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Impacts of climate change on coastal habitats

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EXECUTIVE SUMMARY

Coastal margin habitats (sand dunes and beaches, machair, saltmarsh, shingle and beaches, maritime cliffs) constitute a transition zone between terrestrial and marine habitats. They are doubly sensitive to climate change, experiencing changes in rainfall, temperature, storminess, etc., but also habitat loss due to coastal erosion and sea-level rise. Sediment supply and sediment transport are key natural processes these habitats require for a natural, dynamic state, on which their unique biodiversity depends.

Coastal erosion and sea-level rise may increase or reduce sediment supply, depending on local context. However, change in the character or extent of these habitats is certain, requiring proactive management response. Where fixed landward assets prevent natural migration, habitat loss will occur due to coastal squeeze; in other locations roll-back or managed realignment should be considered as management options. Coastal water tables may rise due to sea level rise, or fall due to changing rainfall, depending on local context. Both may have serious impacts on coastal biodiversity, and on other coastal land uses.

Coastal margins are highly important for ecosystem service provision, primarily leisure and recreation, and coastal defence. Climate change may increase leisure uses but will create significant challenges for coastal defence, requiring integrated management of sediment budgets across all habitats.

INTRODUCTION

The coastal margin habitats covered in this review comprise terrestrial habitats along the coast. In their natural state they form a transition zone between marine and terrestrial systems, and are influenced by both. The coverage differs from previous score-cards in the inclusion of saltmarsh as a coastal margin habitat following the definitions used in the UK National Ecosystem Assessment (UKNEA, 2011). The coastal margin habitats considered here are:

- sand dunes and sandy beaches
- machair
- saltmarsh
- shingle structures and beaches
- hard rock and soft rock maritime cliffs and slopes (including maritime grassland and heath)

Coastal grazing marsh is not included in this review as it is largely a product of human intervention in the coastal floodplain; however, it may be affected by sea-level rise and managed realignment (Mieszkowska, 2010). Saline lagoons are not covered as these are considered to be a marine habitat.

1. WHAT IS ALREADY HAPPENING?

Habitat descriptions

Coastal margin habitats comprise roughly 0.6 % of the UK land area (Jones *et al.*, 2011). These habitats are strongly influenced by physical processes. The sedimentary habitats are the result of deposition of largely marine-transported shingle and sand, and re-mobilisation of this sediment by wind, waves or tides. All are naturally dynamic systems which exhibit episodic or gradual morphological and vegetation change depending on the availability and movement of sediment, and on rates of vegetation succession, soil development and climatic conditions. Disturbance or erosion reintroduces early successional stages, which support many rare species of plants, invertebrates and vertebrates. The heterogeneity of habitats of different age and structure contributes to the high biodiversity of these coastal margin systems. Table 1 shows the area of each habitat and projected changes over time. Below we provide a brief description of these habitats, emphasising those aspects where climate change is most likely to have an influence. We also discuss some of the wider coastal processes affecting these habitats in the context of climate change.

Coastal evolution and coastal processes

Coastal margin habitats are linked to the marine environment through coastal processes and maritime influences. They are shaped by waves (height and direction), tides, nearshore currents, wind, fronting beach width, sediment availability, extreme events, exposure, rainfall, groundwater and air temperature. The interactions of the geological, biological, chemical and human influences give the coastal margins of the UK a unique and varied character (May and Hansom,

Table 1: Current and estimated past and future area of coastal margin habitats in the UK (hectares). Cliff extent measured in km length. From Beaumont et al. *(2010), Jones* et al. *(2011).*

	Area (ha)						
	1900	1945	1970	1990	2000	2010	2060
Sand dune	102,200	86,900	74,600		71,600	70,900	65,500
Machair		20,200				19,700	18,500
Saltmarsh		51,200			44,500	44,500	44,500
Shingle		10,900		5,900		5,900	5,700
Maritime cliffs and slopes				4,600			4,600

2003). Sediment transport by marine and aeolian processes is essential for shaping supralittoral coastal habitats and driving coastal change (Pye *et al*., 2007). However, past and current human activities such as grazing, agriculture, coastal defence or industry are land uses that also shape the present configuration and the ongoing evolution of the coastal margins, often preventing change. Despite this, sea-level rise and other climate change impacts will have a major influence on coastal evolution and processes, and therefore on the coastal margin habitats.

Nature conservation importance

The wide variety of landforms, soil types, and hydrological influences in coastal margin habitats, together with their function as a refugium for many lowland species lost to agricultural intensification in other habitats means that they support a high diversity of species relative to their extent (Jones *et al*. 2011). For example, in England, sand dune, maritime cliff and shingle coastal habitats, with an estimated total extent of 31,200ha, support 148 UK BAP species (Webb *et al*., 2010) compared to coastal and flood plain grazing marsh, with an estimated 235,000 ha in England supporting 47 UK BAP species. Many of the coastal species are adapted to the extreme conditions at the coast and the cyclical processes of succession associated with erosion and accretion.

Most coastal habitats are represented in designated sites under national and international conservation legislation. Coastal sand dunes, saltmarsh, machair, coastal vegetated shingle and maritime cliff and slope are all UK BAP Priority Habitats, and forms of coastal grassland and heathland are covered by other BAP Priority Habitat definitions such as lowland heathland and lowland acidic grassland.

Nearly a third of England's most important protected areas for wildlife (sites with an international designation) occur in the coastal zone. A high proportion is inter-tidal, but coastal grazing marsh and coastal wetlands are also significant. Almost 20% of all English SSSIs with geological features are at the coast. Over half of all Areas of Outstanding Natural Beauty have a coastal element; 6 out of 9 national parks in England have a coastline. Erosion is causing some features in SSSIs to effectively migrate beyond the boundaries of the designated site, particularly relevant for coastal soft cliffs with high recession rates.

Sensitivity to climate change

Coastal margin habitats are affected by climate change in a number of ways. These include direct influences of changing climatic envelopes on species distributions, and indirect impacts through loss (or gain) of habitat due to sea-level rise, altered coastal processes, and other impacts mediated by changes in hydrology, river flows, storminess, etc. The evidence for impacts on each habitat is discussed below

1.1 Sand dunes

a. Description

Coastal sand dunes are formed from sand (0.2-2mm grain size) that is blown inland from the beach, and becomes stabilised by vegetation (Packham and Willis, 1997). Typically, phases of mobility and natural coastal dynamics lead to a sequence of dune ridges, which increase in stability and age further away from the sea. The main vegetation types are dry dune grassland and dune slacks – a seasonal wetland, with dune heath on some acidic sites. Scrub and natural dune woodland are relatively sparse in the UK, although large areas of dune have been artificially forested with pines. Sand dunes support a high diversity of plant, insect and animal species, many of which are rare. They are particularly important for specialists dependent on bare sand or early successional habitats, including the natterjack toad, which requires early-stage dune slacks for breeding, and the sand lizard, which requires open bare areas for basking and breeding burrows. Dune slacks have a high botanical diversity. Sand dunes are also important for geomorphological conservation. Many UK sites are notified as SSSI/ASSI for these interests and several are of international importance for active coastal processes.

b. Extent and regional pattern, trends

Sand dunes occur all around the UK, with a total area of over 70,000 ha (Jones *et al*. 2011), but are most extensive in Scotland (CP regions 1, 7), north-west and south-west England and Wales (CP regions 5, 6). Over the last 100 years, it is estimated that Great Britain has lost 30-40% of its dune systems to a range of pressures (Doody, 2001). Historically these pressures have been agricultural land claim and afforestation, and infrastructure for industry, leisure and tourism including golf courses. Losses due to sea-level rise and coastal erosion have been relatively small, although many dune sites have hard engineering to maintain their sea defence role (see sections on Ecosystem Services)...In England and Wales, surveys between 1999 and 2003 indicated a net balance between erosion and accretion, although this differed by region: 35% of the total dune frontage showed evidence of net erosion or has been protected by defence works, 35% showed net stability and 30% showed seawards accretion (Pye *et al*., 2007). West coast sites showed the highest percentage of eroding and protected frontages (38%), while the south coast sites showed the lowest (7%). The majority of protected dune frontage is found in CP Region 2.

c. Natural and other processes likely to be affected by climate change

Sediment transport is a natural part of dune dynamics. Dunes release sediment to the beach plain during storm events, which is then later returned to the dune system by marine and aeolian transport and mobile sand inland may be re-worked by wind. Dunes are affected by other natural and anthropogenic drivers: Vegetation growth and soil development may be accelerated by both nitrogen deposition and warmer temperatures (Jones *et al*. 2008), Effective rainfall (the balance of rainfall minus evapotranspiration losses) is the dominant influence on dune water table fluctuations (Jones *et al*., 2006; Clarke and Sanitwong Na Ayutthaya, 2011). Water table elevation will also be increased by sea-level rise, which raises the hydrological base level, an effect that may be partially offset in some locations by reduced hydrological gradients due to coastal erosion (Clarke and Sanitwong Na Ayutthaya, 2011). Long-term leaching of sandy soils can lead to acidic surface layers suitable for dune heath development, and leaching rates are a function of rainfall. The UK distribution of many dune species and some NVC vegetation sub-communities is governed by their climate envelopes (Rodwell, 2000). Consequently, species composition may change, with potential consequences for habitat resilience.

1.2 Machair

a. Description

Machair forms a distinctive coastal grassland only found on the Atlantic coast of north and west Scotland and western Ireland (Angus, 2006). It is associated with calcareous sand, blown inland by strong prevailing winds from beaches and mobile dunes. 'Machair' refers to a relatively flat and low lying sand plain formed by dry and wet (seasonally waterlogged) short-turf grasslands above impermeable bedrock, a habitat termed 'machair grassland'. However, the 'machair system' has a more functional usage to include the beach zone, a cordon of mobile and semi-fixed foredunes, dune slacks and grassland, swamps, lochs (some of them brackish), saltmarsh, and sand blanketed adjacent hillslopes. As a result of the range of habitats encompassed by the machair system some overlap exists with other coastal margin habitats. Often associated with a landward sloping gradient there is commonly an inland transition to heath and mire which can include sand-affected peatland. Machair has a very long history of management by people over several millennia, the term owing as much to its cultural context as it does to its natural context. In modern times this has involved a mix of seasonal extensive winter cattle grazing and low-input low-output rotational cropping of oats and rye, and a small amount of bere barley. This traditional mixed management sustains varied dune, fallow and arable weed communities and the periodic ground disturbance and seasonal absence of stock supports important breeding bird populations. The wider machair system has a rich invertebrate fauna.

b. Extent and regional pattern, trends

The global 'machair grassland' extent is about 25,000 ha, with 17,500 ha in Scotland and the remainder in western Ireland. The largest extents in Scotland are in the Western Isles (10,000 ha, mainly in the Uists), Coll and Tiree (4,000 ha), Orkney (2,300 ha) western Scottish mainland (1,000 ha) and Shetland (180 ha). The full geographical extent of the wider 'machair systems' is believed to be in the region of 40,000 ha, with some 30,000 ha in Scotland and 10,000 ha in Ireland. Whilst this traditional agriculture and habitat is associated mainly with the Uists, the other machair areas have witnessed a marked decline in traditional land management with a corresponding decline in habitat condition and supported wildlife.

c. Natural and other processes likely to be affected by climate change

There are perhaps four main drivers related to climate change that will potentially impact on Scottish machair: accelerating relative sea-level rise, ongoing reduction in sediment supply temperature changes, and changes in storminess. Several of these factors are in-combination effects and have varying levels of probability but any changes will impact on species distribution and composition to the advantage of more aggressive species.

1.3 Saltmarsh

a. Description

Coastal saltmarshes (also known as 'merse' in Scotland) are concentrated at the landward edge of intertidal regions within estuaries and sheltered coastlines around the UK. The composition of saltmarsh flora and fauna is determined by complex interactions between frequency of tidal inundation, salinity, suspended sediment content and particle size, slope, and herbivory. In general, total species richness increases with elevation leading to a characteristic zonation of the vegetation (Doody, 2008). Two saltmarsh plant communities are designated under the Habitats Directive Annex 1 habitats (Mediterranean and thermo-Atlantic halophilous scrubs and *Spartina maritima* swards), associated with the upper marsh transition zone. They are important breeding and refuge habitats for waterbirds and fishes and are a winter food source for passerines.

Saltmarshes sequester 30-343g C m^{-2} y^{-1}; an order of magnitude greater than that of peatlands (20-30 g C m^{-2} y^{-1}) (Chmura, 2009), although there is some debate about the accuracy of the Chmura (2009) estimates for saltmarsh which did not correct for soil carbonate content and should be considered an over-estimate (Patricia Bruneau, SNH, Pers. Comm). Plant productivity is the main contributor to these high rates of carbon sequestration. Greenhouse gas emissions from saltmarsh soils are assumed to be low due to the inhibition of methane production by sulphate deposition from tidal flooding (Yu and Chmura, 2010), although methane hotspots can occur in upper saltmarsh (Ford *et al*., 2012b). Saltmarshes are effective natural coastal defences. The vegetation acts as a baffle for waves and considerably reduces wave and tidal energy, in addition to trapping sediment raising the marsh profile above the effect of all but the largest waves and tides (Bouma *et al.*, 2005, Feagin *et al.*, 2011). Awareness of the important role they play in flood defence has led to recognition within UK flood risk management and saltmarsh redevelopment plans (Nottage and Robertson, 2005).

b. Extent and regional pattern, trends

Saltmarshes account for approximately 24% of the English coastline, 11% of the Welsh coastline and 3% of the Scottish coastline (www.ukbap.org.uk/PriorityHabitats.aspx).The five largest sites (Wash, Inner Solway, Morecambe Bay, Burry estuary, Dee estuary) account for one third of the UK total. Major saltmarsh losses have occurred prior to the 1980s due to widespread, large scale reclamation for agriculture or development (Morris *et al.*, 2004). Losses also occur due to erosion, which takes a number of different forms, most commonly including the landward retreat of the seaward edge, either as a cliff or steep 'ramp', or an expanding internal dissection of the marsh by the widening creeks. Erosion predominantly affects lower marsh communities which are more vulnerable to wave action, although mid and high saltmarsh are susceptible to internal erosion through creek expansion. The most recent Biodiversity Action Plan review in 2008 documents the status and extent of saltmarsh habitats as still in decline (www.ukbap.org.uk/PriorityHabitats.aspx). However, there have been gains in saltmarsh extent, particularly on the larger west coast marshes (e.g. the Dee, Ribble, Solway Firth and Morecambe Bay), largely accounted for by the expansion of lower marsh transitional plant communities over intertidal mud and sand flat, and by expansion of *Spartina anglica* (common cord-grass). Managed realignment also contributes to new habitat creation. Nonetheless saltmarsh losses continue to exceed gains (Rupp-Armstrong and Nicholls, 2007). Estimates of net losses vary, ranging from 4.5 % over 20 years (French, 1997) up to 2 % per year (Nottage and Robertson, 2005).

c. Natural and other processes likely to be affected by climate change

Wind-wave climate has the most influence on the horizontal extent of saltmarshes, while relative sea-level rise has a major influence on the medium and long term evolution of saltmarshes and mostly affects their vertical growth (Allen and Pye, 1992). Evidence from Holocene sedimentary sequences suggests that vertical saltmarsh accretion is able to keep pace with projected rates of mean sea level rise, with the essential sediment supply being provided by accelerated erosion of soft cliffs, beaches and the seaward edge of the marshes themselves (Pye and French, 1992; van der Wal, D., Pye, K., 2004.). However, in some larger estuaries there may be insufficient sediment available to maintain the areas of saltmarshes and tidal flats at current levels and, particularly where saltmarshes are backed by embankments for coastal defence, they may suffer coastal squeeze (Hansom *et al.*, 2001) Even where accretion is able to keep pace with sea level rise, the loss of fronting saltmarsh will lessen coastal defence value. The BRANCH assessment of the vulnerability of saltmarsh and mudflats in NW Europe showed how population increases and coastal defences have led to an increasing proportion of both habitats in the high and very high vulnerability classes (Zhang *et al.*, 2007).

1.4 Shingle

a. Description

Shingle, technically termed gravel, is defined as sediment in the range 2-200 mm. It is a globally restricted coastal sediment type. The origin of coastal shingle varies according to location. In southern England, much of it is composed of flint eroded out of chalk cliffs, while in northern and western Britain shingle derives from deposits transported to the coast by rivers or glacial outwash. The vegetation communities of shingle features depend on the amount of finer materials mixed in with the shingle, and on the hydrological regime. The classic pioneer species on the seaward edge include sea kale, *Crambe maritima*, Babington's orache, *Atriplex glabriuscula*, sea beet, *Beta vulgaris*, all species that can withstand exposure to salt spray and some degree of burial by sediment. Further from the shore, where conditions are more stable, more mixed plant communities develop, leading to mature grassland, lowland heath, moss and lichen communities, or even scrub. Some of these communities appear to be specific to shingle, and some are only known from Dungeness. Some shingle sites contain natural hollows which develop wetland communities, and similar vegetation may develop as a result of gravel extraction. Shingle structures may support breeding birds including gulls, waders and terns. Diverse invertebrate communities are found on coastal shingle, with some species restricted to shingle habitats. Shingle structures are of significant geomorphological interest.

b. Extent and regional pattern, trends

Shingle beaches are widely distributed round the coast of the UK, where they develop in high energy environments, although some shingle in Scotland is found in sheltered sea lochs (Murdock *et al.*, 2011). In England and Wales, it is estimated that 30% of the coastline is fringed by shingle. However most of this length consists of simple fringing beaches within the reach of storm waves, where the shingle remains mobile and vegetation is restricted to ephemeral strandline communities able to grow and set seed in one growing season and making use of nutrients from decaying seaweed and other debris. The major vegetated shingle structures surveyed in 1987-1991 by Sneddon and Randall (1993a,b; 1994a,b) totalled some 5000 ha in England, 700 ha in Scotland and 100 ha in Wales. They have since been resurveyed by exeGesIS and Doody (2008) and GeoData (Murdock *et al.*, 2010; 2011). The latter suggesting areas of 4276 ha in England and 1100 ha in Scotland. Projected change in shingle area is shown in Table 1. Dungeness, in southern England, is by far the largest site, with over 2000 ha of shingle, and there are only five other structures over 100 ha in extent in the UK. The main concentrations of vegetated shingle occur in East Anglia (Region 2) and on the English Channel coast (Region 3), in north-east Scotland (Region 1), and in north-west England and south-west Scotland (Region 5). The Welsh coast has a number of small sites. This habitat is poorly represented in Northern Ireland, where the key site is Ballyquintin in County Down.

c. Natural and other processes likely to be affected by climate change

Sea-level rise and changes in sediment supply are the most important processes affecting shingle. In a global context, shingle beaches are in decline (Gribbin, 1984). Analysis of recent change in England 1990-2008, for key sites suggested a slight loss in area (~10% loss), with five sites showing net loss and four sites net gain (Murdock *et al.*, 2010). Studies at two sites on the south coast of England (East Sussex, Region 3) also indicate the importance of the condition of the sediment, where annual weight loss of flint shingle by attrition (mechanical breakdown of particles) could be as high as 1.9% per year (Dornbusch *et al.*, 2002). The importance of new sediment input is critical to sustaining shingle beaches, but is often prevented by coastal defences.

1.5 Maritime cliff and slope

a. Description

Maritime cliffs and slopes comprise any form of sloping faces through to vertical faces on the coastline where a break in slope is formed by failure and/or coastal erosion. On the seaward side, the cliff slope extends to the limit of the supralittoral zone. On the landward side the boundary is less clear, but is often understood to include the zone affected by saltspray deposition, typically ~50 m, occasionally up to 500m (Jones *et al.*, 2011), although in practice agricultural land or infrastructure frequently occur closer to the cliff top than this, and the remaining strip of natural vegetation is considerably narrower. Coastal cliffs are broadly classified as 'hard cliffs' or 'soft cliffs'. Hard cliffs are formed of rocks resistant to wave erosion and subaerial weathering, such as gneiss, basalt, granite, sandstone and limestone, but can also include softer rocks, such as chalk. Vertical or sub-vertical profiles are common since the restricted amount of debris produced by failure is easily removed by wave activity. Soft cliffs are characterised by less resistant rocks like shales or unconsolidated materials such as glacial till that produce large volumes of failure debris that is removed slowly by wave activity. In addition, soft cliffs experience frequent failures and landslips, driven by groundwater seepage. Shallower slopes result and these are more easily colonised by vegetation and develop a wider range of habitats. The vegetation of maritime cliff and slopes varies with exposure to wind and salt spray, the lithological composition and stability of the substrate, its water content and, on soft cliffs, the time elapsed since the last slope failure. Maritime vegetation occurs where there is greatest wave and wind exposure. In extreme conditions, such as in the Northern and Western Isles of Scotland saltmarsh species are common on cliff-tops. Hard cliffs support specialised higher plants largely on ledges and in crevices. Soft rock cliffs with successional phases of failure support rare and notable invertebrates, particularly bees and wasps, beetles and flies (Howe, 2003).

b. Extent and regional pattern, trends

Approximately 4,060 km of the UK coastline has been classified as cliff (in reality hard rocky coast), with an estimated 1,084 km in England, 2,455 km in Scotland and 522 km in Wales (JNCC). In the UK hard cliffs are widely distributed on more exposed coasts and occur in the south-west and the south-east of England, and in more resistant lithologies in north-west and south-west Wales, western and northern Scotland and on the north coast of Northern Ireland. Soft cliffs are more restricted to the east and central south coasts of England and in Cardigan Bay and north-west Wales. England and Wales are estimated to have lengths of 255 km and 101 km respectively. Of the 255 km 80% of this is found in the seven counties Devon, Dorset (Region 4), Humberside, Norfolk, Suffolk (Region 2), Isle of Wight (Region 3), and Yorkshire (Region 1). Shorter lengths of soft rock cliffs occur in Scotland and Northern Ireland. The UK holds a significant proportion of soft cliff in north-western Europe (Whitehouse, 2007).

c. Natural and other processes likely to be affected by climate change

Cliff profiles are highly variable given their control by both detailed structural architecture and lithology (May and Hansom, 2003) and with the geomorphological character of the hinterland. Marine erosion of exposures is critical to their function and sea-level rise will increase basal undermining. Enhanced rainfall in the future may also lead to increased slope failure, particularly affecting the movement of groundwater in softer lithologies. Soft cliff erosion is an important source of sediment. The areas with the most rapid rates of recession are on the south and east coasts of England (Regions 2 and 3). For example, Holderness cliff erosion is estimated to supply 3M m^3 a year of fine sediment into the marine system, most of which is transported to the Lincolnshire coast and the Humber (HR Wallingford, 2002). Coastal erosion risk management leads to stabilisation. It is estimated that in the 100 years up to the 1990s, 860km of coast protection works have been constructed to reduce erosion (Lee, 2001), reducing sediment input by an estimated 50%. Schemes to extend or replace coast protection are still being proposed, often in response to reactivation of landslides. Recently, high levels of rain have reactivated landslides on the Dorset coast at Lyme Regis, Dorset (Region 4) and Cayton Bay, Yorkshire (Region 1). Because the frequent failure of soft rock cliffs propagates inland to threaten human assets, such cliffs with no artificial coast protection are a rare resource in the British Isles and in Western Europe.

2. WHAT COULD HAPPEN?

The present-day coast and its evolution is still strongly influenced by the effects of the last glaciation, through the distribution of sediment and its subsequent constant re-working over the last 10,000 years. Available sediment has been declining since the last glaciation. The continuation of sea-level rise can either transport sediment towards the land or 'strand' the sediment offshore, making it unavailable to the coast through natural processes. A review by Hopkins (2007) recognised that sea-level rise is the most serious threat to wildlife at the coast. There will be specific impacts for individual coastal habitat types, but it is important that the mosaic of habitats at the coast is considered as a whole In addition there will be different levels of impact depending on geographic location, topography of the land behind, existing and previous human interventions. This makes detailed predictions of change difficult. In particular the following issues will need to be considered for the coastal margin as a whole:

• Relative sea-level rise will alter the mosaic of habitats. There will be complex morphodynamic responses over different spatial and temporal scales, including impacts on longshore drift.

• Coastal cells will respond differently depending on types of coast, sediment supply, and the legacy of past human intervention/current practices.

• Impacts will be greater where there is a sediment deficit.

• Storm surges will affect the potential of systems to adjust to new equilibrium states.

• Groundwater tables and land drainage may be affected as sea-levels rise, with implications for low-lying land behind the coast. In addition, sediment movement can block outfalls.

The impacts of coastal change have been investigated by the National Trust for its land holdings in England, Wales and Northern Ireland, using the UKCIP02 projections. These studies have led to development of the coastal policy of the National Trust in these countries, where they are significant landowners at the coast. A landscape scale study of climate change impacts on the Broads, using the UKCIP02 projections (Natural England, 2009) also highlighted the issue of addressing these in relation to freshwater habitats.

The 'Futurecoast' study in England and Wales for Defra to inform Shoreline Management Plans, provides a qualitative assessment of the evolution of the open coast over the next century, including the magnitude of shoreline change. There are now a number of tools available to improve understanding of risk to human assets from flooding and erosion and the potential shoreline management needs. The need for planning for change was also highlighted in the 'Future Flooding' report. Understanding how these integrate with conservation management of the coast in the light of climate change is essential. Defra projections for sea-level rise are used for planning for flood risk management, and may be higher in some areas than others. The need for making space for the natural development of coastal habitats and rivers is recognised in England Biodiversity Strategy adaptation principles (Smithers *et al.*, 2008). The size of sites is a crucial factor in their vulnerability. Small sites, particularly the case for linear coastal habitats are at much greater risk from changes in management or in sediment transport than larger sites.

A range of factors need to be considered based on recent updates from the UK Climate Impact Programme (UKCP09) as follows:

• Sea-level rise relative to land levels will have impacts on all coastal habitats. The predicted ranges (adjusted for land movement) of sea-level rise are 21-68 cm for London and 7-54cm for Edinburgh over the next century, with potentially greater increases after that.

• Storm surge frequencies may increase (for example, beyond the 1 in 50 storm surge events that are the largest currently experienced in the Bristol Channel and Severn estuary). If these coincide with high tide events extensive flooding will result.

• Significant wave height: projected increases in mean and extreme winter wave height in south and south-west of the UK

• Annual average temperature is predicted to rise by 1 to 3 °C or more during the century, with the largest increases in the south and east of England.

• Warming is likely to be greater in autumn and winter than in spring and summer.

• In winter, minimum temperatures are predicted to rise more rapidly than maximum temperatures, reducing the diurnal temperature range, while in summer, maximum temperatures will rise more rapidly than minimum temperatures, increasing the diurnal range.

• Variability of winter temperature between years is likely to decrease with cold winters becoming rare and fewer days with frost.

• Variability of summer temperatures is likely to increase, with very hot summers becoming more common.

• Annual precipitation will probably increase by 3-5% by 2050, with greater increases in winter and autumn and no change or a decrease in summer.

• Year-to-year variability of seasonal precipitation will likely show changes, such that the frequency of dry summers will double and wet winters treble by 2080.

• More of the increased precipitation is likely to occur in intense storm events than at present, especially in winter.

• Evapotranspiration is likely to increase year round but particularly in autumn and summer. Windstorms may be more frequent than in the last few decades, although there is high uncertainty attached to this prediction.

2.1 Sand dunes

UK sand dune area is projected to show average losses of 2% over 20 years due to sea-level rise (www.ukbap.org.uk/ukplans.aspx?ID=28). Extrapolating the trend suggests losses of 8% by 2080. By region, habitat losses are likely to be greater than this average in England, lower in Scotland, and close to average in Wales and Northern Ireland, based on relative rates of sea-level rise around the UK (Shennan *et al.* 2009). In Wales, an assumed sea-level rise of 0.41 m by 2100 (the median value based on IPCC predictions), will lead to significant net loss of dune area at some sites, notably Morfa Dyffryn, Newborough Warren, Whiteford Burrows and Kenfig. However, at sites where sediment supply rates are expected to remain high there is likely to be continued net gain, notably at Laugharne-Pendine, Morfa Harlech and Ynyslas. Even at these sites, there will still be erosion, with shoreline retreat on sections of exposed coastal frontage, especially at the up-drift ends of sediment transport cells. At the remaining sites in Wales, there is likely to be little net change (Pye and Saye, 2005). In Scotland, more stable parts of some mainland dune systems could remobilise as relative sea-level rises, especially on the outer Firths (Pethick, 1999) but these systems are part of wider functional systems that often include saltmarsh which binds sediment and may lead to lags in sediment mobilisation. Sea-level rise may trigger dune remobilisation (Pye *et al.*, 2007), but temperature, precipitation, wind speed/direction, and rainfall patterns will affect the development of dune landforms. Higher water tables may reduce volumes of blowing sand on beach plains, Management of over-stabilized dune systems in the context of sea-level rise will depend largely on the level of local impact. Rollback is one possible solution (i.e. allowing dunes to migrate landward). However, as most dune systems in Wales are highly stabilized by vegetation, intervention to rejuvenate natural dynamic processes will be necessary and this is underway at Kenfig Burrows. Beach cleaning is a management issue which could reduce embryo dune formation and further reduce the resilience of a natural dune system that is already under pressure from climate change. Where protection of infrastructure prevents sand exchange with beaches, this will affect sediment transport, potentially leading to increased risk of erosion elsewhere within the sediment cell. Alternatively, release of stored sediment may lead to small areas of new dune formation elsewhere.

The likely results of projected changes in temperature and rainfall are uncertain. The predicted rise in temperature may extend the northwards range of dune plants and invertebrates with a southern distribution. While those with a northern distribution may retreat north such as the dune grass *Leymus arenarius*, and the semi-fixed dune grassland *Ammophila arenaria-Festuca rubra-Hypnum cupressiforme* subcommunity both of which are close to their southern limit in Wales. Most dune plant species in this part of the world use the C3 pathway in photosynthesis enabling them to better utilize any increase in CO_2 levels. It is possible that dune grasses will grow more rapidly as temperatures rise (Carter, 1991), This would exacerbate effects of nitrogen deposition, both leading to denser vegetation, stabilised dunes, and further loss of the bare sand habitat important for many dune specialist species. Warmer, wetter conditions as evidenced from the Holocene stratigraphic dune record are also likely to favour further stabilization and soil development, but this may be offset or even reversed by a higher incidence of summer droughts and intense storm events. Rates of recent soil development in dunes have been linked to climatic variation over the last 60 years, with faster soil development associated with warmer periods (Jones *et al.*, 2008).

Dune slack communities are strongly dependent on hydrological regime, which is in turn dependent on the fine balance between rainfall and evapotranspiration. Modelling work predicts drastic falls in water table of over 1 m by 2100 under UKCIP02 medium range climate predictions for a site in north-west England (Clarke and Sanitwong Na Ayutthaya, 2011). Recent work characterising ecohydrological requirements for dune slack communities suggests that, based on those predictions, hydrological conditions currently supporting wet slacks will favour dry slack communities by 2050, and may only support dry dune grassland by 2080 (Curreli *et al.*, 2013). The climate change impacts on dune slacks remain a major knowledge gap.

2.2 Machair

On-going research by Universities, SNH and SEPA have focused on the impacts of sea level change, coastal erosion and habitat vulnerability. Work by Rennie and Hansom (2011) suggests that Scotland's observed tidal record now lies at the 95% projection of the UKCP09 High Emission Scenario with isostatic uplift now contributing little to offsetting the effect of relative sea-level rise on the Scottish coast. Other work that includes historical analyses with time-series maps spanning in excess of 100 years, together with Digital Terrain Models (DTMs) from a network of representative sites, demonstrates widespread coastal recession and steepening on machair coasts and elsewhere (Hansom, in press). Although the impact of increasing storm wave heights over time may be more significant drivers of machair change than either storm frequency or sea-level rise, there are few reliable long term data in this regard. SNH studies of the impact and causes of the severe storm of 2005 (a single event that may not be directly linked to climate change) have highlighted the vulnerability of the low-lying coastal machair of the Hebrides. Angus *et al.* (2011) suggested that the widespread impact of the 2005 storm (Dawson *et al* 2007) may have been due to the in-combination effect of rapid rise of sea level due to low atmospheric pressure, wind-driven storm waves and high tide all serving to raise water levels well above normal, even during storm conditions. Extensive marine flooding and wave erosion led to loss of machair during the 2005 event. Machair systems more generally may be becoming more vulnerable to climate change than previously thought and recent remote sensing using LiDAR and air photography DTMs have confirmed earlier observations by Hansom and Angus (2006) that the dune cordon located along the machair coastal edge was narrowing over time. If marine erosion continues to lower the coastal edge and move it landward, then the vulnerability of machair to climate change will increase, particularly since much of the machair grassland displays a negative landward gradient. Such information is key to contingency planning for extreme events and in building long-term plans for machair sustainability . However, since machair is partly a product of a crofting system that is being replaced by more intensive practices then uncoupling the human-driven effects from the effects of climate change will prove problematic.

There is limited knowledge of the impacts of more frequent flooding in the future on the seasonal lochs and drainage of the machair. Flooding recovery after the 2005 event demonstrated a poor understanding of hydrological processes in low-lying machair areas and the effects of longer or more frequent saline flooding is unknown, both at the habitat and land use levels. Machair drainage is complex and reliant on human-constructed drains cut during the nineteenth century. Recent lack of maintenance, exacerbated by rising sea levels have reduced the hydraulic gradients available for machair drains both to evacuate freshwater and reduce marine penetration. In the 200 years since installation, the hydraulic gradients of the machair drainage systems have been lowered so that the fall has reduced by an estimated 10%. The machair of the future may well be a narrower, more loch studded and wetter habitat than present with net displacement of machair (an uncommon habitat) by saltmarsh (a more common habitat) and with enhanced saline intrusion altering the species composition of its lagoons (Angus and Hansom, 2004; Angus *et al*, 2011) .

2.3 Saltmarsh

Overall saltmarsh extent may decrease further with predicted increases in sea-level rise, storm surge and relative wave height. Increased wave energy generated by rising wind strengths is predicted to contribute to increased erosion of the seaward edges of saltmarshes. UKCIP predictions for 2090-2099 of 29.8-45.6 cm sea-level rise (Medium emissions scenario), and over 1m exceedences of present-day high tides further support the predicted increase of erosion rates for UK saltmarshes. Model predictions for UK saltmarshes at risk forecast an increase from 30% currently vulnerable to 43% under the 2080s high sea-level rise scenario because of the lack of opportunity for autonomous adaptation through inland migration (Zhang *et al*., 2007). Greatest impacts are likely to occur in the Eastern Channel regional sea where changes in sea-level rise and storm surge are forecast to be most severe (Murphy *et al*., 2009). The predicted increase in precipitation (50% central estimate prediction) in west Scotland and the Minches, Scottish Continental Shelf, northern and southern North Sea may enhance sediment supply to salt marshes via freshwater runoff, but increased water flow could increase erosion rates relative to sedimentation processes. In contrast, a reduction in precipitation is forecast for the East and West Channel, Celtic Sea and Irish Sea areas which may result in a reduced supply of sediment to saltmarsh systems (http://ukclimateprojections.defra.gov.uk/content/view/1779/544/). Linkage of regional climate scenarios with local geomorphological and hydrological data is therefore imperative to allow accurate predictions at the regional seas scale. In addition it is possible that future elevated levels of carbon dioxide will allow some species (e.g. *Puccinellia maritima*) to be outcompeted by others (e.g. *Spartina anglica*) and impacting on species distribution (Gray and Mogg, 2001).

2.4 Shingle

Sea-level rise will impact on shingle beaches and structures. Because many key sites are found in areas with greatest projected sea-level rise (Regions 2 and 3) there could be a disproportionate impact. There will be complex morphodynamic responses over different spatial and temporal scales. Increased levels of wave and tidal energy and subsequent erosion will cause some features in protected sites to migrate beyond the designated boundaries e.g. at Kessingland in Suffolk (Region 2) (Doody, 2004; Rees, 2006). Movement of sediment may not always be acceptable where there are important assets. Particularly important is Dungeness (Kent, Region 3) where the presence of a nuclear power facility will require the beach in front of the power stations to continue to be replenished until, and beyond, decommissioning.

Increased erosion will occur because of increased wave attack resulting in undermining and cliffing along the seaward beach front; storm surges affecting the potential of systems to adjust to new equilibrium states and preventing seaward expansion through build up of beach ridges. As a result there is likely to be landward migration of narrow beaches, leading to 'coastal squeeze' if their migration is prevented by large infrastructure, rising ground or coastal defence structures. There will also be a greater risk of collapse of shingle ridges, especially on artificially profiled beaches. Sea defence structures built at the rear of shingle beaches will be more susceptible to undermining as beach levels drop, and will become more difficult and costly to maintain as the availability of material for beach feeding is depleted.

Climate is the major variable affecting community distribution and species range of shingle vegetation (Farrell and Randall, 1992). The northern oysterplant (*Mertensia maritima*), for example, has disappeared from several southern localities in both Great Britain and Ireland, attributed to a warming climate (Randall, 2004). The rarity of this habitat makes it vulnerable to low rates of recolonisation after disturbance. Changes in patterns of precipitation or temperature will affect vegetation composition. Water retention is poor and evapo-transpiration is likely to increase year round but particularly in autumn and summer, leading to greater impact of summer droughts. Warmer temperatures may also favour invasive species, especially garden escapes. Larger shingle structures supporting freshwater aquifers such as Dungeness, may become vulnerable to saline water intrusion (Burnham and Cook, 2001). Because of the dynamic nature of shingle beaches storms may remove most vegetation. Recovery depends on the number of surviving plants and available propagules, and takes time. Increasing storminess in the last two decades appears to have had a considerable effect on western British foreshore vegetation - particularly in 1967, 1988 and 1989. However long-term recovery is rarely monitored.

2.5 Maritime cliff and slope

Under climate change, higher sea levels and more frequent storms will cause increased marine erosion at cliff toes. On hard cliffs, rocky shore platforms may have more marine scour/wave attack at cliff foot due to beach lowering, and may ultimately be lost with sea-level rise, because they can't accrete like soft sediments. Headlands form natural hard points and may promote changes in the shape of intervening bays and beaches. In soft cliffs, high levels of winter rainfall may promote greater risk of landslides, leading to more demands for coast protection. Old landslide complexes are likely to reactivate more rapidly than expected as groundwater pressure increases. The balance of bare ground to successional vegetation may be altered on soft cliffs, with potential loss of mosaics important for scarce invertebrates, but conversely may create greater areas of the new habitat necessary for early successional species. Warmer temperatures may favour invasive species. For example the introduced alien Hottentot fig (*Carpobrotus edulis*) grows at 50 cm per year and smothers important native species on cliffs in southern England resulting in a change in species composition and a need for management (Frost, 1987).

Warmer temperatures may also promote suitable conditions for thermophilic species. Increased disturbance may favour invasive species. Changes in intensity of land use of cliff top land may reduce potential for colonisation of eroding slopes by semi-natural vegetation.

3. KNOWLEDGE GAPS

The top priority knowledge gaps that need to be addressed in the short term to provide better advice to be given to policy makers are:

a. Accurate information on the extent of coastal margin habitats

Due to recent activity on inventories of these habitats (e.g. saltmarsh, shingle), there is a slowly emerging baseline of habitat area and condition. However, major knowledge gaps remain for some habitats, particularly cliffs, and of the extent of habitats outside designated (SAC, SSSI, etc.) sites. There is a strong need for either consistency of methodology between surveys, or inter-comparison exercises where methods have been changed, in order to separate genuine change in extent or condition over time from differences due solely to methodology, which may be considerable.

b. Sediment transport and the interconnection of coastal margin habitats

There is increasing recognition by policy makers of the interdependence of coastal margin habitats on sediment transport, but this knowledge is rarely applied in coastal management. More information is needed on how sea level rise will affect both sediment supply, and sediment transport on UK coasts, and the implications for coastal margin habitats.

c. Coastal water tables

Sea-level rise will affect groundwater and land drainage in coastal locations. The implications for many coastal margin habitats, and indeed all coastal areas are significant, but have been little considered so far. Climate change will also impact recharge to coastal aquifers, with major implications for biodiverse dune slack wetlands.

There is broad concensus among most coastal margin specialists that these are high priority knowledge gaps (see NEA Coastal Margins chapter, Jones *et al.*, 2011). In addition, there are a number of other knowledge gaps. Across all coastal margin habitats, coastal change needs to be fully evaluated at a coastal cell level against the UKCP09 predictions for a wide range of climatic factors to improve confidence in predictions and reduce uncertainty. This needs to include the responses of key species across a range of habitats, and the degree to which habitat locations which are already degraded may alter species responses to climate change. Also, interactions of climate change and other factors such as nutrient deposition may exacerbate future change. Some habitat-specific knowledge gaps are highlighted below:

3.1 Sand dunes

Expanding the predictive work on shoreline change in Wales (Pye and Saye, 2005) to the rest of the UK will help understand where the greatest changes could occur. More information is needed on the restoration of processes and habitats to enable more effective site management under climate change. Better understanding of the eco-hydrological requirements of dune slacks is urgently required.

3.2 Machair

There is limited knowledge of the impacts of more frequent flooding in the future on the seasonal lochs and drainage of the machair. Understanding a wide range of hydrological and topographical relationships will be important to inform the human response to both extreme events and longer-term trends.

3.3 Saltmarsh

Linkage of regional climate scenarios with local geomorphological and hydrological data is imperative to allow accurate predictions at the regional seas scale.

3.4 Shingle

Whilst there is reasonable knowledge of the status and evolution of the major shingle structures much less is known about the long lengths of shingle beaches. There is a need to assess the status of shingle beaches in relation to changing sea levels and human activities, and determine the shingle beaches' vulnerability. There are differing views about the impact of offshore dredging on the coast. Given the importance of shingle foreshore to sea defence this issue needs research that is more active. Restoring shingle vegetation is difficult and there is only very limited research.

3.5 Maritime cliffs and slopes

A UK-wide vegetation survey of maritime cliffs ideally using Phase II (National Vegetation Classification) methodology is needed. The relationship between sediment supply from erosion of cliffs and transport to other coastal or marine habitats will become increasingly important to coastal management. Information is needed on the impacts of potential increased erosion on invertebrate communities on cliff slopes.

4. SOCIO-ECONOMIC IMPACTS

Ecosystem services

Coastal margin habitats provide a range of ecosystem services, covered in more detail in Chapter 11 of the UK National Ecosystem Assessment (Jones *et al*. 2011), with an estimated value of £48 billion (Firn Crichton Roberts 2000; COREPOINT 2007). Their greatest importance is for cultural services, particularly leisure and recreation, and for the regulating service of flood risk reduction. Other ecosystem services provided by the coast include carbon sequestration, water supply and purification, and provision of habitat for biodiversity. A number of published studies discuss Ecosystem Services for dunes (Everard *et al*., 2010; Ford *et al*., 2012a) and saltmarsh (Everard, 2009).

Seaside tourism is estimated to be worth £17 billion annually (Pugh and Skinner, 2002), with the coast attracting 270 million visits per year (Cooper, 2009), being particularly important in Wales (VEP, 2006). Few studies have so far looked at climate change impacts on tourism, but a study at two sites in East Anglia, Holkham and Cley, suggests that warmer summers are likely to increase visitor numbers under climate change, despite reductions in beach area due to sea-level rise (Coombes and Jones, 2010). There may be conflicts between rising tourism numbers in future and shore-bird breeding success, particularly in the context of declining beach-width due to erosion (Coombes *et al*., 2008), and also between beach management practices linked to blue-flag status, trampling pressures and the requirements of natural processes and species in these habitats.

Flood risk reduction is provided both directly by beaches, dunes shingle ridges and saltmarsh which act as barriers absorbing or attenuating wave energy at the coast, and indirectly by the provision of sediment from coastal erosion, especially of cliffs. Sediment supply and transport are essential to the natural functioning of these soft coast buffering structures. Roughly 18% of the UK coastline has some form of artificial coastal protection, with 45% of the English coast protected (Table 2). Flood defence provided by soft coast habitats is estimated to be worth £3.1 - 33.2 billion in England (Jones *et al*., 2011).

A study for Defra characterised the flood defence importance of 158 dune localities in England and Wales (Pye *et al*., 2007). From a flood risk management perspective, large sites provide the greatest capacity to absorb impacts of sea-level rise. However, many small sites which take the form of a narrow fringing barrier, are of considerable significance. In England, dunes protect urban areas along the Sefton coast (Region 5) and in Lincolnshire (Region 2), and protect more extensive areas along the Dunwich to Sizewell frontage in Suffolk, which form part of the defence against tidal flooding of the Minsmere Levels, along the Happisburgh to Winterton coast in Norfolk protecting an extensive low-lying area of northeast Norfolk which includes The Broads. In Essex,fronting saltmarsh maintains defence integrity along 370km of coast and provides huge cost savings (Leggett and Dixon, 1994), while shingle protects extensive areas along the southern English coast (Region 2). In Wales, dunes protect parts of Pwllheli in Gwynedd and the north Wales coast (Region 5).In Scotland, and Northern Ireland, dunes are of lesser importance for flood defence, but machair provides a defence function in the Western Isles.

The climate change impacts need to be addressed in the development of coastal management strategies. Rising sea levels and greater storm frequency will increase erosion and the movement of material, making flood risk reduction more difficult. Planning for future flood risk management needs to take account of the response of the shoreline to climate change, and be more adaptive than has been practised in the past. Where maintenance of key infrastructure and natural assets is not critical, roll-back may be the most sustainable option in the long-term.

A review of the implications of sea-level rise for the UK (de la Vega-Leinhart and Nicholls, 2008) suggests that although the UK has the potential to adapt to sea-level rise, there are a number of barriers to implementation. For example, public acceptance of coastal change is still very low, and funding of innovative approaches is limited. The new Shoreline Management Plans for England and Wales are increasingly geared towards long-term sustainable solutions rather than a 'hold the line' approach. The 'pathfinder' projects in England explore a range of situations where coastal change is an issue for local communities. In 2010, a revised beach management manual was published to help guide engineers and other beach managers to more sustainable methods of managing flood risk on low-lying coasts.

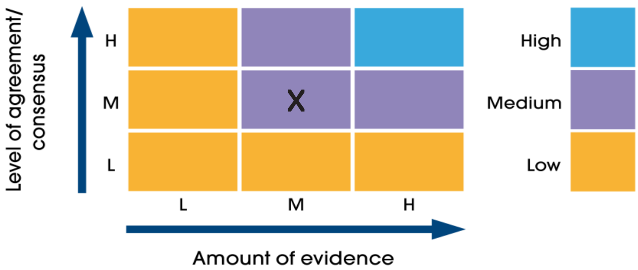
The integration of coastal management with land-use and marine planning will become more important in future, under the broader context of Integrated Coastal Zone Management. The economic value of coastal habitats and coastal processes needs to be more widely understood and promoted: this is often difficult due to the public and political expectation that risk of flooding and erosion can and should be controlled.

Researchers working in this area

There are a number of key researchers working on ecosystem services and valuation. The Tyndall Centre for Climate Change Research (Milligan *et al*., 2006) is working on stakeholder dialogue and coastal change. The Centre for Ecology and Hydrology is working with Plymouth Marine Laboratories and others on quantification and valuation of carbon sequestration in coastal margins, and with the University of Glasgow on quantifying and valuing coastal defence in Scotland. There is a NERC BESS (Biodiversity and Ecosystem Services) project led by the University of St Andrews with a wide range of partner institutions, working on coastal margins (CBESS - A hierarchical approach to the examination of the relationship between biodiversity and ecosystem service flows across coastal margins).

5. CONFIDENCE ASSESSMENTS

What is already happening?



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 and ForeSight projects). Levels of confidence are the same as previous reporting in 2010.

What could happen?

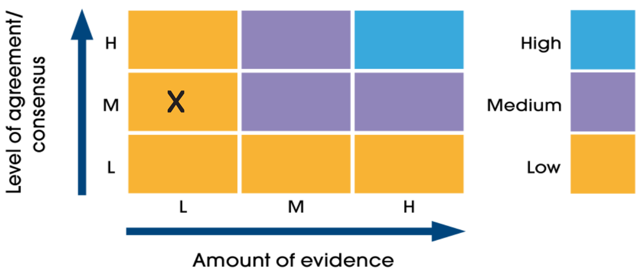


Table 2: Summary of the length of UK coastline with erosion and protection. Source: Gatliff et al. *(2010).*

Region	Coast length	Length of coast eroding		Coast length with defence works and artificial beaches	
	km	km	%	km	%
North-east England	297	80	26.9	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	100.0
East England	555	168	30.3	382	68.8
South-east England	788	244	31.0	429	54.4
South-west England	1,379	437	31.7	306	22.2
England	4,273	1,275	29.8	1,947	45.6
Wales	1,498	346	23.1	415	27.7
Scotland	11,154	1,298	11.6	733	6.6
Northern Ireland	456	89	19.5	90	19.7
UK	17,381	3,008	17.3	3,185	18.3

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. Nevertheless, especially for eroding soft-cliff coastlines, model predictions of coastal retreat are becoming increasingly reliable and useful for coastal zone planning and management. Levels of confidence are the same as previous reporting in 2010.

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