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Assessing the influence of sea walls on the coastal vulnerability of a pinned, soft-cliff, sandy coastline

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Abstract

Coastal defences have long been employed to halt or slow coastal erosion. Their impact on local sediment flux and ecology has been studied in detail through field studies and numerical simulations. 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 defended 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, represented both as a defended example with major sea walls included and a natural example where no sea defences exist.

Using a mesoscale numerical coastal evolution model, stochastic wave climate data are perturbed gradually to assess the sensitivity of the coastal morphology to changing wave climate for both the defended and natural 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 the increased sediment availability along this part of the coast. Multiple defended structures, including those separated by several kilometres, were found to interact with each other, producing a complex imprint on 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 socio-economic implications (Pendleton, 2010). In an attempt to reduce the loss of property under strongly erosional conditions, it was the policy in the UK to build solid defences to halt land loss (Scott Wilson, 2009). This ethos has been subsequently replaced with the adoption of managed retreat, however, around 44 % of the English and Welsh coastlines are currently defended against erosion to some degree (DEFRA, 2010). Coastal defence strategies typically follow either a "soft" option defence, i.e. beach nourishment; or a "hard" option defence, i.e. 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 of these environments. For the UK, the majority of sea walls and promenades 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 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); where the influences of multiple defended structures interact, determining an accurate quantification of their impacts is made more difficult.

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 these may protect locally, 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 experiencing significant littoral drift. They act to locally reduce longshore sediment transport and trap sediment to protect the beach. They 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, groin emplacement strategies are best coupled to complementary beach nourishment (Dean et al., 2013). Groins 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. They 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 fix locations not only mediated the coastline locally but could alter the evolution of the coastline tens of kilometres away. Ells and Murray (2012) extended this study to simulate the effects of sea walls on mesoscale coastline evolution. They found that protection through either nourishment or hard-structure intervention resulted in accretion up-drift; that nourishment produced either accretion or erosion downdrift (depending on the surrounding coastline shape); and that hard-structure stabilization reliably caused increased divergent sediment flux down-drift, leading to increased erosion relative to an unprotected coast.

In this paper, the influence of seawall structures on the mesoscale evolution of a soft-cliff sandy coastline is studied. Specifically, we focus on understanding the difference between the predicted behaviour of defended and undefended coastline in the face of changes in wave climate anticipated over the coming century. This paper extends the work of Barkwith et al. (2013) which assessed 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 soft-cliff, sandy coastal systems.

2 Holderness coastline

The Holderness coastline formed as the North Sea basin flooded during the Holocene period (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). The Spurn Head spit, extending off the southern tip of the coast, and Humber estuary are simulated in the model a sediment store and sink respectively. However, as their interactions and dynamics are complex (see Ciavola, 1997) they are not included in the analysis. 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 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 to 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 occurred in 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 coast line cliff top since the mid-nineteenth 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 socio-political constraints, the removal of the larger sea defences protecting major towns and infrastructure is untenable; 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, significant wave height varied between 0.2 m 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 s to 18.8 s. The dominant mode in wave direction was from the northeast, with a secondary mode from the south-east. 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. (2013), 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 brief description of the modelling components is contained in this paper. For a detailed review of the modelling procedure, the reader is directed to Barkwith et al. (2013).

A modified version 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) has been 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., 2013; 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; 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 temporary 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 below the scale of the model time step, 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. Barkwith et al. (2013) used 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 were defined to be readily erodible at rates consistent with those known from the Holderness coast. Sea walls were represented with the same erosion rate as the chalk headland for the calibration phase in the Barkwith et al. (2013) study. However, sea wall defences were not included in the main phase of the study because the authors were interested in the natural morphological response to a changing wave climate. In this study, we retain the same calibration setup in the main phase of the modelling, to assess the influence of sea defences on the mesoscale morphology.

The model was discretised into uniform cells, 100 m in width, and run with a daily timestep. Boundaries for the east and west of the domain consist of a no-flow condition, and 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 Humber estuary is characterised as a sediment sink at the southern boundary of the model. 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.

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, Barkwith et al. (2013) applied a stochastic calibration approach. An ensemble of 2000 models with varying rock and beach sediment properties was used in the calibration. Following a ten year spin-up period (required to reach a dynamic steady state), erosion was simulated for a period of fifteen years. The wave climate for each member comprised two years of observed daily significant wave height, angle and period, cycled sequentially for the duration of the model run. The ensemble member with the lowest Root Mean Square Error (RMSE) when compared to the observed recession rates compiled by Montreuil and Bullard (2012) was selected to provide the initial properties for the model simulations, run for the coming century.

An ensemble of modified wave climates that consists of 1350 members drives the future simulations. The wave climate in each ensemble member was perturbed by selecting changes at random from ranges of ±20° rotation in wave direction and ±0.4 m in significant wave height. These variations were applied linearly over the ninety year simulation. The defended and undefended coast scenarios used 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 compare the evolution of the two scenarios, baseline runs were undertaken, where no perturbations were applied to the wave climate over the 90 yr simulation period.

Barkwith et al. (2013) concluded 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. The analysis of the results focuses on the patterns and rates of coastline change evident from the defended simulations. These

results are compared to coastline evolution predicted under undefended conditions lacking sea defences.

4 Results and analysis

Absolute erosion over the 90 yr simulation period is presented for the baseline undefended and defended scenarios in Fig. 2. 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. 3a) in the northern section (Sect. 1) of the model does not appear to have had a significant impact on surrounding recession rates under the differing wave climates. In the central section (Sect. 2), maximum absolute erosion values are similar to both the defended and undefended scenarios, at ca. 150 m over most of this part of the coast. Under clockwise rotation of wave direction and increased significant wave height, absolute erosion can actually 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 (Sect. 3) have less absolute erosion on their up-drift sides. In the southern-most part of Sect. 3 this leads to an overall reduction in erosion when sea defences are included in the simulation. Relative total (Fig. 3c and d) and percentage (Fig. 3e and f) erosion for the suite of ensemble members, as subtracted from the 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 positive and negative 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 causes the extreme values of percentage of baseline erosion at the location of sea wall structures (Fig. 3e and f), where a small change in absolute erosion may nevertheless equate to a large percentage change.

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 Sects. 1 to 3. When considering the coast as a whole, under counter-clockwise 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, whether with or 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 defended coast to the same wave climate perturbations has an equal chance of also reducing the relative erosion. In Sect. 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 dampened by the presence of defended structures. Under a clockwise rotation, erosion relative to the baseline peaks at around 10° and reduces again with further rotation. In the defended scenario, the relative erosion peak is at a maximum where there is no rotation, reducing rapidly as clockwise rotation is applied. The response for the central section (Sect. 2; Fig. 4c) also shows considerable variability. In Sect. 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.

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. (2013) to increased protection in the southern sector of the coast provided by the increased availability of sediment. With sea defences included, this relationship is greater, resulting in a stronger inverse relationship between erosion and wave height. This relationship is not so well defined in Sect. 1 (Fig. 5b) and there is little correlation between perturbation in wave height and erosion rate for either the defended or undefended scenarios. In Sect. 1, the lower range in erosion rate results from the influence of rotation of the wave direction. Both Sects. 2 and 3 (Fig. 5c and d respectively) show similar patterns manifest in a greater range in erosion rate as significant wave height increases. In Sect. 2, the undefended and defended coastlines respond similarly to change in wave height. In Sect. 3, this relationship is increasingly inverse for the southern section of the defended scenario when compared to the undefended coast. This suggests that the increase in sediment availability affords the coast greater protection from erosion.

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 and 5), behaviour averaged along the coast as a whole does not reflect the variations seen in detail for each of the three sections. In Sect. 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 Sect. 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 Sect. 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 clockwise rotation in wave direction; even small clockwise rotations cause a significant reduction in relative erosion. This can be explained by a reduction in longshore transport of sediment resulting from the higher onshore wave angles (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. Coastal simulations indicate that the impact of structures on erosion rates is minimal in the up-drift sections of the coastline, where sea defences do not heavily modify the available sediment load. This is manifest here in the similarity of the absolute erosion rates for undefended and defended scenarios. Further south, on the leeward 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 angle 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 Sect. 1, the effect of changing wave climate on erosion is damped with sea defences included. In Sects. 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 localized 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.

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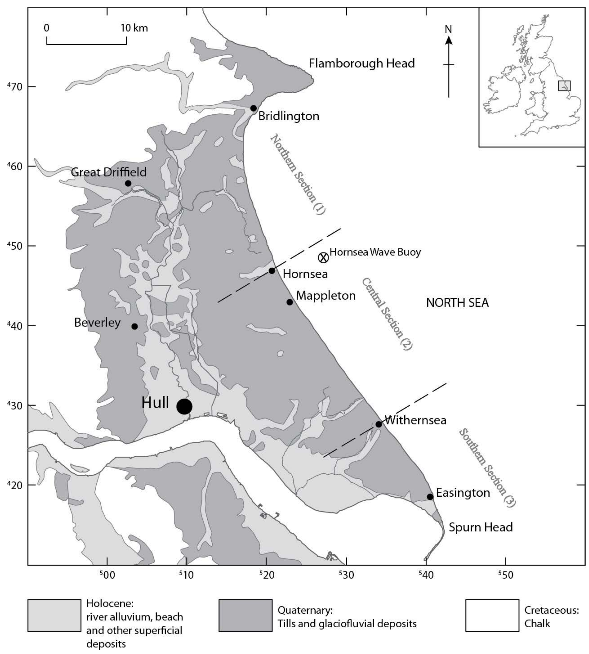

Fig. 1. Geological composition of the Holderness coast (main) and the location of the region within the UK (insert). Also indicated are the positions of the Hornsea wave buoy, from which wave climate was recorded, and the division into northern, central and southern coastline regions, as referenced by the sea walls at Hornsea and Withernsea (dashed lines), to aid analysis. Modified from Barkwith et al. (2013).

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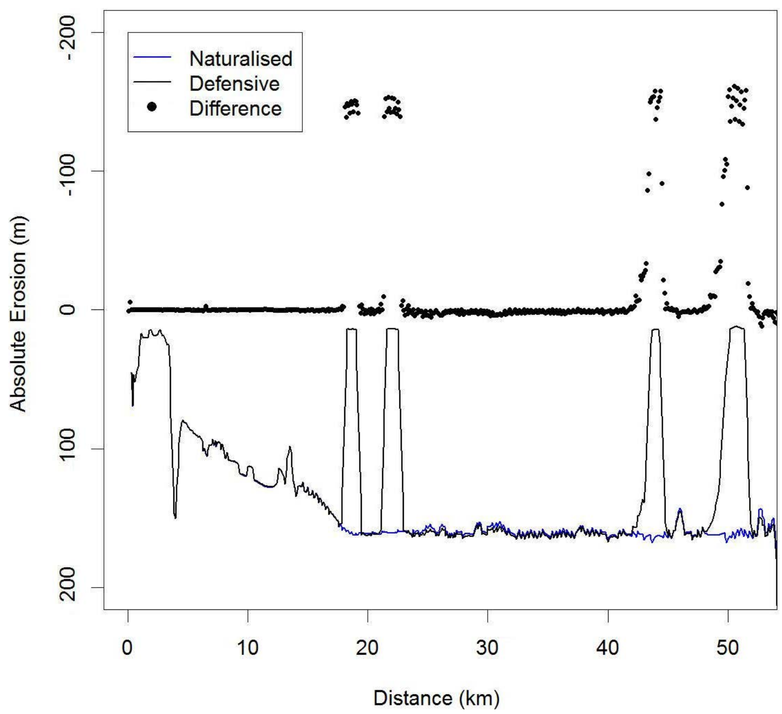

Fig. 2. Absolute erosion after ninety years of simulation for the undefended (blue line) and defended (black line) coastlines under the baseline wave climate (2009–2010 repeated cycle). The difference between these scenarios is highlighted by the black points.

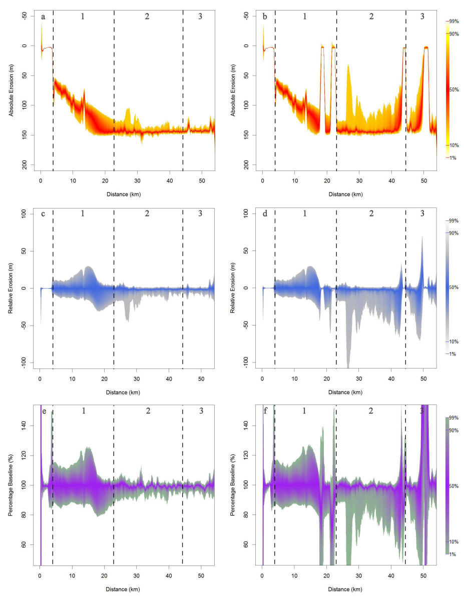

Fig. 3. Simulated erosion for the Holderness coastline **(a, b)**: simulated absolute change in coastline position (2010 to 2100) predicted using an ensemble of future wave climates for undefended **(a)** and defended **(b)** coasts. **(c, d)**: Relative change in coastline position (relative to baseline simulation) for each member of the ensemble, for the undefended and defended simulations respectively. **(e, f)**: Percentage change in erosion relative to the baseline simulation for the undefended and defended 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.

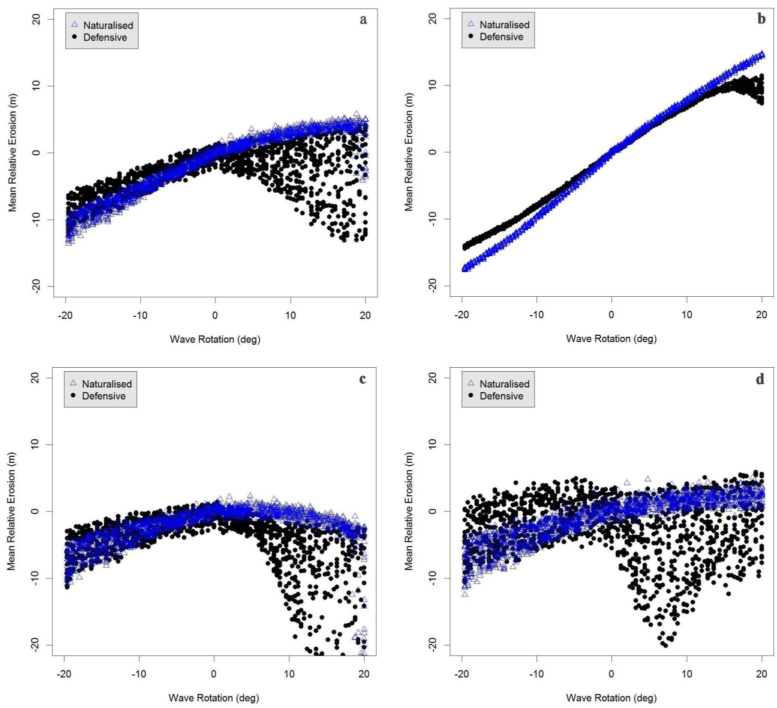

Fig. 4. Perturbation in wave direction plotted against spatially averaged mean relative erosion for the entire coast **(a)** and northern **(b)**, central **(c)** and southern **(d)** sections. Anticlockwise rotation of wave direction is negative, clockwise rotation is positive. Negative values in mean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

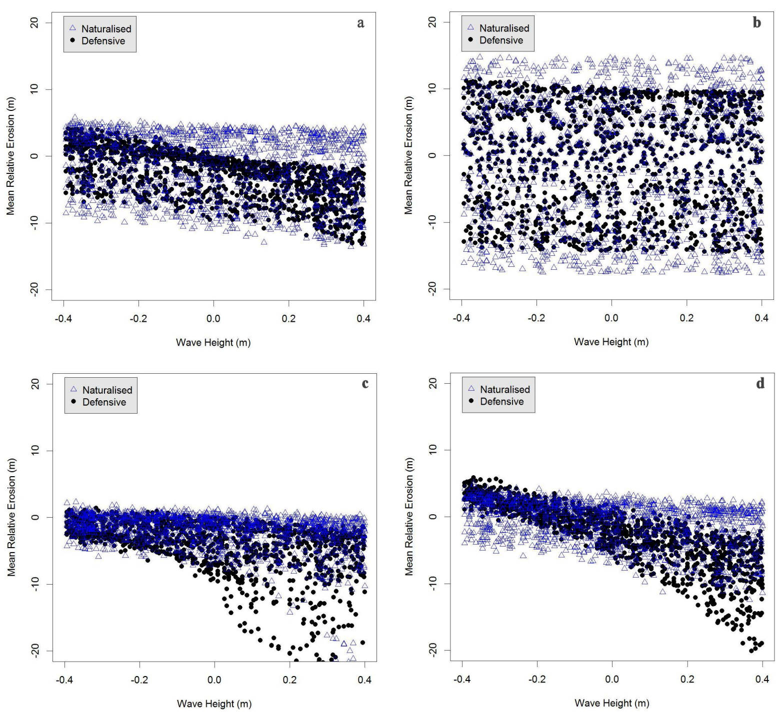

Fig. 5. Perturbation in significant wave height plotted against spatially averaged mean relative erosion for the entire coast **(a)** and northern **(b)**, central **(c)** and southern **(d)** sections. Negative values in mean relative erosion indicate a reduction in coastal erosion compared to the baseline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

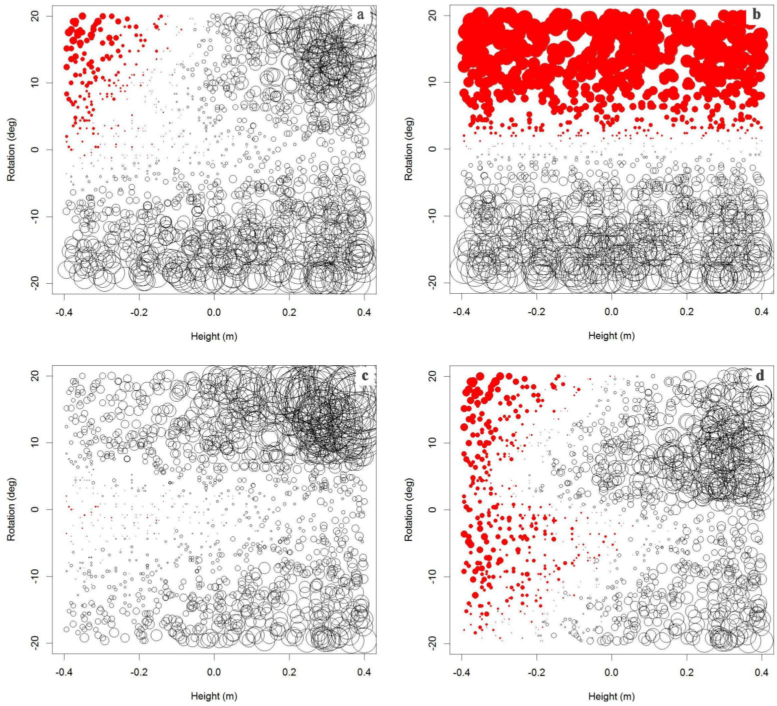

Fig. 6. Plots of perturbation in wave direction and significant wave height for each member of the ensemble for; the entire coast **(a)** and northern **(b)**, central **(c)** and southern **(d)** sections. The size of each symbol is proportional to the change in mean relative erosion rate imparted by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