Impacts of climate change on coastal geomorphology and coastal erosion relevant to the coastal and marine environment around the UK

G. Masselink[1], P. Russell[1], A. Rennie[2], S. Brooks[3] and T. Spencer[4]

[1] Coastal Processes Research Group, School of Biological and Marine Sciences, Plymouth University, Plymouth, PL4 8AA, UK
[2] Scottish Natural Heritage, Inverness, IV3 8NW, UK
[3] Department of Geography, Birkbeck, University of London, London, WC1E 7HX, UK
[4] Cambridge Coastal Research Unit, Department of Geography, University of Cambridge, Cambridge CB2 3EN, UK

EXECUTIVE SUMMARY

A large proportion of the coastline of the UK and Ireland is currently suffering from erosion (17% in the UK; 19.9% in Ireland) and of the 3700 km coastline of England and Wales 28% is experiencing erosion greater than 10 cm per year. In Scotland, 78% of the coast is considered 'hard or mixed', and is unlikely to erode at perceptible rates, 19% is 'soft/erodible', whilst 3% has artificial defences. Since the 1970s, 77% of the soft/erodible coast in Scotland has remained stable, 11% has accreted seawards and 12% has eroded landwards.

As a result of relative sea-level rise, reduced nearshore sediment supply from offshore and longshore sources and vulnerability to extreme storms and human interference are all expected to increase due to climate change. Coastal erosion rates are expected to increase in the future and presently stable or accreting coasts may enter into an erosion phase.

The natural response of coastal systems to sea-level rise is to migrate landwards, through erosion of the lower part of the nearshore profile and deposition on the upper part. The roll-over model is applicable to estuaries, barriers and tidal flats. Rocky coasts are undergoing a continual state of erosion by their nature, and they retreat even under stable sea-level conditions. Where the coast is protected by engineering structures, coasts generally experience a steepening of the intertidal profile, or 'coastal squeeze'.

Coastal erosion is, however, strongly determined by site-specific factors and usually it is these that determine the coastal response, admittedly against a backdrop of a slowly receding coastline due to sea-level rise. Any predictions

Citation: Masselink, G., Russell, P., Rennie, A., Brooks, S. and Spencer, T. (2020) Impacts of climate change on coastal geomorphology and coastal erosion relevant to the coastal and marine environment around the UK. *MCCIP Science Review 2020*, 158–189.

doi: 10.14465/2020.arc08.cgm

Submitted: 07 2018
Published online: 15th January

of *general* coastal response due to climate change are therefore rather meaningless and will have a low/medium confidence. However, if a detailed study is conducted and long-term coastal change data are available, then *local* or *regional* predictions of coastal response to climate change can have medium/high confidence, especially if adjustments are made for accelerated sea-level rise.
In the absence of a clear understanding of the coastal-change processes, and therefore a reliable predictive tool, the default position is to assume that present-day coastal change will persist; however, it is very likely that stretches of coast currently undergoing erosion will experience increased erosion rates due to sea-level rise.

The coastal management strategy for a section of coast (e.g. hard coastal defences, beach nourishment, managed re-alignment) is a key aspect for determining the long-term response of the coast to climate change impacts, including sea-level rise. An adaptation approach that involves working with nature (e.g. beach nourishment, managed retreat), rather than against (e.g., construction of hard defences), is emerging as the key coastal management paradigm to cope with coastal erosion.

1. INTRODUCTION

Coastal erosion and flooding are often considered separate physical hazards, but they are intrinsically linked and are both generally associated with high water levels and energetic wave conditions during storms. Coastal geomorphology plays a key role here, in that different types of morphology exhibit different vulnerabilities, as well as providing the coastal flooding pathway in the Source–Pathway–Receptor model. The Environment Agency estimates that approximately 700 properties in England are vulnerable to coastal erosion over the next 20 years (Figure 1), and a further 2000 may become vulnerable over the next 50 years (https://www.gov.uk/government/publications/flood-and-coastal-risk-management-national-report). Without coastal protection, these figures could increase to about 5000 properties within 20 years and about 28,000 in 50 years. According to the Committee for Climate Change (CCC), in their 2018 report '*Managing the Coast in a Changing Climate*', between 2005 and 2014 over 15,000 new buildings were built in coastal areas at significant risk of coastal flooding and/or erosion (https://www.theccc.org.uk/publication/managing-the-coast-in-a-changing-climate/). If current trends continue, this figure is likely to reach 27,000 new properties by 2022. But, according to the CCC, these figures may in themselves be a considerable under-estimate. If the government meets its ambitious house-building targets, in the next five years up to 90,000 homes might well be built in areas of significant annual flood risk from all sources of flooding, including coastal flooding. A major storm event (e.g. the North Sea storm surge on 5 December 2013; storm Eleanor on 3 January 2018; storm Emma on 3 March 2018) or a series of storm events (e.g. winter

2013/14) can spike erosion and flooding impacts costs in a given year. For example, the economic cost resulting from the damage to the Dawlish Railway line during the 2013/14 winter is estimated at between £60 million and £1.2 billion (DMF, 2014). Sea-level rise is often considered a key factor in causing coastal erosion and coastal flooding, and concerns about both hazards have mounted in the light of increased rates of sea-level rise and possibly increased storminess predicted due to climate change.

Figure 1: Coastal erosion at Happisburgh, Norfolk, from 1996 to 2012. The erosion recorded in these photographs is extreme and to a large degree the result of the removal of coastal defences; Poulton et al., 2006). (Source: https://blog.geographydirections.com/2013/11/01/adapting-to-coastal-change-understanding-different-points-of-view-in-coastal-erosion-management/)

In England and Wales, responsibility for the management of coastal erosion rests with the Environment Agency (EA) and Natural Resources Wales (NRW), respectively, together with Coastal Councils. In Scotland, the Coastal Protection Act (1949) empowers, but does not compel Local Authorities to protect land from erosion, and the legal responsibility to protect from coastal erosion remains with the landowner. All countries have developed national strategic guidance for coastal (and river) management that is focused on sustainable development being firmly rooted in all flood risk management and coastal erosion decisions and operations. At a local and regional level, strategic guidance for coastal management is provided through (non-statutory) Shoreline Management Plans (SMPs; https://www.gov.uk/government/publications/shoreline-management-plans-smps). The plans provide a large-scale assessment of the risks associated with coastal processes and present a long-term policy framework to reduce these risks to people by identifying the most sustainable approach to managing the flood and coastal risks in the short-term (0–20 years), medium-term (20–50 years) and long-term (50–100 years). The complete coastline of England and Wales is covered by SMPs and the second generation SMPs are currently under review. In Scotland, part of the developed Scottish coast has SMPs, with the remainder of the shore relying on generic national policies, although the recent Dynamic Coast project depicts past changes and projects these forward to 2050 and 2100 (http://www.dynamiccoast.com/).

Contrary to common beliefs, coastal erosion is not solely and simply linked to sea-level rise, and *the key message of this report is that coastal erosion is a complex process that has a variety of causes, with rising sea level being only one of them* (cf. Cazenave and Le Cozannet, 2014). Moreover, whereas climate change and sea-level rise are gradual and long-term processes, coastal erosion and flooding are highly episodic short-term processes, and there is a significant disconnect between the associated timescales. Importantly, whereas climate change and relative sea-level rise are global and regional phenomena, respectively, coastal erosion is a local process.

It is also important to consider that coastal evolution and shoreline trends, such as erosion, are related to process interactions and sediment linkages between different coastal landform units; therefore, erosion of one stretch of coast is likely to cause accretion elsewhere. Sediment is generally recycled around the coastal system on a variety of different spatio-temporal scales. An example of this on a large spatial scale (> 50 km) is the study by Montreuil and Bullard (2012) on the east coast of England. Here, the rapid erosion of the Holderness cliffs to the north of the Humber is, in part, counterbalanced with accretion on beaches along the north Lincolnshire coast to the south of the Humber. The amount of accretion in Lincolnshire corresponds to around 29% of the volume of sediment eroded from Holderness, and increased cliff recession rates of the Holderness coast as a result of sea-level rise may even lead to increased accretion and shoreline progradation along the north Lincolnshire coast (the remaining 71% of eroded sediment ends up in the Humber estuary, including the ebb tidal delta and Spurn Head spit system, or is transported further afield, perhaps even up to the Dutch Wadden Sea). Such a pattern is partly replicated at the national scale in Scotland where the proportion of coast experiencing erosion and accretion are comparable at present (Hansom *et al.*, 2017). On a smaller spatial scale (*c*. 10 km), process interactions and sediment linkages are also apparent. Many beaches and barrier systems in the UK and Ireland are so-called ‘drift-aligned systems’, meaning that their configuration, dynamics and stability are largely controlled by longshore sediment transport processes and even small changes to the net littoral drift rate (or direction) can have major implications for the shoreline position. For example, Benacre Ness is a cuspate depositional feature on the coast of Suffolk that has an area of over 8000 m^2 and stretches alongshore for 4 km (Brooks and Spencer, 2010). It provides a protective function to the cliffs behind and adjacent to it, as it extends from the cliff base towards the sea by over 300 m. The apex of the ness extended northwards by 600 m between 2012 and 2016, an average rate of 150 m/yr. As a result, the erosion of the cliffs at the northern end of the feature has ceased, and conversely, the cliffs located to the south of the ness have started to show accelerated retreat as the northward migration of the ness has left them exposed to wave attack.

Section 2 reviews the current erosion rates in the UK and Section 3 reviews what is likely to happen in the future. At the end of the report, adaptation strategies that address coastal erosion problems are briefly discussed (Section 4). Appreciation of climate change impacts on coastal geomorphology requires a basic understanding of the key coastal processes and the main coastal geomorphological environments; these were discussed in sections 1.3 and 1.4 of the 2013 edition of this Report Card (http://www.mccip.org.uk/media/1256/2013arc_sciencereview_09_ce_final.pdf).

2. WHAT IS ALREADY HAPPENING?

An evaluation and synthesis of what is already happening in terms of changes to the coastal geomorphology in the UK is provided here at two levels: the UK wide coastal dynamics are discussed first (Section 2.1), followed by processes occurring to hard- and soft-rock coasts, barrier systems and estuaries (Sections 2.2–2.5). It is important to note that coastal change is not necessarily due to climate change, and that generally multiple factors are implicated that cannot be separated.

2.1 UK coast

According to what is still the most-recent European-wide study into coastal geomorphology and erosion (EUROSION, 2004), the UK coastline is 17,381 km long, of which 3008 km (17.3%) is currently experiencing erosion (Table 1; note that length of coastline increases with decreasing length scale of interest and therefore strongly varies between different studies). The coastline of England is most affected, with 29.8% of its coastline suffering from erosion. The coastline of England is also the most protected with 45.6% of its length lined with coastal defence works (seawalls, groynes) or fronted by artificial beaches. According to the same EU report, Ireland has 4578 km of coastline, of which 19.9% is undergoing erodsion and 7.6% is protected.

In England and Wales, the Foresight Flood and Coastal Defence Project provides estimates of present and future coastal erosion rates (https://www.gov.uk/government/publications/future-flooding). According to their analysis, 28% of the coast is experiencing erosion rates in excess of 0.1 m/yr (Evans *et al.*, 2004; Burgess *et al.*, 2007). A large proportion of the coastline is held in position artificially; however, and a more-realistic estimate of potential erosion is that 67% of the coastline is under threat (Futurecoast, 2002). The National Coastal Erosion Risk Mapping Project (Rogers *et al.*, 2008) has suggested that 42% of the coast of England and Wales is at risk from erosion, of which 82% is undefended. However, this project is only concerned with cliffed coastlines and does not consider coastal floodplains, beaches, barriers and intertidal areas. In Scotland, 78% of the coast is considered 'hard or mixed', and is unlikely to be eroded at perceptible rates (threshold of 1 mm/yr), 19% (3802km) is 'soft/erodible', whilst 3%

(591km) has artificial defences (http://www.dynamiccoast.com/). Since the 1970s, 77% of the soft/erodible coast has remained stable, 11% has accreted seawards and 12% has eroded landward. Through comparisons with the historical baseline (1890s to 1970s), there has been a 22% reduction in the extent of accretion in Scotland, a 39% increase in the extent of erosion, and a doubling of average erosion rates from 0.5 to 1.0 m/yr.

Table 1: Coastal erosion and protection in the UK (EUROSION, 2004). Islands with a surface area smaller than 1 km^2 and inland shores (estuaries, fjords, fjards, bays, lagoons) where the mouth is less than 1 km wide are not included in the analysis.

Region	**Coast length** (km)	**Coast length undergoing erosion** (km)	**Coast length undergoing erosion** (%)	**Coast length with defence works and artificial beaches** (km)	**Coast length with defence works and artificial beaches** (%)
North-east England	297	80	27.0	111	37.4
North-west England	659	122	18.5	329	49.9
Yorkshire and Humber	361	203	56.2	156	43.2
East Midlands	234	21	9.0	234	99.8
East England	555	168	30.3	382	68.9
South-east England	788	244	31.0	429	54.4
South-west England	1379	437	31.7	306	22.2
England	4273	1275	29.8	1947	45.6
Wales	1498	346	23.1	415	27.7
Scotland	11154	1298	11.6	733	6.6
Northern Ireland	456	89	19.5	90	19.7
UK	17381	3008	17.3	3185	18.3
Ireland	4578	912	19.9	349	7.6

Availability of a reliable (accurate) and comprehensive (large-scale) database of coastal change is hugely beneficial for coastal management, not only as a baseline, but also as a basis for (lower-bound) projections. The coastal data collection and collation by Coastal Observatories in the England is very useful in this context. Improved estimates of coastal change may be provided in the future due to advances in satellite remote sensing and associated data analysis techniques (Luijendijk *et al.*, 2018).

Where the coast is protected by engineering structures, the rising sea level results in a steepening of the intertidal profile, known as ‘coastal squeeze’. According to Taylor *et al.* (2004) almost two-thirds of intertidal profiles in

England and Wales have steepened over the past hundred years. A re-evaluation of these results pertaining to the south-east coast of England suggests that steepening is less common (Dornbush *et al.*, 2008), while more-recent research for the Suffolk coast shows beach narrowing and steepening between 1800s and 2010s (Burningham and French, 2017). In the 1800s, only 37.2% of the Suffolk coast had beach widths of under 20 m, while by the 2010s this percentage had increased to 79.5%. The median beach slope was 4.7° in 1800s rising to 6.5° in 2010s. Burningham and French (2017) also note that the percentage of beaches that are steepening along the Suffolk coast is 89%, considerably higher than the 61% estimated by Taylor *et al.* (2004) for the UK as a whole. It would be instructive to consider more fully the temporal variability in these estimates as they are presented as an average over the entire period between the 1880s and 2010s. For example, a recent study for Suffolk by the Environment Agency for the period 1991 to 2006 showed steepening along just 17% with flattening being more prevalent at 34% (EA, 2011).

The effect of eustatic (global) sea-level rise on the coastline in the UK and Ireland, causing coastal erosion and landward migration of the shoreline, must be considered in combination with the changes in the land level associated with glacio-isostatic effects, particularly the isostatic rebound of the formerly glaciated areas in the north, and collapse of the forebulge of areas near the ice margin in the south. Tide gauge data from Scotland show that, for the first time since the last glaciation, eustatic sea-level rise outpaces isostatic rebound (Rennie and Hansom, 2011), although there has been debate over the rate of submergence (Dawson *et al.*, 2012). This switch from relative sea-level fall to relative sea-level rise has important implications for coastal change in Scotland. For example, the Moray Firth has experienced 7000 years of relative sea-level fall, resulting in an emergent coastal landscape characterised by extensive strand plain development. However, the switch to relative sea-level rise has engendered a near-tripling of coastal erosion rates, i.e. an increase from 8% between 1890 and 1970, to 22% since the 1970s (Hansom *et al.*, 2017). All Scotland's firths are expected to be affected by a similar switch in relative sea-level change and are therefore at increasing risk of coastal erosion in the future.

Coastlines do not, however, slowly respond to rising sea levels, but adjust episodically, generally associated with (extreme) storm conditions. The scale of coastal change engendered by extreme storms became apparent over the 2013/14 winter when a number of extremely energetic wave conditions (Dhoop and Mason, 2018) coincided with extreme water levels (Haigh *et al.*, 2016). The resulting coastal impacts, briefly discussed below, highlights the vulnerability of both the south-west and east coast of the UK to storm conditions.

During the winter of 2013/14 the south-west coast of England experienced its most energetic period of waves for at least the last 60 years as a result of an unprecedented sequence of extreme storms from the Atlantic (Masselink *et al.*, 2015). The collective impact of these storm waves was severe and widespread (Scott *et al.*, 2016; Figure 2). For example, large quantities of sand were removed from many beaches and dunes, thereby exposing the underlying rocky shore platform; several gravel barriers were overtopped; and extensive coastal cliff erosion and destruction of hard-rock coastal features, such as arches and stacks, occurred. Impacts on society were also substantial. In addition to widespread flooding of coastal towns, extensive damage occurred to coastal defences, transport lines and coastal properties. The key factor that controlled the beach response was the orientation of the shoreline in relation to the storm wave direction: fully exposed beaches experienced offshore sediment transport, partially exposed beaches rotated due to longshore sediment transport, and relatively sheltered beaches experienced accretion or limited change (Burvingt *et al.*, 2017). Beach recovery has been variable, with virtually no recovery of the dune systems and partial recovery (50–75%) of the beaches (Burvingt *et al.*, 2018).

Figure 2: Pictorial overview of storm impacts along the coast of south-west England (from Scott et al., 2016). (a) The gravel barrier at Westward Ho!, north Devon, experienced overwash during the spring tide of 2/3 January 2014, resulting in the deposition of a large amount of pebbles and cobbles into the local mini-golf course located just behind the ridge. (b1 before; b2 after) The significant storm 'Hercules' on the 5th January 2014 removed large quantities of sand from at Whipsiderry beach, north Cornwall, exposing the underlying rocky shore platform. (c) Hercules caused extensive damage to coastal infrastructure along the north Cornish coast; here the seawall below Fistral Blu bar in Newquay collapsed and damaged the property. (d) The Watering Hole in Perranporth, North Cornwall, the only 'beach restaurant' in the UK, required human intervention to ensure the restaurant remained high and dry after winter storms lowered the beach by several meters. (e) The coastal town of Looe, south Cornwall, got flooded a number of times during the 2013/2014 winter. (f) The coastal dunes at Thurlestone, south Devon, experienced more than 5 m of erosion during the 2013/2014 winter resulting in the collapse of the wooden boardwalk. (g) At the end of the winter, the beach in front of the seawall at Beesands, south Devon, had completely disappeared. (h1 before; h2 after) The road that runs

along the gravel barrier of Slapton Sands, south Devon, became covered with gravel due to overwash occurring during the significant storm 'Petra' on 5 February 2014, but also the 'Valentine's Day' storm on 14 February 2014. (i) This storm caused extensive damage to coastal infrastructure along the south Cornwall and Devon coast; the most costly damage occurred to the London-Penzance railway line at Dawlish, south Devon, with repairs taking almost 2 months and costing £20M.

By contrast, along the east coast, the winter of 2013/14 presented just a single storm that can be held responsible for most of the shoreline change that occurred that winter. The North Sea storm surge of 5 December 2013 generated the highest water levels experienced since the catastrophic 1953 storm. Due to strengthened post-1953 defences, better early warning systems and evacuation planning, no human lives were lost in the 2013 surge. However, in places, water levels in 2013 exceeded those of 1953, especially along the Lincolnshire and North Norfolk coasts. The highest measured water levels, recorded in drift line deposits and watermarks on buildings, reached or exceeded 6.3 m ODN on the North Norfolk coast at Holme-next-the-Sea, Holkham Gap and Blakeney Quay (Spencer *et al.*, 2014, 2015). Along the North Norfolk coast, water levels were up to 0.8 m higher in 2013 than in 1953, while in Suffolk the pattern was reversed with higher levels in 1953 of up to 0.74 m (Spencer *et al.*, 2015). These contrasts arise because of the unique timing of maximum positive surge residual in relation to the tide, with wave height and direction adding to the forcing (Figure 3). For the 5 December 2013 surge, maximum surge residuals were found about 1–2 hours before high tide, occurring coincidentally with high spring tides. Waves were onshore-directed and coincided with the high tide and positive surge in North Norfolk, while for Suffolk the highest onshore waves were over 2 m lower and were not coincident with the timing of maximum still water elevations. There is evidence for retreat in the Suffolk cliffs, barrier breaching and almost 660 ha of flooded land, but shoreline damage was far greater in North Norfolk. The storm impacts from 2013 have been compared to high magnitude storms of the last 10 years (2006–16) by examining cross-shore profiles and aerial photographs, and it has been shown that the 2013 storm generated over double the shoreline retreat experienced in earlier high-magnitude storms occurring in 2006–7 and 2007–8 (Brooks *et al.*, 2017).

2.2 What is already happening: hard-rock-coasts

All hard-rock coasts are undergoing erosion, and cliff erosion is controlled to a large extent by rock strength, with typical cliff recession rates in hard and soft rock of 0.01–0.1 m/yr and 0.1–1 m/yr, respectively, although in unconsolidated glacial and pre-glacial sands and silts rates can be over 7 m/yr (Brooks *et al.*, 2012) These average rates misleadingly give the impression that cliffs retreat gradually and consistently; however, cliff failures tend to be sporadic and are often triggered by extreme rainfall events and/or storms. Quantifying erosion rates on the almost-stable hard-rock coasts and increasing our understanding of the linkages between terrestrial weathering and coastal erosion processes remains, however, problematic, but progress is being made through use of advanced remote sensing techniques that enable the collection of high-resolution data (Earlie *et al.*, 2014). Specifically, application of digital photogrammetry and terrestrial laser scanning along the North Yorkshire coast by Lim *et al.* (2010) has revealed that hard-rock cliff erosion may not be as dominated by high-magnitude and low-frequency events as hitherto thought, and that large, isolated rock falls are in fact part of a larger, continuous magnitude-frequency relationship. Nevertheless, Vann Jones *et al.* (2015) point out that linking hard-rock coastal cliff erosion to environmental drivers is challenging, with weak relationships commonly observed between cliff recession and marine/subaerial forcing.

Many hard-rock coasts are characterised by coastal cliffs fronted by rocky shore platforms, which represents the erosional surface left behind by the retreating cliff. These platforms strongly modulate the wave energy reaching the base of the cliff and are an effective dissipater of wave energy (Poate *et al.*, 2018). Sea-level rise has two virtually unstudied, but important implications for the shore platform, and these are already happening. Firstly, the increased water depths across the platform will reduce the wave energy dissipation across the platform, exposing the base of the cliff to increasing wave-energy conditions. This indirect consequence of sea-level rise is well known for coral reef environments (e.g. Quataert *et al.*, 2015). Secondly, the gradual 'drowning' of the shore platform as a result of increased sea level will lead to a loss of intertidal rock habitat, as demonstrated by Thorner *et al.* (2014).

The effect of climate change on embayed beaches associated with hard-rock coasts is also significant. These beaches are backed by cliffs or higher ground and generally have very limited back-beach accommodation space. They also may be closed systems with no, or very limited net import of sediment due to their embayed settings. Rising sea level will attempt to push these beaches landwards, but, with no space to move into and not sufficient time to create new space through erosion, coastal squeeze will result in a progressively diminishing beach volume until no beach is left. Climate change may also result in the rotation of embayed beaches due to changes in the wave climate, especially the wave direction, causing alterations in the littoral drift rate and/or direction. The narrowing and widening of beaches at opposite ends of embayments has been documented for several locations in the world (e.g. Klein *et al.*, 2002; Ranasinghe *et al.*, 2004), and may become significant in the south-west of England and Wales and the Atlantic coast of Ireland where embayed beaches abound (Jackson *et al.*, 2005; Reeve and Li, 2009; Jackson and Cooper, 2010; Scott *et al.*, 2011; Burvingt *et al.*, 2017). The important role of beaches in reducing the delivery of wave energy to the base of the cliff, and thereby protecting cliffs from erosion, has been pointed out by Earlie *et al.* (2018).

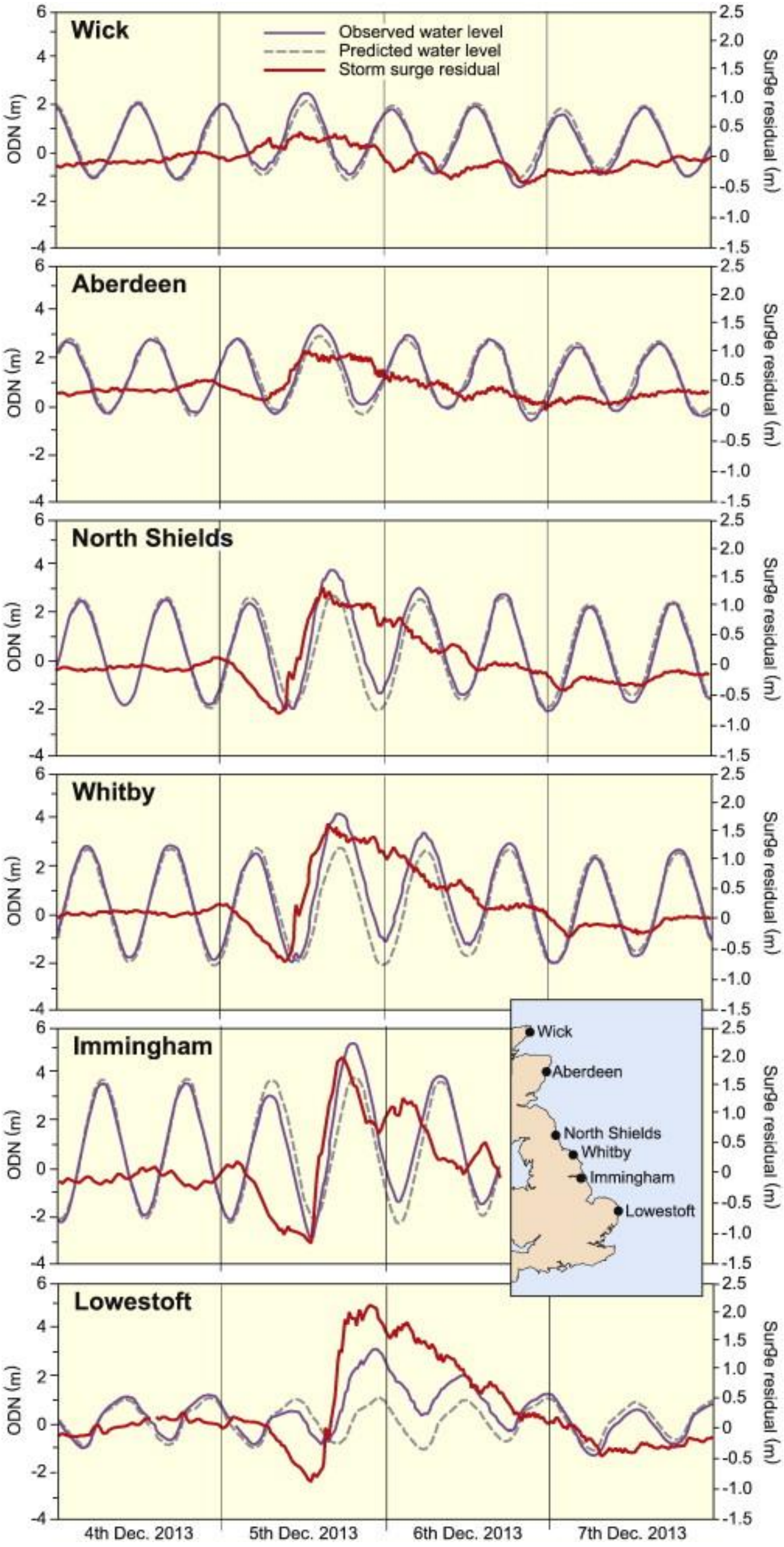


Figure 3: Observed water level (i.e. with meteorological forcing), predicted water level (astronomical tide) and surge residual (observed – predicted level) at six tide gauge stations (see inset for locations) for 4–7 December 2013. (From Spencer et al.*, 2015.)*

2.3 What is already happening: Soft-rock coasts

Recent technological advances in field monitoring and GIS analysis have revealed how fast soft-rock coasts are undergoing erosion (Lee and Clark, 2002; Burningham and French, 2017), and provide better estimation of the timing of sediment delivery to the beach and nearshore zone (Brooks and Spencer, 2012). With alongshore transport, these sediments feed morphological units that can defend the shoreline elsewhere, such as through nearshore sand-bar growth, or through the development of intertidal bars, which form a source of sediment for dunes and barriers. Generally, soft-rock coasts form more-complex systems than hard-rock coasts because of this ongoing sediment mobility and beach/cliff interaction. Sediment redistribution leads to a variety of linked morphologies, including the soft-rock cliffs themselves, as well as inter-fingered low-lying broadlands (Spencer and Brooks, 2013), migrating nesses (Burningham and French, 2014), sand dunes and nearshore/offshore sand bars (Horillo-Caraballo and Reeve, 2008; Suffolk Coastal District Council, 2009). Soft-rock coasts are generally drift-aligned and the beaches represent the morphological expression of the longshore transport system, rather than stable depositional features. As the source of the beach material is cliff erosion, the beaches would not exist were it not for the erosion of cliffs. However, beaches are highly dynamic on many temporal scales, and extreme storms can strip beaches to their basement in a single event. Beach cover at the base of soft-rock cliffs tends to be reconstructed very quickly post-storm, in a matter of weeks.

Soft-cliff retreat occurs through a combination of marine erosion, shallow structural failures and mass failures. Cliff erosion on soft-rock coasts is a highly episodic process, and erosion rates are spatially and temporally highly variable. The following three examples illustrate the approach to the study of soft rock cliffs on very contrasting timescales:

- On a millennial timescale, Hurst *et al.* (2016) derived past cliff retreat rates for chalk cliffs on the south coast of Great Britain using measured cosmogenic nuclides and numerical models. When compared with contemporary recession rates, accelerated erosion has occurred in recent centuries; this they attribute to reduced sediment supply and beach thinning due to both environmental and anthropogenic factors.
- On a centennial scale, Brown *et al.* (2012) found considerable spatial and temporal variability in cliff retreat along the Holderness coast between 1845 and 2005. Their analysis of three 50-year periods (1854–1905, 1905–1952, 1952–2005) found retreat rates varied between 0.8 ± 0.4 and 2.1 ± 0.4 m/yr. While natural reasons underpin these rates, human activity was also found to be important, especially 19th century beach mining and coastal defence construction. Coastal

defences unsurprisingly reduce sediment delivery and modify the sediment budget, usually resulting in a sediment deficit downdrift. For Holderness, defences have changed the pattern of erosion rather than stopping it entirely. Accelerated retreat downdrift of defences threatens societal infrastructure, highlighting the need for a holistic approach to shoreline management.

- On decadal and annual scales, Brooks *et al.* (2012) carried out annual to bi-annual ground survey data and applied GIS techniques to digitised records of changing shoreline position from aerial photography for the Suffolk cliffs since 1992. This study revealed that the cliffs have been retreating by an average of 4.7 m/yr (1992–2010; cf. long-term (1883–2010) recession rates are 3.5 m/yr), again suggesting a more-recent acceleration. However, the analysis revealed considerable decadal-scale variations in cliff recession, within which are nested inter-annual fluctuations in rates of retreat. This has considerable consequences for sediment release, as exemplified by the Covehithe cliffs, where retreat can be 12 m in a single event. There, the associated sediment release is of the order 200,000 m^3. Conversely, in quiescent years or decades, sediment release is very limited, resulting in considerable temporal variability in sediment delivery to the nearshore zone which needs to be planned for by coastal managers.

Considering what might happen in future, with sea-level rise continuously resetting the erosion baseline and storms varying in intensity and direction of approach, there remains the unanswered question as to whether or not we can expect accelerated cliff retreat in future, and what the associated consequences might be for sediment release and supply downdrift. Modelling approaches (e.g. Walkden and Hall , 2005; Dickson *et al.*, 2007; Walkden *et al.*, 2008; Hackney *et al.*, 2013) can be helpful for understanding future system behaviours that we cannot observe, but have limitations in their parametrisation, discretisation and process representation.

2.4 What is already happening: Barrier coasts

There are two models of barrier response to rising sea level (cf. Masselink *et al.* 2011). According to the *Bruun Rule*, the shoreface profile moves upward by the same amount as the rise in sea level, through erosion of the upper shoreface and deposition on the lower shoreface. In comparison, according to the *roll-over model*, the barrier migrates across the substrate gradient without loss of material, through erosion of the shoreface and deposition behind the barrier in the form of washovers and/or tidal inlet deposits. The Bruun Rule is widely used for predictive purposes, but there is very limited support for its validity; some argue it should be abandoned altogether in spite of its potential to quantify erosion rates (Cooper and Pilkey, 2004). There is much stronger evidence for the roll-over model, which is especially appropriate for gravel barriers (Pye and Blott, 2006), strongly wave-dominated barriers and on relatively gentle substrate slopes. However, the model is essentially qualitative since barrier migration is not a steady process, occurring episodically when extreme water levels, often in combination with large waves, result in overwashing of the barrier (Orford *et al.*, 2003). Importantly, if roll-over is allowed to proceed without anthropogenic constraints (e.g. seawalls), the different coastal habitats will be retained, albeit displaced. In this context the changes to coastal dune systems in Wales is of interest. Here, the majority of sand dune sites have experienced an increase in dune area over the last 100–120 years and it is unlikely that net area loss will exceed net area gain over the next 100 years with climate-change induced sea-level rise, provided that there is no further anthropogenic disruption to sediment supply and natural coastal processes, (Pye and Saye, 2005).

The Bruun Rule and the roll-over model are essentially two-dimensional models of shoreline response to sea-level rise that ignore the contribution of longshore sediment transport processes and the presence of additional sources and sinks (although Dean and Houston (2016) have recently extended the Bruun model to include the effects of sediment sources and sinks). Most UK barriers are drift-aligned systems, characterised by relatively high net littoral drift rates of the order of 10^4–10^5 m^3/yr. In such settings, modifications to the longshore transport system (e.g. due to changes in wave climate or coastal engineering structures) are vastly more important in driving coastal change than sea-level rise. For example, the prevailing southward littoral drift rates along the Norfolk coastline are > 500,000 m^3/year (Burningham and French, 2016), and the resulting erosion rates required to service such intense longshore sediment transport are amongst the largest in the UK. For example, the Holderness coast has retreated by *c.* 4 km over the last 2000 years and many villages, including Roman settlements, have been lost to the sea (http://databases.euccd.de/files/000164_EUROSION_Holderness_coast.pdf) whilst on the Suffolk coast between Benacre Ness and Southwold, recession between 1883 and 2008 was between 550 m (in the north) and 250 m (in the south) as the coast becomes more swash-aligned (Brooks and Spencer, 2010). The long-term evolution of drift-aligned coastal systems can be modelled with the one-line coastal evolution model COVE (Hurst *et al.*, 2015), which is specifically designed to deal with variations in the littoral drift rate (and direction) along non-straight coastlines. The interaction between tidal inlets and the adjacent open coasts also requires consideration (Burningham and French, 2006; Ranasinghe, 2016). The type of interaction will depend on the tidal asymmetry of the inlet: when the inlet is ebb-dominant (flood-dominant), sea-level rise may cause an export (import) of sediment, countering (promoting) retreat of the adjacent coast (Stive, 2004).

Although sea-level rise is the long-term driver of shoreline change, extreme water levels and storms are also important for the stability of barrier coasts (Pye and Blott, 2008). In fact, it is the long-term integration of storm response and subsequent recovery, superimposed on a rising sea level, which is responsible for the long-term coastal evolution. The impacts of the 2013/14 winter were already alluded to in Section 2 and apart from the energy level of the storm waves, two additional factors were found to be important in terms of causing coastal impacts. First, the timing of the storm in relation to the tidal stage is critical, with storm impacts maximised when the peak of the storm coincides with spring high tide. This was demonstrated for Liverpool Bay (Dissanayake *et al.*, 2014), south-west England (Masselink *et al.*, 2015) and east England (Brooks *et al.*, 2016). Second, the direction of the storm waves is also important in determining the scale and type of coastal impacts, because wave direction in relation to shoreline orientation controls wave sheltering *versus* exposure, and cross-shore *versus* longshore sediment transport, and the potential for beach rotation (Burvingt *et al.*, 2017). Variability in wave direction explains why the westerly Atlantic storm waves during the 2013/14 winter had the largest impacts on the north coast of Cornwall and Devon, whereas the south-westerly Atlantic storm waves caused most damage to the south coast of Cornwall and Devon (Masselink *et al.*, 2015).

Process-based numerical models are capable of predicting extreme storm impacts (e.g. Dissanayake *et al.*, 2014), including overwash processes on gravel beaches (e.g. McCall *et al.*, 2014, 2015). However, such models are generally not capable of forecasting the slower process of beach recovery. Equilibrium-based modelling approaches, such as developed by Davidson *et al.* (2013), do seem to be able to forecast post-storm recovery quite well. In this approach, wave conditions more energetic than the antecedent conditions (averaged over an extended time, at least several months) result in shoreline retreat, less-energetic conditions cause shoreline progradation.

2.5 What is already happening: Estuaries

Generally, estuaries migrate landwards and upwards with rising sea level through a redistribution of sediment within the estuarine system from outer to inner estuary, accompanied by a widening of the tidal channels, especially in the outer estuary, and this is reproduced by various type of modelling approaches based (e.g. Allen, 1990; Stive *et al.*, 1998; Townend and Pethick, 2002; Townend, 2005; Rossington and Spearman, 2009). An important aspect of the landward movement of the estuarine system is the concurrent deposition of clay and silts onto saltmarshes and tidal flats, because it may enable these environments to ‘keep up’ with rising sea levels (D’Alpaos *et al.*, 2011). The apparent recent increase in Scottish west coast saltmarsh sedimentation rates from 1 to 3 mm/year (last 70-year average) to 6 to 9 mm/year (last 10-year average) is worth noting here, and is attributed to new material from marine/intertidal origin allowing marshes to maintain a quasi-equilibrium with estimated sea-level rise (Teasdale *et al.*, 2011). It is now widely recognised that an ample sediment supply, whether mud, silt, sand or gravel, is essential for the development of natural forms of coastal protection, such as saltmarshes, barriers, beaches and dunes (Hanley *et al.*, 2014).

A Boolean network approach has also been applied to analyse the long-term response of estuaries to sea-level rise (Reeve and Karunarathna, 2009). This analysis supported the widely kept notion that the nature of long-term morphodynamic response to sea-level rise depends on the type of estuary and the availability of external sediment to meet the increasing sediment demand within the system. If the estuary has an abundant influx of external sediment on a continuous basis, then the estuary is able to maintain its geomorphology and reach a stable state. In the absence of adequate supply of external sediment, some of the prominent features such as saltmarshes and spits are likely to recede or disappear altogether during the process of morphological evolution against sea-level rise. The analysis also suggested that moderate human interference in the form of dredging and structural construction does not have a significant impact on the overall geomorphology of estuaries in the long-term.

If the natural response of estuaries to sea-level rise – landward migration – is inhibited by coastal defence structures, the erosion of the seaward edge of saltmarshes and the lower part of the intertidal zone nevertheless occurs (Van der Wal and Pye, 2004). This results in a narrowing of the intertidal zone, or coastal squeeze. The best management solution from a geomorphological perspective would be to relocate the line of defence landwards of its existing position to allow salt marsh and intertidal mud flats to develop landward of those already in existence. This management option is referred to as 'managed re-alignment'. Ideal estuaries for successful re-alignment schemes are those with extensive reclaimed areas, where restoration of the outer estuary produces the sacrificial area for sediment erosion, and restoration of the head of the estuary will act as a sink for these sediments allowing the estuary to transgress (Townend and Pethick, 2002). In this context the recently implemented managed re-alignment scheme on the Steart Peninsula, near Bridgwater in Somerset, is of significant interest as it aims to create over 400 ha of valuable natural habitats including saltmarsh and freshwater wetland, as well as providing coastal protection (http://www.environment-agency.gov.uk/homeandleisure/floods/80793.aspx). Other examples of large managed re-alignment schemes include Wallasea (115 ha) and Medmerry (500 ha).

3. WHAT COULD HAPPEN IN THE FUTURE?

The two main consequences of climate change that have an impact on coastal erosion and coastal geomorphology are sea-level rise and changes to the wave climate (storminess and prevailing wave direction). The global rate of sea-level rise estimated from (satellite) altimetry data over the 25-year period from 1993 to 2017 is 3 ± 0.4 mm/year and accelerating at 0.084 ± 0.025 mm/yr^2 (Nerem *et al.*, 2018); however, not all coastal locations seem to conform to this accelerating trend. For example, Haigh *et al.* (2011) found that the current rate of sea-level rise at 16 sites along the English Channel over the period 1993–2008 was considerably higher than that averaged over the complete data records, but was within the envelope of observed change when compared with other 15-year periods since 1900. In other words, there have been several periods during the 20th Century when the rate of sea-level rise along the English Channel was similar to that at present.

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) predicts that the rise in Global Mean Sea Level (GMSL) by 2100 will be in the range of 0.27–0.61 to 0.53–0.98 m (Table 2), depending on the Representative Concentration Pathway (RCP; RCP is a greenhouse gas concentration (not emissions) trajectory adopted by the IPCC for its fifth Assessment Report (AR5) in 2013. There are four: RCP2.6, RCP4.5, RCP6 and RCP8.5.) used (Church *et al.*, 2013). For the UK, the IPCC climate change projections have recently been updated by UKCP18 using Met Office predictions (Palmer *et al.*, 2018; https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Marine-report.pdf). The UKCP18 GMSL projections are rooted in the materials and methods described AR5, but the main difference between the UKCP18 projections and the IPCC AR5 projections is that the aforementioned includes updated estimates of the contribution from Antarctic ice dynamics. The change in Antarctic ice dynamics brings about more substantive changes to the GMSL projections, systematically increasing the projections, and in particular raising the value of the 95th percentile (i.e. the upper bound of the likely range) by 0.06–0.14 m (Table 2). Additionally, UKCP18 have conducted exploratory sea-level projections for a larger time horizon to 2300, suggesting that UK sea levels will continue to rise over the coming centuries under all RCP climate change scenarios. The GMSL projection ranges at 2300 are approximately 0.6–2.2 m, 0.9–2.6 m and 1.7–4.5 m for RCP2.6, RCP4.5 and RCP8.5, respectively (Table 2).

Because of differences in land-level changes due to the Glacial Isostatic Adjustment (GIA), the projected Relative Sea-Level (RSL) change in the UK is different from the GMSL change; specifically, the projected increase in RSL in England and Wales is larger than in Scotland and Ireland. For example, for RCP4.5, the RSL projections for 2100 are 0.37–0.83 m, 0.35–0.81 m, 0.15–0.61 m and 0.18–0.64 m for London, Cardiff, Edinburgh and Belfast, respectively (Table 2). The geographical difference becomes more pronounced when long-range RSL projections are considered. For London/Cardiff the projection ranges at 2300 are 0.5–2.2 m, 0.8–2.6 m and 1.4–4.3 m for RCP2.6, RCP4.5 and RCP8.5, respectively. The values for Edinburgh/Belfast are substantially lower, with corresponding ranges at 2300 of 0.0–1.7 m, 0.2–2.1 m and 0.7–3.6 m.

Table 2: Summary of projected sea level for UKCP18 and the IPCC AR5 (modified from Palmer et al., 2018).

	Sea-level change at 2100 (m) relative to 1981–2000 average		
	RCP2.6	**RCP4.5**	**RCP8.5**
	Global Mean Sea Level (GMSL) change		
ICCP (AR5)	0.27-0.61	0.36-0.71	0.53-0.98
UKCP18 Global 21st century projection	0.29-0.67	0.38-0.79	0.56-1.12
Extended Global projection to 2300	0.6-2.2	0.9-2.6	1.7-4.5
	Relative Sea Level (RSL) change		
London	0.28-0.70	0.37-0.83	0.53-1.15
Cardiff	0.27-0.69	0.35-0.81	0.51-1.13
Edinburgh	0.08-0.49	0.15-0.61	0.30-0.90
Belfast	0.11-0.52	0.18-0.64	0.33-0.94

According to UKCP18, coastal flood risk in the UK is expected to increase over the 21st century and beyond under all RCP climate-change scenarios. This means that we can expect to see both an increase in the frequency and magnitude of extreme water levels around the UK coastline. This increased future flood risk will be dominated by the effects of relative sea-level rise, rather than changes in atmospheric storminess associated with extreme coastal sea-level events (cf. Haigh *et al.*, 2010).

UKCP18 also provide projections for future wave conditions and 21st century projections of *mean* significant wave height suggest changes of the order 10–20% and a general tendency towards lower mean wave heights, especially in the south-west of the UK and Ireland. Of more significance for coastal impacts, the *maximum* significant wave height is projected to increase off the south-west of the UK and in parts of the Irish Sea, but to reduce off the west of Ireland and in the southern North Sea. This could be explained dynamically by a southward shift in the position of the storm-track (Lowe *et al.* (2009), although this is at odds with the general expectation for a poleward shift in the mid-latitude jet (Barnes and Polvani, 2013). An increase in annual *maximum* significant wave height is also predicted to the north of the UK, related to a change in sea-ice cover due to global warming, leading to increased fetch for northerly winds in Nordic Seas. High-resolution wave simulations suggest that the changes in wave climate over the 21st century on exposed coasts will be dominated by the global response to climate change. The wave projections presented in UKCP18 should be seen as indicative of the potential changes with low confidence.

The Foresight project (*http://www.foresight.gov.uk/OurWork/CompletedProjects/Flood/index.asp*) estimated future coastal erosion rates for England and Wales, and compared these to the benchmark present condition (20–67 m erosion over 100 years).

Depending on the emissions scenario, the amount of erosion predicted to occur over the next 100 years ranges between 82 and 175 m, with the most severe erosion occurring in the east of England (Evans *et al.*, 2004) due to the combination of disequilibrium morphology (shoreline is out of equilibrium with prevailing wave direction and present sea level, which was only reached *c*. 5000 years ago; refer to 2013 MCCIP Report Card) and an easily erodible coastline made of unconsolidated material (mainly unconsolidated glacial and pre-glacial gravels, sands and silts with interbedded clays). Such national, or even regional, predictions of coastal erosion are of limited use, however, because coastal erosion is largely a local process and coastal recession rates are spatially highly variable. Coastal scientists and managers are aware of the importance of geographical variability in coastal change; therefore, a Geographical Information System (GIS) framework is usually adopted to quantify current coastal changes, and assess societal risk of coastal erosion. Examples of such initiatives include Esteves *et al.* (2008) at the local scale, Christie *et al.* (2017) on the regional scale, Rogers *et al.* (2008) at the national scale and Luijendijk *et al.* (2018) on a global scale.

Of most relevance to estimating future shoreline positions, a GIS framework can be used to assess historical shoreline change with the Digital Shoreline Analysis System (DSAS – latest version 4.4) from the USGS (Thieler *et al.*, 2017). This automated method allows for a very high level of spatial densification and a shoreline response model can then be run into the future making assumptions about how the shoreline will respond to future sea-level rise. The UK Environment Agency Planning Epochs are 2025, 2055 and 2105, and the future shoreline position for each of the planning epochs can be mapped under different emissions scenarios. Risk to habitats, societies and infrastructure can then be identified over these different epochs (e.g. how much land of Special Scientific Interest (SSSI) or Special Area of Conservation (SAC) status will be lost? What should we be doing to compensate this loss? What are the implications of no longer being under European legislative control?). Projections of coastal erosion have been made available by the Environment Agency (http://apps.environment-agency.gov.uk/wiyby/134808.aspx). These projections are based on combining existing coastal recession rates with a probabilistic method for assessing the hazard and risk of coastal erosion (resulting from the Risk Assessment of Coastal Erosion project; Halcrow, 2006), and determine coastal erosion risk at the local scale 20, 50 and 100 years into the future. These are widely used as supporting information for coastal planning applications, e.g. cliff-top development.

Predicting future coastal erosion rates remains problematic and in the absence of a clear understanding of the coastal-change processes, including past coastal change and causes of coastal erosion, and therefore a reliable predictive tool, the default position is to assume that present-day coastal change will persist. However, improved predictions of coastal change can be attained using models that take (accelerated) sea-level rise into account (e.g. Brooks and Spencer, 2012). The simplest model for this purpose is:

$$R_2 = R_1(S_2/S_1)^m$$

where R_1 and R_2 are the historical and future shoreline retreat, respectively, S_1 and S_2 are the historical and future rates of sea-level rise, respectively, and m is a response coefficient which generally ranges from 0 (no response) to 1 (instant response). It is very likely that stretches of coast currently undergoing erosion will experience increased erosion rates due to sea-level rise ($m > 0$) and that coastal erosion is likely to affect previously stable adjacent areas. Moreover, the removal of coastal defences, which is likely to increase in response to anticipated and enhanced uptake of the managed re-alignment coastal management strategy, will initially increase coastal erosion rates to allow the coast to 'catch up' ($m > 1$), but may bestow benefits over longer timescales. In summary, therefore, the average coastal recession rates and the proportion of eroding coastlines, in both UK and Ireland, are expected to increase in the future.

A key aspect of climate change impact on coastal geomorphology will be the role of (winter) storms. The North Atlantic Oscillation (NAO; quantified by the normalised pressure difference between the Azores and Iceland) is the dominant mode of winter climate variability in the North Atlantic and exerts a major control on the winter wave conditions in the UK, and wave conditions in Scotland and Ireland. The newly defined West Europe Pressure Anomaly (WEPA; quantified by the normalised pressure difference between the Canary Islands and Ireland) is particularly well correlated with the winter wave conditions in south-west England (Castelle *et al.*, 2017). Positive phases of NAO (and WEPA) represent enhanced westerly airflow and relatively stormy winter wave conditions along the west coast of UK and Ireland, whereas the weaker westerly airflow during negative phases of NAO may allow strong easterly air flow and stormy winter wave conditions along the east coast of England (Brooks and Spencer, 2013). Recent work in the Start Bay embayment in south Devon has suggested a strong link between the positive and negative phases of NAO, the littoral drift direction and rotation of the gravel beaches within the bay (Wiggins *et al.*, 2017). Using a 69-year numerical weather and wave hindcast, Castelle *et al.* (2018) demonstrated that winter-mean wave height, variability and periodicity all increased significantly in the North-East Atlantic, which primarily correlate with changes in the NAO and WEPA climate indices. It is unclear whether this is the result of climate change, as climate models have not reached a consensus about the impact of climate change on NAO and hence the winter storm-wave climate. However, if winter storm conditions become increasingly energetic then this will have major implications for the coastal geomorphology: both hard- and soft-rock cliff erosion rates are expected to increase and barrier coasts will experience a transfer of sediment from the supra- and inter-tidal sediment stores to the subtidal region.

4. ADAPTING TO COASTAL EROSION

It is now widely accepted that, largely due to human-induced climate change, sea level is rising at an accelerated rate and extreme storms may increase in frequency and intensity in the future. Both climate-change impacts will enhance coastal flooding and erosion, and what is currently considered normal in terms of coastal flood frequency and erosion rate, is unlikely to be so in the future. To illustrate the potential threats to the coastal zone, by the end of this century, five million Europeans currently under threat of a 100-year coastal flood event could be annually at risk from coastal flooding (Vousdoukas *et al.*, 2017). The 2013/14 winter has further demonstrated that the UK coastline is vulnerable to extreme storms and associated elevated water levels, especially if the storm peak coincides with spring high tide conditions. Our vulnerability to increased sea level and wave conditions stems largely from our intense occupation and use of the coastal zone, and our desire, if not obsession, to keep the coastline where it currently is. Such stance inhibits the natural adaptation of the coastline, which would be to migrate landwards, without any loss of coastal habitat. There is now the realisation that the default position of defend/hold the line will become prohibitively expensive in the future, and, although it may still remain the preferred management strategy for particularly 'valuable' coastal stretches, we should increasingly try to deal with the anticipated risks and consequences of climate change without obsessing about keeping the coastline where it is. This tends to involve the practice of 'Working with Nature', 'Building with Nature' or 'Working with Natural Processes' (https://www.gov.uk/government/publications/working-with-natural-processes-to-reduce-flood-risk). Successful execution of projects that work with natural processes, whether we are talking about mega-nourishment or managed realignment, requires a robust understanding of the coastal processes involved (e.g. cliff recession rates, sediment fluxes, extreme storm impacts) and reliable numerical models (e.g. SCAPE, ASMITA, XBeach, Delft3D) for prediction of coastal change. A lot of progress has been made in the last decade in both these two areas, opening the way for a wider implementation of more-innovative and sustainable climate change adaptations. A good example of a large organisation that practices what it preaches in terms of working with natural processes is the National Trust through its Shifting Shores policy (https://www.nationaltrust.org.uk/documents/shifting-shores-report-2015.pdf).

One of the most important concepts to have emerged from several decades of (sustainable) coastal zone management is that of *adaptation*, which, in the context of this report, refers to an adjustment in natural or human systems as a means of moderating the adverse impacts of and reducing the vulnerability to coastal erosion. As outlined in Table 2 , there are three basic adaptation approaches: (1) protect, (2) accommodate and (3) retreat, and each of these approaches may be pursued through the implementation of one of more complementary adaptation technologies (Linham and Nicholls, 2012). Most of these adaptation approaches reduce coastal flood risk (e.g. sea dykes, seawalls), some contribute to habitat creation (e.g. wetland restoration, coastal dune construction), and protection can be achieved by means of both hard and soft engineering approaches. It is noted that the three basic adaptation strategies do not quite map onto the four policy options provided in the second generation Shoreline Management Plans (SMPs), which are: hold the line, advance the line, managed realignment and no active intervention – because the adaptations are approaches, whereas the policy options are objectives. Nevertheless, adaptation is an important aspect of these non-statutory policy documents, as illustrated in several case studies discussed by Pontee and Parsons (2012). Early warning systems and evacuation planning for extreme events should also be considered an important aspect of adaptation. The 2013 surge showed the devastating effects of a coincident high spring tide, surge and onshore waves for Norfolk, but did not result in the loss of life, because a large number of people were evacuated based on forecasts of water levels and wave conditions. Availability of robust and reliable coastal flood warning systems will to some extent enable continued occupation in relatively high coastal flood-risk zones. Finally, it is worth emphasising that generally most adaptation is reactive rather than proactive, i.e. in response to immediate threats/risks to coastal infrastructure rather than in anticipation of threats/risks, as funding for reactive projects is less difficult to secure than for proactive projects. This is short-sighted and costly in the long run, but even more concerning is the lack of consideration of climate change impacts in coastal planning, with coastal development in coastal risk zones still routinely approved by local and regional planning bodies. Such a tension regarding the sustainability of some adaptation approaches led Cooper and Pile (2014) to consider approaches within an ‘adaptation-resistance spectrum’. At one end measures involve changing human activities to suit the environment (innovative building design, relocation etc) are contrasted with activities which resist environmental change (higher sea walls, nourishing beaches). They suggest that most adaptive activities fall towards the ‘resistance’ end of the spectrum at present, but *‘measures that involve adaptation of human activities in response to the changing coastal environment are likely to be more sustainable in the longer term, but are politically more difficult to implement’* (e.g. Frew, 2012).

It is of particular importance to develop long-term strategic adaptation plans for the full range of possible climate change outcomes, both in terms of changes in sea level, extreme water level, storminess and wave climate (Nicholls, *et al.*, 2011). An example of such long-range planning is that being considered in the Netherlands and proposed by the Second Delta Commission (http://www.deltacommissie.com/en/advies). In the UK, the Thames Estuary 2100 (TE2100) Project which considers flood management in London and its environs is a good example (http://www.metoffice.gov.uk/services/climate-services/case-studies/barrier). The inclusion of a 50–100 year time horizon in the SMPs is also encouraging, but an even longer-ranging view may be appropriate.

There thus appears to be a portfolio of options available to adapt to climate change impacts and coastal erosion (Table 3). Coastal protection by means of hard engineering structures with the objective to 'hold the line' has been the panacea of coastal zone management for most of the previous century, but soft engineering has increased in prominence over the last 20 years or so, albeit still with the main objective to hold the line. More recently, the concept of 'working with natural processes' and 'building with nature' has come to the fore (e.g. Hanley *et al.*, 2014), and covers several approaches, including dune construction, restoring reclaimed saltmarshes, stop defending eroding coastal cliffs and beach nourishment. Only beach nourishment (or recharge) has a positive influence on the coastal sediment budget, and has been increasingly used since the 1990 in the UK to provide a natural means of coastal protection. The shift from 'hold the line' to 'managed retreat' is clearly documented in the change in the dominant policy advice from the first to the second generation SMPs, as the latter widely advise managed re-alignment as the preferred policy, especially for the longer time horizons (20–50 and 50–100 years). Although managed re-alignment will result in a local increase in the erosion rate, especially where existing coastal defences are being removed, the enhanced erosion may benefit other sections of coast by reducing erosion or even causing accretion. Implementation of such strategy will have significant socio-economic implications and is influenced by financial, conservation, legal and social justice arguments (Cooper and McKenna, 2008), but generally makes sound economic sense.

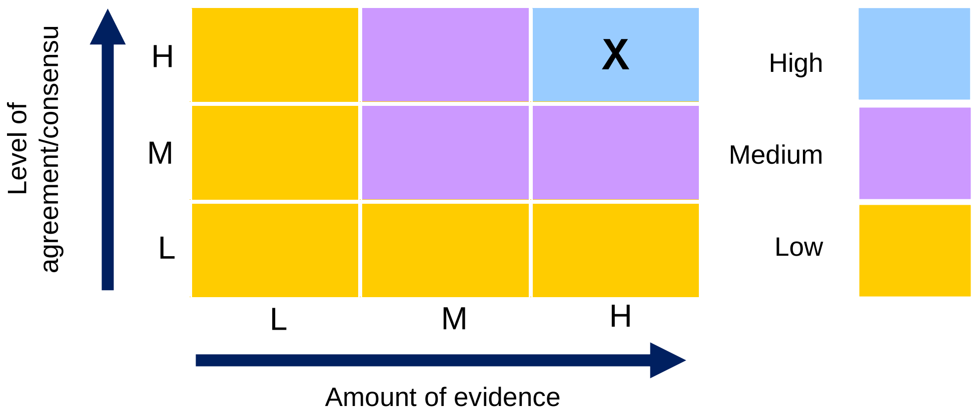
Table 3: Commonly applied coastal adaptation technologies. This table has been modified from Linham and Nicholls (2012) to make it specific to coastal erosion (the original table was related to coastal erosion and flood management).

Adaptation approach	Technology
Hard protection	Seawall/revetments Sea dykes Groynes Detached breakwaters Land claim Raise land areas
Soft protection	Beach nourishment Coastal dune construction Sandscaping
Accommodate	Flood-proofing Wetland restoration Coastal aquaculture
Retreat	Managed realignment Coastal setbacks and zoning

A novel development, pioneered in the Netherlands, is the placement of very large quantities of sediment (> 10M m^3) on the beach and shoreface, so called 'mega-nourishments' or 'sandscaping' (Brown *et al.*, 2016; Luijendijk *et al.*, 2017). Such interventions not only contribute to a long-term positive sediment budget for a very large region (> 10 km), but also serve as a means of nature creation, subscribing to the 'Building with Nature' philosophy (https://publicwiki.deltares.nl/display/BTG/Guideline). The UK's first sandscaping scheme is currently in the planning process and is designed to raise the beach levels to protect the Bacton gas terminal and the nearby villages of Bacton and Walcott (https://www.north-norfolk.gov.uk/sandscaping). Mega-nourishment or sandscaping is still in an experimental phase, but may very well be the future of coastal protection, or at least develop into one of the main adaptation tools to sea-level rise and coastal erosion. Coastal planning in the UK could be tightened to limit development and investment in present and future coastal risk areas to avoid burdening future generations.

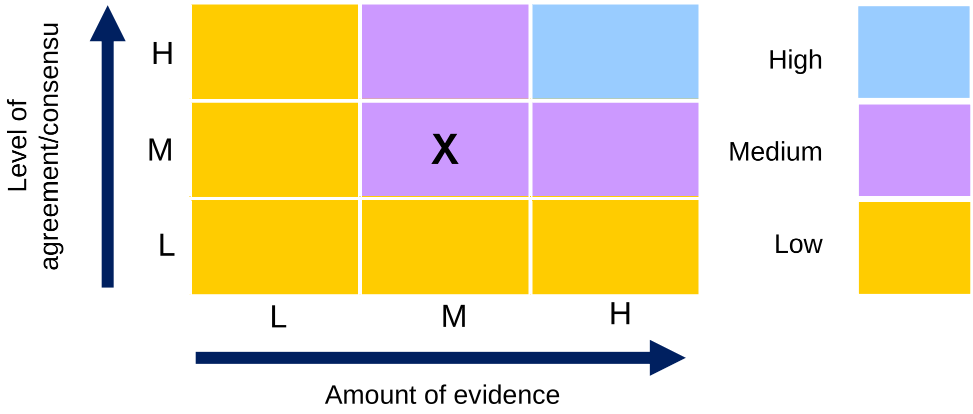
5. CONFIDENCE ASSESSMENT

What is already happening?



High evidence and High agreement
High confidence for the present statement is derived from the detailed and comprehensive studies that have been carried out to assess current coastal erosion rates (EUROSION, Futurecoast, ForeSight, Dynamic Coast projects).

What could happen in the future?



Medium evidence and Medium agreement

Coastal erosion is only partly driven by sea-level rise; therefore, medium confidence in predictions can be achieved for many regions by assuming current erosion rates (which are generally well-constrained) persist. However, coastal erosion is likely to be exacerbated by sea-level rise and coastal response is also susceptible to changes in the wave climate (storminess and wave direction). Since there are uncertainties about these climate-induced changes in coastal forcing factors, and the relation between sea-level rise and coastal erosion is highly non-linear due to the interconnectedness of coastal systems in terms of sediment fluxes and process linkages, high confidence for the future is still some way off. A further complicating factor is the coastal management, in particular the adaptation strategy used to combat coastal erosion. Nevertheless, especially for eroding soft-cliff coastlines, model predictions of coastal retreat are becoming increasingly reliable and useful for coastal zone planning and management.

Knowledge gaps and emerging issues

1. ***Long-term and large-scale coastal system response to sea-level rise*** – Process-based models for open coastlines can at best forecast coastal change over relatively short timescales (< weeks) and small spatial scales (< 1 km). There is a real need for models to be able to predict larger scale (> 10 km) coastal system behaviour over longer timescales (> decades). Simple up-scaling of existing process-based model does not work, and behaviour-oriented or parametric models are not yet at the level to be able to provide reliable quantitative long-range forecasts. The Futurecoast approach of considering the coast as a series of Coastal Behavioural Systems (CBS) is a significant step forward, but our understanding of how these CBSs function remains largely conceptual and this needs to be much more quantitative. In addition, the role of coastal management will need to be incorporated in these models. Only for soft-cliff coastlines there is some predictive capability over long timescales, but this is in part due to

the fact that such systems already have a reasonably well-constrained baseline erosion rate. The inability to reliably forecast long-term coastal evolution remains the key knowledge gap.

2. ***Coastal response to extreme storms and recovery*** – We lack the understanding and ability to forecast the response of coastal systems to extreme storm events, both with respect to the actual storm impacts and the subsequent recovery. This is particularly relevant for wave-dominated barrier coasts, where sand and gravel barriers serve an important natural coastal protection role. Better understanding of and predictive tools for extreme storm response and recovery are required to assess vulnerability of coastal systems to extreme storm events and help identify critical thresholds and tipping points. In combination with predicted changes in sea-level, storm surge statistics and wave climate, such tools can assist with determining coastal resilience to climate change and assist in the design of coastal protection schemes.
3. ***Bio-physical interactions*** – The vast majority of coastal geomorphological research has been, and still is, largely morphodynamical, focussing on the mutual interactions between morphology, hydrodynamics and sediment transport. It is now increasingly appreciated that biological interactions can also play a fundamental role in coastal processes and evolution. Such bio-physical interactions range from the role of extracellular polymeric substance (EPS) on cohesive sediment stability, especially in tide-dominated environments, to the effects of vegetation on the hydro- and sediment dynamics across a range of coastal settings, including coastal dunes, seagrasses meadows and saltmarshes. More needs to be known about these bio-physical interaction so that they can be incorporated into predictive models.

Socio-economic impacts

Coastal erosion is widespread in the UK. The Environment Agency estimates that approximately 700 properties in England are vulnerable to coastal erosion over the next 20 years, and a further 2000 may become vulnerable over the next 50 years. Without coastal protection, these figures could increase to about 5000 properties within 20 years and about 28,000 in 50 years. According to the Committee for Climate Change (CCC), between 2005 and 2014 over 15,000 new buildings were built in coastal areas at significant risk of coastal flooding and/or erosion. By 2022, if current trends continue, this figure is likely to reach 27,000 new properties. But, if the government meets its ambitious house building targets, up to 90,000 homes in the next five years might well be in areas of significant annual flood risk from all sources of flooding, including coastal flooding.

The costs related to coastal erosion are difficult to quantify as they are closely associated with those due to coastal flooding, but the Foresight project estimates damage due to coastal erosion at £15 million per year which may rise to £126 million per year by 2080. However, a major storm event or a series of storm events can spike erosion and flooding impacts costs in a given year. For example, the economic cost resulting from the damage to the Dawlish Railway line during the 2013/14 winter, strictly speaking not coastal erosion damage, is estimated at between £60M and £1.2B.

Increased coastal erosion due to climate change will provide significant opportunities for environmental engineers (mainly coastal engineers) to develop additional, or redesign existing, coastal protection measures, whether in the form of hard engineering structures, or soft engineering practices (beach recharge and managed re-alignment). Increased implementation of beach recharge schemes will have a considerable commercial effect on the aggregate and dredging industry. Mega-nourishment or sandscaping projects will have a particularly large impact in this industry. Depending on how society responds to increased coastal erosion, there can also be a very significant effect on the tourist industry through the loss of beach frontage and recreational beach area.

There is now increased realisation that, against a back drop of relative sea-level rise, reduced nearshore sediment supply from offshore and longshore sources, vulnerability to extreme storms and human interference, all of which are expected to increase due to climate change, current coastal management practices, which are very much focussed on hold-the-line adaption strategies, are not sustainable in the long-term. The second generation Shoreline Management Plans increasingly advocate managed realignment as an alternative adaptation strategy, especially for less developed stretches of coast. In tide-dominated environments (i.e. estuaries), managed re-alignment results in the creation of intertidal habitat and this provides significant opportunities for the tourism industry. A similar effect will be achieved through mega-nourishment or sandscaping projects; the significant increase in the amount of beach area will provide scope for coastal dune development, as well as enhanced recreational facilities. Climate change adaptation should be seen not only as a necessary practice to future-proof our use of the coastal zone, but can also provide opportunities for business, recreation and nature creation.

6. CONCLUSIONS

A large proportion of the coastline of the UK and Ireland is currently suffering from erosion and 28% of the coastline of England and Wales is experiencing erosion greater than 0.1 m per year (i.e. > 10 m over 100 years). In Scotland, 78% of the coast is considered ‘hard’ or ‘mixed’, and is unlikely to erode at perceptible rates, 19% is ‘soft/erodible’, whilst 3% has artificial defences. Since the 1970s, 77% of the soft/erodible coast in Scotland has remained stable, 11% has accreted seawards and 12% has eroded landward. However, as a result of relative sea-level rise, reduced nearshore sediment supply from offshore and longshore sources, vulnerability to extreme storms and human interference, all of which are expected to increase due to climate change, coastal erosion rates are expected to increase in the future and presently stable or accreting coasts may enter into an erosion phase. The natural response of coastal systems to sea-level rise is to migrate landwards, through erosion of the lower part of the nearshore profile and deposition on the upper part, and this roll-over model is applicable to estuaries, barriers and tidal flats. Coastal erosion is, however, strongly determined by site-specific factors and usually it is these factors that determine the coastal response, admittedly against a backdrop of a slowly receding coastline due to sea-level rise. Any predictions of *general* coastal response due to climate change are therefore rather meaningless and will have a low confidence. However, if a detailed study is conducted and long-term coastal change data are available, then *local* or *regional* predictions of coastal response to climate change can have medium confidence, especially if adjustments are made for accelerated sea-level rise. The coastal management strategy for a section of coast (e.g. hard coastal defences, beach nourishment, managed re-alignment) is also a key aspect for determining the long-term response of the coast to climate change effects, including sea-level rise. An adaptation approach that involves working with nature (e.g. beach nourishment, managed retreat), rather than against (e.g. construction of hard defences), is emerging as the key coastal management paradigm to cope with coastal erosion.

REFERENCES

Allen J.R.L. (1990) The Severn estuary in southwest Britain – its retreat under marine transgression, and fine-sediment regime. *Sedimentary Geology*, **66**, 13-28.

Barnes, E.A. and Polvani, L. (2013) Response of the midlatitude jets, and their variability, to increased Greenhouse gases in the CMIP5 models. *Journal of Climate*, **26**, 7117–7135.

Brooks, S.M. and Spencer, T. (2010) Temporal and spatial variations in recession rates and sediment release from soft rock cliffs, Suffolk coast, UK. *Geomorphology*, **124**, 26-41.

Brooks, S.M. and Spencer, T. (2012) Shoreline retreat and sediment release in response to accelerating sea-level rise: measuring and modelling cliffline dynamics on the Suffolk Coast, UK. *Global and Planetary Change*, **80–81**, 165–179.

Brooks, S.M. and Spencer, T. (2013) Importance of decadal scale variability in shoreline response: examples from soft rock cliffs, East Anglian coast, UK. *Journal of Coastal Conservation: Policy and Management*, **18**, 581–593.

Brooks, S.M., Spencer, T. and Boreham, S. (2012) Deriving mechanisms and thresholds for cliff retreat in soft-rock cliffs under changing climates: Rapidly retreating cliffs of the Suffolk coast, UK. *Geomorphology*, **153–154**, 48–60.

Brooks, S.M., Spencer, T., McIvor, A. and Möller, I. (2016) Reconstructing and understanding the impacts of storms and surges, southern North Sea. *Earth Surface Processes and Landforms*, **41**, 855–864.

Brooks, S.M., Spencer, T. and Christie, E. (2017) Storm impacts and shoreline recovery: mechanisms and impacts in the Southern North Sea. *Geomorphology*, **283**, 48–60.

Brown, S., Barton, M.E. and Nicholls, R.J. (2011) Coastal retreat and/or advance adjacent to defences in England and Wales. *Journal of Coastal Conservation*, **15**, 659–670.

Brown, S., Barton, M.E. and Nicholls, R.J. (2012) The effect of coastal defences on cliff top retreat along the Holderness coastline. *Proceedings of the Yorkshire Geological Society*, **59**, 1-13.

Brown, J.M., Phelps, J.J.C., Barkwith, A., Hurst, M.D., Ellis, M.A. and Plater, A.J. (2016) The effectiveness of beach mega-nourishment, assessed over three management epochs. *Journal of Environmental Management*, **184**, 400-408.

Burgess, K., Jay, H., Nicholls, R.J., Green, C. and Penning-Rowsell, E.C. (2007) Assessment of future coastal erosion risk. In *Future Flooding and Coastal Erosion Risks*, [Thorne, C., Green, C. and Penning-Rowsell, E.C. (eds)], Thomas Telford, London, pp. 280–293.

Burningham, H. and French, J. (2014). Travelling forelands: complexities in drift and migration patterns. *Journal of Coastal Research*, **70**, 102–108.

Burningham, H. and French, J. (2016) Shoreline-shoreface dynamics on the Suffolk coast. Final Report for The Crown Estate, https://www.thecrownestate.co.uk/media/1005408/dynamics-on-the-suffolk-coast.pdf

Burningham, H. and French, J. (2017) Understanding coastal change using shoreline trend analysis supported by cluster based segmentation. *Geomorphology*, **282**, 131–149.

Burvingt, O., Masselink, G., Russell, P. and Scott, T. (2017) Classification of beach response to extreme storms. *Geomorphology*, **295**, 722–737.

Burvingt, O. Masselink, G., Scott, T, Russell, P. and Davidson, M. (2018) Climate forcing of regionally-coherent extreme storm impact and recovery on embayed beaches. *Marine Geology*, **401**, 112–128.

Castelle, B., Dodet, G., Masselink, G. and Scott, T. (2017) A new climate index controlling winter wave activity in W Europe: the West Europe Pressure Anomaly (WEPA). *Geophysical Research Letters*, **44**, doi: 10.1002/2016GL072379

Castelle, B., Dodet, G., Masselink, G. and Scott, T. (2018) Increased winter-mean wave height, variability and periodicity in the North-East Atlantic over 1949-2017. *Geophysical Research Letters*, **45**, 3586–3596, doi: 10.1002/2017GL076884

Cazenave, A. and Le Cozannet, G. (2014) Sea level rise and its coastal impact. *Earth's Future*, **2**, 15–34.

Christie, E.K., Spencer, T., Owen, D., McIvor, A.L., Möller, I. and Viavattene, C. (2017) Regional coastal flood risk assessment for a tidally dominant, natural coastal setting: North Norfolk, southern North Sea. *Coastal Engineering*, **134**, 177–190.

Church, J.A., Clark, P.U., Cazenave, A., Gregory, J.M., Jevrejeva, S. *et al*. (2013) Sea level change. In *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.

Cooper, J.A.G. and McKenna, J. (2008) Social justice in coastal erosion management: the temporal and spatial dimensions. *Geoforum*, **39**, 294–306.

Cooper, J.A.G and Pilkey, O.H. (2004) Sea-level rise and shoreline retreat: time to abandon the Bruun Rule. *Global and Planetary Change*, **43**, 157–171.

Cooper, J.A.G. and Pile, J. (2014) The adaptation-resistance spectrum: A classification of contemporary adaptation approaches to climate-related coastal change. *Ocean and Coastal Management*, **94**, 90–98.

D'Alpaos, A., Mudd, S.M. and Carniello, L. (2011) Dynamic response of marshes to perturbations in suspended sediment concentrations and rates of relative sea level rise. *Journal of Geophysical Research: Earth Surface*, **116**, F04020.

Davidson, M.A., Splinter, K.D. and Turner, I.L. (2013) A simple equilibrium model for predicting shoreline change. *Coastal Engineering*, **73**, 191–202.

Dawson, S., Powell, V.A., Duck, R.W., McGlashan, D.J. and Shennan I. (2012) Reply to: Discussion of "Rennie, A.F. and Hansom, J.D. (2011) 'Sea level trend reversal: land uplift outpaced by sea level rise on Scotland's coast'. *Geomorphology* **125**, 193-202". *Geomorphology*, **197**, 188–189, doi:10.1016/j.geomorph.2012.06.029

Dean, R.G. and Houston, J.R. (2016) Determining shoreline response to sea level rise. *Coastal Engineering*, **114**, 1–8.

Delgado-Fernandez, I. (2011) Meso-scale modelling of Aeolian sand input to coastal dunes. *Geomorphology*, **130**, 230–243.

Dhoop, T. and Mason, T. (2018) Spatial characteristics and duration of extreme wave events around the English coastline. *Journal of Marine Science and Engineering*, **6**, 14.

Dickson, M., Walkden, M. and Hall, J. (2007). Systematic impacts of climate change on an eroding coastal region over the 21st Century. *Climate Change*, **84**, 141–166.

Dissanayake, P., Brown, J. and Karunarathna, H. (2014) Modelling storm-induced beach/dune evolution: Sefton coast, Liverpool Bay, UK. *Marine Geology*, **357**, 225–242.

DMF (2014) Holding the Line: Reviewing the impacts, responses and resilience of people and places in Devon to the winter storms of 2013/14. *Devon Maritime Forum*, https://www.devonmaritimeforum.org.uk/library/

Dornbush, U., Williams, R.B.G., Moses, C.A. and Robinson, D.A. (2008) Foreshore narrowing along the coast of southeast England, UK – a re-evaluation. *Journal of Coastal Research*, **24**, 14–24.

EA (2011) Coastal trends report Suffolk (Lowestoft to Languard Point, Felixstowe). Shoreline Management Group, Environment Agency, RP022/S/2011.

Earlie, C., Masselink, G., Russell, P.E. and Shail, R. (2014) Application of airborne LiDAR to investigate rates of recession in rocky coast environments. *Journal of Coastal Conservation: Planning and Management*, **19**, 831–845.

Earlie, C.S., Masselink, G. and Russell, P. (2018) The role of beach morphology on coastal cliff erosion under extreme waves. *Earth Surface Processes and Landforms*, **43**, 1213–1228.

Esteves, L.S., Williams, J.J., Nock, A. and Lymbery, G. (2008) Quantifying shoreline changes along the Sefton coast (UK) and the implications for research-informed coastal management. *Journal of Coastal Research*, **SI56**, 602-606.

EUROSION (2004) Project commissioned by General Directorate Environment of the European Commission, http://www.eurosion.org

Evans, E., Ashley, R., Hall, J., Penning-Rowsell, E., Saul, A., Sayers, P., Thorne, C. and Watkinson, A. (2004) *Foresight. Future Flooding. Scientific Summary: Volume I – Future risks and their drivers*, Office of Science and Technology, London.

Frew, P. (2012) Adapting to coastal change in north Norfolk, UK. *Maritime Engineering*, **165**, 131–138.

Futurecoast (2002) Final Project Report, Defra, http://www.defra.gov.uk/environ/fcd/futurecoast.htm

Hackney, C., Darby, S. and Leyland, J. (2013) Modelling the response of soft cliffs to climate change: a statistical process-response model using accumulated excess energy. *Geomorphology*, **187**, 108–121.

Haigh, I., Nicholls, R. and Wells, N. (2010) Assessing changes in extreme sea levels: Application to the English Channel. *Continental Shelf Research*, **30**, 1042–1055.

Haigh, I., Nicholls, R. and Wells, N. (2011) Rising sea levels in the English Channel 1900 to 2100. *Maritime Engineering*, **164**, 81–92.

Haigh, I.D., Wadey, M.P., Wahl, T., Ozsoy, O., Nicholls, R.J., Brown, J.M., Horsburgh, K. and Gouldby, B. (2016) Spatial and temporal analysis of extreme sea level and storm surge events around the coastline of the UK. *Scientific Data*, **3**, doi: 10.1038/sdata.2016.107

Halcrow (2006) *Risk Assessment of Coastal Erosion (RACE)*, Final Reports, Defra R&D Project FD2324, Defra Flood Management Division.

Hanley, M.E. *et al*. (2014) Shifting sands? Coastal protection by sand banks, beaches and dunes. *Coastal Engineering*, **87**, 136–146.

Hansom, J.D., Fitton, J.M., and Rennie, A.F. (2017) *Dynamic Coast - National Coastal Change Assessment: National Overview*, CRW2014/2.

Horillo-Caraballo, J.M. and Reeve, D.E. (2008) Morphodynamic behaviour of a nearshore sandbank system: the Great Yarmouth sandbanks, UK. *Marine Geology*, **254**, 91–106.

Hurst, M.D., Barkwith, A., Ellis, M.A., Thomas, C.W. and Murray, A.B. (2015) Exploring the sensitivities of crenulate bay shorelines to wave climates using a new vector-based one-line model. *Journal of Geophysical Research: Earth Surface*, **120**, 2586–2608.

Hurst, M.D., Rood, D.H., Ellis, M.A., Anderson, R.S. and Dornbusch, U. (2016) Recent acceleration in coastal cliff retreat rates on the south coast of Great Britain. *PNAS*, **113**, 13336–13341.

Jackson, D.W.T., Cooper, J.A.G. and del Rio, L. (2005) Geological control of beach morphodynamic state. *Marine Geology*, **216**, 297–314.

Jackson, D.W.T. and Cooper, J.A.G. (2010) Application of the equilibrium planform concept to natural beaches in Northern Ireland. *Coastal Engineering*, **57**, 112–123.

Klein, A., Benedet, L. and Schumacher, D.H. (2002) Short-term beach rotation processes in distinct headland bay beach systems. *Journal of Coastal Research*, **18**, 442–458.

Lee, E.M. and Clark, A.R. (2002) *The Investigation and Management of Soft Rock Cliffs*. Thomas Telford.

Lim, M., Rosser, N.J., Allison, R.J. and Petley, D.N. (2010) Erosional processes in the hard rock coastal cliffs at Staithes, North Yorkshire. *Geomorphology*, **114**, 12–21.

Linham, M.M. and Nicholls, R.J. (2012) Adapting technologies for coastal erosion and flooding: a review. *Maritime Engineering*, **165**, 95–111.

Lowe, J.A., Howard, T.P., Pardaens, A., Tinker, J., Holt, J. *et al*. (2009) *UK Climate Projections Science Report: Marine and coastal projections*, Met Office Hadley Centre, Exeter, UK.

Luijendijk, A.P., Ranasinghe, R., de Schipper, M.A., Huisman, B.A. and Stive, M.J.F. (2017) The initial morphological response of the Sand Engine: A process-based modelling study. *Coastal Engineering*, **119**, 1–14.

Luijendijk, A., Hagenaars, G., Ranasinghe, R., Baart, F., Donchyts, G. and Aarninkhof, S. (2018) The state of the world's beaches. *Scientific Reports*, **8**, 6641, doi: 10.1038/s41598-018-24630-6

Masselink, G., Hughes, M.G. and Knight, J. (2011) *Introduction to Coastal Processes and Geomorphology* (2nd Edition), Arnold, London.

Masselink, G., Scott, T., Poate, Russell, P., Davidson, M. and Conley, D. (2015) The extreme 2013/14 winter storms: hydrodynamic forcing and coastal response along the southwest coast of England. *Earth Surface Processes and Landforms*, **41**, 378–391.

McCall, R.T., Poate, T.G., Masselink, G. Roelvink, J.A., Almeida, L.P., Davidson, M. and Russell, P.E. (2014) Modelling storm hydrodynamics on gravel beaches with XBeach-G. *Coastal Engineering*, **91**, 231–250.

McCall, R.T., Masselink, G., Poate, T.G., Roelvink, L.P. and Almeida, L.P. (2015) Modelling the morphodynamics of gravel beaches during storms with XBeach-G. *Coastal Engineering*, **103**, 52–66.

Montreuil, A-L. and Bullard, J.E. (2012) A 150-year record of coastline dynamics within a sediment cell: Eastern England. *Geomorphology*, **179**, 168–185, doi: 10.1016/j.geomorph.2012.08.008

Nerem, R.S., Becklay, B.D., Fasullo, J.T., Hamlington, B.D., Masters, D. and Mitchum, G.T. (2018) Climate-change-driven accelerated sea-level rise detected in the altimeter era. *PNAS*, **115**, 2022–2015.

Nicholls, R.J., Marinova, N., Lowe, J.A., Brown, S., Vellinga, P., de Gusmão, D., Hinkel, J. and Tol, R.S.J. (2011) Sea-level rise and its possible impacts given a 'beyond 4°C world' in the twenty-first century *Philosophical Transactions of the Royal Society A*, https://royalsocietypublishing.org/doi/full/10.1098/rsta.2010.0291

Orford, J., Jennings, S. and Pethick, J.S. (2003) Extreme storm effect on gravel-dominated barriers. Coastal Dynamics 2003, ASCE, paper on CD-ROM.

Palmer, M., Howard, T., Tinker, J., Lowe, J., Bricheno, L. *et al.* (2018) UKCP18 Marine Report. *Met Office, Exeter, UK.* https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Marine-report.pdf

Poate, T., Masselink, G., Austin, M.J., Dickson, M. and McCall, R. (2018) The role of bed roughness in wave transformation across rocky shore platforms. *Journal of Geophysical Research (Earth Surface)*, **123**, doi: 10.1002/2017JF004277

Pontee, N.I. and Parsons, A.P. (2012) Adapting as part of sustainable shoreline management in England and Wales. *Maritime Engineering*, **165**, 113-130.

Poulton, C.V.L., Lee, J.R., Jones, L.D., Hobbs, P.R.N. and Hall, M. (2006) Preliminary investigation into monitoring coastal erosion using terrestrial laser scanning: case study at Happisburgh, Norfolk, UK. *Bulletin of the Geological Society of Norfolk*, **56**, 45–65.

Pye, K. and Blott, S.J. (2006) Coastal processes and morphological change in the Dunwich-Sizewell area, Suffolk. *Journal of Coastal Research*, **22**, 453–473.

Pye, K. and Blott, S.J. (2008) Decadal-scale variation in dune erosion and accretion rates: an investigation of the significance of changing storm tide frequency and magnitude on the Sefton coast, UK. *Geomorphology*, **102**, 652–666.

Pye, K. and Saye, S.E. (2005) The geomorphological response of Welsh sand dunes to sea level rise over the next 100 years and the management implications for SAC and SSSI sites. *CCW Report*, 670.

Quataert, E., Storlazzi, C., van Rooijen, A., Cheriton, O. and van Dongeren, A. (2015) The influence of coral reefs and climate change on wave-driven flooding of tropical coastlines. *Geophysical Research Letters*, **42**, 6407–6415.

Ranasinghe, R. (2016) Assessing climate change impacts on open sandy coasts: A review. *Earth Science Reviews*, **160**, 320–332.

Ranasinghe, R., Symonds, G., Black, K. and Holman, R. (2004) Morphodynamics of intermediate beaches: a video imaging and numerical modelling study. *Coastal Engineering*, **51**, 629–655.

Reeve, D.E. and Li, Y. (2009) Stochastic model for embayed beaches. *Journal Waterway, Port, Coastal and Ocean Engineering*, **135**, 144, doi: 10.1061/(ASCE)0733-950X(2009)135:4(144)

Reeve, D.E. and Karunarathna, H. (2009) On the prediction of long-term morphodynamic response of estuarine systems to sea level rise and human interference. *Continental Shelf Research*, **29**, 938–950.

Rennie, A.F. and Hansom, J.D. (2011) Sea level trend reversal: Land uplift outpaced by sea level rise on Scotland's coast. *Geomorphology*, **125**,193–202.

Rogers, J., Loran, F. and Astle, G. (2008) National coastal erosion risk mapping the first national run. *Proceedings 31st International Conference on Coastal Engineering*, ASCE, pp. 4237–4249.

Rossington, K. and Spearman, J. (2009) Past and future evolution in the Thames Estuary. *Ocean Dynamics*, **59**, 709–718.

Scott, T., Masselink, G. and Russell, P.E. (2011) Morphodynamic characteristics and classification of beaches in England and Wales. *Marine Geology*, **286**, 1–20.

Scott, T., Masselink, G., O'Hare, T., Saulter, A., Poate, T., Russell, P., Davidson, M., and Conley, D. (2016) The extreme 2013/2014 winter storms: coastal response and multi-annual recovery along the southwest coast of England. *Marine Geology*, **382**, 224–241.

Spencer, T. and Brooks, S.M. (2013) Methodologies for measuring and modelling changes in coastal saline lagoons under historic and accelerated sea level rise, Suffolk coast, eastern England. *Hydrobiologia*, **693**, 91–115.

Spencer, T., Brooks, S.M., Moeller, I. and Evans, B. (2014) Where local matters – Impacts of a major North Sea storm surge. *Transactions of the American Geophysical Union* **95**, 30.

Spencer, T., Brooks, S.M., Evans, B., Tempest, J.A. and Moeller, I. (2015) Southern North Sea surge event of 5 December 2013, Water levels, waves and coastal impacts. *Earth Science Reviews*, **146**, 120–145.

Stive, M.J.F., Wang, Z.B., Capobianco, M., Ruol, P. and Buijsman, M.C. (1998) Morphodynamics of a tidal lagoon and the adjacent coast. In *Physics of Estuaries and Coastal Seas*, [Dronkers and Scheffers (eds)], Balkema, Rotterdam, 397–407.

Stive, M.J.F. (2004) How important is global warming for coastal erosion? An editorial comment. *Climatic Change*, **64**, 27–39.

Suffolk Coastal District Council, (2009) Suffolk SMP2 sub-cell 3c: Review of Coastal Processes and Geomorphology. http//www.suffolksmp2.org.uk2009

Taylor, J.A., Murdock, A.P. and Pontee, N.I. (2004) A macro-scale analysis of coastal steepening around the coast of England and Wales. *Geographical Journal*, **170**, 179–188.

Teasdale, P.A., Collins, P.E.F., Firth, C.R. and Cundy, A.B. (2011) Recent estuarine sedimentation rates from shallow inter-tidal environments in western Scotland: implications for future sea-level trends and coastal wetland development. *Quaternary Science Reviews*, **30**, 109–129.

Thieler, E.R., Himmelstoss, E.A., Zichichi, J.L. and Ergul, A. (2017) *Digital Shoreline Analysis System (DSAS) version 4.0—An ArcGIS extension for calculating shoreline change* (ver. 4.4, July 2017), U.S. Geological Survey Open-File Report, 2008–1278.

Thorner, J., Kumar, L. and Smith, S.D.A. (2014) Impacts of climate-change-driven sea level rise on intertidal rocky reef habitats will be variable and site specific. *PLOS One*, **9**, e86130.

Townend, I. and Pethick, J.S. (2002) Estuarine flooding and managed retreat. *Philosophical Transactions of the Royal Society of London Series A - Mathematical Physical and Engineering Sciences*, **360**, 1477–1495.

Townend, I. (2005) An examination of empirical stability relationships for UK estuaries. *Journal of Coastal Research*, **21**, 1042–1053.

Van der Wal, D. and Pye, K. (2004) Patterns, rates and possible causes of saltmarsh erosion in the Greater Thames area (UK). *Geomorphology*, **61**, 373–391.

Vann Jones, E.C., Rosser, N.J., Braina, M.J. and Petley, D.N. (2015) Quantifying the environmental controls on erosion of a hard rock cliff. *Marine Geology*, **363**, 230–242.

Vousdoukas, M.I., Mentaschi, L., Voukouvalas, E., Verlaan, M. and Feyen, L. (2017) Extreme sea level on the rise along Europe's coasts. *Earth's Future*, **5**, 304–323.

Walkden, M. and Hall, J. (2005) A predictive meso-scale model of the erosion and profile development of soft rock shores. *Coastal Engineering*, **52**, 535–563.

Walkden, M., Dickson, M., Thomas, J. and Hall, J. (2008). Probabilistic simulation of long term shore morphology of North Norfolk UK. *Proceedings 31st International Conference on Coastal Engineering*, ASCE, 4365–4377.

Wiggins, M., Scott, T., Masselink, G., Russell, P., Castelle, B. and Dodet, G. (2017) The role of multi-decadal climate variability in controlling coastal dynamics: re-interpretation of the 'lost village of Hallsands'. *Proceedings Coastal Dynamics*, ASCE, 96–107.