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The extreme 2013/2014 winter storms: hydrodynamic forcing and coastal response along the southwest coast of England

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ABSTRACT: The southwest coast of England was subjected to an unusually energetic sequence of Atlantic storms during the 2013/2014 winter, with the 8-week period from mid-December to mid-February representing the most energetic period since at least 1953. A regional analysis of the hydrodynamic forcing and morphological response of these storms along the SW coast of England highlighted the importance of both storm- and site-specific conditions.

The key factor that controls the Atlantic storm wave conditions along the south coast of southwest England is the storm track. Energetic inshore wave conditions along this coast require a relatively southward storm track which enables offshore waves to propagate up the English Channel relatively unimpeded. The timing of the storm in relation to the tidal stage is also important, and coastal impacts along the macro-tidal southwest coast of England are maximised when the peak storm waves coincide with spring high tide. The role of storm surge is limited and rarely exceeds 1 m.

The geomorphic storm response along the southwest coast of England displayed considerable spatial variability; this is mainly attributed to the embayed nature of the coastline and the associated variability in coastal orientation. On west-facing beaches typical of the north coast, the westerly Atlantic storm waves approached the coastline shore-parallel, and the prevailing storm response was offshore sediment transport. Many of these north coast beaches experienced extensive beach and dune erosion, and some of the beaches were completely stripped of sediment, exposing a rocky shore platform. On the south coast, the westerly Atlantic storm waves refract and diffract to become southerly inshore storm waves and for the southeast-facing beaches this results in large incident wave angles and strong eastward littoral drift. Many south coast beaches exhibited rotation, with the western part of the beaches eroding and the eastern part accreting. © 2015 The Authors. *Earth Surface Processes and Landforms* published by John Wiley & Sons Ltd.

KEYWORDS: extreme storms; Atlantic storms; storm response; sandy beaches; gravel beaches

Introduction

There are two main impacts of climate change on coastal processes and environments that significantly affect our long-term use of the coastal zone and coastal vulnerability. First, climate change will result in sea-level rise (Nicholls *et al.*, 2011) and may approach rates experienced during the early and mid-Holocene periods (5–10 mm yr^{-1}) by the end of this century (Woodroffe and Murray–Wallace, 2012). Second, more variable and extreme weather conditions are expected to modify the wave climate, with consequences ranging from regional changes in extra-tropical storm tracks (Dodet *et al.*, 2010; Wang *et al.*, 2012; Woolf and Wolf, 2013), to global increases in tropical storm frequency and perhaps intensity (Knutson *et al.*, 2010). Sea-level rise and extreme storm wave events are clearly operating over different time scales, but their long-term impacts are intrinsically linked. Specifically, the shortening of extreme water level return periods as a result of sea-level rise will progressively enable storm conditions to reach higher elevations (Fiore *et al.*, 2009), thus increasing storm impacts. For many coastal regions, both sea-level rise and changes in the storm wave climate will result in (enhanced) coastal erosion and increased frequency and intensity of coastal flooding.

To mitigate against and adapt to increased coastal hazards due to sea-level rise and changes in the wave climate, predictions of these hazards in relation to climate change, as well as the coastal impacts of extreme storms and the recovery from these storms are required (Masselink and van Heteren, 2014). A major challenge in developing predictive tools (e.g. numerical models) for predicting coastal impacts due to extreme storms is the paucity of observational data collecting during these events with which to develop, calibrate and validate such tools, requiring modellers to extrapolate from less extreme conditions. The most significant short-term (days–weeks) and medium-term (months–years) shoreline changes are driven by large storm events, storm sequences and associated recovery phases, but our understanding of coastal storm response is limited by the quality and appropriateness of the datasets available (Coco *et al.*, 2013). Field observations are rarely sufficiently comprehensive to yield accurate estimates of storm erosion and recovery rates required for future storm impact modelling (Ranasinghe *et al.*, 2013).

Meteorologically speaking, the winter of 2013/2014 was highly unusual (Met Office, 2014). According to Matthews *et al.* (2014), the combination of high cyclone frequency and above-average cyclone intensity resulted in exceptional storminess, causing this winter to be ranked as the stormiest on record for the Ireland–UK domain. On land, these storms caused extreme precipitation and fluvial discharge, resulting in widespread river flooding (Huntingford *et al.*, 2014); on the coast, these storms caused a highly unusual sequence of extremely high water levels (Wadey *et al.*, 2014) and very energetic wave conditions, resulting in coastal erosion and flooding. Although coastal impacts were widespread, ranging from Ireland to Portugal, the southwest (SW) coast of England was particularly and repeatedly impacted due to the storm tracks crossing Ireland and England. The upper panel of Figure 1 shows the time series of the significant wave height H_s measured by the Sevenstones Lightship at the SW tip of Cornwall over the period 1 October 2013 to 1 April 2014 (deployed 30 km offshore in 70 m water depth; refer to Figure 3 for wave buoy location). The 22 storm events that occurred over this 6-month period had an average peak and mean H_s of 8.1 m and 6.1 m, respectively, and an average duration of 28.7 h. For 10 storms the peak H_s exceeded 8 m and during two storms the peak H_s exceeded 10 m. During all these storms, the wave direction was southwesterly to westerly, as is typical for Atlantic storms.

The large number of extreme storms coming in from the Atlantic on a relatively southward track generated many occurrences of very high waves with exceptionally long periods that focused on the SW of England. To illustrate this, the lower panel of Figure 1 shows an 8-week moving average of modelled (1953–2011; WWIII data from Dodet *et al.*, 2010) and measured (2008–2014; data obtained from http://www.previmer.org/) significant wave height at Sevenstones Lightship. It is evident that the 8-week sequence of storms from mid-December 2013 to mid-February 2014 represents the most energetic period of waves, quantified in terms of the 8-week averaged significant wave height ($H_s = 4.4$ m), to have hit the SW coast of England during the last 60 years. This period thus represents at least a 1:60 year event, testifying to the extreme nature of the wave conditions.

The wave conditions recorded offshore are not the same as experienced inshore due to a range of wave transformation processes that result in a reduction of the wave energy (e.g. bed friction, refraction and diffraction; *cf.* Komar, 1997). Nevertheless, unusually high inshore wave conditions (Figure 2) were experienced along the entire coastline of SW England, at exposed as well as relatively sheltered locations, causing widespread damage and disruption. Practically all coastal towns and villages were affected by coastal flooding and/or damage to coastal infrastructure. Erosion of coastal dunes was also widespread and many beaches lost considerable quantities of sediment, exposing the underlying rocky shore platforms or coastal protection structures.

A large number of research methodologies are available for monitoring extreme storm responses along dynamic coastlines, including deployment of 'rapid response' units that record individual storm processes and impacts (Brodie and McNinch, 2009), beach surveys (Stéphan *et al.*, 2012), video monitoring (Poate *et al.*, 2014), airborne LiDAR (Houser, 2013) and satellite imagery (Castelle *et al.*, 2015). Here, we consider a methodology based on the regional monitoring of both the hydrodynamic forcing (wave buoys, tide gauges) and the morphological response (LiDAR and beach surveys) along the coast of SW England to investigate the storm impacts that occurred along this *c.* 1000 km stretch of coast during the 2013/2014 winter. In the following section we provide an overview of the study area and the regional coastal monitoring programme. In the third section we discuss the inshore wave and water-level conditions that occurred over the storm period and

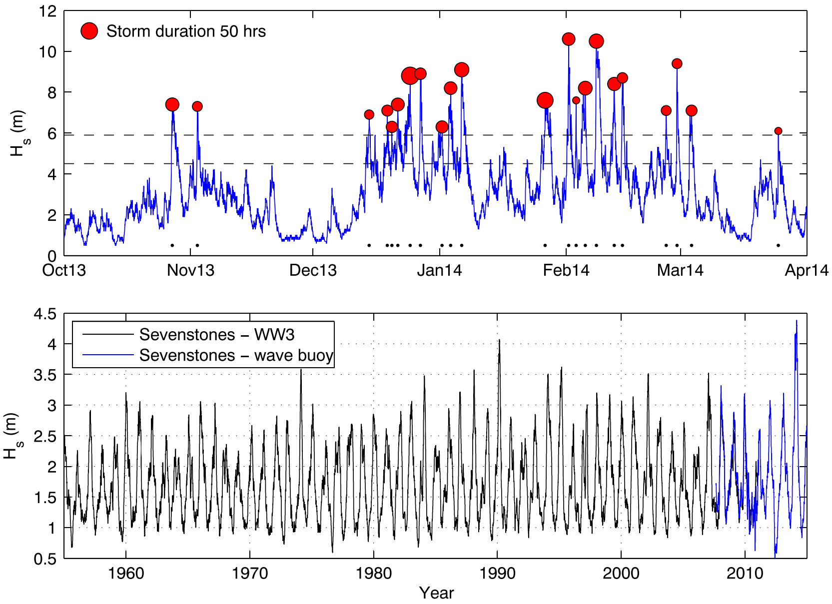

Figure 1. Upper panel shows time series of significant wave height H_S measured at Sevenstones Lightship at the SW tip of Cornwall over the period 1 October 2013 to 1 May 2014 (refer to Figure 3 for wave buoy location). In total, 22 storms were identified over this period (red circles), where a storm is defined as a wave event during which the maximum H_s exceeds the 1% exceedence wave height of 5.9 m, and where the start and the end of the storm event occurs when H_s exceeds or falls below 4.5 m (roughly the 5% exceedence wave height), respectively (horizontal lines). Definition of storm events are site-specific (cf. Almeida *et al.*, 2012), and the H_s thresholds used here were selected because they produced clearly identifiable storm events. The size of the red circles is proportional to the duration of the storm. Lower panel shows time series of 8-week moving average of WWW III modelled (1953–2011) and measured (2008–2014) significant wave height at Sevenstones Lightship. Modelled and measured data were obtained from Dodet *et al.* (2010) and http://www.previmer.org/, respectively. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Figure 2. Left panel shows huge, parallel-incident storm waves (estimated breaking wave height of 8 m) breaking right at the base of the gravel beach at the southeastern end of Chesil Beach, Dorset, UK, during the storm of 05/02/2013 (photo by Richard Broome, reproduced with permission). Right panel shows very large, obliquely-incident storm waves (estimated breaking wave height of 4 m) on Slapton Sands, south Devon, also during the storm of 05/02/2015 (photo represents a video snapshot from the ARGUS camera station deployed at the northern end of Slapton Sands). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

highlight which of the 22 storms caused most damage and why. In the fourth section we present and interpret a large spatial dataset of storm impacts to demonstrate the very extensive regional variability in geomorphic response along the SW coast of England over the 2013/2014 storm period. In the final section we discuss the novel insights obtained into the Atlantic storm response along the SW coast of England and relate the results to previous research into extreme storm impacts.

Regional Coastal Monitoring of Southwest Coast of England

The SW coast of England includes the relatively sheltered southern margin of the Bristol Channel (Somerset), the fully exposed north coast (Cornwall and Devon), and the partially-exposed south coast (Cornwall, Devon and Dorset) which has varying degrees of wave exposure depending on the shoreline orientation and the presence of bays and headlands (Figure 3). Throughout the region, the tides are macro-tidal with the mean spring tide range decreasing steadily from 11 m at Weston-super-Mare along the Bristol Channel, to 7 m at Saunton on the north coast of Devon, to 5.5 m at Sennen at the tip of Cornwall, and then to 3.5 m at Chesil in Dorset (ATT, 2010). The coastline is largely embayed with more than 150 separate beaches and 21 estuaries (Davidson *et al.*, 1991).

The coastline of SW England is highly variable in terms of static (shoreline orientation, geology, sediment size and abundance) and dynamic (waves, tides) boundary conditions, and therefore the resulting beach morphology and beach types are also very diverse (Scott *et al.*, 2011). Most beaches are sandy, but gravel beaches also occur, including pure gravel, mixed sand–gravel and composite gravel beaches (Jennings and Schulmeister, 2002). The geological framework plays an

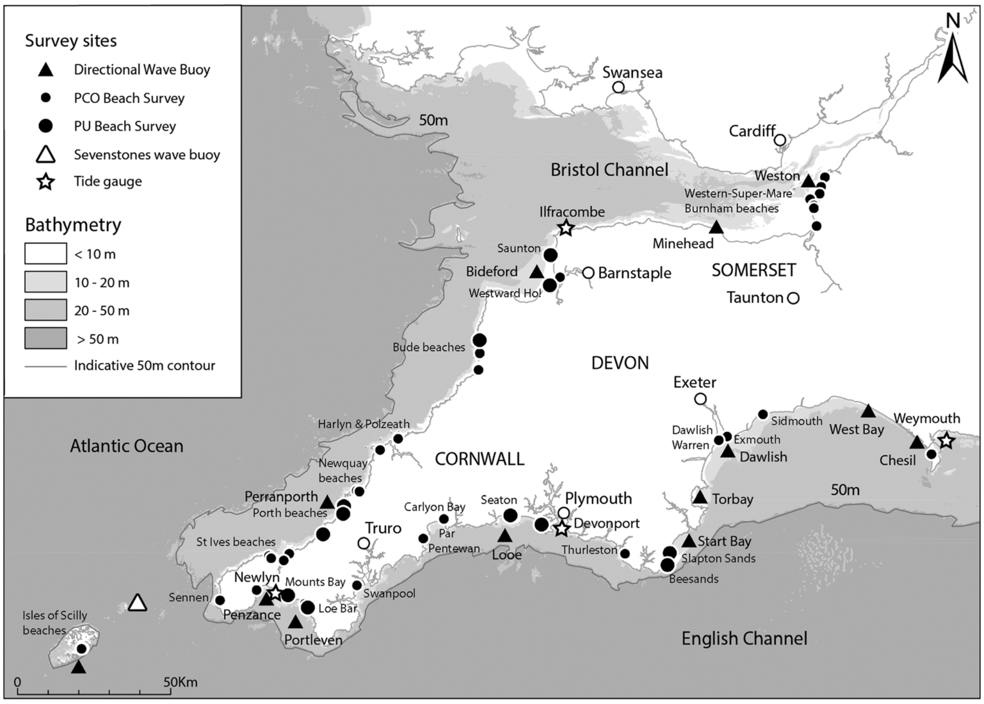

Figure 3. Map of the SW of England showing location of directional wave buoys, tide gauges, beaches monitored by the Plymouth Coastal Observatory (PCO) and sites that are part of the Plymouth University (PU) coastal monitoring programme, some of which are referred to in this paper. The depth contour line represents the 50 m line. Wave buoy codes are: Wst = Weston Bay; Mhd = Minehead; Bdf = Bideford Bay; Prp = Perranporth; Pnz = Penzance; Plv = Porthleven; LoB = Looe Bay; StB = Start Bay; Tob = Torbay; Dwl = Dawlish; WeB = West Bay; Chl = Chesil. Tide gauge codes are: ILF = Ilfracombe; NEW = Newlyn; DEV = Devonport; WEY = Weymouth. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

important role and beaches in SW England are commonly embayed with prominent headlands, are often backed by coastal cliffs, and can be underlain or fronted by rocky shore platforms (Scott *et al.*, 2008). Barrier beaches backed by coastal lagoons, back-barrier estuaries and coastal plains do also occur, but are less common. The length of most beaches is 1–5 km and the longest uninterrupted beach is Chesil beach which is 28 km long.

The coastline of SW England is surveyed every few years by airborne LiDAR commissioned by the Environment Agency (EA). Different sections of the coasts are surveyed in different years, usually at the end of summer, but the whole coastline was flown in the spring of 2014 to help assess the damage caused by the winter storms (available from http://www.channelcoast.org/). The temporal resolution of the LiDAR data is not ideal to determine the impacts of the 2013/14 winter; therefore, LiDAR results will be presented in this paper solely for illustrative purposes.

The Plymouth Coastal Observatory (PCO) routinely conducts, or sub-contracts to conduct, RTK-GPS surveys on a very large number (>50) of beaches in SW England (once a year or 6-monthly); for a subset of these beaches, morphological data has also been collected during the 2013/2014 winter season to record storm impacts (all survey data are available from http://www.channelcoast.org/). The PCO storm response data set includes 38 individual beaches and covers the region from Somerset round to Dorset (Figure 3). The data set comprises 224 transects and the minimum, mean and maximum number of transects per beach is 1, 6 and 22, respectively.

Plymouth University (PU) also regularly monitors a number of beaches in the SW of England using RTK-GPS. Monthly surveys have been carried out since 2006 on Perranporth on the north coast of Cornwall (Masselink *et al.*, 2014; Poate *et al.*, 2014; Stokes *et al.*, 2015) and Slapton Sands on the south coast of Devon (Ruiz de Alegria-Arzaburu and Masselink, 2010). On Perranporth, a 1-km-wide beach section is surveyed using a quad bike, whereas on Slapton Sands 20 cross-shore transects with a 250 m spacing are surveyed on foot. A number of additional beaches (Croyde, Westward Ho!, Praa Sands, Whitsands, Hallsands, Beesands) have also been monitored since the 2013/2014 winter every 3 months, but these data are not discussed in this paper.

To complement the offshore wave conditions collected by the Sevenstones Lightship at the tip of Cornwall (available from http://www.previmer.org/), a network of 12 inshore directional wave buoys, maintained by the PCO, are deployed along the coast of SW England (Figure 3). These buoys collect continuous wave data which are used to compute half-hourly wave statistics (available from http://www.channelcoast.org/). Water levels are recorded at four primary ports (Figure 3). These data are decomposed into the tidal signal and the residual, and are made available at half-hourly intervals from the British Oceanographic Data Centre (BODC; https://www.bodc.ac.uk/data/online_delivery/ntslf/).

Wave Conditions and Water Levels During the 2013/2014 Winter

Inshore wave conditions

The SW coast of England experienced 22 extreme storms from October 2013 to April 2014 (Figure 1), where, for the present purpose, a storm is defined as an event during which the significant wave height H_s exceeds the 1% exceedence wave height of 5.9 m. It is difficult to intuit from the offshore wave height time series which of the storms were the most damaging and where on the coast their influence was most felt. The inshore wave conditions measured by a network of 12 directional buoys deployed in relatively shallow water ($h = 10$–15 m) provides a more appropriate representation of the wave conditions at the coast. To compare the offshore with the inshore wave conditions, for each of the 22 storm events, the following four storm wave statistics were extracted from the inshore wave records: peak and mean significant wave height H_s, and peak wave period T_p and direction during the storm peak.

Figure 4 summarises the comparison between the offshore wave conditions at Sevenstones Lightship and the inshore wave conditions, with the storm wave statistics expressed as box plots in the upper panels. The 12 inshore wave buoy locations fall into three groups: Weston Bay and Minehead, located along the Bristol Channel, are considered sheltered sites and experienced the smallest wave heights (peak H_s and mean H_s are < 2 m and < 1.5 m, respectively). Penzance, Looe Bay, Start Bay, Torbay and Dawlish are all located along the south coast and southeast-facing; therefore, they are only partially-exposed to the westerly Atlantic storm waves. The waves first have to pass the tip of SW England and arrive at the Channel, and then refract and diffract into the mostly embayed locations, resulting in reduced storm wave heights (peak H_s and mean H_s are < 4 m and < 2.5 m, respectively). Peak wave periods are also relatively small ($T_p < 10$ s) and wave directions change from westerly to southerly. The exposed sites are the west-facing Bideford and Perranporth on the north coast, and the southwest-facing Porthleven, West Bay and Chesil on the south coast. These exposed beaches experienced the largest wave heights (peak H_s and mean H_s of 4–5 m and 2.5–3.5 m, respectively) and period ($T_p = 10$–15 s), with wave directions of 270^o on the north coast and 220^o on the south coast. In comparison, the peak H_s and mean H_s at the offshore location, averaged across all storm events, was 8.1 m and 6.1 m, respectively (no offshore peak wave period or direction are available).

The lower panel of Figure 4 compares the time series of the offshore significant wave height H_s, and the identified storm events, with the storm wave peaks at three selected inshore locations that are considered representative for the exposed (Bideford), partially-exposed (Start Bay) and sheltered (Minehead) sites. Generally speaking, the inshore storm wave heights on the north coast, the south coast and along the Bristol Channel are 60%, 25% and 15% that of the offshore wave height, respectively, although on the south coast this depends strongly on the degree of shelter (*cf.* Torbay and Looe Bay). The relative difference between inshore and offshore wave height is reasonably consistent for the north coast and for the Bristol Channel for the different storms, but there are a few storm events where the inshore wave height on the south coast is only marginally less than on the north coast. These events are represented by the positive outliers in the boxplots for the peak and mean storm H_s, and are also evident in the time series of the storm wave conditions (Figure 4 – lower panel). The storm events that particularly stand out in this context are the events of 5 and 14 February 2014 (3rd and 6th event in that month) and to a lesser degree 19 and 24 December 2013 (2nd and 5th event in that month).

The peak wave period T_p during the storm peaks for Bideford is also plotted in Figure 4 (lower panel). There were several storms during the 2013/2014 winter with extremely large T_p values (>20 s) for the exposed sites – see the outliers in the peak storm T_p plot of Figure 4 (middle left panel). The storm event on 06/01/2013 stood out in particular in terms of large waves and an extremely long period. For Bideford, the T_p was 18 s during this storm (Figure 4 – lower panel), and for Perranporth, Porthleven and Chesil, T_p during the storm

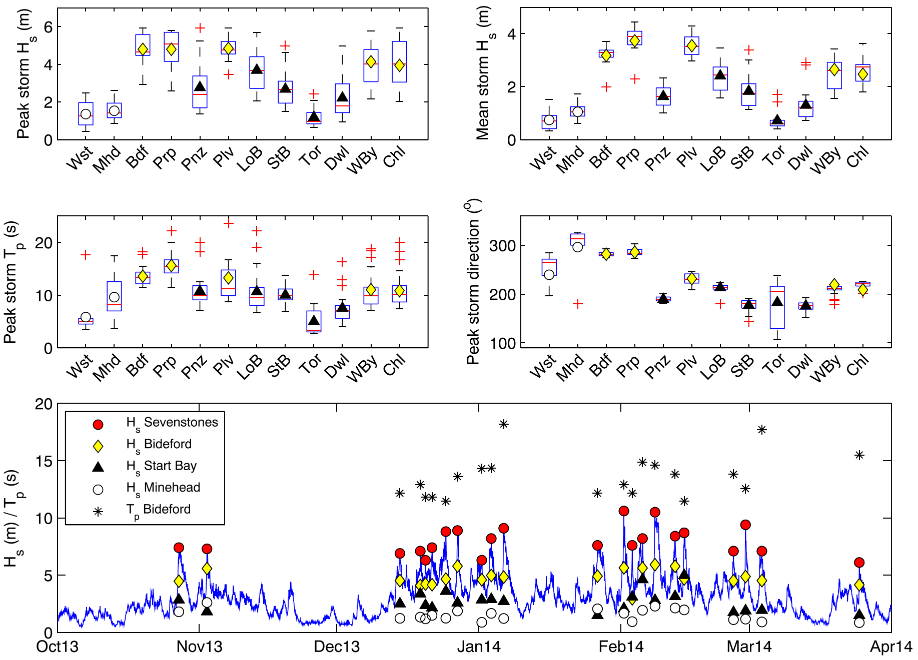

Figure 4. Boxplots of the peak storm significant wave height H_s (upper left panel), mean significant wave height H_s during the storm event (upper right panel), peak storm peak wave period T_p (middle left panel) and the peak storm wave direction (middle right panel) for the 12 different inshore wave buoys and taking into account all 22 identified storm events (refer to Figure 3 for the inshore wave locations and location codes). For each box, the central red horizontal mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points the algorithm (up to 99.3% coverage assuming a normal distribution) considers to be not outliers, and the outliers are plotted individually as red plusses. The yellow diamonds, black triangles and white circles are the mean values, and represent the exposed, partially-exposed and sheltered buoy locations, respectively. The lower panel shows time series of significant wave height H_S measured at Sevenstones Lightship at the SW tip of Cornwall over the period 1 October 2013 to 1 April 2014 with the red circles representing the storm peaks. The other symbols represent the storm peaks at Bideford (yellow diamonds), Start Bay (black triangles) and Minehead (white circles), and these sites are presentative of exposed, partially-exposed and sheltered buoy locations, respectively. The peak wave period T_p at the storm peak at Bideford (asterisks) is also plotted. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

peak was 22 s, 24 s and 20 s, respectively. Wave power, or wave energy flux, is a function of wave height and period, and a doubling of the wave period represents a doubling of the wave power; therefore, wave period is an important factor in assessing storm impacts.

Storm wave field and storms tracks

The ratio between the offshore wave height at Sevenstones Lightship and the inshore wave conditions along the south coast can be related to the wave field generated by the storm, obtained from predictions using the Met Office WWIII model (Figure 5). A key role is played by the storm track, which is the path of the depression (see Scott *et al.* (submitted) for more information). When a storm crosses the British Isles north of Ireland, the centre of the wave field generated by the storm tends to be north of 50° latitude, such as occurred during the 06/01/2014 and 01/02/2014 storm events (Figure 5 – upper panels). In that case, offshore wave conditions off the SW coast of England are still very energetic, but there is limited scope for the storm waves to propagate up the Channel and wave conditions along the south coast are relatively modest (peak $H_s = 2.7$ m and 2.1 m during 06/01/2014 and 01/02/2014, respectively, at Start Bay; see Figure 4 – lower panel). When a storm tracks across Ireland, the centre of the storm wave field tends to be south of 50° latitude and this occurred during the 05/02/2014 and 14/02/2014 storm events (Figure 5 – lower panels). In that case, storm waves can propagate relatively unimpeded into the Channel, causing very energetic wave conditions along the south coast (peak $H_s = 4.6$ m and 5.0 m during 05/02/2014 and 14/02/2014, respectively, at Start Bay; see Figure 4 – lower panel). A 200 km shift in storm wave field, related to the storm track, can therefore make a very significant difference to the storm wave conditions along the south coast and the associated coastal impacts.

The storm track also has a significant influence on the wave direction. Unfortunately, the Sevenstones Lightship does not record the offshore wave direction and the direction of the waves recorded at the inshore buoy sites are rather site-specific. The direction of the offshore waves for the four storms in Figure 5 was obtained from the output of the Met Office's 8 km grid WWIII wave model (Table I). The model predictions show that the offshore waves during the first two Atlantic storms were from WSW-W, and by the time they reached the north and south coast, they were incident from W and WSW, respectively. The offshore waves during the last two storms were from SW, and on the north and south coast they were from WSW-W and SSW, respectively. It is thus clear that a more southerly storm track generates waves approaching from a more southerly direction, and this is particularly significant for the wave conditions along the south coast.

Water levels

In addition to the characteristics of the storm (H_s, T_p, wave direction, storm duration, location of wave field, storm track), the water level over the storm event is also very important in determining the potential impact of storms. Both the tidal stage (spring tides versus neap tides) and the (positive) tidal residuals (storm surge) coincident with the peak of the storm are relevant. The upper two panels of Figure 6 show the 6 month time

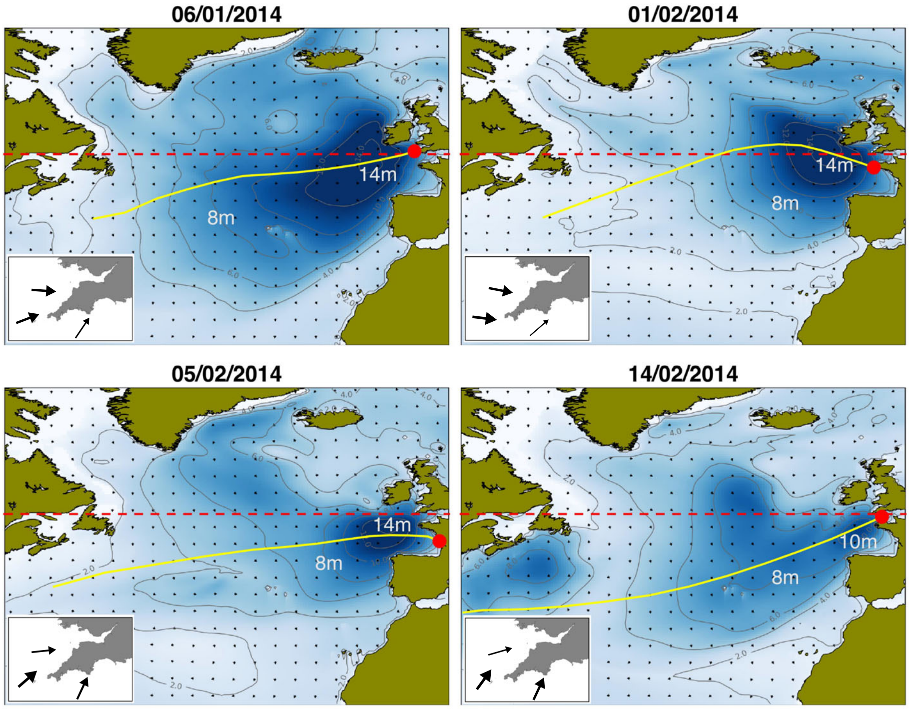

Figure 5. Significant wave height H_s prediction according to Met Office wave model (WWIII) for the three storms having most impact that occurred during the 2013/2014 winter (06/01/2014, 05/02/2014 and 14/02/2014), and the storm with the largest offshore significant wave height (01/02/2014). The wave maps represent the time during which the storm waves peaked at the Sevenstones Lightship. The yellow line represents the track of the peak westerly-directed offshore wave height, the red circle its subsequent landfall, and the horizontal red line represents 50^0 N latitude. The inset in each of the storm wave plots represents the SW coast of England with the arrows representing the inshore wave height (thickness and length of arrow) and direction modelled by the Met Office 8-km grid WWIII model for 20–30 m water depth along the north coast, off the tip of Cornwall and along the south coast (refer to Table I). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Table I. Summary of the storm statistics for the four storm shown in Figure 5 according to the Met Office 8 km grid WWIII model. The model node just seaward of the Isles of Scilly has been used to represent the offshore wave statistics, and for the north and south coasts the outputs for all model nodes in 20–30 m water depth along the respective coasts have been averaged. The modelled storm statistics represent the average significant wave height H_s, the peak wave period T_p and wave direction Dir over a 6-h period centred round the storm peak

	06/01/2014 storm			1/02/2014 storm			05/02/2014 storm			14/02/2014 storm		
	H_s (m)	T_p (s)	Dir (^{o})	H_s (m)	T_p (s)	Dir (^{o})	H_s (m)	T_p (s)	Dir (^{o})	H_s (m)	T_p (s)	Dir (^{o})
North coast	6.78	19.2	274	8.02	17.6	281	5.61	17.1	264	5.13	13.8	254
Offshore	8.44	19.5	249	8.70	18.3	277	9.24	17.1	229	9.38	14.7	216
South coast	5.09	17.1	214	4.13	13.5	229	6.88	15.0	206	7.61	13.6	205

series during the 2013/2014 winter of the water level and the tidal residual measured at Devonport, south Devon. Along the largely macro-tidal coastline of SW England, the water-level variability over a lunar tidal cycle is considerable, and the difference between neap high tide and spring high tide is commonly > 1.5 m (or even > 2 m along the Bristol Channel), and the timing of storms in relation to the lunar tidal cycle has a significant influence on the potential coastal storm impacts because it determines the vertical ‘reach’ of the storm waves on the coast. Figure 6 (upper panel) shows that both clusters of storms at the start of January and February in 2014 coincided with relatively large spring tides.

The tidal residuals also need to be taken into account and it is interesting to note that during the particularly stormy periods from mid-December 2013 to mid-January 2014, and over the first half of February 2014, the inshore water levels at Devonport were almost permanently elevated by up to 0.5 m (Figure 6 – second panel). Nevertheless, in contrast to observations along the east coast of England during the 2013/2014 winter (Spencer *et al.*, 2015), positive residuals related to storm surge play a minor role along the SW coast of England and rarely exceed 1 m. The exception is the storm event that occurred on 14/02/2014, during which the storm surge reached 1 m at Devonport, giving rise to one of the highest water levels over the period, despite the fact that the spring tides during this events were not particularly large (Figure 6 – upper two panels). Wadey *et al.* (2014) analysed the 1915–2014 Newlyn sea-level record to place the 2013/2014 winter in a longer-term context and found that the storm event on 3 February 2015 generated the highest sea level on record, despite only having a skew surge of 0.45 m. It is important to realise that coastal flooding is not only related to the tide level and storm surge, but that wave-driven set-up and runup are also important and may in fact dominate the vertical reach of the sea during storms. This is especially pertinent along steep gravel beaches, where vertical wave runup can be up to twice the significant wave height (Poate *et al.*, 2015).

The lower two panels of Figure 6 show the peak high tide level and maximum residual during the identified storm events for the

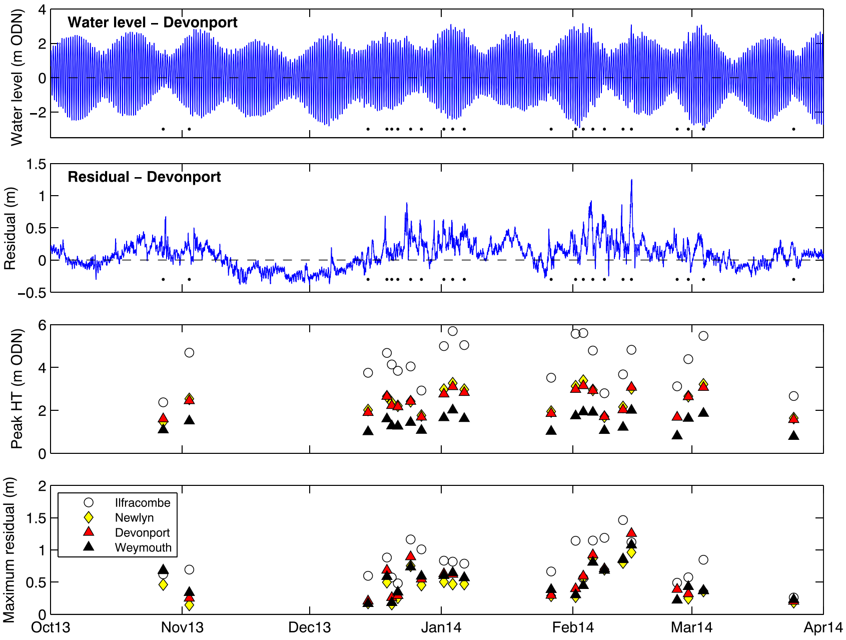

Figure 6. Time series of water level and tidal residual (upper two panels) measured at Devonport, south Devon, over the period 1 October 2013 to 1 April 2014. The small black marks represent the identified storm events from the Sevenstones offshore wave record. For each storm event, the maximum high tide (HT) level and the maximum tidal residual (storm surge) was determined for four locations along the SW coast of England (lower two panels; refer to Figure 3 for the location of tide gauges). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

four locations for which tidal data are available. The tide range is maximum in the Bristol Channel (Ilfracombe) and decreases along the south coast in an eastward direction from Newlyn, to Devonport, and to Weymouth (Figure 6 – third panel). Similarly, the storm surge is also largest in the Bristol Channel, and there is not much difference in the maximum residual along the south coast (Figure 6 – bottom panel). The 14/02/2014 storm (6th event in that month) was associated with the highest storm surge along all three south coast locations. The storm of 03/1/2014 and 03/02/2014 (2nd events in those months) were characterised by the highest high tide levels at all locations.

Regional Variability in Coastal Impacts

Qualitative assessment of coastal impacts on coastal infrastructure

The entire coastline of SW England was affected by the unusually energetic 2013/2014 winter season; however, the storm impacts were spatially and temporally highly variable: different sections of coast were affected by different storms events. A ‘storm impact timeline’ can be constructed from media reports and unpublished reports by government agencies (Cornwall Council, 2014; Devon Maritime Forum, 2014; Environment Agency, 2014; Met Office, 2014; Siggory and Wiggins, 2014). Most significantly, these sources indicate that the main storms in terms of offshore wave conditions were not necessarily the events having most impact. The four storm events that had the most significant storm impacts on the coastal infrastructure and coastal communities were the events of 03/01/2014, 06/01/2014, 05/02/2014 and 14/02/2014. These events are the main ones that are specifically mentioned in these unpublished reports and also the events that feature most extensively in the media.

The storm on 03/01/2014 was characterised by one of the highest water levels that occurred during the 2013/2014 winter period due to spring tide conditions and a *c.* 0.5 m storm surge (Figure 6 – lower two panels). Although some damage occurred to coastal structures (e.g. seawall at Ilfracombe and Westward Ho! in north Devon), the major impact was extensive coastal flooding, in particular in north Devon, although several coastal towns in south Devon were also affected (Environment Agency, 2014). There was no reported damage or flooding specifically associated with this storm event in Cornwall.

The storm on 06/01/2014 (named ‘Hercules’) had a major impact on the coast of Cornwall, and a large number of towns, ports and harbours suffered storm damage and extensive coastal flooding (Cornwall Council, 2014). It was also reported that many beaches were significantly affected through beach lowering and dune erosion, especially on the north coast of Cornwall. The Met Office (2014) pointed out that the wave heights during the storm event of 06/01/2014 were not particularly unusual for the northeast Atlantic, but that two factors stand out: (1) the track of the storm fell at a relatively low latitude; and (2) peak wave periods were exceptionally long even compared with storms of similar wave height occurring in December (Figure 4 – lower panel). Notably, the 06/01/2014 storm event is not mentioned in the storm impact report for Devon (Environment Agency, 2014).

Despite the relatively modest offshore wave conditions (Figure 1), the storm on 05/02/14 (named ‘Petra’) had the greatest impact on the south coast of Devon and Cornwall (especially Devon). In addition to the energetic wave conditions at all inshore locations, this storm was also characterised by gale-force wind conditions from the south (Environment Agency, 2014).The most costly consequence was the damage to and the subsequent closure of the railway line at Dawlish, south Devon, which cost £20 M to repair and is estimated to have cost the regional economy between £60 M and £1.2 B over the 2-month duration of the closure (Devon Maritime Forum, 2014). Extensive coastal flooding and damage to buildings, harbours and coastal defence structures occurred in most towns on the south coast of Devon and Cornwall (Cornwall Council, 2014; Environment Agency, 2014). Beach erosion was also reportedly widespread along sections of the south coast of Cornwall and Devon (Siggory and Wiggins, 2014), and the gravel barrier of Slapton Sands was overwashed, covering the road with gravel.

The storm on 14/02/2014 (‘Valentine’s Day’) was relatively modest in terms of inshore wave conditions (Figure 4 – lower panel), but, similar to the storm on 03/01/2014, was characterised by one of the highest water levels that occurred during the 2013/2014 winter period due to spring tide conditions and a *c.* 1 m storm surge (Figure 6 – lower 2 panels). It was also characterised by gale-force wind conditions from the south (Environment Agency, 2014). Limited damage was reported from the Cornish coast, with the exception of Penzance in south Cornwall, where structural damage was reported to the coastal defences, tidal causeway and the harbour wall (Cornwall Council, 2014). Most impacts were felt along the south coast of Devon, including further damage to the Dawlish Railway, the gravel beaches in Start Bay, overwashing of the Slapton Sands barrier and coastal flooding (Environment Agency, 2014).

LiDAR data

In terms of spatial coverage, digital elevation models (DEMs) derived from LiDAR data are vastly superior to those based on RTK-GPS surveys discussed in the following section. Unfortunately, although post-storm LiDAR surveys were carried out immediately after the 2013/2014 storm season, the dates for the pre-storm surveys is highly variable and ranges from 2010 to 2013. Therefore, care should be taken in interpreting the morphological difference between the pre- and post-storm DEMs, although analysis of available long-term morphological data sets (from Perranporth and Slapton Sands; Scott *et al.*, 2015, submitted) gives a very clear indication that the morphological changes that occurred during the 2013/2014 winter were far greater than experienced since at least 2008.

A comparison of pre- and post-storm LiDAR data for selected sites is provided in Figure 7. The morphological response at Bude, north Cornwall, is representative of north coast beaches and displays 1–2 m of beach lowering across the entire intertidal (Figure 7(a)). Where there is limited morphological response, this is because there is only a very thin veneer of sediment on top of a shore platform (upper section of the northern part of Bude). The storm response at Sidmouth, south Devon, and Carlyon, south Cornwall, both show alongshore redistribution of sediment; at Sidmouth the presence of multiple coastal defence structures (offshore breakwaters, groynes and seawall) creates several sediment cells (Figure 7(b)), whereas Carlyon beach experienced a beach-wide rotation (Figure 7(c)). Many beaches on the south coast exhibited a rotation due to the strong eastward littoral drift driven by the Atlantic storm waves.

Pre-and post-storm beach survey data

The PCO storm data set comprises 224 individual cross-shore transects from 38 beaches. Each transect has been surveyed between two and four times during 2013 and 2014, and all profiles were visually inspected and quality-controlled prior to analysis. For each transect, the pre- and post-storm survey dates were selected that best reflect the morphological changes over the 2013/2014 winter storm period. Subsequently, for each transect pair (i.e. the pre- and post-storm profile), the most appropriate start of the profile (usually top of dune or coastal protection structure) and the elevation cut-off above which to compute the sediment volume changes (usually as low as possible, up to –2.5 m ODN) were identified. The change in beach sediment volume seaward of the start of the profile and above the elevation cut-off was then computed for each transect pair to reflect the volumetric changes that occurred over the 2013/2014 storm period. It is worth noting that the computed changes in the beach sediment volume represent changes to the dune, backshore and intertidal beach area, but does not include the subtial zone. Slapton Sands on the south coast of Devon is not part of the PCO beach monitoring programme, but the 20 cross-shore transects on this beach have been surveyed very regularly by PU since 2006 (Ruiz de Alegria-Arzaburu and Masselink, 2010). These data have therefore been added to the PCO data set.

The storm impacts expressed in terms of changes in the beach sediment volume are summarised in Figure 8, which shows the along-coast variation in the beach sediment volume change for each transect. The dominant morphological response as a result of the extreme storms has been erosion,

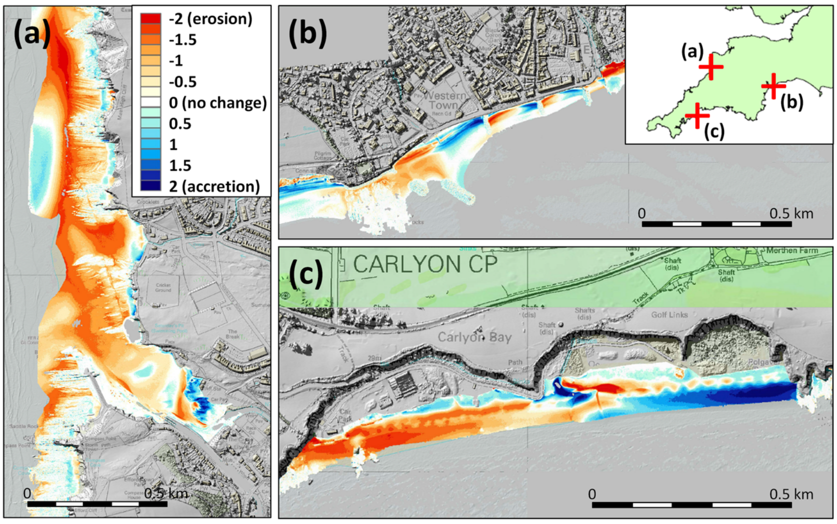

Figure 7. Elevation change derived from LiDAR for three beaches in SW England: (a) Bude, north Cornwall, flown on 08/10/2010 and 01/03/2014; (b) Sidmouth, south Devon, flown on 04/11/2013 and 09/02/2014; and (c) Carlyon, south Cornwall, flown on 21/03/2012 and 01/04/2014. © Crown copyright and database rights 2014 Ordnance Survey 100024198. © Environment Agency copyright and/or database rights 2014. All rights reserved. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

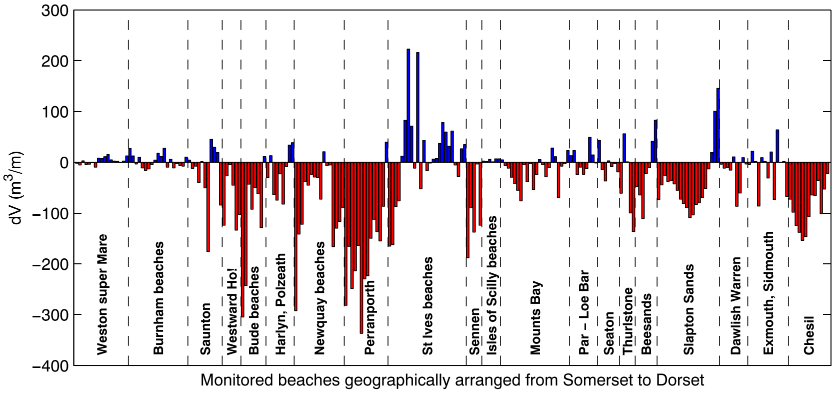

Figure 8. Regional variability in coastal response, quantified by the change in beach sediment volume dV in m^3 per unit meter beach width ($m^3\ m^{-1}$), along the coast of SW England during the 2013/2014 winter. Study sites have been positioned along the x-axis to run in an anticlockwise fashion from the northwest (Weston super Mare, north Somerset) to the southeast (Chesil, Dorset) of the study area. Every bar represents a single beach profile and the profiles have been grouped for the different beaches. Some neighbouring beaches with only a small number of profiles have been combined (e.g. Bude, Newquay, St Ives, Isles of Scilly, Par and Loe Bar, Exmouth and Sidmouth). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

with 66% of transects showing a decrease in beach volume (average loss = 68 $m^3\ m^{-1}$) and 34% showing an increase in sediment volume (average gain = 26 $m^3\ m^{-1}$). A total of 38 transects (17%) lost more than 100 $m^3\ m^{-1}$ and one transect lost more than 300 $m^3\ m^{-1}$. The mean change in beach volume, taking all 244 transects into account, was a decrease of 36 $m^3\ m^{-1}$. There is a surprising lack in the coastal literature on storm-driven sediment volumetric change to place these values in a wider context; the vast majority of storm impact studies only report changes in elevation, beach profile and/or shoreline position (Castelle *et al*., 2015). Changes to sandy barrier morphology due to hurricanes are widely reported, but net volumetric changes across the barrier tend to be limited (*c.* 10 $m^3\ m^{-1}$) because, due to barrier overwash processes, erosion of the beach and dune area are near-balanced by backbarrier deposition (Priestas and Fagherazzi, 2010). Coastal dune erosion during extreme storms can be quite extensive, representing sediment volumetric losses in excess of 10 $m^3\ m^{-1}$, but often the eroded dune sediment is deposited on the intertidal beach, limiting net sediment losses (Suanez *et al*., 2012). The maximum beach sediment losses reported here for some of the north coast beaches are comparable with those reported by Loureiro *et al*. (2012) for an exposed Atlantic embayed beach exposed to > 5 m storm waves; in other words, a beach setting and storm conditions similar to that described here.

A considerable geographical variation in the storm response is apparent. Modest changes in sediment volume (<20 $m^3\ m^{-1}$), mostly sediment gains, are generally observed for the beaches in Somerset and on the Isles of Scilly. These small volumetric changes are somewhat misleading, however, because at both locations several transects have experienced up to 5 m erosion of the low (1–3 m high) frontal dune system without significant losses in the intertidal beach volume. Significant beach volume losses have occurred at most other beaches along the SW coast of England, especially those around Bude (Crooklets, Widemouth), Newquay (Fistral, Towan, Portreath, Porthtowan), Perranporth, Sennen and Chesil. Intertidal and subtidal beach surveys on Perranporth show that the intertidal beach erosion is almost exactly balanced by accretion in the subtidal nearshore bar region (cf. Masselink *et al*., 2015; Scott *et al*., submitted). This strongly suggests that the storm-driven sediment transport is mainly in the offshore direction. Beaches with both accreting and eroding transects are also apparent, for example those around St Ives, Beesands and Slapton Sands. In St Ives Bay, the northern part of the bay experienced erosion, while the southern part accreted; the gravel beaches of Beesands and Slapton Sands both experienced erosion at the southern end of the beach and accretion on the northern end (cf. Masselink *et al*., 2015; Scott *et al*., submitted). Alternating sections of erosion/accretion also occurred along the groyned beaches of Exmouth and Sidmouth (*cf.* Figure 7(b)). Such rotational beach response is indicative of eastward sediment transport in the alongshore direction, consistent with large waves approaching obliquely from the Atlantic.

PU beach survey data

Figure 8 nicely documents the geographical variability in the coastal response along the SW coast of England during the 2013/2014 winter. Unfortunately, it is not possible to attribute the beach response to specific storm events on the basis of these data sets alone due to the coarse temporal resolution of the measurements. However, monthly survey data are available for two of the beaches, Perranporth on the north coast of Cornwall and Slapton Sands on the south coast of Devon, and the measurements over the 2013/2014 winter (Figure 9) can be related to the storm wave conditions experienced at a finer temporal resolution.

The beach volume change over the 2013/2014 winter period on Perranporth is shown in the left panels of Figure 9. Some erosion (50 $m^3\ m^{-1}$), followed by recovery (10 $m^3\ m^{-1}$), occurred during the first energetic period up to the start of December, when two storms occurred. Subsequently, over the 8-week period from the start of December to the end of January, a total of 10 storms were experienced, and 30 $m^3\ m^{-1}$ of sediment was lost from the beach. Then, during the first two weeks of February, when six storms occurred in quick succession, a further 50 $m^3\ m^{-1}$ sediment was lost and another 20 $m^3\ m^{-1}$ was eroded from the beach during the last two weeks of February, when two storms occurred. During March and April, when the two final storms of the 2013/2014 winter season occurred, the beach underwent rapid recovery, and the beach gained 75 $m^3\ m^{-1}$ over this 2-month period.

The beach volume change at three different locations along the 5 km long gravel barrier of Slapton Sands is shown in the right panels of Figure 9. The first energetic period up to the start of December did not have much of an impact. However, very significant changes occurred during the second energetic period from mid-December to the end of January, when nine storms occurred: both the southern end of the beach and the

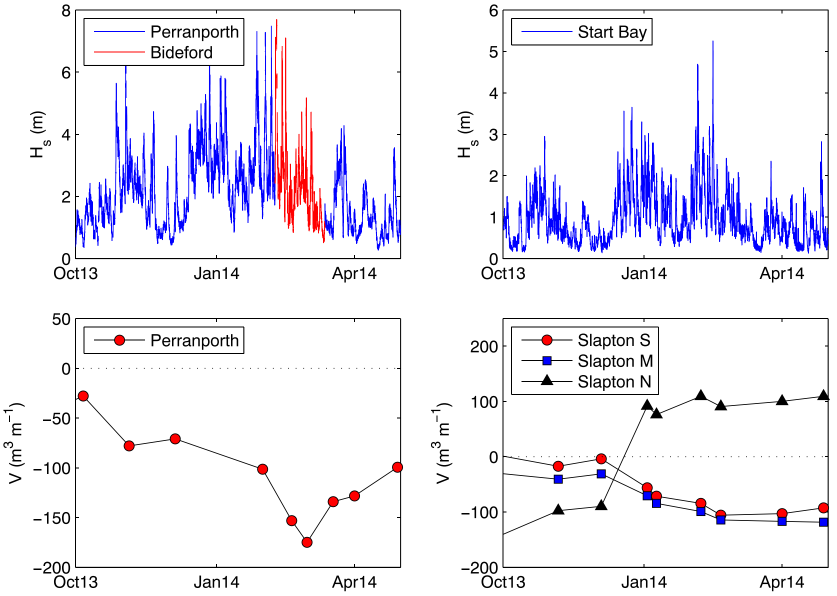

Figure 9. Concurrent time series of significant wave height H_s (upper panels) and beach volume V (lower panels) for Perranporth on the coast of north Cornwall (left panels) and Slapton Sands in Start Bay on the coast of south Devon (right panels). For Perranporth, the beach volume has been computed over a 350-m-wide survey area. For Slapton Sands, three profile lines are plotted, representing the south end of the beach (red circles; P0), the middle section (blue squares; P9) and the north end of the beach (black triangles; P19). The Slapton Sands data are strongly suggestive of a northeastward longshore sediment transport. The values for the beach volumes are relative to that at the start of the surveys in 2006. The Perranporth wave buoy lost its mooring during the storm of 05/02/2014 and the missing data have been replaced by that of the nearby Bideford wave buoy. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

central section progressively lost *c.* 100 m^3 m^{-1}, while the northern end of the beach gained *c.* 200 m^3 m^{-1}. During the third energetic period in February and the first week of March, when a further nine storms occurred, these trends continued, but the rate of change was much reduced. It is interesting to note that the most disruptive storms on Slapton Sands occurred on 05/02/2014 and 14/02/2014, when part of the middle section of the barrier, and the A379 road that runs across the crest of the barrier, was overwashed. During the same event, many houses at the seafront in Torcross at the southern end of the barrier were damaged by waves crashing over the seawall.

Discussion

The coastline of SW England was subjected to a highly unusual sequence of storms during the 2013/2014 winter, with peak wave conditions during 22 individual storm events exceeding the 1% exceedence significant wave height of 5.9 m. Four of these Atlantic storms stood out in terms of their coastal impacts: 03/01/2014, 06/01/2014 ('Hercules'), 05/02/2014 ('Petra') and 14/02/2014 ('St Valentine's Day'). None of the storms that occurred over the 2013/2014 winter were particularly exceptional in terms of their wave heights. The 06/01/2014 storm was probably the most unusual because of the exceptionally long peak wave periods ($T_p > 20$ s) and the Met Office (2014) note that the combination of significant wave height and peak period is likely to mark out this storm as a one in 5–10 year event in the SW of England, based on experience of waves over the last 30 years. The 06/01/2014 storm is also the event that caused most widespread damage on the south Atlantic coast of France (Castelle *et al.*, 2015).

The key statistics for the 22 Atlantic storms are summarised in Table II, including the offshore wave conditions at Sevenstones Lightship, and the inshore wave conditions and the maximum high tide (HT) levels during the storm peak at various locations along the SW coast of England. Correlating the various storm parameters provides some insights into why certain storms had greater impacts than others. The 03/01/2013 storm was characterised by the highest water levels during the peak of the storm along the entire SW coast of England; the 06/01/2014 storm was unique because of its extremely long wave period; the 05/02/2014 storm was characterised by the second-most energetic wave conditions on the south coast, spring tide conditions and gale force southerly winds; and the 14/02/2014 storm had the largest waves along the south coast, as well as one of the highest high tide levels and gale force southerly winds. It is interesting to note that the three storms with the most energetic offshore wave conditions (01/02/2014, 08/02/2014 and 28/02/2014) and the two storms with the longest offshore storm duration (24/12/2013 and 26/01/2014) did not stand out in terms of coastal impacts; the principal reason is that the peaks of these storms did not coincide with extreme high tide levels. In addition, the inshore wave conditions are not linearly correlated to the offshore wave conditions. Especially on the south coast, the inshore wave conditions are strongly dependent on the storm tracks. The 02/05/2013 and 14/02/2014 storms were characterised by much more energetic inshore wave conditions on the south coast than the 06/01/2014 storm (Figure 4; Tables I and II), despite significantly less energetic offshore wave conditions (Figure 1); this is directly ascribed to the more southerly storm track of the February storms (Figure 5), enabling large waves to propagate up Channel relatively unimpeded. The role of gale force southerly winds during these two February storms must also be considered – these winds would have generated their own waves superimposed on the Atlantic swell waves.

Regional analysis of extreme storm response using beach profile data from 244 cross-shore transects measured on 39 beaches in the SW of England, supplemented with airborne LiDAR survey data, highlights the importance of site-specific conditions for determining the coastal storm impacts. As such, the response to storm impacts along the SW coast of England showed significantly more variability than along the 110 km Gironde coast of France where the coastal response (dune and beach erosion) was largely uniform along the coast, with

Table II. Summary of the storm statistics during 2013/2014 winter. For each storm characteristic (column), the three highest values are bolded and underlined

	Sevenstones lightship				Maximum high tide level during storm				Bideford wave buoy		Start Bay wave buoy	
Strom number	Date and time of peak of storm at	Peak H_s (m)	Mean H_s (m)	Duration (h)	Maximum HT Ilfracombe (m ODN)	Maximum HT Newlyn (m ODN)	Maximum HT Devonport (m ODN)	Maximum HT Weymouth (m ODN)	Peak H_s (m)	Peak T_p (s)	Peak H_s (m)	Peak T_p (s)
1	27/10/2013 13:00	7.4	6.1	32	2.37	1.47	1.61	1.09	4.47	12.6	2.84	9.6
2	02/11/2013 16:00	7.3	5.7	18	4.70	2.54	2.45	1.51	5.58	14.0	1.82	10.0
3	14/12/2013 18:00	6.9	5.8	17	3.75	2.02	1.90	1.00	4.53	12.2	2.51	9.2
4	19/12/2013 05:00	7.1	5.4	23	4.68	2.65	2.65	1.60	4.10	12.9	3.37	8.0
5	20/12/2013 08:00	6.3	5.2	24	4.14	2.36	2.22	1.27	4.23	11.8	2.37	9.6
6	21/12/2013 19:00	7.4	5.7	31	3.84	2.21	2.17	1.27	4.17	11.8	2.16	9.8
7	24/12/2013 19:00	8.8	6.1	**56**	4.05	2.42	2.42	1.44	4.66	11.5	**3.61**	**12.2**
8	27/12/2013 08:00	8.9	6.3	25	2.93	1.76	1.69	1.07	5.79	13.6	2.59	8.3
9	01/01/2014 15:00	6.3	5.5	28	5.00	2.97	2.76	1.66	4.60	14.3	2.85	7.7
10	03/01/2014 17:00[a]	8.2	6.3	30	**5.70**	**3.27**	**3.11**	**2.02**	4.98	14.4	2.89	11.5
11[1]	06/01/2014 10:00[b]	9.1	6.3	**39**	5.04	2.97	2.84	1.62	4.83	**18.2**	2.72	11.5
12	26/01/2014 21:00	7.6	6.4	**47**	3.52	1.95	1.85	1.02	4.92	12.2	1.49	10.3
13[2]	01/02/2014 15:00	**10.6**	**6.9**	30	**5.57**	**3.13**	2.98	1.75	**5.64**	12.9	2.09	10.3
14	03/02/2014 11:00	7.6	5.5	10	**5.60**	**3.39**	**3.15**	**1.93**	2.94	12.2	3.10	8.3
15[3]	05/02/2014 17:00[c]	8.2	6.4	35	4.79	2.96	2.93	1.91	5.63	14.9	**4.62**	9.6
16[4]	08/02/2014 10:00	**10.5**	**8.2**	38	2.80	1.70	1.71	1.06	**5.92**	14.6	2.82	**12.5**
17	12/02/2014 19:00	8.4	6.1	32	3.67	2.16	2.03	1.21	**5.78**	13.8	3.15	9.1
18[5]	14/02/2014 19:00[d]	8.7	**6.7**	21	4.82	3.03	**3.08**	**2.00**	4.67	11.5	**4.99**	**13.8**
19	25/02/2014 13:00	7.1	5.4	19	3.12	na	1.68	0.81	4.50	13.8	1.75	10.3
20	28/02/2014 04:00	**9.4**	6.4	19	4.39	2.66	2.64	1.63	4.88	12.6	1.90	11.2
21	03/03/2014 18:00	7.1	6	23	5.47	3.22	3.07	1.86	4.53	**17.7**	1.94	11.2
22	25/03/2014 00:00	6.1	5.1	10	2.67	1.64	1.57	0.79	4.16	**15.5**	1.49	6.9

Storm names: [1]Hercules; [2]Brigid; [3]Petra; [4]Ruth; [5]Valentine's Day.

[a] Coastal flooding in north and south Devon.

[b] Extensive beach and dune erosion, damage to coastal infrastructure and coastal flooding in north and south Cornwall.

[c] Extensive beach erosion, damage to coastal infrastructure and coastal flooding in south Devon and south Cornwall.

[d] Further damage to coastal infrastructure and localised beach erosion and coastal flooding in south Devon.

some minor alongshore variations related to the subtidal bar morphology (Castelle *et al.*, 2015). The considerable spatial variability in storm response along the SW coast of England is attributed to the embayed nature of the coastline and the associated variability in coastal orientation. The inherited geology therefore plays a very significant role in determining the storm dynamics (Short, 2010).

It is generally assumed that beach stability is related to the beach morphodynamic state, and that flatter dissipative beaches are more stable than steeper reflective beaches (Wright and Short, 1984; Qi *et al.*, 2010; Rangel-Buitrago and Anfuso, 2011). This generalisation does not apply to the present data set which shows large sediment losses during the 2013/2014 winter that are similar for low gradient (intertidal $\tan\beta < 0.02$) dissipative beaches (e.g. Bude, Newquay, Perranporth) and steep (intertidal $\tan\beta > 0.1$) reflective beaches (e.g. Slapton Sands and Chesil). The difference here is that the sediment losses are achieved across a > 400 m wide intertidal zone on the dissipative beaches (representing an average beach lowering of *c.* 0.3 m), whereas on the reflective beaches the sediment is removed from a zone < 100 m wide (representing an average beach lowering of *c.* 2 m; *cf.* Poate *et al.*, 2015). Thus, the storm impacts on the reflective beaches were more noticeable, but not necessarily more significant. There is also an interesting disjoint between coastal impacts as reported in the media (evidenced by damage to coastal infrastructure and coastal flooding), and in the form of beach erosion. The storms of 06/01/2014 and 05/02/2014 are considered to have had the most impact along the north and south coast, respectively; however, neither of these storms was associated with the largest beach sediment losses (Figure 9).

The beaches along the north coast of SW England lost a large amount of supra- and intertidal sediment to the offshore with many cross-shore transects losing more than 100 m^3 per unit meter beach width. On many beaches, the removal of sediment exposed a rocky shore platform (Figure 7(a)), testifying that it is not uncommon that beaches consist of only a relatively thin veneer of sediment (<1–2 m; Scott *et al.*, 2008) and conform to the geologically semi-constrained beaches defined by Jackson and Cooper (2009). A few north coast beaches gained sediment as a result of the storms, notably beaches whose alignment deviated significantly from the general SW-NE orientation of the north coast. The best example of this occurred on the beaches around St Ives, which are situated along a large northwest-to-northeast facing bay. The northwest-facing beaches (and dunes) in the northern and most exposed part of the bay suffered significant sediment losses, while the northeast-facing beaches in the southern and more sheltered part experienced an increase in the intertidal sediment volume. So, the storm response on north coast beaches was overwhelmingly offshore sediment transport with some locations exhibiting redistribution of sediment related to shoreline orientation. The sediment eroded from the beach was mainly deposited in large subtidal bar systems, located at a depth of 6–8 m below mean sea level (Masselink *et al.*, 2014). Subtidal bathymetric surveys on Perranporth indicate that the bar is migrating onshore and that sediment is returned to the beach; by the end of the summer of 2014, the beach had recovered by 50% (Scott *et al.*, submitted).

The storm response of the beaches along the south coast of SW England was less longshore-uniform than along the north coast, alluding to the importance of longshore sediment transport processes. As the Atlantic storm waves propagate up the

Channel and into the south coast embayments, their wave direction changes from westerly to southerly; therefore, they tend to strike the prevailing SW-NE beaches on the south coast at a large oblique angle (Figure 2 – right panel). Two exceptions are Porthleven and Chesil, which are southwest-facing and where the wave approach tends to be short-parallel (Figure 2 – left panel). The large incident wave angle along most of the south coast beaches generated strong littoral drift from west to east (or southwest to north east, depending on shoreline orientation). On many south coast beaches, this alongshore sediment redistribution resulted in rotation, with the western part of the beaches narrowing and the eastern part widening (Figure 7(c)). Such a response was previously observed on Slapton Sands in south Devon as a result of extended periods of southerly wave conditions (Ruiz de Alegria-Arzaburu and Masselink, 2010); coastal structures (breakwaters and groynes) seem to accentuate this behaviour (Figure 7(b)). On many south coast beaches, the erosional losses exceeded the accretionary gains, and it is likely that in addition to alongshore sediment distribution within the same beach system, offshore sediment transport and headland bypassing also occurred during the storms. Monthly beach surveys on Slapton Sands indicate that there has been no post-storm beach recovery (Scott *et al*., submitted).

The sequence of storms experienced during the 2013/2014 winter can be used to address the role of antecedent wave conditions in storm response. Splinter *et al*. (2014) used the XBeach numerical model to hindcast the cumulative erosion impact of a sequence of historical storms that affected the Gold Coast, Australia, and found that the individual storm volumes were influenced by the antecedent state of the beach (i.e. prior cumulative erosion), but that the sequence of the storms did not significantly affect the total eroded volumes. Coco *et al*. (2013) argued that beach response to the first storm of the season is likely to be more pronounced than changes caused by subsequent events. On the other hand, Castelle *et al*. (2007) documented a case whereby the offshore bar migration during the first storm left the beach relatively unprotected and caused disproportional beach erosion during subsequent storms of less intensity. Investigating the role of antecedent conditions yields conflicting results for the Perranporth and Slapton Sands storm response time series (Figure 9). On Perranporth, the erosive response is muted at the start of the 2013/2014 winter sequence and is most pronounced at the end of the sequence of storms (February to March). This is similar to that observed by Castelle *et al*. (2007) and may be related to the relatively deep and seaward position of the subtidal bar system (Scott *et al*., submitted), leaving the beach more exposed to the storms that occurred later in the winter season. On Slapton Sands, on the other hand, most of the storm response occurs during the first half of the 2013/2014 winter. Despite the fact that the most energetic wave conditions were experienced during February, beach sediment losses were limited, suggesting, perhaps, that the beach was approaching a high-energy equilibrium state. One caveat, however, is that on Slapton Sands the response to the two most energetic storms (05/02/2014 and 14/02/2014) was barrier overwash. This process could have been enhanced by the 'denuded' state of the beach, while at the same time such storm response may limit beach sediment losses, because the mobilised sediment is retained within the beach system through the washover deposit.

It has been proposed that beaches that are attuned to high-energy wave conditions may be relatively insensitive to all but the most extreme storm waves (Cooper *et al*., 2004). None of the storms experienced during the 2013/2014 winter were exceptionally rare in terms of their wave heights; however, the storm impacts along the relatively high energy north coast of Cornwall and Devon were very significant. Using a combination of beach surveys and XBeach numerical modelling, Karunarathna *et al*. (2014), demonstrated that storm-induced beach erosion resulting from a cluster of storms is much higher than that due to a single storm with wave power that is equivalent to the wave power of the storm cluster. The persistently extreme wave energy level, and the limited time for post-storm beach recovery, during the 2013/2014 winter is the likely reason for the extreme coastal impacts recorded along the SW coast of England over this period.

The analysis of the rich extreme storm response dataset described in the paper is ongoing. Scott *et al*. (submitted) places the observations in a longer-term context and addresses the post-storm recovery of the beaches. Burvingt *et al*. (in prep) discusses a geo-statistical analysis of the pre- and post-storm LiDAR data set consisting of *c*. 150 individual beaches, while Masselink *et al*. (in prep) conducts an inter-site comparison of the storm response using data sets from UK and France. The novel insights into the Atlantic storm response along the SW coast of England presented in this paper, and future work, have been facilitated by the extensive regional monitoring that takes place, both in terms of hydrodynamic forcing and morphological response. Especially along such a varied coastline, such a regional approach is vital for increasing our understanding of extreme storm impacts and providing data for numerical modelling.

Conclusions

1. The southwest (SW) coast of England was subjected to an unusually energetic sequence of storms during the 2013/2014 winter, with peak wave conditions exceeding the 1% exceedence significant wave height of 5.9 m for 22 separate storm events. The 8-week period from mid-December 2013 to mid-February 2014 was the most energetic wave period since at least 1953.
2. The storm events with the most energetic offshore storm conditions did not have the largest impacts in terms of beach and dune erosion, coastal flooding and damage to coastal infrastructure. The storm events that did stand out in terms of their coastal impacts were characterised by the most energetic inshore wave conditions and the concurrence of the peak of the storm with extreme high tide levels.
3. The inshore wave conditions on the north coast are reasonably well described by the offshore wave conditions off the tip of SW England with a *c*. 60% wave height reduction. The correlation between offshore and inshore wave conditions on the south coast is much less straightforward and is strongly controlled by the storm track. A relatively southerly storm track, with the storm tracking across Ireland rather than tracking to the north of Ireland, enables storm waves to propagate up the English Channel relatively unimpeded, generating the most energetic inshore wave conditions along the south coast.
4. A regional analysis of the geomorphic response of 39 beaches on the SW coast of England highlights the importance of site-specific conditions for determining the coastal storm impacts. The considerable spatial variability in storm response along the SW coast of England is attributed to the embayed nature of the coastline and the associated variability in coastal orientation.
5. The response on practically all north coast beaches to the westerly storm waves was offshore sediment transport due to the prevailing shore-parallel wave approach. Many north coast beaches experienced extensive beach and dune erosion, and some of the beaches were completely stripped of sediment, exposing a rocky shore platform.

6. On many south coast beaches, the combination of southerly inshore storm waves and SW-NE oriented beaches resulted in large incident wave angles and strong eastward littoral drift. As a result many south coast beaches exhibited rotation, with the western part of the beaches eroding and the eastern part accreting.
7. Novel insights into the Atlantic storm response along the SW coast of England have been facilitated by the extensive regional monitoring that takes place, both in terms of hydrodynamic forcing and morphological response; such regional approach is vital for increasing our understanding of extreme storm impacts and providing data for numerical modelling.

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