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THE ROLE OF MULTI-DECADAL CLIMATE VARIABILITY IN CONTROLLING COASTAL DYNAMICS: RE-INTERPRETATION OF THE 'LOST VILLAGE OF HALLSANDS'

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Abstract

The 'Lost Village of Hallsands' refers to the inundation by the sea and subsequent destruction of a small fishing village in Start Bay, Devon (UK) in 1917. The generally accepted cause was the artificial removal of a large amount of gravel from the beach in front of the village. More recently, a decade of coastal monitoring of the beaches in Start Bay, including Hallsands, and analysis of the inshore wave conditions has highlighted the bi-directional wave climate in the bay and its control on littoral drift. The two dominant wave directions, southerly and easterly, drive opposing longshore sediment transport and initiate beach rotation over a variety of temporal scales, ranging from event-scale to multi-decadal. Beach rotation over the longer time scales is correlated with the winter North Atlantic Oscillation (NAO) index. Here, we propose that the demise of the village of Hallsands was significantly exacerbated, if not caused, by multi-decadal fluctuations in NAO. Specifically, an extended phase of positive NAO from 1900 to 1930 would have caused a reduction in the winter-averaged contribution of high-energy easterly wind waves at Start Bay, driving northward dominated sediment transport and a clockwise beach rotation. This in turn would have led to a narrowing of the beaches in the southern part of Start Bay, including the beach in front of Hallsands village, and a widening of those beaches in the north. The narrow beach in front of Hallsands would have left the village unprotected from the easterly storm waves that destroyed the village. Rotational responses have been recorded at other comparable beaches around the UK and beyond, and the atmospheric drivers identified here have wide ranging implications for coastal erosion and flood defense, as well as coastal zone management and planning.

Key words: beach rotation, sediment transport, morphodynamics, erosion, atmospheric variability, coasts and climate

1. Introduction

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 be strongly affected by large-scale shifts in patterns of atmospheric and oceanic variability. Similar to the El Nino Southern Oscillation (ENSO) in the Pacific (Barnard et al., 2016), the winter-averaged North Atlantic Oscillation (NAO) has been shown to explain multi-annual change in beach morphology (nearshore bar configuration) at an exposed sandy beach located in South West England (Masselink et al., 2014).

Studies of the morphological response to storms at a mixture of different beaches in the south west of England have identified a split response based on shoreline orientation and beach type (Masselink et al., 2015, Scott et al., 2016). Where incident storm waves were shore normal to exposed sandy beaches, significant levels of cross-shore sediment transport were observed, with material deposited either as nearshore bars, or potentially beyond onto the inner shelf through the formation of mega rips (Short, 2010). Conversely, embayed beaches orientated at oblique angles to incident storm waves experienced a significant longshore response, with sediment transported in the same direction as wave approach, resulting in erosion and narrowing of the beach face at the up-wave extent, and accretion and widening of the beach face at the down-wave extent. This variation in longshore sediment distribution from one end to another is known as "rotation" (Klein et al., 2002). Beach rotation as a phenomenon has been observed worldwide and its driving mechanisms may be varied. It has classically been attributed to oblique incident wave angles driving sediment alongshore (Short and Masselink, 1999); however, further studies have suggested that variations in alongshore gradients in wave energy result in increased or decreased cross-shore sediment exchange, leading to an out of phase erosion and accretion at embayment extremities. When measured, this response manifests itself as a similar rotational observation (Harley et al., 2011). Regardless of the dominant mechanism by

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which rotation is caused, wave height along shore, and incident wave direction can both be altered by embayment alignment and curvature, refraction and shadowing from headlands and islands (Thomas et al., 2011) and the presence of offshore sand or mud banks (Dolphin et al., 2011).

Along the south coast of England, the storm track is a key factor in controlling both wave height and direction. Masselink et al. (2015) observed that storm tracks with low pressure centers following a more southerly trajectory, allowed waves to propagate up the English Channel unimpeded, resulting in larger inshore wave heights along the south coast than comparatively more energetic storms that tracked further north. These westerly Atlantic storm waves are obliquely incident at many south-facing Channel beaches, accentuating wave littoral drift to the east.

Scott et al. (2016) identified that although alongshore response within many embayed beaches showed patterns of rotation, overall net sediment change was negative within intertidal zones, indicating a loss of sediment through either cross-shore processes (offshore transport and/or barrier over wash), or between sub-embayment's via subaqueous headland bypassing (Ojeda and Guillén, 2008). Although rotational redistribution of beach sediment may only result in a small residual change in overall sediment budget at a particular site, spatial variation in beach volume, in addition to profile height and shape, can still present increased risk of erosion, coastal flooding and damage to infrastructure. It is important therefore, to not only quantify and record a change in beach width or sediment volume, but to also predict and understand the key drivers of these events, as well as assess their likelihood over longer temporal and wider spatial scales.

In this study, we examine if improved understanding of links between decadal atmospheric variability, winter wave climate and beach morphological response to storms can help to provide new insights into past geomorphological change at a semi-sheltered gravel barrier beach in the south west of England. Specifically, we examine the famous historic account of a series of events that led to the storm destruction of a small fishing village called Hallsands, located in Start Bay along the South Devon coast, on the 26th January 1917. The generally accepted cause of the loss of the village is attributed solely to the removal of gravel (by human intervention) from the coastal zone, for which there is some quantitative evidence (May and Hansom, 2003). We investigate long-term morphological control exerted by local wave climate forcing and assess the extent to which the role of large-scale atmospheric variability may help explain multi-decadal morphological change in Start Bay, including its contribution to the fate of the 'Lost Village of Hallsands'.

To enable assessment of multi-decadal controls on beach dynamics, a number of datasets were analysed: (1) a decade of intra-annual RTK-GPS coastal monitoring surveys, collected by Plymouth University (PU) and Plymouth Coastal Observatory (PCO), throughout the beaches in Start Bay (including Hallsands) between 2007-2016 providing a continuous inter-annual record of morphological change; (2) local wave climate records from a directional wave buoy (Slapton Sands; 10 m depth) providing short-to-medium term patterns of morphodynamic response; (3) large-scale climatic variability was examined through relationships between key medium-long-term wave forcing parameters (UK Met Office WaveWatch III 30-yr hindcast waves) and a winter-averaged climate index (NAO); and finally significant variability in decadal climatic controls were examined in context of the 'Lost Village of Hallsands', re-examining the role of multi-decadal climate variability in bi-directional beaches dominated by alongshore sediment transport processes and beach rotation (Scott et al., 2016).

2. Morphodynamic Setting (Contemporary Understanding)

Start Bay is a 12-km long embayment comprised of four interconnected gravel barrier beaches located on the south coast of Devon, UK (Figure 1). The bay is aligned roughly SSW-NNE and the wave climate 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 embayment is meso to macrotidal with neap and spring ranges of 1.8 m and 4.3 m respectively. The bays main beaches are named from the south to north as; Hallsands, Beesands, Slapton Sands and Blackpool Sands. Between each sub-embayment lie rocky outcrops that separate each beach at high tide, trapping laterally moving sediment as it is transported alongshore. Behind the beach face at both Slapton Sands and Beesands,

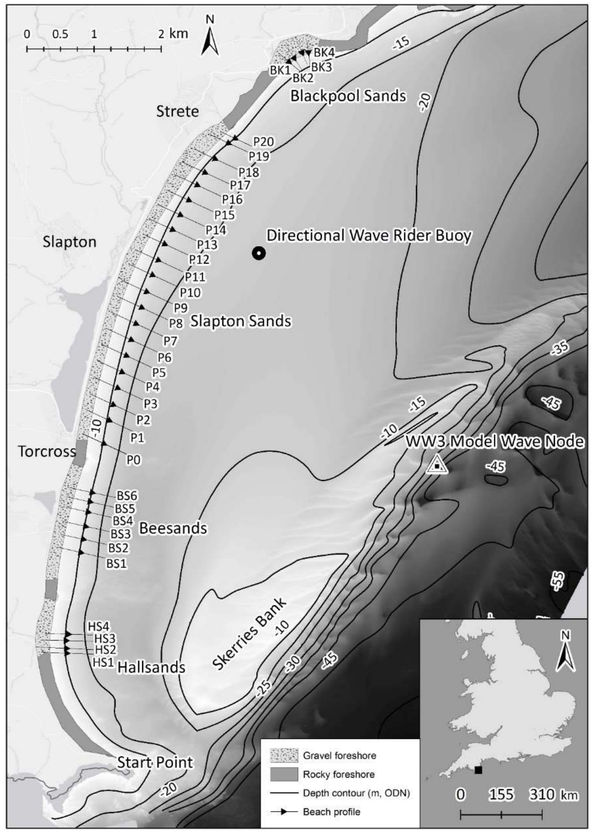

Figure 1. Location map showing Start Bay, South Devon, UK. Nearshore bathymetry from 2013 (UKHO, http://aws2.caris.com/ukho/) and associated contours (m, ODN), highlight the location of Skerries Bank. Survey profile locations for each beach are shown as arrows pointing offshore and are labelled accordingly. The foreshore is identified as either gravel or rock, and the location of the Directional Wave Rider Buoy (PCO, http://southwest.coastalmonitoring.org/), and the WaveWatch III Model Node is shown to the east of Slapton Sands

freshwater is held above mean sea level in two lagoons known as Slapton Ley and Widdecombe Ley. The gravel barrier at Slapton Sands rises to 5–6 m above mean sea level with a steep reflective beach face (tanβ = 0.1) composed of fine gravel (D_{50} = 2–10 mm).

The barrier position has remained relatively stable over the last 3000 years, allowing the sediment (mainly flint) to be reworked by the sea. Within Start Bay, sediment is finer to the east due to the lateral grading of material, with coarser grains transported south west with larger, steeper easterly waves, and finer grains being well sorted and transported north east with smaller but more frequent southerly swells.

South of the bay lies Start Point, a rocky headland offering some shelter from longer period southerly waves. Skerries Bank, an offshore banner bank, sits east of the main beaches in the southern half of the embayment and is -5 m Ordnance Datum Newlyn (ODN) at its shoalest (Hails, 1975a). These two features play a crucial role in modulating the wave climate within Start Bay. Refraction and dissipation of large southerly waves around Start Point means wave energy is reduced through transformation over Skerries Bank, and inshore wave heights are lowered accordingly. During storms, the bank provides some protection from both easterly and southerly waves, dissipating their energy as they pass over the shallow section. This results in a pronounced alongshore gradient in inshore wave conditions, with significant wave heights decreasing from the north to south of the embayment (Ruiz de Alegria-Arzaburu and Masselink, 2010). The impact of Skerries Bank on nearshore wave transformation means quantitative estimation of sediment transport rates cannot be inferred from the offshore wave climate alone, however the bi-directionality of incident waves can be a relative indicator of longshore transport direction.

Maximum water depth between the gravel barrier and Skerries Bank is -15 m ODN, deeper than the estimated depth of closure (-10m ODN). This fact, combined with the distinct difference in sediment type between the four gravel barriers and the sands of Skerries Bank suggests there is no movement of sediment between the two (Hails, 1975b). Furthermore, the entirety of Start Bay is bound by headlands, and the system is considered a closed sediment cell, with no sediment sources except for some confined areas of cliff erosion (Ruiz de Alegria-Arzaburu and Masselink, 2010).

The beaches of Start Bay, particularly Slapton Sands, are similar to many gravel barriers and beaches located along the south coast of England and its morphological response is considered representative of other reflective gravel beaches in storm-affected, fetch-limited channel coast environments. Start Bay as a whole is a well-studied example of an assumed closed sediment cell in which a bi-directional wave climate drives beach rotation under prevailing easterly and southerly storms.

3. The Story of The Lost Village of Hallsands

One of the most well-known coastal erosion case studies in the UK is the loss of Hallsands, which combines human intervention with complex coastal and atmospheric processes, which ultimately led to the demise of a small community. To this day, the definitive cause of the destruction is not fully agreed upon, and whilst the general consensus points to the localized extraction of gravel, the long-term timescales of climatic variability and associated geomorphic response may have played an additional yet equally important role in the events that unfolded.

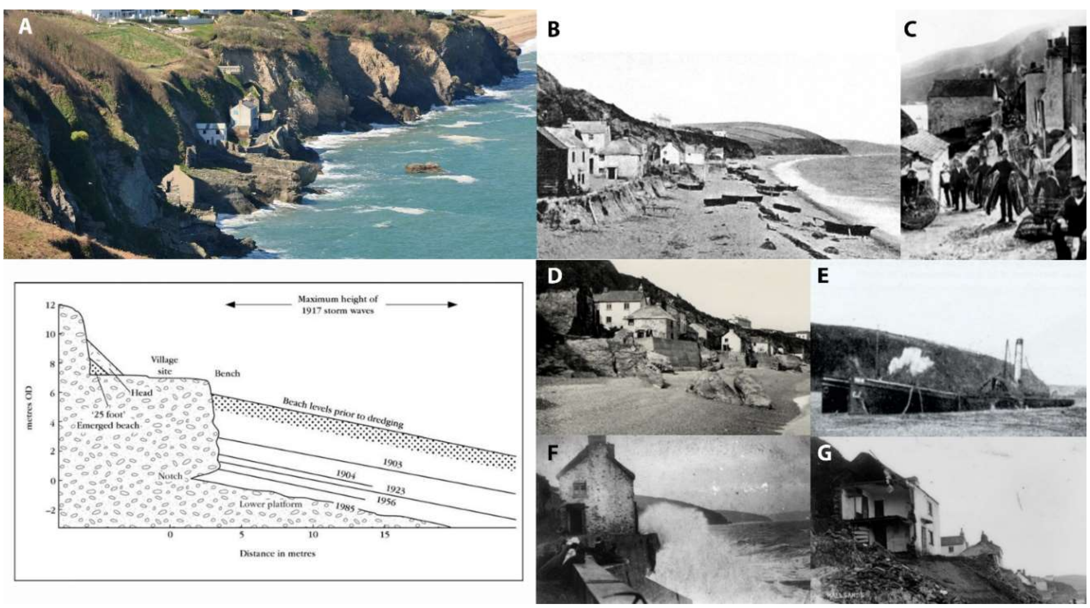

Figure 2. Photographic timeline before and after the loss of village (1894 – 2012). Photos courtesy of Cookworthy Museum, Kingsbridge, Devon. A) 2012, Hallsands, showing the rock platforms where the original houses stood; B) 1894, fishing boats on the beach; C) 1900, the road into the village; D) 1904, lowered beach levels following the commencement of dredging; E) 1898, dredging boats extracting shingle; F) 1901, storm waves reaching the village; G) 1917, and destruction of the village following easterly storms. Lower Left: Cross sectional surveys recorded through the 20th century showing the progressive lowering of the beach (Mottershead, 1986)

In 1897, an extension to the Devonport Dockyard in Plymouth (UK), required significant quantities of sand and other materials for its construction. The local contractor, Sir John Jackson obtained a license from the Board of Trade to commence dredging from the beaches and nearshores of Hallsands and Beesands (May and Hansom, 2003). Between 1897 and 1902 up to 1,600 tonnes was removed daily (Figure 2. D), and the beach face became progressively narrower (Figure 2. C) as dredging continued.

In November 1900, cracks began appearing in some of the houses and the sea wall foundations undermined. Villagers petitioned their member of parliament regarding the damage to their houses, and in the winter of 1900-1901, storms hit the village causing damage to sea walls (Figure 2. E), whilst removing shingle and gravel from gaps in the rock platform behind. The lack of foundations caused buildings to collapse at these points, and thus the dredging license was revoked in 1902 when the beach level had fallen by at least 3 m.

Civil Engineer, R. Hansford Worth (1904), refuted the claim that the beach would be resupplied with sediment from offshore, and conducted a set of beach level surveys in 1904, 1909 and 1923 (Figure 2. Lower Left). Using photographs from before and after the commencement of gravel removal, he estimated that approximately 400,000 m^3 of gravel was taken from Hallsands by the dredging operations of Sir John Jackson (May and Hansom, 2003). Over the 1,100 m stretch of shore face that was designated for extraction, unit volume losses per meter of beach width are therefore calculated at ~364 m^3/m. Worth estimated the level of gravel to have fallen by 6 m, equating to 97% of the former beach volume being lost by the time dredging had ceased (Worth (1904), cited in May and Hansom (2003)); however, the diagram from Mottershead (1986), suggests that the volume losses could have been less than this, and the beach only reached such a heavily depleted state later in the 20th century (Figure 2. Lower Left). Coastal defenses were constructed behind the significantly narrower beach, and proved effective up until January 1917, when a northeasterly gale brought about a storm with reported wave heights allegedly greater than 12 m, crashing into the village during high spring tides. Most of the buildings were destroyed and the village was abandoned (Figure 2. F). At the time of the disaster, locals attributed the cause to the extraction of the gravel. Since then, work by Hails (1975b) has asked the question of whether this claim has ever been scientifically addressed. Further surveys were repeated by Robinson (1961), and concluded the beach had continued to erode to a level lower than ever previously recorded. To the south of the village there are no sediment sources to replenish the beach through longshore transport processes, and the beach at Hallsands has become progressively narrower over the last century (Figure 2. Lower left).

Today, the site of the original village is devoid of almost any beach, and a rock platform is exposed below the shelf on which the remnants of the original houses stand (Figure 2. G). The story of Hallsands' lost village is often cited as an example of anthropogenic interference with a finely balanced system, and the catastrophic effects of exploiting natural resources.

4. Short-Term: Impact of Extreme 2013/14 Winter in Start Bay

During the winter of 2013/14, the south west of England was subjected to numerous, exceptionally high-energy Atlantic Storms, producing the largest recorded wave heights in 60 years (Masselink et al., 2015). Within Start Bay, the most destructive storms occurred on the 04/02/2014 and the 14/02/2014, with significant wave heights recorded at the Start Bay Wave Buoy reaching 4.69 m and 5.25 m respectively. Compared to similar magnitude storms in this period, both storms tracks were south of 50° latitude and resulted in larger waves reaching the south coast. As a result, these two storms were calculated as having wave height return periods greater than 50 years (Siggery and Wiggins, 2014) and caused the most extensive impacts at the beaches of Start Bay. Increased beach erosion was recorded at Hallsands, Beesands and along most the length of Slapton Sands. Significant amounts of gravel over wash onto the road along the barrier at Slapton caused local disruptions, whilst houses were damaged behind the seawall at Torcross. The road at Beesands was completely lost by the end of February 2014 and had to be re-routed.

Due to the southerly nature of these extended storm events, strong northwards transport of sediment at Beesands and Slapton Sands resulted in a pronounced rotational response (Figure 3. Left). Significant sub-aerial erosion was recorded at the southern end of the beaches, whilst accretion was observed at the north, with material collecting against rocky headlands, before potentially bypassing into the next embayment. Mechanisms and pathways for this plausible transport is highlighted in the shore profiles (Figure 3. Right). Erosion and accretion has clearly occurred at respective ends of embayments, extending down into the subtidal extent (< -2 m ODN).

Assessment of inter and subtidal pre and post winter surveys (Wiggins, in prep), has identified that a significant volume of morphological change occurred within Start Bay, of the order of 700,000 m^3, moving from the south to the north of the embayment in the space of four months.

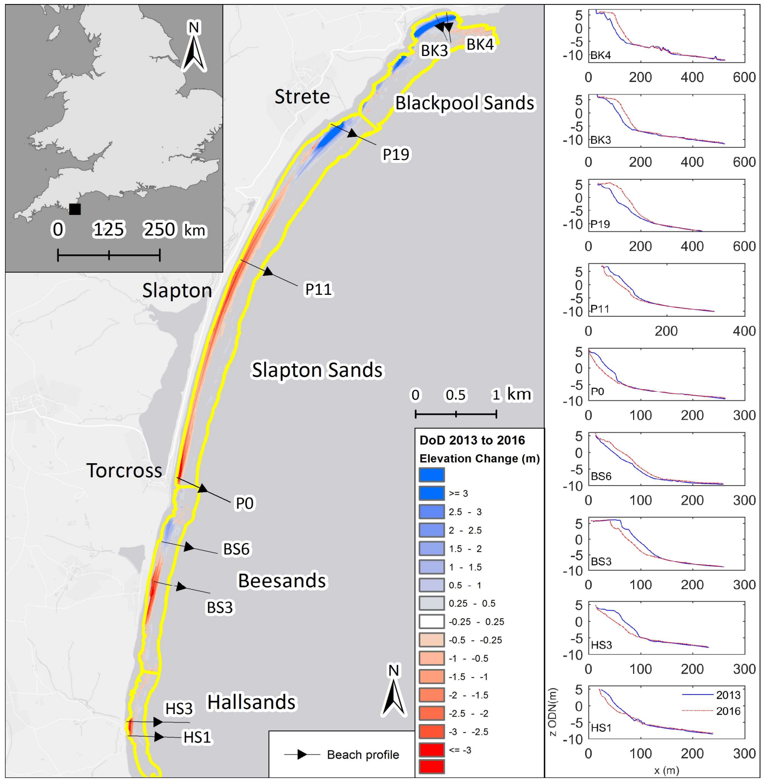

Figure 3. Left: Digital elevation model of difference (DoD) of Start Bay from 2013 to 2016 (Wiggins, in prep), including subaerial and subtidal extents. Right: Subaerial to subtidal profiles extracted from digital elevation models, from 2013 (blue) and 2016 (red)

5. Medium-Term: Multi-Annual Embayment Dynamics

Quasi-quarterly RTK-GPS topographic profiles across the whole of Start Bay (Figure 1) were collected by PCO from 2007 to 2016. Unit volume differences relative to the first survey have been calculated for each profile over this period and results are presented in Figure 4, highlighting the medium-term changes to the beach volume over the last ten years.

The northern embayment at Blackpool Sands, and profiles in the northern extent of Slapton, have gained material steadily since 2007, whilst the central and southern section of Slapton Sands has shown a negative trend in volume difference. The same response is visible at Beesands, with volume losses in the south and gains in the north. The profiles at Hallsands have shown a quasi-stable response, with positive and negative changes to beach volume occurring from 2007 until the stormy winter of 2013/14, after which the beach volume has significantly decreased, and has remained depleted in the years since, with little recovery evidenced by the data.

The significance of the 2013/14 storm response is clear from the volume change plots, as the largest profile volume changes occurred over this period. Profiles in the northern sections of sub-embayments, which accreted during the storms, have generally remained relatively stable, and in some cases have continued to increase in volume. Conversely, profiles in the south have continued to erode and only recently shown small signs of recovery. Further investigation into the wave forcing shows the response of embayments to the bi-directional (easterly and southerly) wave climate of Start Bay. Intertidal beach profiles at Slapton Sands, surveyed monthly by Plymouth University, provide a high frequency record of morphological response within Start Bay's largest sub embayment. Examining the beach volume record for P1 and P18, at the southern and northern extents respectively (Figure 1), an out of phase response is observed between the two profiles (Figure 5).

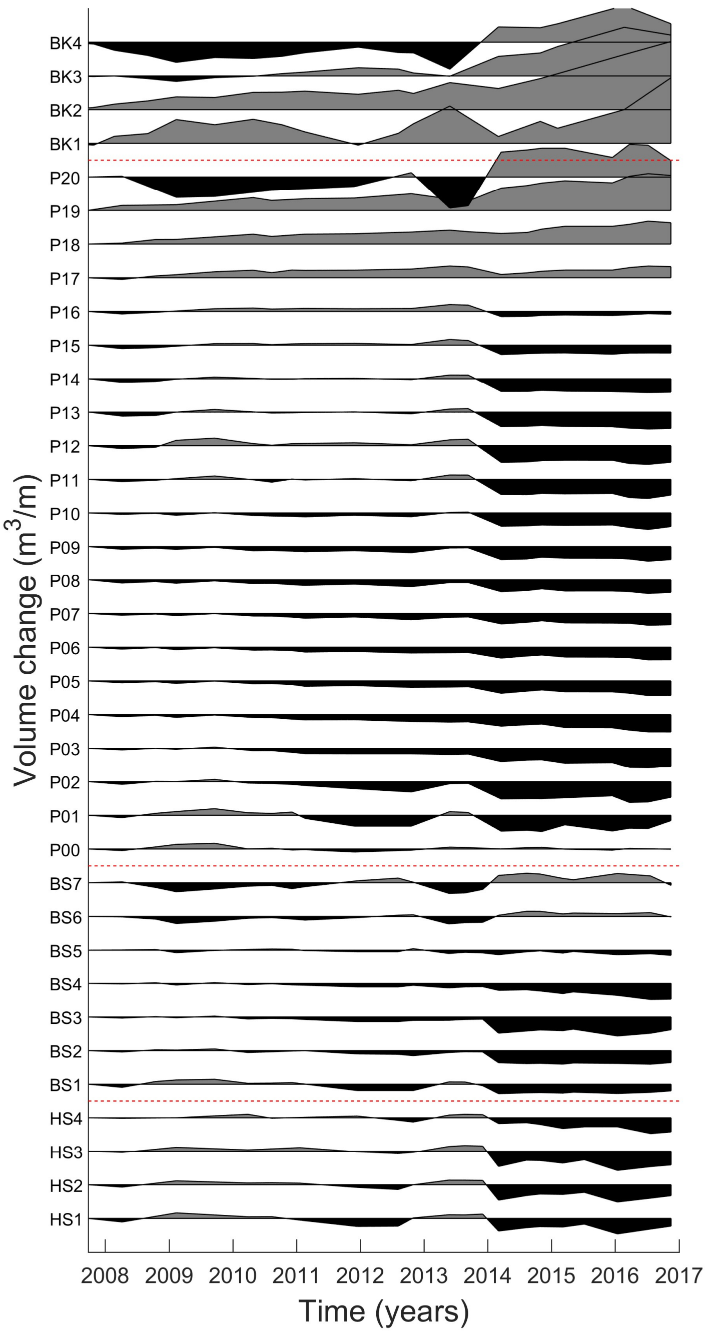

Figure 4. Volume change time series for surveyed profiles Start Bay, collected between 2007 and 2016 by PCO. Profiles are displayed from north to south (top to bottom), with Blackpool Sands at the top of the figure, and Hallsands at the bottom. The red dashed line indicates the separation of sub-embayments by headlands. Volume change at each profile is shown relative to the first survey in 2007, and represents volume change as a unit of beach width (m^3/m). Areas of black below the line indicate periods of negative volume change, whilst the grey areas above the horizontal lines indicate positive change

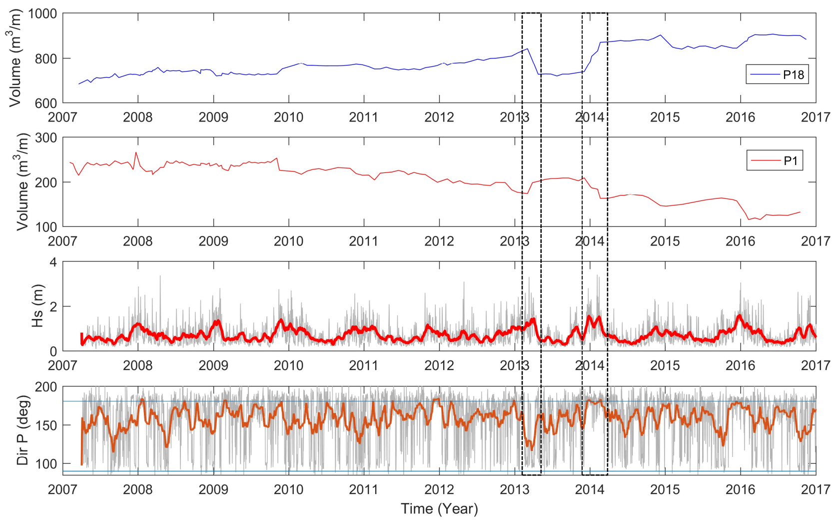

Figure 5. (From top to bottom) Monthly beach volume at Slapton Sands profile 18 since 2007, monthly beach volume at Slapton Sands profile 1 since 2007, significant wave heights (Hs) for the Start Bay wave buoy (one day average in grey, four week average in red), peak direction (Dir P) of waves recorded by the Start Bay wave buoy (one day average in grey, four week average in orange, blue horizontal lines represent 90 degree (east) and 180 degree (south) wave directions. The dashed black boxes highlight the easterly event in early 2013, as well as the southerly storm events of the winter of 2013/2014

Since 2010, P1 beach volumes have been slowly depleting, whilst volumes at P18 have been simultaneously increasing. The changes in direction of littoral drift is apparent when observing the influence of each of the predominant wave directions (southerly and easterly). Under prolonged significant easterly wave events, such as that recorded by the wave buoy at the beginning of 2013 (Figure 5), a reduction in beach volume is observed at P18, whilst a simultaneous increase of volume is recorded at P1, highlighting the longshore transport of sediment to the south (anti-clockwise rotation). After the calm summer of 2013, the significantly energetic winter of 2013/14 demonstrates the strong dominance of southerly wave events. This is matched with a marked decrease and increase in beach volume at P1 and P18 respectively. Since 2013/14, the trend has continued with P1 reaching its lowest volume on record after the winter of 2015/16.

Ultimately, the fate of beach volume, and hence beach width within Start Bay, depends upon the balance and magnitude of easterly and southerly wave events. The current medium-term trend of depleting beach volume in the south and accreting in the north cannot always have been the case, as there are no sediment sources south of Hallsands. The next section explores the potential for atmospheric climate indices to explain the current trends in wave climate and hence the observed beach alignment.

6. Long-Term: Decadal Variability in Forcing

The link between sediment transport within the embayment and the direction of incident waves has been highlighted by the morphological record in both the medium-term and event driven timescales. Short-term clustering of storms from a particular direction have the potential to move significant volumes of sediment, realigning the embayment to the dominant wave direction. Therefore, previous orientations of the coastline may be inferred from models of the long-term wave climate.

Hindcast modelled wave data (WaveWatch III, Met Office) shows changes in the wave climate back to 1980 for a model node located east of Start Bay, shown by the black triangle east of Slapton Sands in Figure 1. The wave rose (Figure 6. Right) clearly shows the bi-directionality of the multi-decadal wave climate from 1980 to 2016, highlighting the dominance of the southwesterly over easterly waves. The south west waves at this location are propagating in the offshore direction from Start Bay, and their characteristics at the near shore are affected by refraction and attenuation from Skerries Bank. Figure 6 (Left) shows the modelled data at the node location for the month of February 2014 (which had the most significant storms of that winter), plotted in conjunction with the waves measured at the Start Bay Directional Wave Rider buoy, located in 10m of water east of Slapton Sands (Figure 1). The top panel of Figure 6 (Left) clearly shows the decrease in significant wave height from offshore to the near shore due to interaction with the bank, and potentially from tidal currents. The peak period of the waves is retained from offshore to nearshore, but the direction changes from south-westerly to southerly (bottom panel) illustrating the impacts of wave transformation and refraction over the Skerries Bank (cf. inshore wave rose in Ruiz de Alegria-Arzaburu and Masselink (2010)).

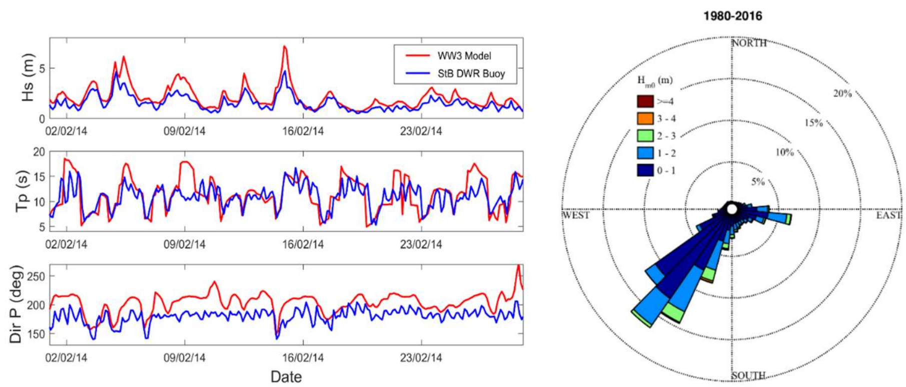

Figure 6. Left: from top to bottom; Significant wave height (Hs), peak period (Tp), peak direction (Dir P) for WaveWatch III Modelled wave data (red), and measured wave buoy data (blue) for the month of February 2014. Right panel: WaveWatch III model node wave rose for the years 1980 – 2016

Using the entire modelled data record, waves are divided into those propagating from the south west quadrant (direction 150°–240°) and those from the east quadrant (direction 60°–150°). For each winter, the total contributions of wave power from these two directions was summed and compared with the total wave power. Since 1980, the long-term trend of the modelled wave data shows a dominance of westerly wave power over easterly (Figure 7). The two most energetic winters were 1990 and 2014, almost solely attributable to south west waves. In all but a few cases (e.g. 1986, 1995), easterly wave power contributes less than 40% of the total winter wave power.

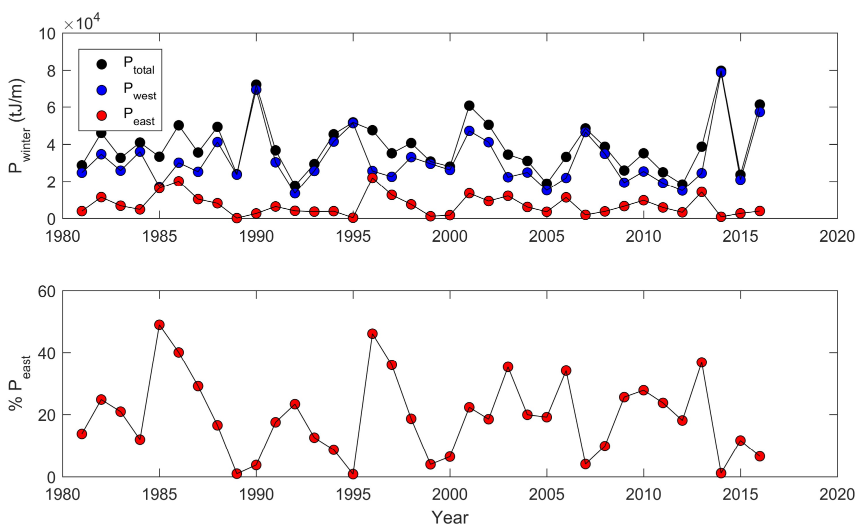

Figure 7. Top: winter (DJFM) wave power total (black), westerly (blue) and easterly (red). Bottom: easterly wave power as a percentage of the total wave power for each winter. Note that data plotted in the lowest panel for, e.g., 2014 includes Dec 2013 and Jan, Feb, Mar 2014

Winter averaged values of NAO are compared with the winter average values for the modelled wave parameters (Figure 8. Upper Left). Winter NAO is significantly and negatively correlated with wave power from the east, both in absolute terms and relative terms (both r = -0.64; p = 0.0000). Winter NAO is only weakly correlated with wave power from the south west quadrant, which can be attributed to the increased northward position of storm tracks during positive NAO winters, however, the larger of the westerly wave events are still associated with a positive winter NAO.

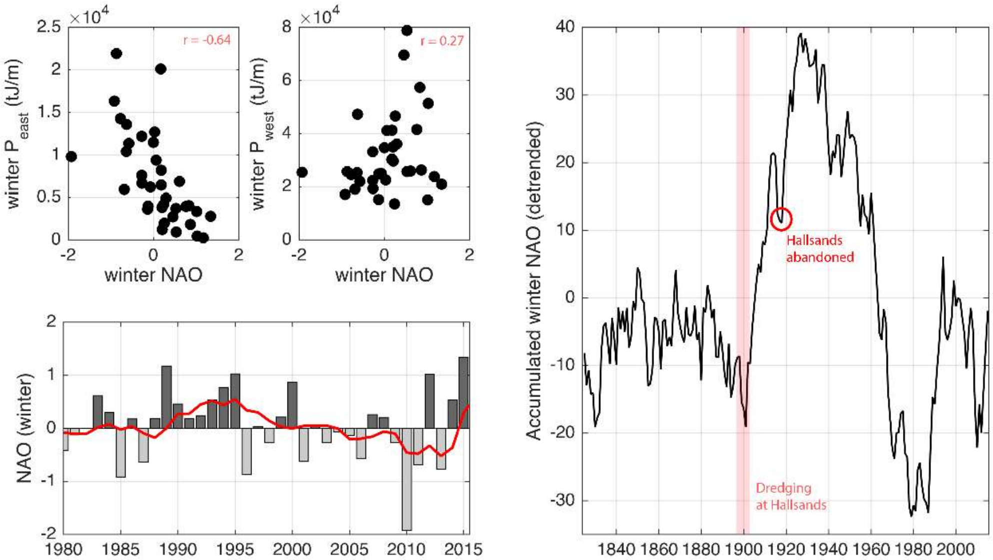

Figure 8. Upper left: Relationships between accumulated winter easterly/westerly directed wave power and winter NAO (1980-2015) (http://www.cpc.ncep.noaa.gov) . Lower left: Winter NAO and 5-yr averaged record (red). Right: long-term time series of detrended accumulated winter NAO (DJFM) annotated with key events (period of dredging and a date of abandonment of Hallsands Village). NAO data were from the Climatic Research Unit, University of East Anglia, web site (www.cru.uea.ac.uk)

Castelle et al. (2017) highlights the influence of the phase of the NAO on the wave and wind climate of the North Atlantic (Figure 9). Positive winter averaged NAO leads to increased significant wave heights and pronounced westerly winds in the northern latitudes of the North Atlantic, whilst negative NAO winters are characterized by a decrease in wave heights and an increase in easterly winds.

The negative correlation between NAO and easterly wave power highlighted in Figure 8, suggests that the NAO can be used as a proxy for the balance of easterly and westerly wave events over decadal and centurial timescales, enabling the estimation of embayment dynamics and coastline alignment based on long-term records of the NAO. The lower left panel of Figure 8 shows the winter NAO index from 1980 to 2015, and highlights the significant reversal from negative to positive NAO from 2013 to 2014, which coincides with the storm driven rotation of Start Bay during that winter. From 1987 to 1995 there was a similar shift towards a persistent positive winter NAO, indicating that sustained phases of a particular winter NAO have been recorded in recent decades. Examining the long-term cumulative detrended time series of winter NAO since 1830 (Figure 8. Right), highlights that prior to the dredging of Hallsands in 1897, the winter NAO index exhibited a relative balance of positive and negative phases. This could have led to a continued period of stability within the embayment, with reversals in littoral drift maintaining the beach volume at Hallsands. Coincidental to the commencement of the dredging, from 1900 onwards, the record shows a positive trend in winter NAO values for almost 30 years, even after the dredging stopped in 1902. The pronounced cumulative dominance of positive NAO winters in this period could have led to sustained southerly wave events, with little to no contribution of easterly events, resulting in the gravel of Start Bay being driven northwards, significantly reducing the volume of the remaining beach in front of Hallsands (supported through available beach level assessment of the time; Figure 2). In 1917, the year of Hallsands destruction, the winter NAO reversed to a significant negative phase, with, in turn, an increased likelihood of high-energy easterly wave events. This coincides with the period where easterly storm waves reached Hallsands with no beach left to stop them.

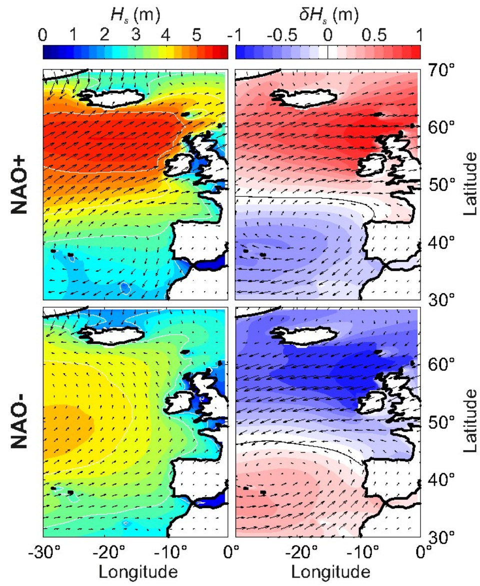

Figure 9. Influence of positive (top) and negative (bottom) NAO on winter averaged Hs (left panels) and corresponding anomaly (right), with 10m surface wind vectors overlaid. Positive and negative phases were addressed by averaging the five winters with the largest and smallest index values from 1950-2016. By order of decreasing importance, the five winter years considered for each index phase are NAO+ (2015, 1989, 1995, 2012, and 2000); NAO− (2010, 1964, 1969, 1963, and 1977), where, for instance, 1977 means the DJFM 1976/1977 winter. Adapted with permission from Castelle et al. (2017)

Discussion and Conclusions

The short and medium-term morphological response of the reflective gravel barriers in Start Bay suggests that the embayment rotates in alignment with the dominant direction of incident waves. Intertidal and sub-tidal volume changes within and between sub-embayments, monitored during a period of extreme storms in 2013/14, provide evidence that quantities of gravel, similar to those reported to have been dredged from Hallsands, are able to be transported readily. This signature is apparent following clusters of storm events (such as those observed in the winter of 2012/13 and 2013/14), and in parallel with a longer term decadal trend of persistent north-dominated littoral drift. The modelled long-term wave climate suggests that a decrease in easterly wave events is correlated with increases in winter NAO. The long-term record shows that dredging at Hallsands occurred at the beginning of an extended positive phase of winter NAO. This would have resulted in a reduced contribution of easterly waves at Start Bay and an increase in westerly-directed storm waves in the north east Atlantic, contributing to the dominance of southerly inshore waves at Start Bay and extended levels of northward littoral drift. This would have left Hallsands further depleted of remaining gravel, and even more vulnerable to the episodic easterly storm waves, which ultimately destroyed the village.

To further understand the dynamics of Start Bay and the Hallsands disaster, a localized nearshore wave climate should be used to drive decadal simulations of shorelines and headland bypassing. Further exploration of other atmospheric indices such as the new West Europe Pressure Anomaly (WEPA) may enable predictions and hindcasts into the impact of southerly storms over the longer term, especially if used with an extended historical morphodynamic record in Start Bay. This could provide evidence that confirms the impact of climate indices on the equilibrium plan shape of the embayment, an approach which could then be replicated at similar sand/gravel embayments that exhibit comparable rotational responses to storm events and bi-modal wave climates.

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