Earth Surf. Dynam., 2, 233–242, 2014
www.earth-surf-dynam.net/2/233/2014/
doi:10.5194/esurf-2-233-2014

Earth Surface Dynamics
Open Access

Coastal vulnerability of a pinned, soft-cliff coastline, II: assessing the influence of sea walls on future morphology

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Received: 15 October 2013 – Published in Earth Surf. Dynam. Discuss.: 26 November 2013
Revised: 3 March 2014 – Accepted: 3 April 2014 – Published: 23 April 2014

Abstract. Coastal defences have long been employed to halt or slow coastal erosion, and their impact on local sediment flux and ecology has been studied in detail through field research and numerical simulation. The non-local impact of a modified sediment flux regime on mesoscale erosion and accretion has received less attention. Morphological changes at this scale due to defending structures can be difficult to quantify or identify with field data. Engineering-scale numerical models, often applied to assess the design of modern defences on local coastal erosion, tend not to cover large stretches of coast and are rarely applied to assess the impact of older structures. We extend previous work to explore the influences of sea walls on the evolution and morphological sensitivity of a pinned, soft-cliff, sandy coastline under a changing wave climate. The Holderness coast of East Yorkshire, UK, is used as a case study to explore model scenarios where the coast is both defended with major sea walls and allowed to evolve naturally were there are no sea defences.

Using a mesoscale numerical coastal evolution model, observed wave-climate data are perturbed linearly to assess the sensitivity of the coastal morphology to changing wave climate for both the defended and undefended scenarios. Comparative analysis of the simulated output suggests that sea walls in the south of the region have a greater impact on sediment flux due to increased sediment availability along this part of the coast. Multiple defence structures, including those separated by several kilometres, were found to interact with each other, producing complex changes in coastal morphology under a changing wave climate. Although spatially and temporally heterogeneous, sea walls generally slowed coastal recession and accumulated sediment on their up-drift side.

1 Introduction

Soft sediment coastlines are highly dynamic environments, where the interaction of sea and land are constantly changing in response to natural and anthropogenic forcing with significant socioeconomic implications (Pendleton, 2010). In an attempt to reduce the loss of property under strongly erosional conditions, it has been general policy in the UK to build solid defences to halt land loss (Scott Wilson, 2009). This approach has been subsequently replaced with the adoption of managed retreat, however, around 44 % of the English and Welsh coastlines remain defended against erosion to some degree (DEFRA, 2010). Coastal defence strategies typically comprise “soft” engineering, usually beach nourishment, or “hard” engineering solutions. The latter consists of building structures designed to directly protect the coastline and fix its position (e.g. sea walls, riprap), encourage beach formation (e.g. groynes, jetties), or reduce the wave energy experienced at the shore (e.g. breakwaters) (Kamphuis, 2000). These structures, often placed on soft sediment coastlines, modify the sediment flux and hence the erosional and depositional processes. In the UK, the majority of sea walls were built during the Victorian era, with little knowledge of the impact on the environment (Brown et al., 2012; Bruun, 1995). More recently, advances in numerical simulation have allowed the impact of the placement of such structures to be assessed in detail with regard to the immediately surrounding area (e.g. Hanson, 1989). The difficulty with these approaches is that there are often non-local impacts to mesoscale morphology (defined as features up to tens of kilometres long, changing at the annual to decadal scale) that are difficult to quantify with field data or the commonly employed engineering-scale models (e.g. Ells and Murray, 2012; Slott et al., 2010). Furthermore, complex, non-linear interactions between multiple defence structures, wave forcing and sediment transport at the mesoscale are difficult to elucidate and quantify using local-scale models and field data.

The local effects of engineered coastal defences on coastline morphology and sediment transport are well known, and have been modelled using one-line modelling approaches (e.g. Hanson, 1989). Typically, whilst such defences may protect the local coast, interruption to longshore transport often causes down-drift increases in coastal erosion (Dean et al., 2013). Barrier structures (groynes and groyne fields) are favoured on coastlines subject to significant littoral drift. They act to reduce the local longshore sediment transport, trapping sediment to protect the beach. Barriers also set up gradients in longshore transport, which result in accretion of sediment on the up-drift side and erosion down-drift due to the loss of protective sediment influx (Kamphuis, 2000; Bruun, 1995; Bakker et al., 1970). Hence, groyne emplacement strategies are best coupled to complementary beach nourishment (Dean et al., 2013). Groynes generate an offshore current and may result in increased loss of sediment to the offshore (Kraus et al., 1994). Eventually natural bypassing will occur as the beach areas between groynes are filled and littoral transport occurs by transport around or over the groynes, or due to groyne permeability. Loss of sediment offshore during storm events may result in the areas between groynes needing to "refill", resulting in potentially significant down-drift erosion.

Sea walls are built in locations where it is desirable to stop coastal erosion and pin the coast. Potential increases in offshore sediment transport may result in a diminished beach fronting a sea wall. This sediment might otherwise contribute to beaches protecting the shoreline down-drift from the seawall structure. In addition, the prevention of erosion due to presence of the sea wall may also reduce the sediment supply to the coastline (Kamphuis, 2000; Kraus and McDougal, 1996).

Relatively few studies have investigated the mesoscale and far-field influence of coastal defences on coastline morphology and sediment transport. Bruun (1995) highlighted that barriers (e.g. groynes) influence local coastline development down-drift, enhancing erosion due to changes in local wave climate by refraction or diffraction. Barriers can also result in a wave of increased erosion propagating down the coastline, potentially over several kilometres, due to the modification of the longshore sediment transport budget. These observations are supported by studies that have modelled mesoscale coastline evolution under conditions of beach nourishment (Ells and Murray, 2012; Slott et al., 2010). The authors found that nourishment at fixed locations not only mediated the coastline locally but can alter the evolution of the coastline tens of kilometres away. Ells and Murray (2012) extend this study to simulate the effects of sea walls on mesoscale coastline evolution. Their findings indicate that protection through either nourishment or hard-structure intervention results in accretion up-drift; that nourishment produces either accretion or erosion down-drift (depending on the surrounding coastline shape); and that hard-structure stabilisation generally causes increased divergent sediment flux down-drift, leading to increased erosion relative to an unprotected coast. Dickson et al. (2007) simulate the influence of climate change on an eroding coastal region at the decadal scale, focussing on the impacts of changing offshore wave height and direction, and the effect of sea level rise. Although not the main focus, the impact of engineered structures was also simulated through comparison of various coastal management and future wave-climate scenarios. The sensitivity of the erosional response to these scenarios, however, was not explored in detail.

In this paper, the influence of seawall structures on the mesoscale evolution of a soft-cliff, sandy coastline is studied through the use of the Coastline Evolution Model (CEM), developed by Ashton, Murray and others (Ashton and Murray, 2006a, b; Valvo et al., 2006; Ashton et al., 2001). Specifically, we focus on understanding the difference between the predicted behaviour of defended and undefended coastline in the face of wave-climate changes anticipated over the coming century. This paper extends the work of Barkwith et al. (2014), which assesses the sensitivity of erosion of an undefended pinned, soft-cliff, sandy coastline under a modified wave climate. The Holderness coastline of East Yorkshire is used as case study to develop a generalised understanding of the evolution of defended, pinned, soft-cliff, sandy coastal systems. The use of the term pinned in this instance refers to the low recession rate at the northern end of the coastline due to the influence of the chalk headland.

2 Holderness coastline

The Holderness coastline formed as the North Sea basin flooded during the Holocene Epoch (Shennan et al., 2000). The study domain is bounded by Flamborough Head in the north, where little sediment is thought to bypass into the littoral cell (Scott Wilson, 2009), and Easington in the south (Fig. 1). Flamborough Head is composed of slowly eroding Cretaceous chalk cliffs ca. 35 m high. The remaining 55 km of coast to the south of Flamborough Head is composed largely of Devensian glacial till and other deposits; these range between 2 and 35 m in thickness, thinning towards the

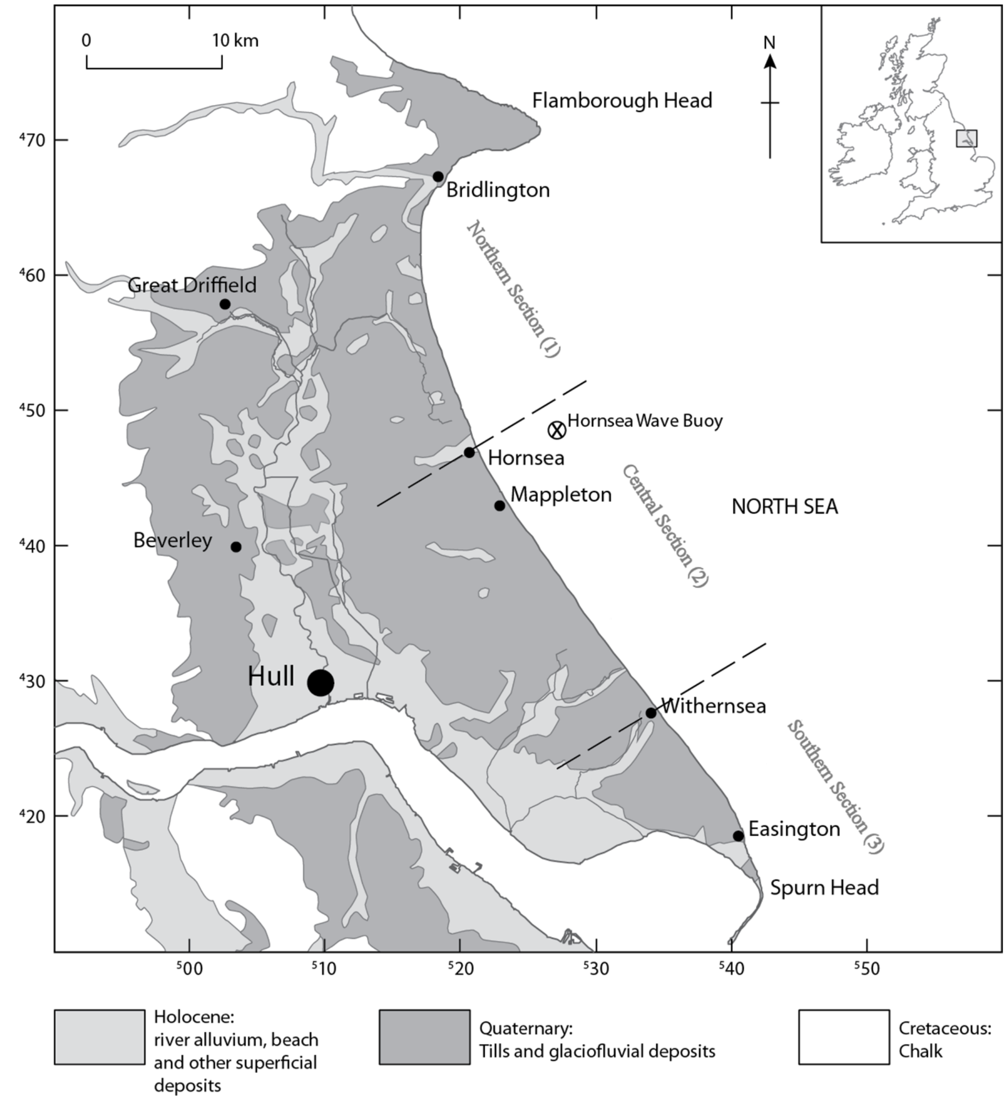

Figure 1. Geological composition of the Holderness coast (main) and the location of the region within the UK (insert). Also indicated are the positions of the Hornsea wave buoy, from which wave climate was recorded, and the division into northern, central and southern coastline regions, as referenced by the sea walls at Hornsea and Withernsea (dashed lines), to aid analysis. Modified from Barkwith et al. (2014).

south (Quinn et al., 2009; Catt, 2007). The glacial cliffs are easily eroded and are thought to be the dominant source of the littoral sand at the coast. Erosion occurs through wave action undercutting the cliff base, causing cliff collapse. The result is a rapidly eroding coastline. Recession rates for the Holderness coast have been documented in recent studies by Montreuil and Bullard (2012), Brown et al. (2012) and Quinn et al. (2009). Average recession rates are on the order of 1–2 $\mathrm{m\,a^{-1}}$, but may be an order of magnitude greater during storm events, or local, large-scale collapses.

There has been a long history of defending the Holderness coastline from erosion (Brown et al., 2012). The earliest chronicled sea defences along this coastline were in place during the Abbacy of Burton between 1396 and 1399 (Burton, 2012). From the 19th century onwards there was a policy of building large-scale sea walls at seaside towns, many popular as tourist destinations. Smaller-scale defence features, including groynes, revetments and rock armour have also been used at various locations along the coastline. Brown et al. (2012) document the changing position of the Holderness coastline cliff top since the mid-19th century, focusing particularly on areas adjacent to coastline defences. They found increased cliff retreat rates for up to several kilometres on the down-drift side of coastal defences, and attributed these to a negative gradient in longshore transport resulting in reduction of the natural beach defence. More recent, the repair of smaller-scale features has ceased, and in some cases, defences have been completely removed, allowing the coast to develop naturally (Brown et al., 2012). However, due to sociopolitical constraints, the removal of the larger sea defences protecting major towns and infrastructure is untenable and maintenance and repair will continue for the foreseeable future.

The offshore wave climate for the Holderness coastline is currently being recorded by the Hornsea Directional Waverider III Buoy (CCO, 2013). Deployed in June 2008, the buoy provides data on significant wave height, period and direction, amongst other parameters. Between 2009 and 2010, the wave input period used for this study, significant wave height varied between 0.2 and 3.5 m, with an annual mean of 0.9 m. The mean wave period for the same period was 7.8 s, ranging from 2.6 to 18.8 s. The dominant mode in wave direction was from the northeast, with a secondary mode from the southeast. There have been several studies that have focussed on the evolution of the North Sea wave climate, with respect to possible future climate change scenarios over the forthcoming century (for example, Sutherland and Wolf, 2002). The range of scenarios used and uncertainty in future storm and North Atlantic Oscillation (NAO) prediction make the North Sea wave climate difficult to predict (Bladé et al., 2012; DEFRA, 2010; Woollings, 2010).

3 Modelling

The model, calibration and setup are the same as those described by Barkwith et al. (2014), but with the addition of sea wall defences, represented by essentially non-eroding coastline. For clarity, model simulations that include sea wall structures in the future simulations are termed “defended” and those without such structures termed “undefended”. A description of the modelling components, calibration procedure and the ensemble approach are contained in this section of the paper. For further details of the modelling procedure, the reader is directed to Barkwith et al. (2014).

3.1 CEM description

A modified version of the CEM (Ashton and Murray, 2006a, b; Valvo et al., 2006; Ashton et al., 2001) is implemented to represent numerically the processes within the coastal domain of interest. The model uses the Coastal Engineering Research Center (CERC) equation (Komar, 1971) to determine long-shore sediment flux. The CEM code has been modified to accept observed wave-climate data and include sediment input from cliff recession (Barkwith et al., 2014; Limber and Murray, 2011). Changes to the coastline position through time are functions of beach geometry and width (Ashton and Murray, 2006a); sea cliff height, lithology and cohesion (Limber et al., 2008); shoreface and offshore wave angles; wave shadowing by protruding coastline features; and wave energy delivered to the shore after attenuation through shoaling and refraction (Adams et al., 2002). Representing the long-term results of relatively short-term processes, the model implicitly averages over short-term events, such as cliff collapses, and over sub-grid scale, spatially random, heterogeneous features. Such features, including heterogeneity in the geological substrate, the presence of fractures and grain size variability, are assumed to be evenly distributed within each cell (Dickson et al., 2004; Trenhaile et al., 1998; Clark and Johnson, 1995). Temporal processes active at frequencies below the scale of the time step in the model, such as tides, are also handled implicitly (List et al., 2006).

Different erosion rates for different lithologies can be specified within the version of the CEM used in this study. We use this facility to define the chalk cliffs at Flamborough Head as highly resistant to erosion. Conversely, the glacial till forming the remainder of the coast is defined as readily erodible, at rates consistent with those known from the Holderness coast. Sea wall defences have a near-zero erosion rate and, at the decadal scale, exhibit a similar erosional response as the chalk headland. Therefore, to avoid unnecessary modification of the code, the sea wall defences are assigned the same erosion potential as the chalk cliffs.

The model is discretised into uniform cells, 100 m in width, and run with a daily time step. Eastern and western domain boundaries consist of a no-flow condition, with a specified condition of zero sediment flux into the model from the north; this explicitly represents the absence of sediment transport around Flamborough Head. The Spurn Head spit, extending off the southern tip of the coast, and Humber estuary are simulated in the model as a sediment store and sink respectively. However, as their interactions and dynamics are complex (see Ciavola, 1997) they are not included in the analysis. Lithological and shoreface properties have been measured at specific locations along the coastline (Newsham et al., 2002). The data are spatially limited and are not representative of the coastline as a whole. Therefore, calibration was required to define these properties within the model before predictive simulations could be undertaken.

3.2 Calibration

Calibrating the model to observational recession data, by modifying the beach and rock properties, allows greater confidence to be placed in the initialisation of future simulation. Cliff erosion provides sediment which is subsequently transported along the coast via longshore drift. Not calibrating the model to observations of coastal retreat may significantly alter the amount of sediment in the system and therefore the system response to a changing wave climate.

Beach and rock properties (notably the erosional resistance and the fraction of fine-grade material in the eroding substrate and beach material) are initialised to be spatially homogenous within the modelling framework. To determine these values we apply a stochastic calibration approach using an ensemble of 2,000 models with varying rock and beach sediment properties. The wave climate for each member comprises 2 years (2009 and 2010) of observed daily significant wave height, angle and period, cycled for the duration of the simulation period.

Each ensemble member is initialised with a 10-year spin-up period, required to reach a dynamic steady state. Dynamic steady state is achieved when the amount of sand being transported along the coastline shows a repeatable response to a particular set of driving factors. Spin-up is undertaken using the 2-year, repeating, recorded wave-climate data and the response to the same events analysed to ascertain whether steady state has been achieved. Sediment transported along the coast is checked for the 8th and 10th year of spin-up for each ensemble member, to establish whether steady state has been attained. Following the spin-up phase, erosion is simulated for a period of 15 years for each ensemble member. This period matches that over which the observed recession rates were compiled by Montreuil and Bullard (2012). The simulated recession rates are compared to observed rates and the ensemble member with the lowest root mean square error (RMSE) is selected to provide the initial properties for the main modelling phase, which is run for the remainder of the current century.

3.3 Simulation setup

An ensemble of modified wave climates consisting of 1350 members drives the future simulations. The ensemble approach allows the sensitivity of coastal erosion to small changes in driving factors to be explored. The technique is suited to studying this stretch of coastline as it is a non-linear system (Barkwith et al., 2014) and the future driving wave climate is uncertain. The background wave climate for each ensemble member is formed from the 2 years (2009 and 2010) of observed daily significant wave height, angle and period, and is cycled for the 90 years of simulation. This wave climate is perturbed for each member by selecting changes at random from ranges of ±20° rotation in offshore wave direction and ±0.4 m in significant wave height. These variations are applied linearly over the 90-year simulation. The defended and undefended coast scenarios use the same set of wave perturbations to allow comparison when assessing the impact of the sea wall defences on the evolution of the Holderness coastline with a changing wave climate. In order to elucidate the evolution of the coastline, baseline simulations are undertaken for the defended and undefended scenarios. Both baselines consist of a single 90-year simulation with no perturbations applied to the cycled, observed wave climate.

Barkwith et al. (2014) conclude that the sensitivity of erosion on the natural coast to changing wave climates is controlled by the current morphology of the Holderness coastline, via changing shoreline angle; the reduction in wave energy in the "shadowed" zone created by Flamborough Head; and the greater availability of beach sediment in the southern region of the model. To aid assessment of the impact of sea defences on erosion rates, the coastline was divided into three sections (Fig. 1) and cumulative erosion rates were averaged spatially for each section. Section 1 extends from Flamborough Head southwards to Hornsea and includes the sea walls at Skipsea and Hornsea. Section 2 starts at the southern end of the Hornsea sea wall and continues to Withernsea, up to and including the sea wall along the town promenade. Section 3 extends from Withernsea south of the defences to Easington, where a long sea wall section protects the Easington Gas Terminal.

4 Results and analysis

Analysis of the results focuses on the patterns and rates of predicted coastline change evident from the inclusion of defences in the simulation. Results are presented and compared for the undefended and defended scenarios. Our analysis initially examines the spatial distribution of absolute and relative erosion along the Holderness coastline for the entire ensemble. By spatially averaging the relative erosion for each ensemble member, and plotting this value against the wave perturbation factors, the influences of rotating the wave climate and changing the wave height are examined. Finally the combined influences of a changing wave direction and height on erosion rates are explored, focussing on the difference between the undefended and defended scenarios.

4.1 Absolute and relative erosion

Absolute erosion over the 90-year simulation period is presented for the baseline (i.e. with no wave-climate modification) undefended and defended scenarios in Fig. 2. Total amounts of erosion appear very similar between these two scenarios away from the locations of sea defences. Reduced erosion is observed in the defended scenario on the up-drift flank of sea walls at Withernsea and Easington. The range of absolute erosion values under the same ensemble of wave perturbations is shown in Fig. 3a (undefended) and Fig. 3b (defended). Positive values represent a landward migration of the coast (i.e. erosion) and negative values land accretion. When compared to the undefended scenario, the sea wall at Skipsea (location included in Fig. 2) in the northern section (1) of the model does not appear to have a significant impact on surrounding recession rates under the differing wave climates. In the central section (2), maximum absolute erosion values are similar in both the defended and undefended scenarios, at ca. 150 m over most of this coastal section. Under clockwise rotation of wave direction and increased significant wave height, absolute erosion can be reduced in the stretches of coast between the sea wall structures, by as much as 100 m, when compared to the baseline simulation. Although the pattern of reduced erosion is spatially heterogeneous, the peaks correspond with the regions of lowest absolute erosion for the undefended scenario. Under the majority of simulated wave climates, the sea walls in the south at Withernsea and Easington (section 3) have less absolute erosion on their up-drift sides. In the southernmost part of section 3 this leads to an overall reduction in erosion

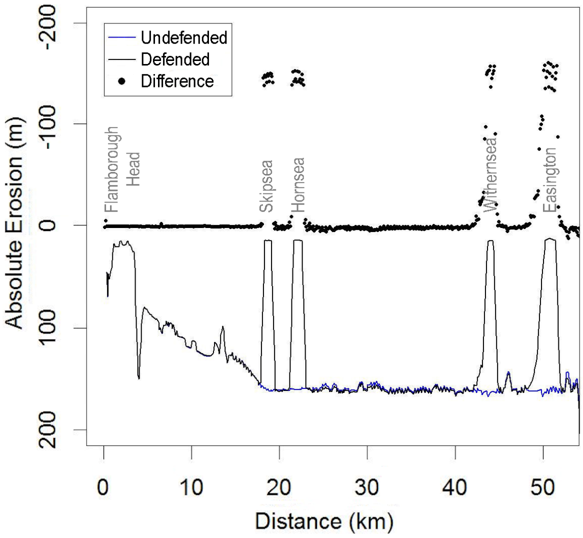

Figure 2. Absolute erosion after 90 years of simulation for the undefended (blue line) and defended (black line) coastlines under the baseline wave climate (2009–2010 repeated cycle). The difference between these scenarios is highlighted by the black points. Flamborough Head and the towns with sea wall defences that are included in the model are labelled in grey text at their respective location on the coastline.

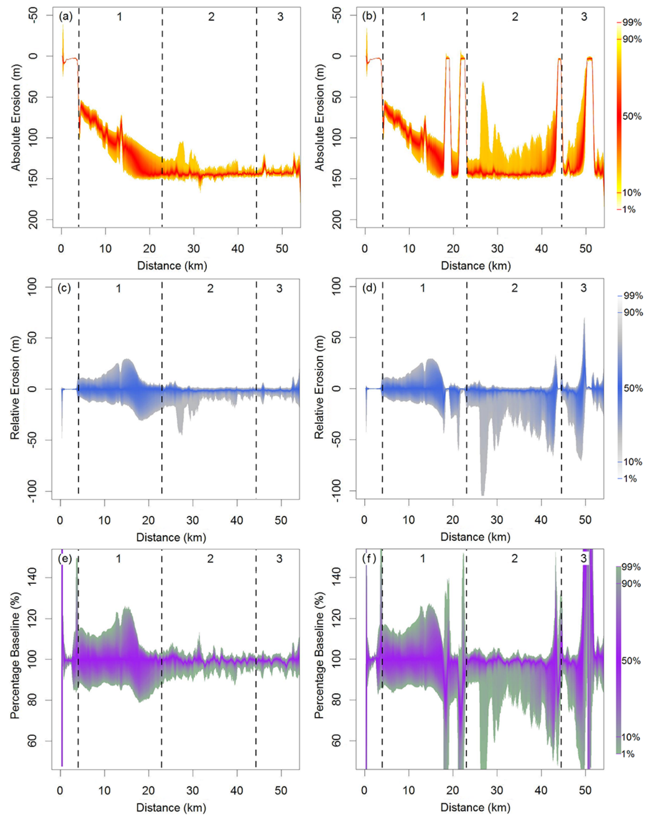

Figure 3. Simulated erosion for the Holderness coastline. Simulated absolute change in coastline position (2010–2100) predicted using an ensemble of future wave climates for undefended **(a)** and defended **(b)** coasts. Relative change in coastline position (relative to baseline simulation) for each member of the ensemble, for the undefended **(c)** and defended **(d)** simulations respectively. Percentage change in erosion relative to the baseline simulation for the undefended **(e)** and defended **(f)** simulations, respectively. The range of colours in each plot represents the ensemble percentiles as given on the right of the figures. The regions 1, 2 and 3 refer to the three coastal sections facilitating along-coast comparison, as defined in the text.

when sea defences are included in the simulation. Relative total (Fig. 3c, d) and percentage (Fig. 3e, f) erosion for the suite of ensemble members, as subtracted from the respective baseline, reflect the spatially heterogeneous recession pattern of the absolute erosion. Although there is a reduction in absolute erosion on the up-drift sides of the sea walls at Withernsea and Easington, the increased and decreased regions of relative erosion suggest that the recession rate is highly dependent on the perturbations of the wave climate. The low erosion rates assigned to sea wall structures during model initialisation cause the extreme values of percentage of baseline erosion at the location of sea wall structures (Fig. 3e, f), where a small change in absolute erosion may nevertheless equate to a large percentage change.

4.2 Wave direction

Spatially averaging the erosion for each ensemble member, relative to baseline erosion, allows the influence of wave-climate perturbations to be compared for both the undefended and defended scenarios. The data presented in Fig. 4 reveal the influence of wave-climate rotation on erosion rate, for the coast as a whole and each of coastal sections 1–3. When considering the coast as a whole, under counterclockwise rotations in wave climate (Fig. 4a), there tends to be a reduction in relative erosion for both the defended and undefended scenarios, with the coastal defences resulting in a lesser response at extremes in rotation.

Under clockwise rotations, there is a marked difference in the erosional response with and without sea defences. The undefended scenario suffers an increase in relative erosion with a clockwise rotation. However, due to the reduction in longshore transport of sediment, the response of the defended coast to the same wave-climate perturbations has an equal chance of also reducing the relative erosion. In section 1 (Fig. 4b) there is a well-defined relationship between the angle of rotation angle and the relative erosion for both scenarios. Differences in response appear at the extremes of wave rotation, where the overall change in erosion rate for the ensemble members is damped by the presence of defended structures. Under a clockwise rotation, erosion relative to the

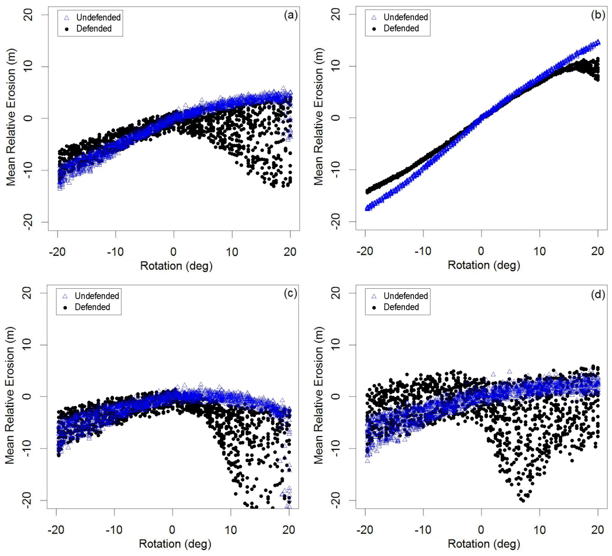

Figure 4. Perturbation in wave direction plotted against spatially averaged mean relative erosion for **(a)** the entire coast, **(b)** the northern section (1), **(c)** the central section (2), **(d)** and the southern section (3). Counterclockwise rotation of wave direction is negative, clockwise rotation is positive. Negative values in mean relative erosion indicate a reduction in coastal erosion in comparison to the baseline simulation.

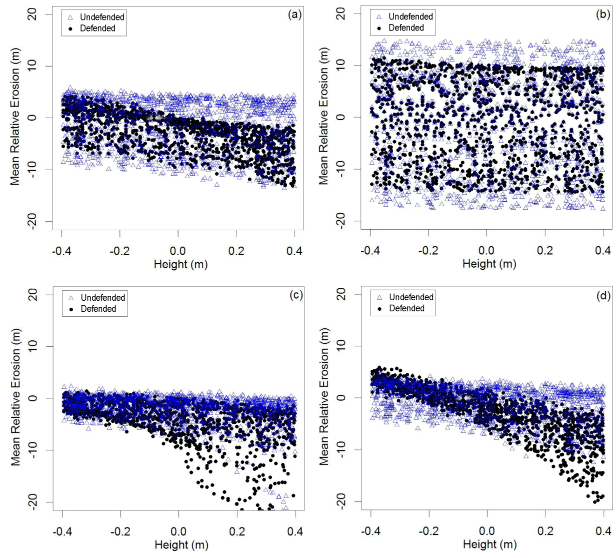

Figure 5. Perturbation in significant wave height plotted against spatially averaged mean relative erosion for **(a)** the entire coast, **(b)** the northern section (1), **(c)** the central section (2), **(d)** and the southern section (3). Negative values in mean relative erosion indicate a reduction in coastal erosion compared to the baseline simulation.

baseline peaks at around 10° and reduces again with further rotation. In section 2, under the defended setup, the relative erosion peak is at a maximum where there is no rotation, reducing rapidly as clockwise rotation is applied (section 2; Fig. 4c). It is under these clockwise rotations where the response differs significantly between the defended and undefended coastlines. The undefended coast exhibits a relatively narrow band of erosional responses, while the defended coast shows considerable variability. In section 3 (Fig. 4d), the undefended response of erosion to rotations in wave direction is similar to the overall trend in erosion. When sea defences are introduced, complex patterns of erosional response merge, with large ranges of increased and decreased erosion rates at all rotations.

4.3 Wave height

For the undefended scenario, the relationship between perturbation in wave height and relative erosion for the whole coast (Fig. 5a) is less well defined than the relationship between rotation of wave direction and erosion (Fig. 4a). The reduction in mean erosion rates with an increase in wave height for the natural scenario was attributed by Barkwith et al. (2014) to increased protection in the southern sector of the coast provided by the increased availability of sediment. With sea defences included, this relationship is intensified, resulting in a stronger inverse relationship between erosion and wave height. This relationship is not so well defined in section 1 (Fig. 5b) and there is little correlation between perturbation in wave height and erosion rate for either the defended or undefended scenarios. In section 1, the lower range in erosion rate results from the influence of rotation of the wave direction. Both sections 2 and 3 (Fig. 5c, d, respectively) show similar patterns manifest in a greater range in erosion rate as significant wave height increases. In section 2, the undefended and defended coastlines respond similarly to change in wave height. In section 3, the relationship between wave height and erosion is increasingly inverse for the defended scenario when compared to the undefended coast. This suggests that the increase in sediment availability affords the coast greater protection from erosion.

4.4 Combined impact

Perturbations in significant wave height and wave direction for the coast as a whole and for each region are plotted for the defended scenario in Fig. 6. The size of the symbols in Fig. 6 is proportional to the relative erosion, compared to the baseline; red indicates increased erosion and open circles indicate reduced erosion. When the coast is considered as a whole, increased erosion occurs when wave height is decreased and the rotation in wave direction is clockwise. However, as with the plots assessing the individual influence of significant wave height and rotation of wave direction (Figs. 4, 5), behaviour averaged along the coast as a whole does not reflect the variations seen in detail for each of the

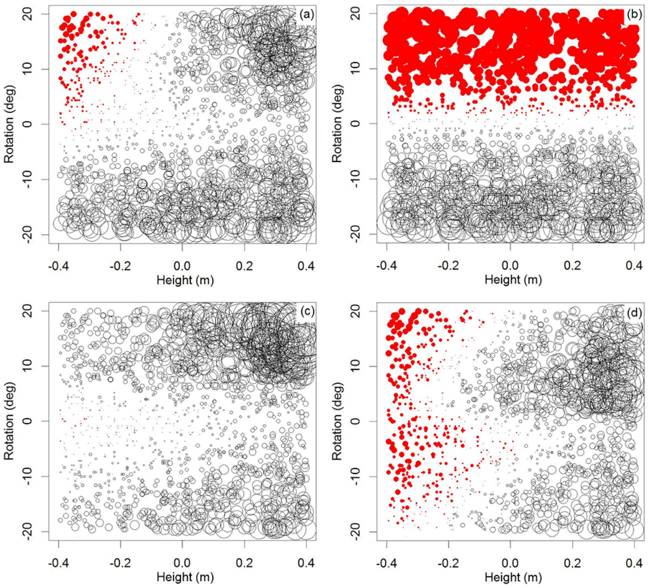

Figure 6. Plots of perturbation in wave direction and significant wave height for each member of the ensemble for **(a)** the entire coast, **(b)** the northern section (1), **(c)** the central section (2), **(d)** and the southern section (3). The size of each symbol is proportional to the change in mean relative erosion rate imparted by that wave climate in comparison to the baseline scenario. Red dots represent increased erosion relative to the baseline and empty circles reduced erosion.

three sections. In section 1, there is no correlation between wave height and erosion. Thus, increased erosion occurs at all significant wave heights under clockwise rotations of the wave direction (Fig. 6b). For section 2, in the centre of the coastline, peak erosion rates occur under the baseline wave climate, perturbations of the wave climate resulting in either similar or reduced erosion rates (Fig. 6c). The most complicated relationships occur in section 3 (Fig. 6d), where the divide between increased and reduced erosion is dependent on the combination of height and rotation perturbations. The near-vertical divide in the results suggests that perturbation of the significant wave height has a slightly greater influence on the erosion rate. There is also a strongly non-linear response to a clockwise rotation in wave direction; even small clockwise rotations cause a significant reduction in relative erosion. This is likely explained by a reduction in longshore transport of sediment, resulting from lower offshore wave angles just up-drift of a defended stretch of shoreline. The reduction of transport tends to decrease the sediment-flux divergence for some distance up-drift of the structure (Ashton and Murray, 2006a, b; 2001).

5 Conclusions

Defended structures have an impact on their immediate surroundings, on the adjacent mesoscale coastal morphology and consequently the vulnerability of the coast to changes in wave climate. Model simulations indicate that the impact of structures on erosion rates is minimal in the northernmost section of the coastline, where the sea defences at Skipsea and Hornsea do not heavily modify the available sediment load. This is manifest in the similarity of the absolute erosion rates for undefended and defended scenarios. In the central and southern sections and particularly on the up-drift side of the sea defences, differences in patterns of absolute erosion are more prominent.

Although coastal recession rates are similar for the majority of ensemble members under the defended and undefended scenarios, ensemble members with absolute erosion at the 20th percentile or below have increased beach thicknesses where sea defences are included. This increase in beach sediment is sufficient to protect the cliffs from erosion and reduce recession rates. These mesoscale effects extend over 15 km of coastline and are most prevalent when a +10° rotation is applied to the wave direction and significant wave heights are increased. Increased wave heights allow greater volumes of sediment to be transported from the north and the clockwise (positive) changes in wave climate lead to a “trapping” of sediment on the up-drift side of sea defences by reducing sediment flux around these structures.

The sensitivity of the coastline to changes in wave climate is also modified due to sea wall defences. In section 1, the effect of changing wave climate on erosion is damped with sea defences included. In sections 2 and 3, the interaction of defences and sediment transport create complex, non-linear responses, as revealed by the patterns of relative erosion. While the sensitivity to wave-climate changes is similar in central and southern regions for undefended coast, for the defended coast the behaviour in these sections differ markedly. The results suggest that multiple sea defences can have a coupled impact on erosional sensitivity. These specific impacts of coastal defence interactions are dependent on the sediment supply, the local recession rate of the coastline, the proximity of surrounding defences, wave climate, and the morphology of the coastline.

Future wave climates are unlikely to be similar to the simply perturbed current wave climate used in this study. We assume that weather patterns will be the same as they were in 2009–2010, and there has been no attempt to reflect possible changes in storminess. However, by using an ensemble approach, the range of likely effects on the morphological characters of the Holderness coastline is captured. When compared to the results of field studies of the impacts of defensive structures on coastal erosion rates (for example Brown et al., 2012), the simulated results do not represent well the increase in erosion rates often associated with the down-drift side of solid defences. This discrepancy could arise partly because the large-scale model, assuming shore-parallel contours, neglects localised complex wave refraction and shoaling patterns around the ends of structures, and the consequent effects on currents and sediment transport. However, in the model the large-scale reduction of alongshore sediment flux caused by a protruding defended coastline segment can cause enhanced down-drift erosion (Ells and Murray, 2012). The fact that the defended locations protrude seaward of the regional coastline trend, increasing wave-shadowing effects, could explain the unexpected lack of erosion down-drift of the defences in our results. The present simulation does, in any case, allow the impacts of individual and multiple coastal defences on recession rates to be assessed in this complicated environmental system, providing an important complement to field-based study.

Acknowledgements. The authors are grateful to Vanessa Banks of the British Geological Survey for reviewing this paper and returning feedback that lead to its improvement. This paper is published with the permission of the Executive Director of the British Geological Survey (NERC), and was supported by the Climate and Landscape Research programme at the BGS.

Edited by: G. Coco

References

Adams P. N., Anderson R. S., and Revenaugh J: Microseismic measurement of wave energy delivery to a rocky coast, Geology, 30, 895–898, 2002.

Ashton A. and Murray A. B.: High-angle wave instability and emergent shoreline shapes: 1. Modeling of sand waves, flying spits, and capes, J. Geophys. Res. Earth Surf., 111, F04011, doi:10.1029/2005JF000422, 2006a.

Ashton A. and Murray A. B.: High-angle wave instability and emergent shoreline shapes: 2. Wave climate analysis and comparisons to nature, J. Geophys. Res. Earth Surf., 111, F04012, doi:10.1029/2005JF000423, 2006b.

Ashton A., Murray A. B., and Arnoult O: Formation of coastline features by large-scale instabilities induced by high-angle waves, Nature, 414, 296–300, 2001.

Bakker, W., Breteler, E. K., and Roos, A.: The dynamics of a coast with a groyne system, Coast. Engin. Proc., 1, 1001–1020, 1970.

Barkwith, A., Thomas, C. W., Limber, P., Ellis, M. A., and Murray, A. B.: 2014. Coastal vulnerability of a pinned, soft-cliff coastline, I: Assessing the natural sensitivity to wave climate, Earth Surf. Dynam., in press, 2014.

Bladé I., Liebmann, B., Fortuny, D., and van Oldenborgh, G. J.: Observed and simulated impacts of the summer NAO in Europe: implications for projected drying in the Mediterranean region, Clim. Dynam., 39, 709–727, 2012.

Brown, S., Barton, M. E., and Nicholls, R. J.: The effect of coastal defences on cliff top retreat along the Holderness coastline, P. Yorks. Geol. Soc., 59, 1–13, 2012.

Bruun, P.: The Development of Downdrift Erosion, J. Coastal Res., 11, 1242–1257, 1995.

Burton, E A.: Chronica Monasterii de Melsa, a Fundatione usque ad Annum 1396, Volume III, Editor Bond, E. A., Cambridge University Press, 2012.

Catt, J. A.: The Pleistocene glaciation of eastern Yorkshire: a review, P. Yorks. Geol. Soc., 56, 177–207, 2007.

CCO: Channel Coastal Observatory, http://www.channelcoast.org/data_management/real_time_data/charts/?chart=72 (last access: 15 July 2013), 2013.

Ciavola P.: Coastal dynamics and impact of coastal protection works on the Spurn Head spit (UK), Catena, 30, 369–389, 1997.

Clark H. C. and Johnson M. E.: Coastal Geomorphology of Andesite from the Cretaceous Alisitos Formation in Baja California (Mexico), J. Coastal Res., 11, 401–414, 1995.

Dean, R., Walton, T., Rosati, J., and Absalonsen, L.: Beach Erosion: Causes and Stabilization, Coastal Hazards, Springer, New York, USA, 319–365, 2013.

de Boer G.: Spurn Head: its history and evolution, T. I. Brit. Geogr., 34, 71–89, 1964.

DEFRA: Charting Progress 2. Feeder Report: Ocean Processes, Department for Environment Food and Rural Affairs, on behalf of the UK Marine Monitoring and Assessment Strategy community, Nobel House, London, UK, 290 pp., 2010.

Dickson, M. E., Kennedy D. M., and Woodroffe C. D.: The influence of rock resistance on coastal morphology around Lord Howe Island, southwest Pacific, Earth Surf. Proc. Land., 29, 629–643, 2004.

Dickson, M. E., Walkden, M. J. A., and Hall, J. W.: Systemic impacts of climate change on an eroding coastal region over the twenty-first century, Clim. Change, 84, 141–166, 2007.

Ells, K. and Murray, A. B.: Long-term, non-local coastline responses to local shoreline stabilization, Geophys. Res. Lett., 39, L19401, doi:10.1029/2012GL052627, 2012.

Hanson, H.: GENESIS: a generalized shoreline change numerical model. J. Coastal Res., 5, 1–27, 1989.

Kamphuis, J. W.: Introduction to Coastal Engineering and Management, Advanced series on ocean engineering, 16, Word Scientific, New Jersey, 2000.

Komar P. D.: The mechanics of sand transport on beaches, J. Geophys. Res., 76, 713–721, 1971.

Kraus, N. C. and McDougal, W. G.: The effects of seawalls on the beach: Part I, an updated literature review, J. Coastal Res., 12, 691–701, 1996.

Kraus, N. C., Hanson, H., and Blomgren, S.H.: Modern functional design of groyne systems, Coast. Engin. Proc., 1, 1327–1340, 1994.

Limber, P. W. and Murray, A. B.: Beach and sea cliff dynamics as a driver of rocky coastline evolution and stability, Geology, 39, 1149–1152, 2011.

Limber P. W., Patsch K. B., and Griggs G. B.: Coastal sediment budgets and the littoral cut-off diameter: A grain-size threshold for quantifying active sediment inputs, J. Coastal Res., 24 (supplement 2), 122–133, 2008.

List, J., Farris, A. H., and Sullivan, C.: Reversing storm hotspots on sandy beaches: spatial and temporal characteristics, Mar. Geol., 226, 261–279, 2006.

Montreuil, A.-L. and Bullard, J. E.: A 150-year record of coastline dynamics within a sediment cell: Eastern England, Geomorphology, 179, 168–185, 2012.

Newsham, R., Balson, P. S., Tragheim, D. G., and Denniss, A. M.: Determination and prediction of sediment fields from recession of the Holderness Coast, NE England, J. Coastal Conserv., 8, 49–54, 2002.

Pendleton, L. H.: The economic and market value of coasts and estuaries: what's at stake?, Coastal Ocean Values Press, Washington, DC, USA, 2010

Quinn, J. D., Philip, L. K., and Murphy, W.: Understanding the recession of the Holderness Coast east Yorkshire, UK: a new presentation of temporal and spatial patterns, Q. J. Eng. Geol. and Hydroge., 42, 165–178, 2009.

Scott Wilson: Humber Estuary Coastal Authorities Group (HECAG), Flamborough Head to Gibraltar Point Shoreline Management Plan 2, Scott Wilson, Basingstoke, Hampshire, UK, 2009.

Shennan, I., Lambeck, K., Flather, R., Horton, B., McArthur, J., Innes, J., Lloyd, J., Rutherford, M., and Wingfield, R.: Modelling western North Sea palaeogeographies and tidal changes during the Holocene, Geol. Soc., London, Special Publications, 166, 299–319, 2000.

Slott, J. M., Murray, A. B., and Ashton, A. D.: Large-scale responses of complex-shaped coastlines to local shoreline stabilization and climate change. J. Geophys Res. Earth Surf., 115, F03033, doi:10.1029/2009JF001486, 2010.

Sutherland, J. S. and Wolf, J.: Coastal defence vulnerability 2075, HR Wallingford Report SR590, Wallingford, UK, 2002.

Trenhaile A. S., Pepper D. A., Trenhaile R. W., and Dalimonte M.: Stacks and notches at Hopewell Rocks, New Brunswick, Canada, Earth Surf. Proc. Land., 23, 975–988, 1998.

Valvo L., Murray A. B., and Ashton A.: How does underlying geology affect coastline change? An initial modeling investigation, J.Geophys Res. Earth Surf., 111, F02025, doi:10.1029/2005JF000340, 2006.

Woollings, T.: Dynamical influences on European climate: an uncertain future, Phil. Trans. R. Soc. A, 368, 3733–3756, 2010.