant proportion of eroded intertidal sediment (50%) recovered within 10 months, the bathymetric record suggests this was initially sourced from available sediment around the low water region (and potential from alongshore redistribution) during the low energy spring/summer 2014 wave conditions (4-month Hs = 0.92 m; lowest since 2006). Significantly, no significant change was observed in the offshore bar morphology between April and September 2014. The offshore (storm) bar deposits, approximately 400 m offshore of the mean low water position and consisting of an equivalent proportion of the eroded intertidal material, remained static until the onset of the first significant high-energy swell wave events of the autumn (November 2014). Once mobilised, a rapid reduction/redistribution in sub-tidal sediments occurred (−235 m^3/m) pre winter 2014/15, followed by a significant onshore bar migration (c.80 m) in early 2015.

These observations indicate that a decoupled beach recovery process can occur after extremely energetic winters. Initial recovery of available sediment occurs rapidly (within several months) post-storm, but sediment retained in the sub-tidal bar system may not be activated and made available to supply the upper beach until the onset of higher-energy longer-period swell events that are able to mobilise sediment at depth (particularly if the offshore bar has experienced severe offshore translation and lowering). This process would lead to the requirement of a multi-annual beach recovery sequence interrupted by winter erosional events.

6.2. Slapton Sands

Slapton Sands is a 4-km long gravel barrier beach located on the south coast of Devon (Fig. 2). The beach is aligned roughly SSW-NNE and the wave climate here is directionally bi-modal receiving short fetch wind and diminished Atlantic swell waves from the south and wind waves from the east (Ruiz de Alegria-Arzaburu and Masselink, 2010). The barrier rises to 5–6 m above mean sea level with a steep reflective beachface (tanβ = 0.1) composed of fine gravel (D_{50} = 2–10 mm). Slapton Sands is one of many gravel barriers and beaches located along the south coast of England and its morphological response

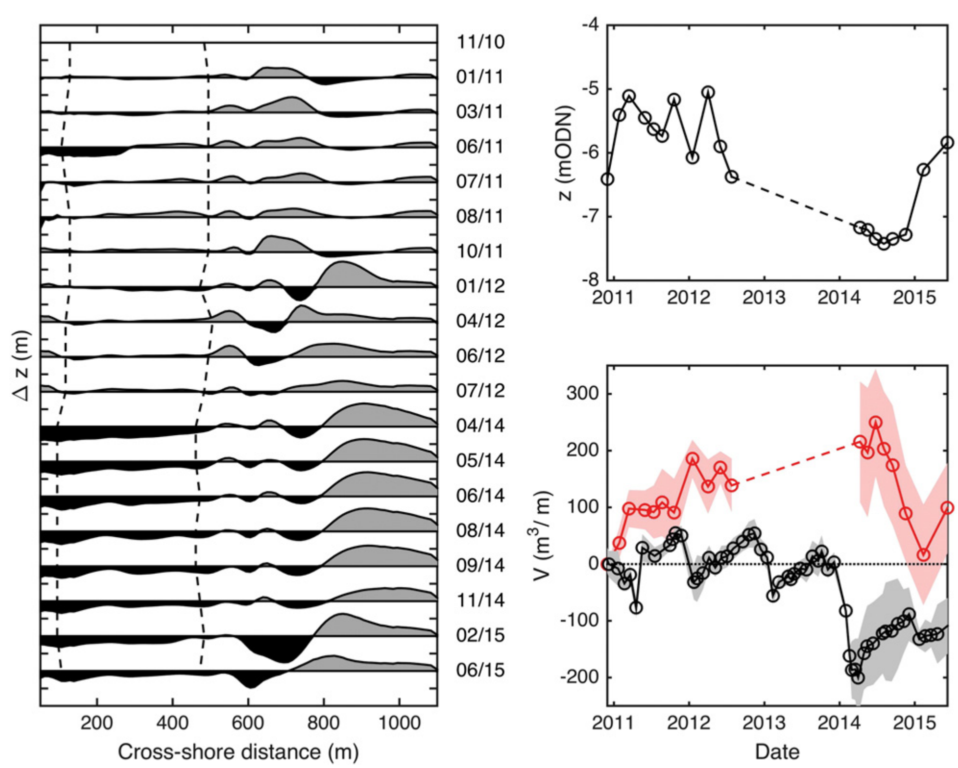

Fig. 10. Perranporth subtidal response and recovery. Left panel shows cross-shore profile change across the inter- and subtidal zone at Perranporth between Nov 2010 and June 2015. Changes relative to reference accreted beach in Nov 2010. Surveys were collected at approximately 6-weekly intervals with a data gap between July 2012 and April 2014. Dashed vertical lines showcross-shore locations of mean low and high water shorelines. Upper right panel shows mean outer bar crest elevations for each survey (mODN). Lower panel shows relative sub-tidal and intertidal volume change (m^3/m alongshore) from 2010 reference volume (red and black respectively), bounded regions are alongshore standard deviation.

is considered representative of many reflective gravel beaches in storm-affected fetch-limited channel coast environments (McCall et al., 2013).

In contrast to Perranporth, the Slapton Sands morphological time series is an example of a rotational response to storms, where alongshore redistribution of sediment is the dominant mechanisms for embayment scale morphological change. Slapton displays a long-term erosional trend at the southern end (P5; Fig. 11), particularly apparent during winter periods of southerly storms. At the northern end, transect P18 experiences long-term accretion punctuated by erosion during relatively infrequent easterly storms sequences (e.g., early 2013). Both the long-term trend and the seasonal fluctuations in beach volume are the result of alongshore imbalances in the littoral drift and thus demonstrate beach rotation. Interestingly, transect P10 from the middle beach has remained relatively stable in the long-term but suffered significant erosion during the 2013/14 winter (region of most significant overwash events, with back-barrier lagoon).

The most significant events in the record were associated with beach changes that occurred over a 2-month period during easterly storms in 2013 (P5 = +20 m^3/m; P10 = +56 m^3/m; P18 = −96 m^3/m) and the southerly storms of 2014 (P5 = −44 m^3/m; P10 = −101 m^3/m; P18 = +110 m^3/m). The response reflects significant imbalances between total hours of easterly (W_e; 45°–135°) and southerly (W_s; 135°–225°) waves that exceeded 2.5 m (1% exceedence H_s), as indicated by the Start Bay wave buoy record (Fig. 11; 8-week moving sum of W_e and W_s). While the 8-week averaged H_s signal can be seen in the beach response, unlike the Perranporth example, the direction of change is governed by the storm direction. With the exception of the seasonal higher frequency event/seasonal scale alongshore redistributions of sediment, the beach volumes appear to follow a long-term trend of sediment redistribution from south to north within the Slapton embayment.

Slapton Sands has exhibited progressive rotation for at least 8 years (Fig. 11) and, based on anecdotal information, at least for several decades. To explore the long-term trends in beach dynamics and storm activity further for Slapton Sands, the local UK Met Office long-term (1949–present) hourly mean wind record was used as a proxy for estimating the occurrence of easterly (W_e) and southerly (W_s) short-fetch wind waves. Wave heights were estimated using the SMB method to provide deep-water wave heights based upon observed easterly and southerly component wind speeds and durations (Coastal Engineering Research Center, 1984; Fig. 12). Interestingly, the late-1980s saw the end of a sustained period of higher easterly storm activity; since this period there has been a declining trend in easterly wave events >2.5 m, representing approximately a 75% reduction in 10-yr averaged easterly storm activity over the last 30 years (Fig. 12). This decline in easterly storms waves occurred whilst southerly storm activity remained relatively constant over the same period. Prior to this, between 1950 and the late-1980s, there had been an increase in southerly W_s up to approximately 400 h/yr. The relative balance between 10-year averaged W_e and W_s shows a 30% contribution of easterly storms between the 1950s until the late-1980s (Fig. 12; lower panel), after which there is a significant increase in the relative contribution

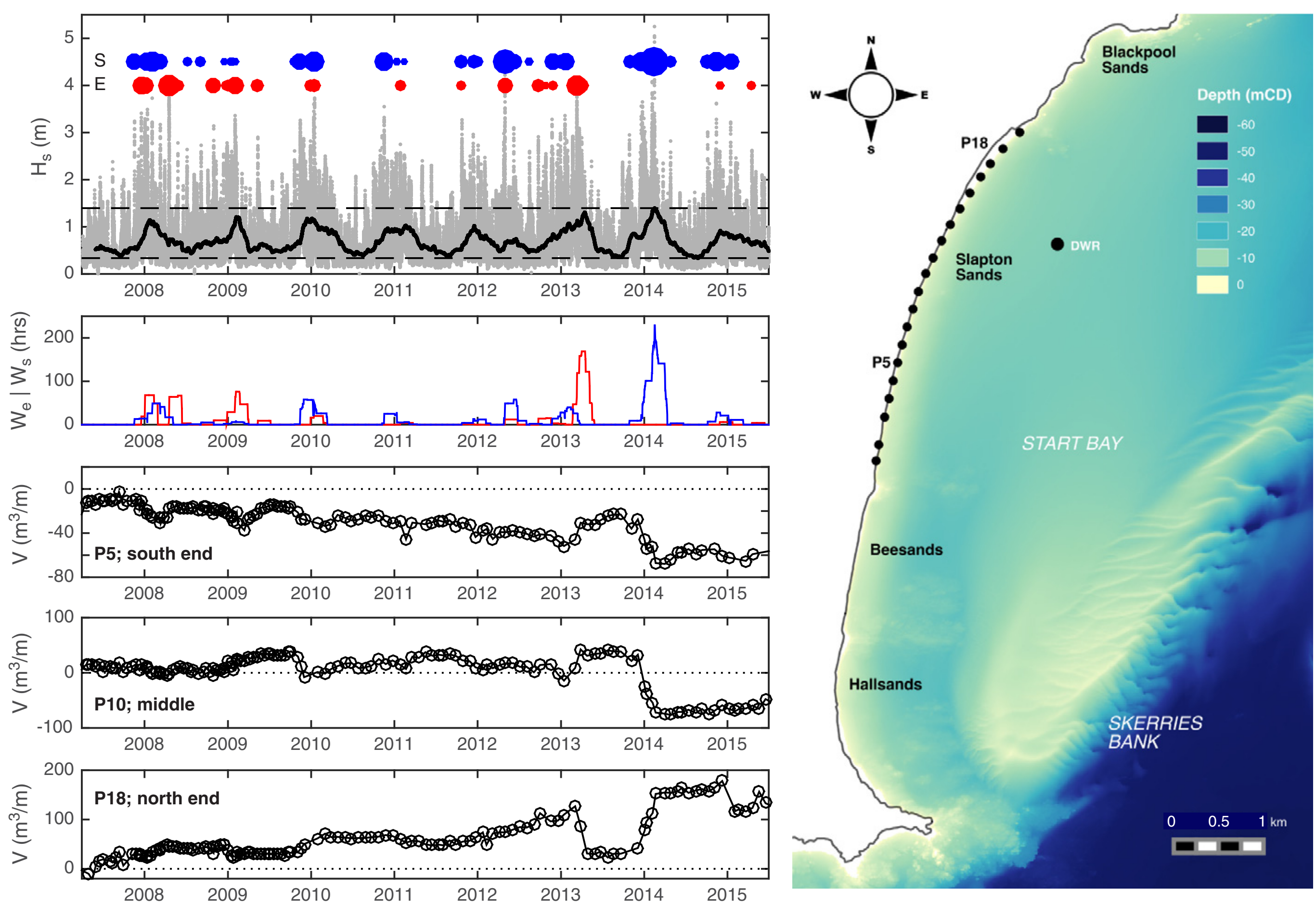

Fig. 11. Intertidal morphological change at Slapton Sands. Right panel shows multi-beam bathymetric survey of Start Bay with location of directional wave buoy (DWR), and cross-shore profile locations. Left panel (from top) shows 8-year time series of wave height H_s (grey is 30-min average, black is 8-week moving average) and wave events greater than H_s (1%) = 2.5 m with event direction (easterly red and southerly blue) and peak wave heights (circle size) indicated; 8-week moving sum of duration of easterly (red) and southerly (blue) wave events > 2.5 m; beach sediment volumes V (m^3/m) for three locations along Slapton Sands (P5, P10 and P11) relative to a reference volume in early 2007.

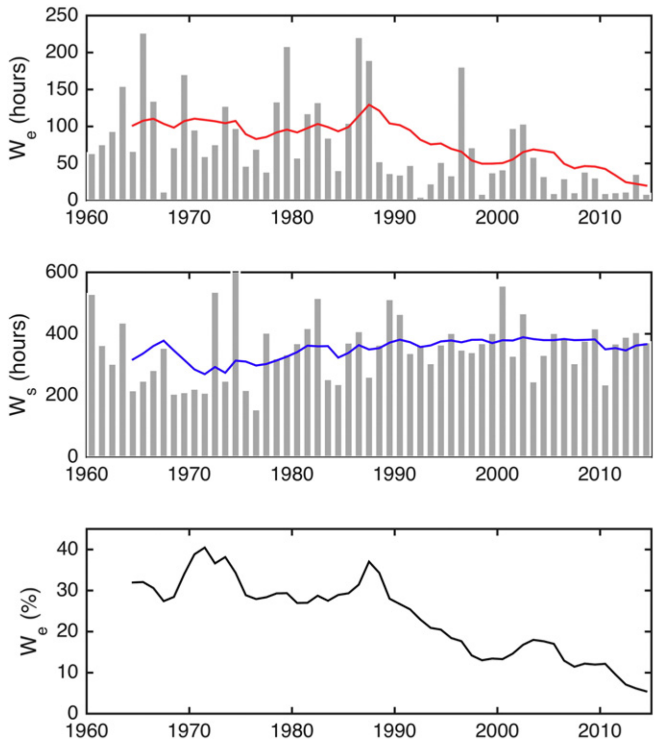

Fig. 12. Long term contribution of east and south storms at Start bay. Upper panels show histograms of hourly frequency of easterly wave events (W_e) > 2.5 in grey with the red and blue lines indicting the 10-year moving average (backwards-looking) for easterly and southerly events, respectively. Wave heights are calculated from local wind records using simple SMB method (Coastal Engineering Research Center, 1984). Lower panel shows the percentage contribution of 10-year average W_e to the W_s/W_e balance.

of southerly storms, reaching a maximum in the last decade with 10-year averaged W_s representing >90%.

6.3. Loe Bar

Loe Bar is a 4.3-km long, reflective gravel barrier on the exposed southwest coast of Cornwall (Fig. 1). The beach is comprised of fine gravel ($D_{50} = 3$ mm) and a steep reflective profile ($\tan\beta = 0.118$), it is also backed by a freshwater lagoon (Loe Pool) and the barrier is approximately 250 m wide from pool to sea (Poate et al., 2015). The site is orientated to the southwest and is exposed to the full force of southwesterly storm waves that approach from a shore normal direction. The storm response at Loe Bar can be considered representative of exposed reflective gravel beaches in the region (e.g. Chesil Beach).

As described in Section 5.3, morphological records show that Loe Bar experienced overwash events during the 2013/14 winter. Fig. 13 illustrates the morphological timeseries between 2007 and 2015 (19 surveys) from a long-term monitored profile section. Pre and post storm (August 2013 and March 2014) profiles show a similar response to 3D surveys collected by PU shown in Fig. 8, with a loss of 70 m^3/m seaward of the bar crest and gains of 49 m^3/m landward representing overwash deposits, extending 150 m to Loe Pool. During 2013/14 the bar crest elevation was reduced by 0.3 m and migrated landward by 20 m.

When considering volume changes to the back and front barrier beach within a 7-year timeseries, the 2013/14 overwash events represent the only significant change (overwash accumulation) in back barrier volumes. Front barrier volumes were also at their most eroded state post 2013/14 winter. No recovery in crest elevation or position occurred post 2013/14 winter and front barrier volumes surprisingly continued to reduce until late 2015 (<−100 m^3/m) with alongshore redistribution of sediment and 3D beach cusp morphodynamics possible contributors to this observed change (Poate et al., 2015). Back barrier sediment volumes showed no significant change post 2013/14 winter as there is no

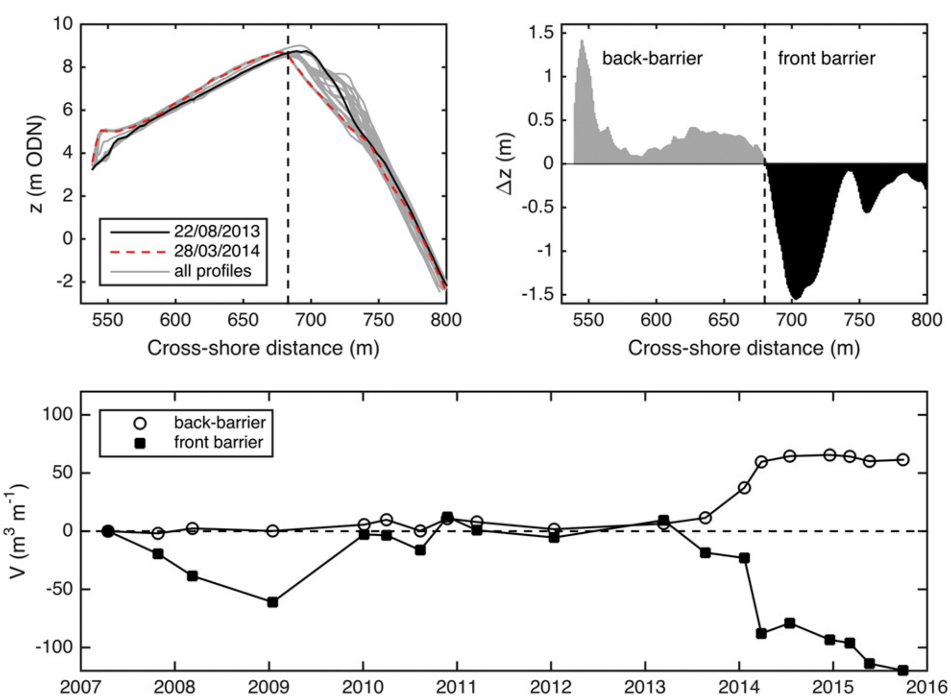

Fig. 13. Inter and supra-tidal morphological change at Loe Bar. Upper left panel shows cross-shore profile change between 2007 and 2015. All profiles are shown in grey, and pre and post 2013/14 winter profiles in black and red, respectively. Upper right panel shows elevation change across the pre and post 2013/14 winter profiles. Bottom panel shows timeseries of back and front barrier volume change (open circles and black squares, respectively) between 2007 and 2015.

short-term mechanism to return back barrier sediment to the active beachface.

It is useful to consider the potential frequency of overwash events through examining the forcing mechanisms. Fig. 14 shows the 30-min hydrodynamic forcing conditions at Loe Bar between 2012 and 2015 (timeseries constrained by availability of proximal wave buoy record). Wave records from the Porthleven nearshore wave buoy (Fig. 1; 12 m water depth) located directly offshore of the site, provided H_s and T_m (converted to T_e using Cahill and Lewis (2014)), combined with beach slope to compute statistical run-up heights based on Poate et al. (2016) where runup height $(R_{ht}) = 0.39\ \tan\beta^{0.5}\ H_s\ T_e$. Development of this runup equation was partly based on field data collected by Poate et al. (2016) at Loe Bar. When combined with water level elevations (*WL*; tide plus surge) from the nearby Newlyn tide gauge (Figs. 1 and 14), potential for overwash events can be ascertained. Since 2012, it is clear from the 30-min runup elevation timeseries (R_{elv}) in Fig. 14 that potential overwash events where runup exceeds bar crest elevations are extremely rare and computed overwash potential during winter 2013/14 is extremely significant. Computed 30-min R_{elv} values exceed the bar crest for 38.5 h during the 2013/14 winter while only exceeding crest elevation for 5 h previously (since Jan 2012). It should be noted that while the forcing timeseries is short, 2011/12 and 2012/13 winter were representative of energetic winter periods with multiple wave events where H_s exceeded 5 m.

The morphological and hydrodynamic forcing timeseries from Loe Bar demonstrates the significance of extreme overwash events on long term beach volumes where sediment can be lost on a permanent basis to the back barrier region (if no breaching events occur). Predicted (and observed) overwash events during 2013/14 winter (at least 5 tides, over three periods) indicate that permanent change can occur over individual storms unlike observations at exposed sandy (e.g. Perranporth; offshore response) and sheltered sand/gravel (e.g. Slapton; rotational response) beaches where cumulative impacts of winter averaged conditions can be more significant.

7. Discussion

Long-term regional morphological monitoring of 38 beach sites along the embayed macro-tidal coasts of the southwest of England provided a unique opportunity to assess the morphological impact due to an extremely energetic 2013/2014 winter season. During this winter, the peak in observed 8-week averaged H_s reached 4.4 m, which represented at least a 1:50 year return period (based on GEV analysis of annual 8-week maxima; Coles, 2001) and analysis of a 60-year hindcast wave model record (validated by offshore wave buoy measurements) by Masselink et al. (2016) suggests that with the exception of the far north region (Ireland), the 2013/2014 winter was the most energetic since 1948. A significant post-winter morphological response was observed, with many of the diverse beach sites in the beach dataset in their most depleted state since morphological records began (~10 years). Total sediment volume loss and intertidal beach lowering throughout the exposed west coast (intermediate/dissipative) beaches was dramatic, exceeding $-100\ m^3/m$ (reaching $300\ m^3/m$) and representing a lowering of ~0.5 m in many cases. Cross-shore redistribution of beach sediments occurred in both landward (reflective beaches) and seaward directions (intermediate/dissipative beaches) through swash (overwash and dune scarping) and surf zone processes (bed return flow and rip currents), respectively. This dominant cross-shore response of exposed intermediate/dissipative beaches was in stark contrast to the rotational response observed throughout semi-sheltered intermediate/reflective sand and gravel beaches, particularly on the south coast, where unusually southerly storm tracks enhanced alongshore redistribution of sediment and shoreline realignment due to the oblique storm wave approach, leading to significant erosion (accretion) at upwave (downwave) embayment boundaries, respectively. Absolute profile volume changes of $>100\ m^3/m$ meant that absolute mean beach level changes were >2 m in some cases.

Previous studies (Cooper et al., 2004; Castelle et al., 2007; Vousdoukas et al., 2012; Coco et al., 2014; Splinter et al., 2014) have

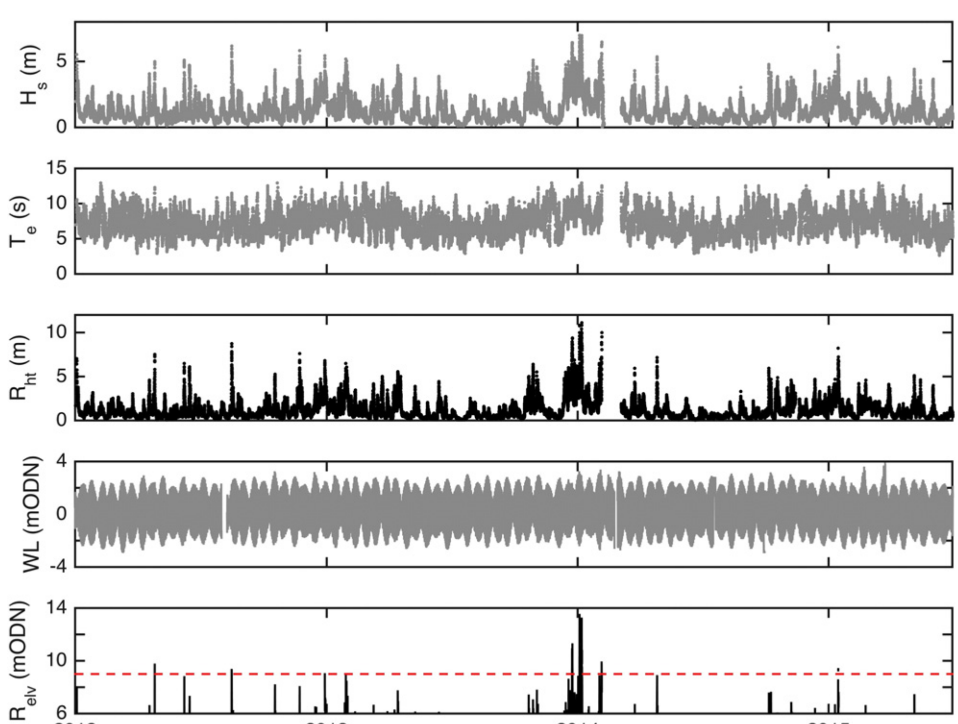

Fig. 14. Hydrodynamic forcing and computed runup timseries for Loe Bar between 2012 and 2015. Panels show 30-min timeseries of (from the top down): significant wave height (H_s); peak energy period (T_e); computed runup height (R_{ht}); combine tide and surge water level (WL); and runup elevation R_{elv}, where red dashed line is barrier crest.

highlighted the intrinsic link between beach state and coastal vulnerability (coastal flooding and inundation), controlled by the level of erosional response of beach facies (dune and supra-tidal beach volumes, nearshore sandbars) to storms and the rate and extent of beach recovery. Therefore the time period over which beach-fronted coasts are more vulnerable to storms is a direct function of their recovery rates and hence antecedent beach state. This study has shown that the complex and geographically variable response to the winter 2012/13 storms (offshore, alongshore and onshore; or subtidal bar formation, rotation and overwash), seen throughout the west coast of Europe (Blaise et al., 2015; Castelle et al., 2015; Poate et al., 2015; Suanez et al., 2015), will require both fundamentally different and site-specific sediment transport mechanisms and hydrodynamic forcing sequences to facilitate full post-storm recovery. These have implications for the prediction of the extent and timescales of recovery, and therefore future vulnerability to storms (Ranasinghe et al., 2013). Overwash sediments will likely be lost to the active beach in the long-term, while we have seen that cross-shore recovery can vary from hours on gravel beaches (Poate et al., 2015) to multi-year periods on sandy beaches.

Similar to observations by Birkemeier (1979), Wang et al. (2006), Splinter et al. (2011) and Senechal et al. (2015), initial beach recovery observed at Perranporth, characterised by cross-shore erosional response, was rapid, recovering 50% of 2013/14 eroded volume (above low water) within 10 months. This initial very rapid recovery was associated with increasing alongshore standard deviation of profile volume, which has been previously observed at Perranporth (Scott et al., 2011; Masselink et al., 2014; Poate et al., 2014; Stokes et al., 2015) and associated with increasing three-dimensionality in sand bar morphology during accretionary phases, observed in beach state transitions worldwide (e.g., Wright and Short, 1984; Lippmann and Holman, 1990; Ranasinghe et al., 2004; Plant et al., 2006). Regular bathymetric surveys at Perranporth suggest that, contrary to the common view that cross-shore dominated beaches recover during post-storm calm periods (summer swell wave conditions; Komar, 1999), post-storm high-energy swell events and the generation of strongly three dimensional morphology are a vital ingredient in the recovery of pre-storm beach volumes, mobilising offshore storm deposits and providing a conduit for onshore transport through the inner bar trough region, respectively (e.g., Plant et al., 2006). It is well documented that beach recovery to pre-storm volumes can take multiple years, if at all (e.g., Thom and Hall, 1991; Suanez et al., 2012), often citing the time required for supra-tidal beach and dune recovery. In reality, beach recovery is complex and involves an interconnected beach system (throughout dunes, upper/lower intertidal, and sub-tidal) where rates of beach volume and shoreline recovery vary throughout the system depending of mobilisation potential, disequilibrium and inherent sub-system response timescales.

The importance of disequilibrium forcing in relation to antecedent conditions is well known to control cross-shore beach morphological response (Yates et al., 2009; Davidson et al., 2013; Castelle et al., 2014; Masselink et al., 2014). While the winter 2013/14 responses on exposed beaches were significant, the disequilibrium in wave heights ($Hs/\overline{Hs}$) to the long-term annual mean, during the winter period was much greater for the semi-sheltered south coast due to the unusually southerly track of the winter depressions. This was a contributing factor, alongside wave angle, to the magnitude of gross volume change within south coast embayments that displayed a clear rotational response dominated by the alongshore redistribution of sediment. Unlike the more cross-shore dominated rotational response documented, for example, at Australian beaches by Harley et al. (2015). The more reflective nature of many of the south coast beaches meant that a mean loss of -50.9 m^3/m throughout led to a significant mean lowering of -64 cm. Importantly, annual recovery data shows (work in preparation) at these sites only experienced 6.8 m^3/m of recovery on average with 48% of profiles recovering <10% of pre-winter volume.

It is clear that re-balancing this alongshore redistribution of sediment would require a cumulatively equal and opposite recovery event. The timescales of this recovery cycle were examined for Slapton Sands, where a multi-annual record showed intermittent and fluctuating event (storm sequence) driven recovery response (easterly storms) within a decadal erosional (rotational) trend throughout the morphological record (south end of embayment). The southerly-dominated winter storms of 2013/4 had a dramatic impact on the beach, and were not balanced by easterly wave events that would drive equivalent alongshore sediment transport processes in the opposite direction. In contrast, evidence from a 2-month easterly storm cluster during early 2013 suggested that the system would potentially respond rapidly to short-term high-energy storm events/sequences as the embayment reversed the longer-term rotational trend. Ultimately, the winter 2012/13 events left the southern end of the beach severely depleted and the lack of subsequent easterly recovery events meant the beach remained highly vulnerable to further storm impacts during the subsequent winter.

As identified by Coco et al. (2014) and Masselink et al. (2015), the response of geographically variable beaches to a sequence of storms is difficult to anticipate and relates to both geomorphological setting (beach type, antecedent conditions, sediment supply and geological setting) and individual storm characteristics (severity, frequency, duration and track), not to mention water levels. While intra-cluster characteristics of storms are critical for understanding response to storm sequences (Ferreira, 2006; Coco et al., 2014; Splinter et al., 2014), the long-term records from Perranporth and Slapton Sands show that where the cycle of response is multi-annual, the frequency and characteristics of high-energy storm clusters and subsequent interim periods are also critical to the long-term balance of beach sediments. Masselink et al. (2014) have previously shown that, on exposed sandy beaches, winter averaged H_s and associated morphodynamic indices are strongly correlated with the winter NAO index, that displays an unpredictable 3- to 7-year cyclical behaviour. This significant relationship ($r = 0.625$) persists throughout the extended timeseries (1953–2015) of Sevenstones 5-year averaged winter H_s. The winter NAO has been shown to explain about one third of winter storm variations, particularly in recent decades (Feser et al., 2015).

These relationships suggest connectivity between wave forcing and hence morphological response, to longer-term climatic oscillations. Significantly for Slapton Sands, long-term wind data suggests that there have been significant changes to the regional weather patterns that have resulted in a multi-decadal trend towards an increasing southerly-dominated storm wave climate (and reduction in Easterly storms) since the 1990s. While little is known about the impact of decadal climate variability on the specific wave forcing along the south west of England, recent studies in Atlantic metocean science (e.g. McCarthy et al., 2015) clearly show the presence of multi-decadal cycles in the Atlantic Ocean influence regional climate phenomenon, providing evidence that on multi-decadal timescales, the ocean integrates NAO forcing and returns it to the atmosphere as the Atlantic Multi-decadal Oscillation (AMO). Hakkinen et al. (2011) showed that winters with more frequent atmospheric blocking events (blocking of westerly airflow and storms) where linked to positive AMO events (warm Atlantic Ocean). These cycles are undoubtedly important for coastal evolution and further understanding will only be gained by comparison with long-term morphological datasets. This is exemplified by a recent study of Barnard et al., 2015 where the collection of long-term (up to 40-year) beach morphological datasets throughout the Pacific, provided evidence that coastal erosion varies most closely with El Niño/Southern Oscillation. It is therefore clear that through the ongoing collection of long-term supra-, inter- and sub-tidal morphological datasets, an improved understanding of beach recovery processes including multi-annual to multi-decadal forcing oscillations will be critical to future assessments of coastal vulnerability.

8. Conclusions

1. In the southwest of England the 2013/14 winter contained an unprecedented sequence of very energetic wave conditions occurring over a 3-month period. The peak value of the 8-week averaged significant wave height (8-week mean offshore $H_s = 4.4$ m) represented the largest sequence of storm wave heights within a 60-year wave record. GEV analysis of annual maxima in peak 8-week average wave heights found a minimum return period of 1 in 50 years and a best-fit estimate of order 1 in 250 years. Significantly for the southwest of England, the 2013/14 storms were also characterised by unusually southerly storm tracks.
2. Analysis of storm impacts at 38 beaches in the southwest of England showed response was geographically highly variable: all sites with dunes experienced significant erosion; many gravel barriers overwashed (event-scale); exposed west coast beaches were dominated by cross-shore transport processes (seasonal-scale) leading to significant loss of sediment offshore; semi-sheltered sites exposed to more oblique wave forcing (event/seasonal scale) were dominated by a rotational response due to alongshore redistribution, with less net intertidal loss.
3. Mechanisms and timescales for beach recovery displayed strong inter-site and intra-site variations. Multi-annual morphological records at Perranporth (cross-shore dominated), Slapton Sands (rotation dominated) and Loe Bar (overwash) showed that recovery processes are multi-annual (Perranporth and Slapton) or quasi-permanent (Loe Bar), often comprising of seasonal to decadal signals. In each case, the mechanisms for recovery were found to be intrinsically linked to the storm response mechanisms.
4. It is highlighted here that post-storm recovery does not necessarily occur during calm periods; in the case of both Perranporth (sand) and Slapton (gravel), high-energy (low steepness and alternate angle, respectively) wave events appear to be essential for mobilisation/recovery of deep offshore storm bar deposits and for beach counter-rotation. We have shown that site-specific recovery processes are very complex and stochastic, with rates of beach volume and shoreline recovery shown to vary throughout the beach system depending of mobilisation potential, disequilibrium and inherent sub-system response timescales.
5. Multi-annual morphological records highlighted the significance of multiannual storm clustering/sequencing, storm tracks and resultant variations in wave angle, in controlling the impact that extreme events have on contrasting sand/gravel beaches in exposed/sheltered locations. It is argued that important regional wave forcing characteristics, that are intrinsically linked to the NAO, AMO and multi-annual atmospheric variability. It is therefore likely that decadal metocean variability in regional winter wave characteristics (height, period and direction) are strongly linked to beach morphological state and coastal vulnerability.

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