Shore and cliff sensitivity to accelerating sea level rise

FCERM Research & Development Programme

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Contents

Executive summary

This study offers the first quantification of the sensitivity of coastal cliff toe erosion to future relative sea level rise around England and Wales. We tackle specific questions about how this may be expected to vary around the coast. The study has adopted projections of future sea level from the United Kingdom Climate Projections project (UKCP18), which account for land level changes, and it has assumed a scenario of wave growth.

Since relevant observational data are sparse, the study has progressed through model simulations. We used an open-source numerical modelling tool (SCAPE), which has been peer-reviewed, and applied it in practical coastal management studies. For 82 adjacent coastal regions we developed models (typically a few 10s of kilometres long); these were run multiple times to explore shore response to different sea level trajectories.

The simulations extended to 2300 and began around 10,000 years before the present day. Historic sea levels (in the late Holocene) proved important in determining future sensitivity for regions in the north; higher historic sea levels were associated with higher sensitivity. Generally, higher tidal ranges and larger waves tended to reduce sensitivity.

Historic sea levels are uncertain, but exploring the consequences of this was beyond the scope of the study. Instead, a conservative approach was followed, in which historic sea levels were chosen that would tend to cause an overestimation rather than an underestimation of sensitivity. Although this approach was generally successful, it resulted in physically unrealistic present-day conditions for 16 regions, and no results could be derived for those. Further modelling with more realistic historic sea levels would be beneficial.

The outputs were processed to provide regional indicators of cliff toe sensitivity to sea level rise. This approach allowed the study to be rolled out because it avoided problems specific to local geologies. Where appropriate, these indicators might be used to predict future change by combining them with observations of past recession. In this way, the historic shore recession is used as a proxy for the resistance of local geology to marine erosion.

Such predictions might, where appropriate, be carried out to support local studies, strategic studies or revisions of Shoreline Management Plans. The method informs the updated National Coastal Erosion Risk Map, published in 2025. It is envisaged that typical users could include staff from local authorities, Environment Agency, Natural Resources Wales and Natural England, other regulators with coastal responsibilities, engineering practitioners and organisations interested in quantifying the impacts of climate change at the coast.

1 Introduction

1.1 Purpose

The prediction of coastal cliff erosion is complex and uncertain. The process typically involves adopting the historic rate of change as a ‘baseline’ condition, which is then modified by factors that represent the effects of sea level rise and, if necessary, human interventions, and changes in the natural system. This work aims to build understanding of the first of these factors; the effects of sea level rise.

Sea level rise is accelerating (for example, Nerem and others, 2018). The rates of rise around the UK are already higher than they have been for several thousand years. The UK Climate Projections (UKCP18) show sea level rise by 2100 of between 0.29 metres and 1.15 metres in London and 0.27 to 1.13 metres in Cardiff (relative to average levels between 1981 and 2000). By 2300, this increases to 0.5 to 2.6 metres (for both cities). Other sources argue that there is a reasonable probability of much larger rises, for example, Bamber and others (2019) found that:

“… a global total (sea level rise) exceeding 2 m by 2100 lies within the 90% uncertainty bounds for a high emission scenario. This is more than twice the upper value put forward by the Intergovernmental Panel on Climate Change in the Fifth Assessment Report.”

Sea level rise drives coastal erosion and so increased coastal losses must be expected. The coastal management community has a responsibility to understand the consequential losses of coastal settlements and infrastructure so that they can support decision-making.

Overall increases in coastal cliff erosion are certain, although this will not occur in all areas, but the acceleration of this recession (the sensitivity of cliff toe retreat rates) is much less clear. If sea level rise increases by a factor of 10, does this mean that cliff recession will grow by the same multiple, or will it be smaller or greater? Similarly, how will this sensitivity vary around the coastline?

This study addresses that question specifically for cliff/shore platform coasts with a perched beach (or no beach); a coastal type that is very common, but which has not previously received a great deal of attention in academic studies of sea level rise. It aims to provide:

- quantified indicators of cliff toe sensitivity
- insights into how this may vary around the coastline

The indicators are presented in the accompanying spreadsheet tool (Environment Agency, 2025a), method report (Environment Agency, 2025f) and quick start guide (Environment Agency, 2025b).

Wave conditions are also expected to change with the climate, but there is greater uncertainty about how this will happen. To avoid underestimating future sensitivity, this project has applied a conservatively estimated scenario of wave growth to all simulations, which is described in section 3.5.2.

It is emphasised that this study does not predict future shorelines, and the results will not be meaningful for all coastal cliff locations. It is further emphasised that this work is not intended to replace the kind of detailed assessment that might be carried out with a site-specific numerical model.

1.2 The need for model-based approaches

A pivotal issue is the fact that sea level rise has been low and relatively constant over the period of time that reliable observations of shore change have been available. This means that an observation-based approach is not yet possible, and it is necessary to rely on conceptual and numerical models.

The tools already available to quantify sensitivity are limited in number (see, for example, reviews by Bray and Hooke, 1997; and Brooks and Spencer, 2012). The most commonly used methods have arisen from the early work of Bruun (1962), which was subsequently adapted for a range of different shore configurations and situations, including coastal cliffs, by Dean (1991). That adaptation, and other variants of the Bruun rule, continue to be recommended for cliff sites. A Bruun-based method was adopted, for example, to account for the effect of sea level rise on coastal cliff retreat in the creation of the Environment Agency's first National Coastal Erosion Risk Map (NCERM) (Halcrow, 2007). In addition, a single Bruun-based method is offered by CIRIA's Beach management manual (Rogers and others, 2010) and the Dean adaptation is given by the Soft Cliffs Handbook (Lee and Clark, 2002).

Bruun conceptualised the shore as a deep beach backed by dunes. Many of the shores of England and Wales are, however, backed by cliffs and fronted by shore platforms, although these are often obscured by beach material. There are strong reasons to expect the responses of cliffed shores to be different to those of beach shores, and this calls into question the reliability of Bruun-based approaches (see section 2.3 for further discussion).

1.3 Main questions

The slow development of predictive tools suitable for cliffs reflects the difficulty of the problem. The erosion of cliffed shores is influenced by, among other things, highly complex hydrodynamic and pneumatic processes, many lithological properties, accumulated and mobile sediments, subaerial weathering, landsliding and human interventions. A further problem is the difficulty that modellers have had in developing tools that have a degree of reliability when used to represent medium to long time periods (that is, the decades to centuries over which sea level rise drives shore change). Moreover, coastlines are long and highly diverse. In this context, it is unsurprising that tools are limited in number, or that some basic important questions have attracted relatively little attention, including:

- how sensitive shore recession might be to accelerating sea level rise?

and how this might vary:

- with the historic rate of sea level rise?
- with tidal range?
- with wave climate?
- from region to region around the coast?
- over time?

1.4 Background to this study

These questions have been explored through a series of studies funded, since 1999, by the Engineering and Physical Sciences Research Council (Walkden and Hall, 2005); North Norfolk District Council (Walkden and Hall, 2011); the Tyndall Centre for Climate Change Research (Dickson and others, 2007; Dawson and others, 2009); and the Environment Agency Managed Research Programme (Royal Haskoning and others, 2007; Walkden and Dickson, 2008).

These studies have used peer-reviewed concepts developed for cliff/platform shores, rather than others adapted from work on deep beaches; and a peer-reviewed numerical model (SCAPE, see section 2), which has proved useful for addressing abstract research questions and practical coastal management problems. They have argued that much of the complexity in the physical processes can be represented in relatively abstract terms, and that important insights can be gained by focusing attention on the main drivers of change and the feedbacks within shore systems through which form and stability emerge. There is substantial academic interest in this type of approach (for example, Van Maanen, and others, 2016) and it has shown promise in building understanding of long-term geomorphic processes (for example, Ashton and others, 2001), and in providing the kinds of projections needed for integrated long-term coastal management (for example, Dawson and others, 2009; Walkden and Hall, 2011).

This project is a continuation of that work, which has been funded by the Joint Flood and Coastal Erosion Risk Management Research and Development Programme. The sources of the modelling tool, concepts and methods used in this work are illustrated in Figure 1-1.

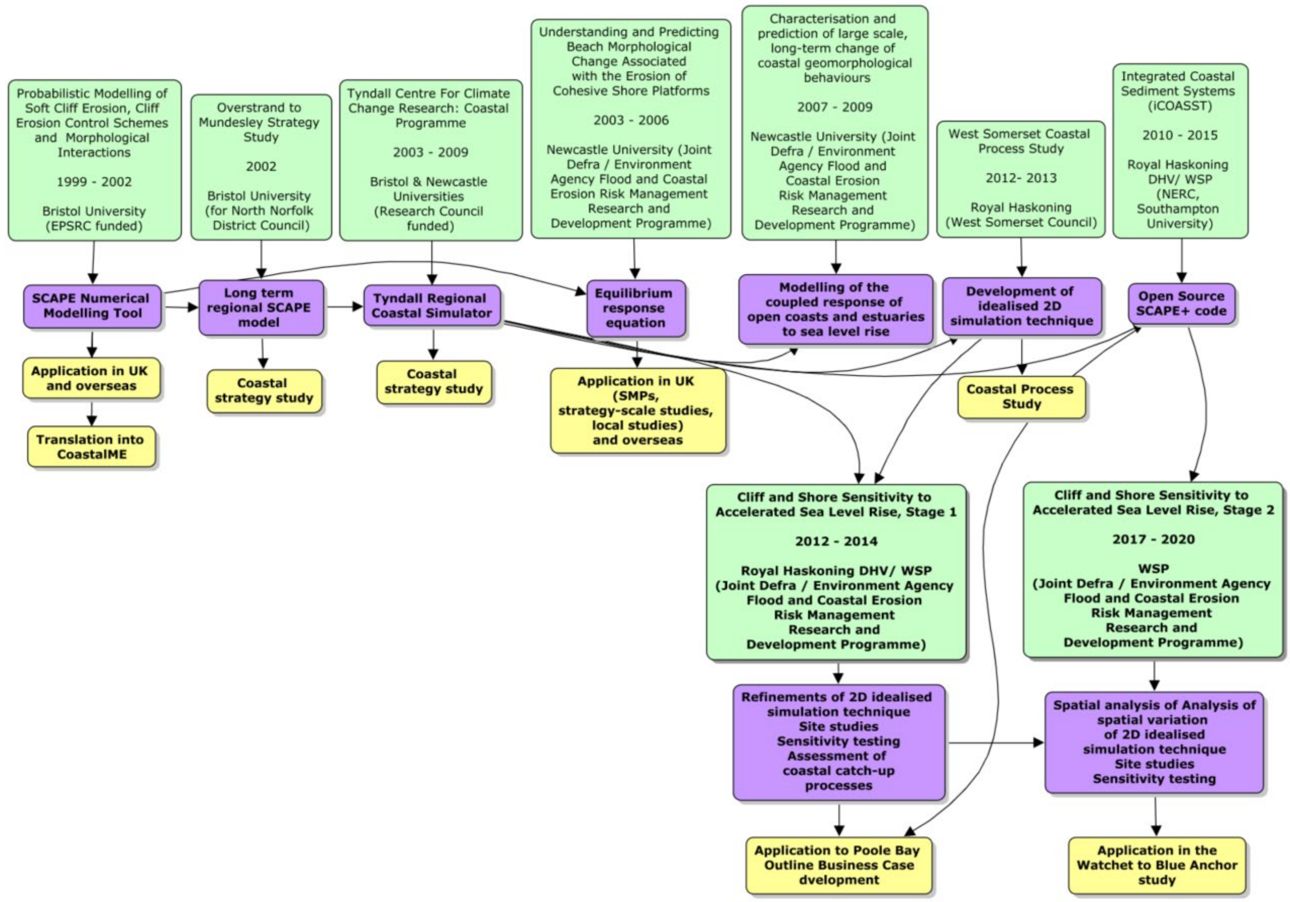

Figure 1-1: Flow chart describing the research (green), methods (purple) and applied studies (yellow) contributing to this work.

Figure 1-1 shows 7 areas of research – along with the methods they produced – that have contributed to his project. The research was carried out between 1999 and 2015 and includes work by the University of Bristol, the University of Newcastle and Royal Haskoning. The figure also lists 8 applied studies of the methods.

This main stage of the project builds on insights gained during a scoping study (Environment Agency, 2025d) to provide answers to the last 2 questions in section 1.3; how sensitivity of cliffed shores might vary around the coast of England and Wales, and how this may change over time.

1.5 Indicators of cliff toe sensitivity

The results are expressed in terms of indicators of cliff toe sensitivity to (UKCP18) sea level rise', that is, factors by which recession may accelerate. These are referred to as recession sensitivity indicators (RSI). Where appropriate, these indicators might be used to calculate future change, by combining them with information on historic recession; this is described in the accompanying method report (Environment Agency, 2025f). In this way, historical shore recession is used as a proxy for the resistance of geology to marine loading, and alongshore variations can be accounted for.

It is stressed that these indicators do not represent shore recession directly, and this can lead to apparently counter-intuitive conditions. For example, surge is an important driver of cliff recession in parts of the east coast of England, so that cliffs subject to higher surge may retreat more rapidly. However, it does not follow that such cliffs will be more (or less) sensitive to accelerated sea level rise; their rates of retreat may be higher, but the acceleration of this retreat may not.

1.6 Two-dimensional representation

To make progress on this challenging problem, resources were used where they were judged to be most beneficial. Simplifications had to be made, and the drawbacks and advantages of these were considered and, where possible, sensitivities were tested (Environment Agency, 2025e). The shore was modelled in 2 dimensions (2D). Although SCAPE can be used to represent 3-dimensional coasts (see, for example, Walkden and Hall, 2005; Dickson and others, 2007; and Walkden and others, 2015), that approach was beyond the resources available to this large-scale study. Instead, a 2D approach was adopted, in which regions of shore (typically several 10s of kilometres in length) were treated as one unit. In this way, local detail was sacrificed to gain general understanding of regional variations. This simplification made the study possible, but it had important implications, particularly with respect to the natural variability of beaches and geology.

1.7 Beach variability

Beaches interact with shore platforms and cliffs, influencing profile shapes, recession rates and the plan shape of the coast. Although SCAPE is designed to capture some of these interactions (see, for example, Walkden and Hall, 2005; Dickson and others, 2007; Walkden and others, 2015), that was not feasible for this study.

Sensitivity testing during the scoping stage of the project (Environment Agency, 2025e) showed that, where beaches were shallow, shore profile sensitivity to accelerated sea level rise was only weakly sensitive to beach volume. Neglecting a beach in the representation of such a shore resulted in a modest increase in conservatism, that is, the results without a beach tended to be somewhat larger than those where a beach was explicitly represented.

Consequently, beaches were not included in the models prepared in this main project stage, but the indicators of sensitivity derived from those models can be expected to represent sites with modest beaches. This simplification was made because it greatly reduced the number of necessary simulations but it is far from ideal. Its implications are discussed in section 6, along with suggestions for further work.

1.8 Geological variability

The highly variable nature of geology is a great challenge to coastal cliff research. This variability calls for studies of the detail of different settings, to understand the processes that drive changes and the characteristics of the shore that resist them. Such work is needed to develop better models and so make improved predictions of future recession under sea level rise.

However, it is important to recognise that such studies carry certain limitations. The coastline of the UK is extremely variable in terms of its geology and environmental settings, but the number of researchers exploring these questions is small, and so progress is slow. The short timeframe of most observational studies is a further problem, because it tends to focus attention on fast and localised erosive processes, rather than on drivers of erosion over decades to centuries. This means that it will be some appreciable time before localised detailed studies can provide general answers to the important questions listed above.

In the more abstract approach used here, geology is treated as a homogenous material with a single strength parameter. In each model, the geology is shaped, tide by tide, by wave erosive forces distributed across the tidal range and gradually lifted (or lowered) by the rising (or falling) sea level. In this idealised representation, attention is instead directed to the effects of the tides, wave climate and the historic sea levels.

In addition, no attempt is made to match the strength of the model shore to local conditions. Instead, the model is used to represent an extended region of shore containing many geological units, but across which the tidal range, wave climate and the history of sea level rise are broadly similar. This is why the study offers indicators of cliff toe sensitivity rather than predictions of future cliff position.

2 The modelling tool

The SCAPE (Soft Cliff And Platform Erosion) numerical modelling tool was selected for this study at its inception; a review of other modelling tools was not, therefore, within the project scope.

Its strengths include:

- capacity to represent change over the medium to long-term (decades to centuries)
- academic peer-review and high citation (for example, Walkden and Hall, 2005)
- open-source availability
- a record of successful application in both academic and applied coastal management studies

It has also been accepted as a tool capable of providing useful insights into the effects of climate change; for example, SCAPE-based work is cited in the fourth and fifth assessment reports of the Intergovernmental Panel on Climate Change.

2.1 Background

SCAPE is a modelling tool that can be applied to cliff/platform coasts, with or without a beach. It represents processes but does so in abstract and behavioural terms and is typically used to simulate change over timeframes of decades to centuries. It is also used to model the short-term rapid responses of cliffs to the removal of coastal protection (for example, Walkden and Hall, 2005; Dawson and others, 2009; Walkden and Hall, 2011; Walkden and others, 2016; and WSP, 2019).

SCAPE was originally developed under an Engineering and Physical Sciences Research Council grant at Bristol University between 1999 and 2002 by Mike Walkden and Jim Hall (Walkden and Hall, 2005). Adaptations and developments were later made with the support of Mark Dickson (Dickson and others, 2007), with funding from the Tyndall Centre for Climate Change, and by John Barnes, with funding from Southampton University and the iCOASST research project. SCAPE was made ‘Open Source’ during the iCOASST project. The Open Source version was adopted for this study and improved before use. The improved version (and details of the changes made) may be obtained from the Mike Walden GitHub directory A brief summary of various commercial and research applications can be found in the iCOASST section of the Channel Coastal Observatory web portal.

SCAPE is a quasi-3D model in that the coast is described as a series of shore-normal profiles, which interact through the exchange of sediment. It was developed to allow the representation of long periods of time and engineering interventions. It was also designed so that run times would be short enough to explore uncertainty by applying probabilistic techniques, including multiple simulation.

2.2 Process representation

SCAPE calculates the shaping of the shore over long periods, typically tracking dynamic feedback between the profile shape, beach depth and processes of erosion. A major strength for this study is that it accounts explicitly for the effect of relative sea level rise or fall on shore profile shape. Sea level rise, for example, is represented as a gradual downward shift in the model, which increases water depths and so allows larger waves closer to the upper platform and cliff. This, in turn, increases the slopes encountered by the breaking waves, affecting the distribution of erosion and subsequent profile shapes.

In this work, SCAPE has been used to represent the coast in 2 dimensions. In this application, the beach was assumed to have zero volume, and so did not influence profile development (also, in 2D mode, the beach volume is not changed by sediment moved along the shore or released from the cliff). Figure 2-1 illustrates the main interactions that control model behaviour in this mode.

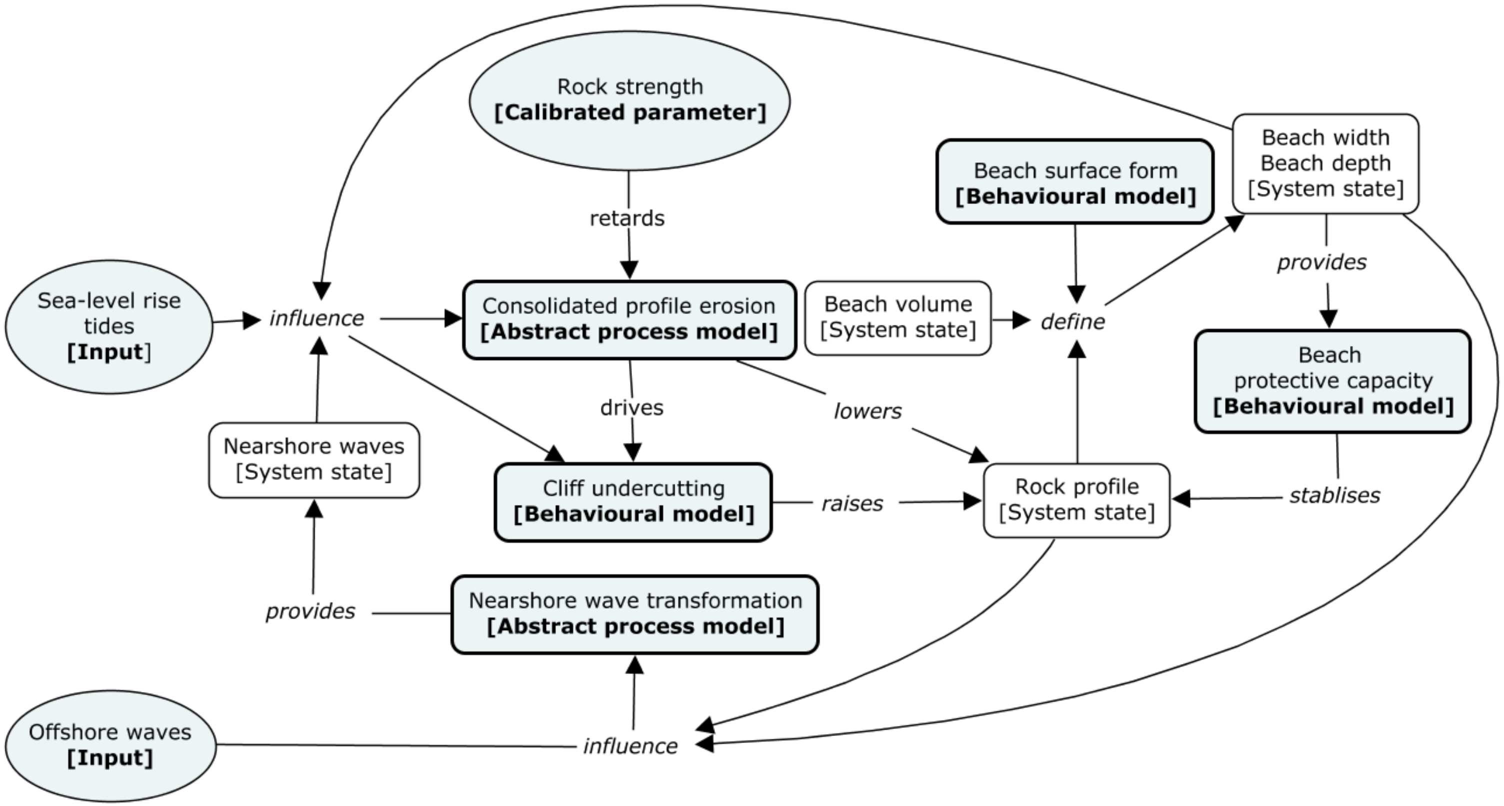

Figure 2-1: Flow chart illustrating the feedback processes active within the SCAPE model when applied in 2-dimensional mode

Figure 2-1 shows the feedback processes active within the SCAPE model. It shows 2 inputs: sea level rise and offshore waves. These inputs feed into the models which are: 3 behavioural models (beach surface form, beach protective capacity and cliff undercutting); 2 abstract models (consolidated profile erosion, nearshore wave transformation); and a calibrated model (rock strength). The flowchart also shows the interactions between the models and system states (these are rock profile, nearshore waves, beach width and beach depth).

SCAPE has process-based and behavioural modules representing the platform, cliff and beach, as well as hydrodynamic loads. This is necessary to capture interactions and feedback that regulates the behaviour of such coasts. The process descriptions are relatively abstract to minimise run times and so allow simulation of long periods and exploration of model sensitivities. At every model time step (one tidal period), data describing wave height, period and direction, tidal amplitude, and rate of relative sea level rise are read from input files and the system state (rock profile, beach width, beach depth, nearshore wave conditions) is recalculated.

The wave conditions are assumed to be constant throughout a tidal time step. Wave transformation due to shoaling and refraction is calculated using linear wave theory. If required, a beach is represented as a surficial layer on the rock.

Quasi-3D SCAPE beach volumes are determined from the erosion and composition of the rock and from losses through wave-driven sediment transport. However, as described in section 1.7, beach volume and sediment transport are not represented in the 2-dimensional models used here. So, to prevent continual beach growth, the rock is not treated as a sediment source. When used, the beach is assumed to have a surface form defined by:

$$d = Ax^{2/3}$$

Where d is the depth of water, x is the offshore distance from the still water line and A is a factor controlling slope, which is typically identified using observational data (Bruun, 1962; Dean, 1991).

The lower surface of the beach is defined by the shore platform surface. As the model runs, and the platform surface evolves, the beach surface is translated horizontally until the correct beach volume is encompassed. The beach profile rises with long-term relative sea level rise. Beaches generally protect the shore platforms that they cover. Based on observational data (Ferreira and others, 2000), a simple rule was adopted whereby beach depths greater than 0.23 times the wave breaker depth were assumed to be fully protective. It was further assumed that this protective capability decreased linearly for shallower beaches.

No differentiation is initially made between the cliff face and shore profile; this boundary emerges through model iteration. This is an essential reason why simulations are typically begun many centuries before the present day; it allows time for the emergence of the shore platform, cliff face and the boundary between them (outputs from such a simulation can be found in the Results section of this report, as shown in Figure 5-4).

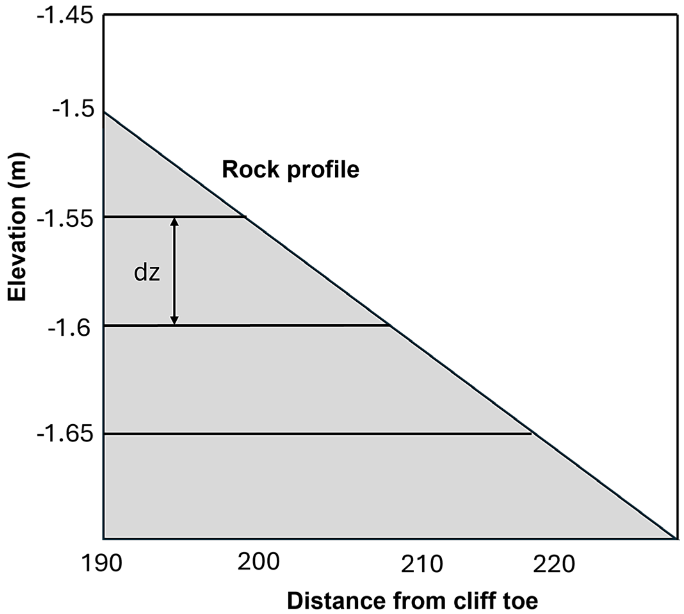

Figure 2-2: Graph describing the representation of the in-situ erosional surface.

In Figure 2-2 the SCAPE rock profile is represented as a vertical stack of horizontally aligned elements of height (dz), the seaward edge of which makes up the exposed face of the shore platform and cliff. The rock profile decreases in elevation (y-axis in metres) as the distance from the cliff toe (x-axis, unitless for this conceptualisation) increases.

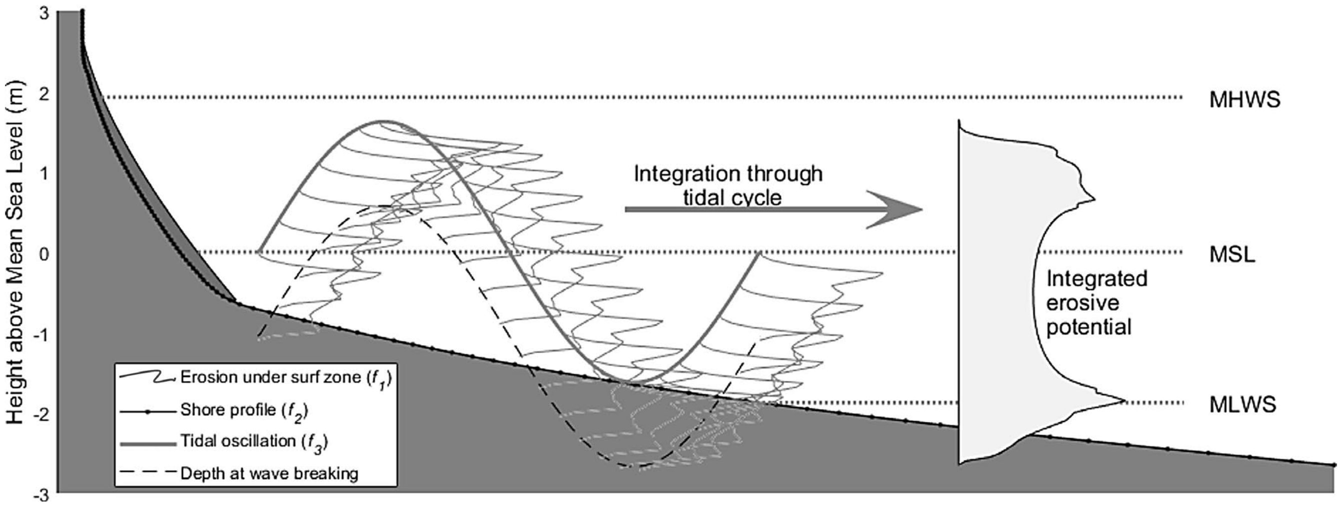

Figure 2-3: Graph describing the integration of erosive potential.

Figure 2-3 illustrates the conceptual shore profile and the integration of erosive potential for a single tidal time step. The y-axis is height above mean sea level (MSL) in metres (ranging from -3 m to + 3 m). At every stage of the tidal oscillation, the breaking wave field has the potential to erode the rock surface. This is represented by a function f_1. The seaward extent of f_1 is approximately equal to the water depth at which waves begin to break. To obtain the total erosive potential over a tidal cycle the instantaneous distribution of erosion must be integrated over the tidal period.

As can be seen in Figure 2-3, the integrated erosive potential tends to be concentrated at the tidal extremes, simply because this is where the water level spends the most time. Importantly, the actual erosion experienced by any exposed rock element also depends on (the tangent of) its slope. This means that gently sloping elements (generally lower in the profile) tend to erode less than the (typically higher) steeper elements.

The function f_1 is a dimensionless distribution of rock erosion under a breaking wave field. The function f_2 is the tidal variation in water level, which is represented as a sinusoid about mean sea level. The function f_3 is the slope of each rock element and, therefore, changes throughout the simulation in response to the calculated erosion. Gradually the model iterates towards a profile form that is in (non-static) equilibrium with the input conditions. Sea level rise (or fall) is represented as a gradual downward (or upward) shift in the model, changing the part of the shore exposed to wave attack.

In more formal terms, every time step the erosion of each element (Δy) is calculated with the expression:

$$\frac{\Delta y}{\Delta t} = H_b^{13/4} T^{3/2} K^{-1} f_1(f_2(t) - z) \tan(f_3(z))$$

Where horizontal and vertical dimensions are y and z, respectively, t is time, H_b is the breaking wave height, T is the wave period and K is a calibration term representing rock strength and some hydrodynamic constants, (units $m^{9/4}s^{2/3}$, see Kamphuis, 1987; and Walkden and Hall, 2005).

This coastal system, and, therefore, the dynamically stable emergent profile form, is regulated through feedback. This may be illustrated by considering the interaction of the cliff and shore platform. A sequence of events that cause high cliff toe retreat tend to widen the platform and raise the cliff toe. This reduces the erosive capability of subsequent waves at higher sections of the profile. This negative influence continues until ongoing processes narrow and lower the platform. Therefore, a period of unusually high cliff toe retreat is followed by a period of unusually low retreat, and the long-term average is stabilised. Such behaviour also regulates smaller scale profile morphology. Figure 2-4a, Figure 2-4b, and Figure 2-5 illustrate model iteration towards (non-static) equilibrium.

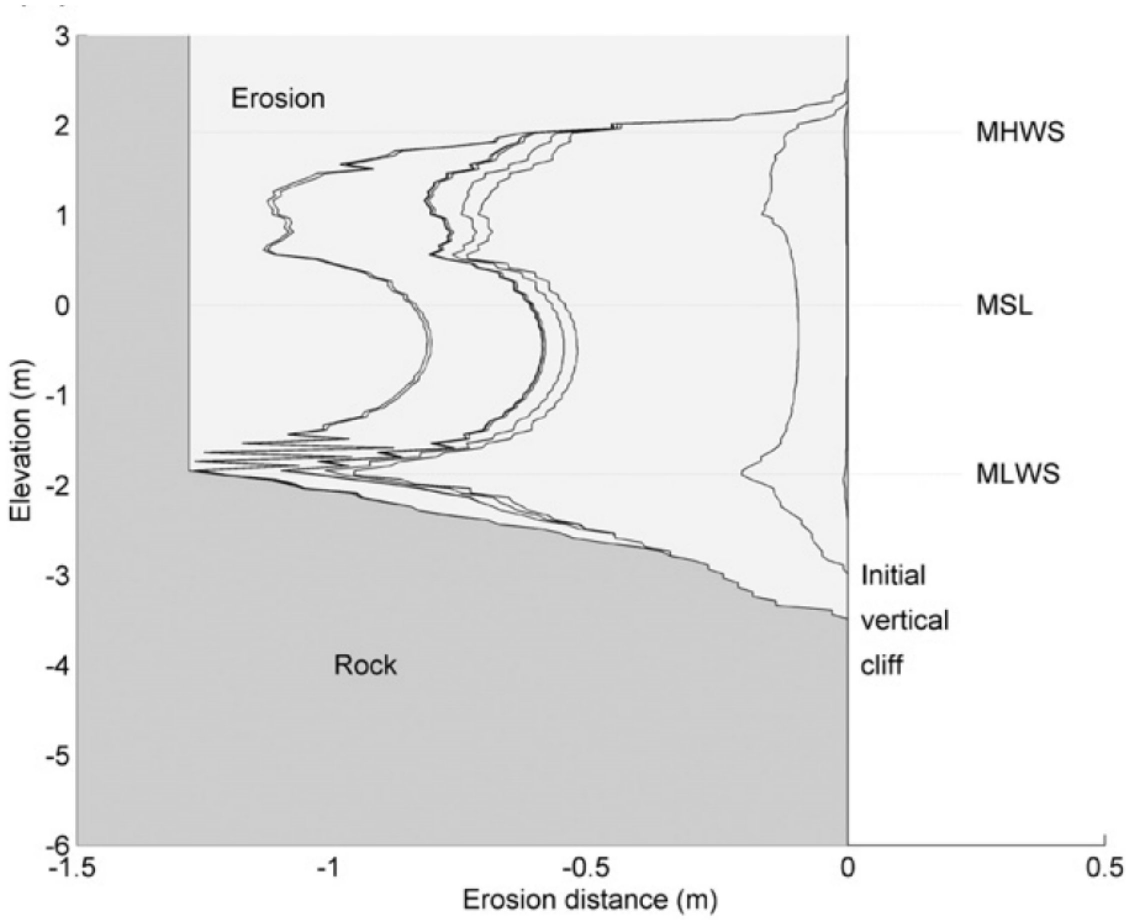

Figure 2-4a: Profiles that result from the first 10 recession events (time steps 1 to 10 of a particular simulation) acting on an initially vertical profile.

Figure 2-4a, shows elevation on the y-axis from -6 m to +3 m and erosion distance from -1.5 m to +0.5 m. The mean high water spring level (MHWS), MSL, and mean low water spring level (MLWS) are indicated. The graph demonstrates that the shore platform begins to form, and the cliff toe becomes clearly demarked. The profiles are far from smooth because of spatial variation in erosion caused by differences in wave height and tidal range and by local feedback between slope and erosion.

The effect of the concentration of erosion at around high and low tide can be seen in the development of 2 notches. The overhangs above these notches are assumed to collapse along a vertical plane (that is, leaving a vertical cliff) every 10 erosion events. Such overhangs and failures become smaller and less frequent as the profile evolves.

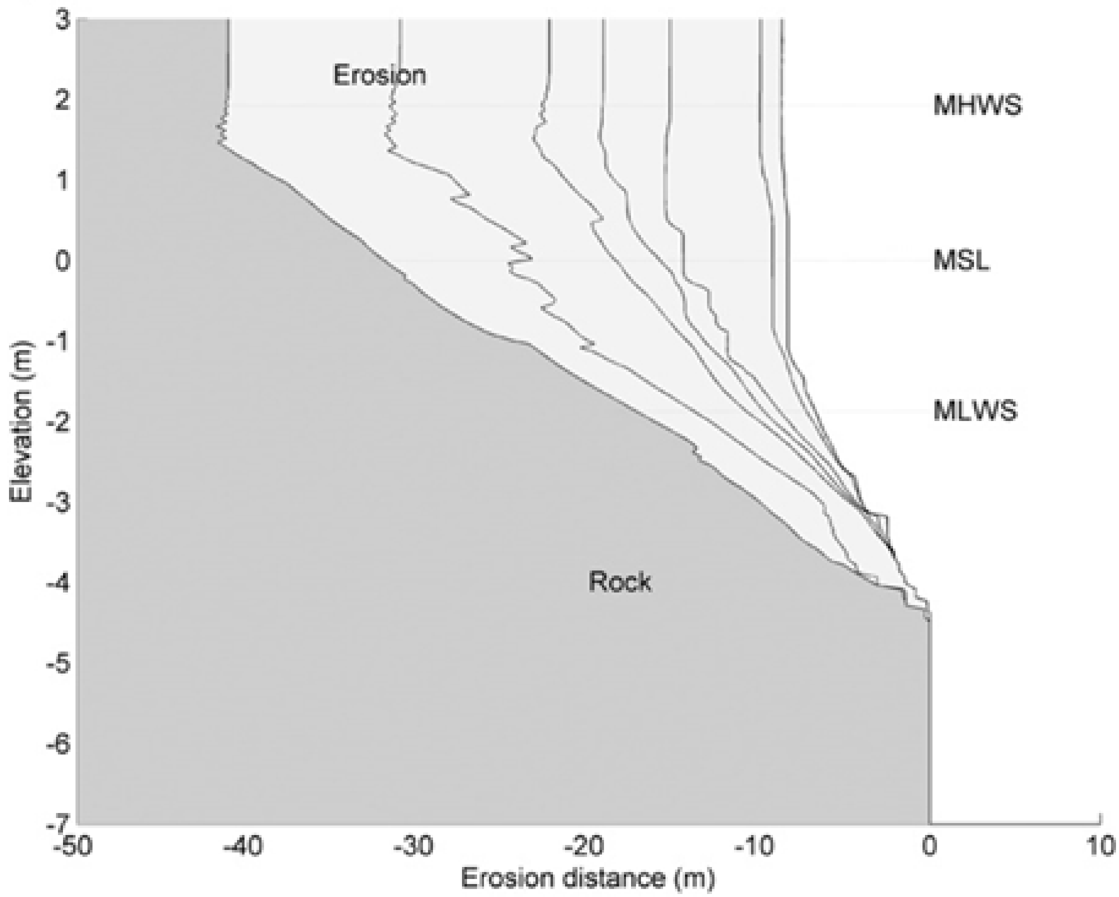

Figure 2-4b: Illustrating the evolution of the same profile between time steps 100 and 700.

Figure 2-4b, shows elevation on the y-axis from -7 m to +3 m and erosion distance on the x-axis from -50 m to +10 m. The MHWS, MSL and MLWS are indicated. The graph illustrates the emergence of a distinct shore platform, and its intersection with the cliff face translates upwards, reaching approximately 1.5 m above MSL.

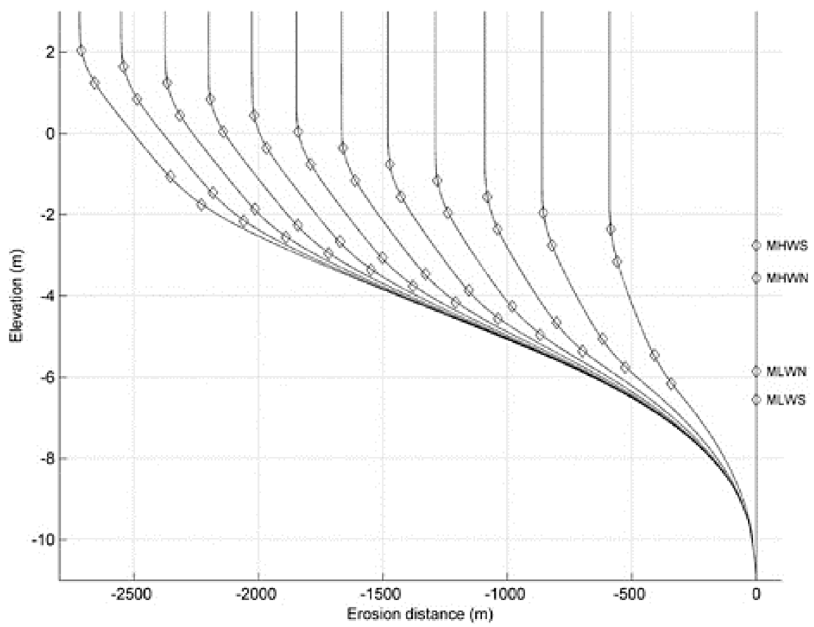

Figure 2-5: Twelve profiles illustrating later stages in the emergence of a SCAPE profile.

In Figure 2-5, the y-axis is elevation from -11 m to + 3 m, and the x-axis is erosion distance from – 3,000 m to 0 m. The profiles become smoother and more stable, and the influence of relative sea level rise on profile shape becomes evident. Eventually, the profile achieves non-static equilibrium and no longer changes (on average) relative to the (rising) sea level. In this state, the starting conditions have no effect on the profile state.

SCAPE can be used in this way to develop emergent non-static equilibrium coastal profile forms from site-specific data. Normally, such equilibrium models are then perturbed, perhaps by introducing some management intervention or (as in the case of this study) by changing the rate of relative sea level rise. The resulting changes in shore profile shape, and particularly the recession rate at the top of the profile, can then be used to inform coastal management decisions.

SCAPE models respond to changes in the rate of relative sea level rise. Figure 2-6 shows output from an example SCAPE simulation that illustrates a profile's development during a period of sea level rise (between 1800 and 2100). Note that retreat of the profile has been normalised against change across a baseline period (1920 to 2020); the reasons for this are discussed in section 4.

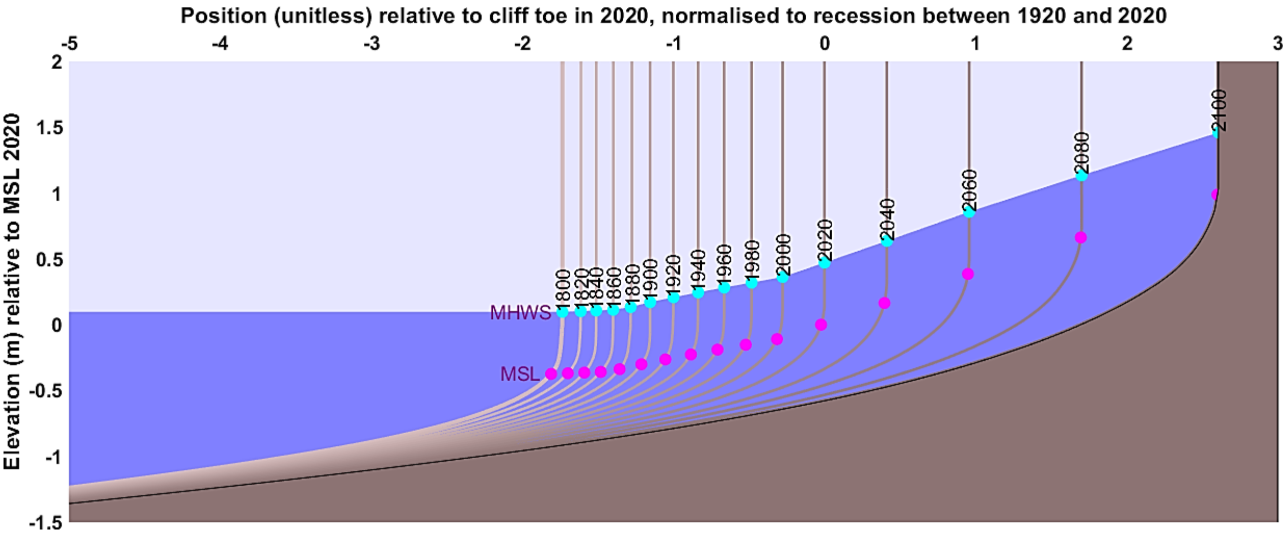

Figure 2-6: Model output showing cliff response to sea level change.

In Figure 2-6, the y-axis is elevation (in metres) relative to mean sea level in 2020. The x-axis is position (unitless) relative to cliff toe in 2020, normalised to recession between 1920 and 2020. The figure shows a sequence of output profiles, in 20-year stages from 1800 to 2100, responding to sea level change at the Isle of Purbeck. The profiles during the early 19th century are quite similar and are equally spaced. Accelerated sea level rise can be seen by the end of that century, and the profile shape begins to respond. Higher sea levels allow waves to break on higher elevations in the profile. These are steeper, and so the waves break more aggressively, and are better able to erode material. The profile retreats more quickly as a result, but also responds by changing shape. The sea level change and the resulting recession through the 20th century are noticeably higher than those of the 19th century, but far more rapid change occurs through the 21st century. The last stage of the simulation (the last 20 years) shows the same retreat as was seen in the first 140 years (that is, a 7-fold increase has occurred), and the profile has become noticeably steeper.

The nature of the non-static equilibrium reached depends on the characteristics of model and the inputs. If the internal properties of the model, such as rock strength, are held constant and the inputs are statistically stable, then the model will tend towards steady state equilibrium (see, for example, Chorley and Kennedy, 1971) in which the profile form constantly fluctuates about some unchanging mean.

If an input, such as sea level rise, changes through time, then dynamic equilibrium emerges, that is,

> "… balanced fluctuations abut a constantly changing systems condition [e.g. profile shape or cliff recession rate] which has a trajectory of unrepeated average states through time." (Chorley and Kennedy, 1971)

The objective in this study is to simulate different states of dynamic equilibrium for different regions around England and Wales, as the rate of sea level rise changes over time.

2.3 Comparison with the Bruun conceptualisation

As noted in the introduction, the most widely used conceptualisation of shore response to sea level rise was originally proposed by Per Bruun (1962). This describes the behaviour of a deep beach backed by a dune following a rise in sea level, and is illustrated in Figure 2-7.

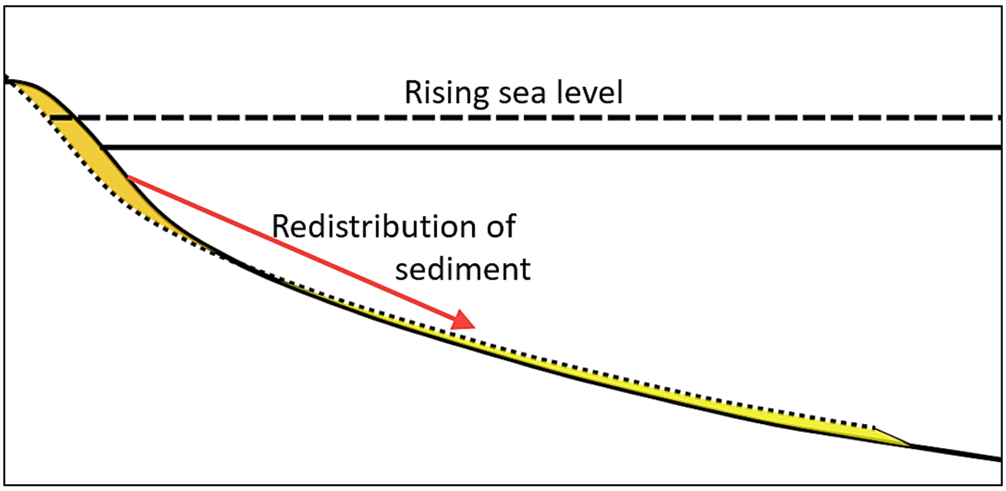

Figure 2-7: The Bruun conceptualisation.

Figure 2-7 describes an equilibrium beach/dune shore profile before and after a rise in sea level. The conditions before the rise in sea level are indicated by a solid horizontal black line (the sea level) and a solid shore profile (the original surface of the beach and dune). The higher sea level increases the elevation of the shore profile, but not its shape. The total volume of sediment is conserved and so the profile translates landward as it rises. In the process, sediment is assumed to move from the upper part of the profile to the lower part (indicated in the figure by the yellow zones). Conservation of form and of volume are assumed and this allows the calculation of landward displacement (the shore recession).

Important limitations arise from the basic assumptions of Bruun's conceptualisation, which include:

- conservation of profile form
- instantaneous response (that is, the profile immediately and fully adapts to the new sea level)
- constant depth of closure
- conservation of sediment

None of these are true for cliff/platform shores.

The main strength of the Bruun-based methods adapted for cliffed shores is that they represent a relationship between recession rate and beach volume, and so allow departure from the last of these assumptions; however, they are still subject to the first three.

A major strength of the study presented in this report is that it represents a relationship between recession rate and profile shape (avoiding assumption 1) and quantifies the time that this takes to happen (avoiding assumption 2); assumption 3 is also avoided. However, to avoid resource-intensive 3-dimensional modelling, assumption 4 is, in effect, made by this study. This has the effect of increasing the level of conservatism of the outputs.

This contrast has implications when applying the results of this study, and this is returned to in the final section of this report.

3 Model inputs

The coastline of England and Wales was represented with a set of regional 2-dimensional SCAPE models. For simplicity and reasons of cost, the study aimed to include the entire coastline, avoiding the need to review the prevalence of cliffed shores in each unit. During the scoping stage of this study, it was considered that around 50 regions could be represented with the available computing resource; this was, in fact, increased to 82. The models were driven by a small number of region-specific parameters and by timeseries of waves, tides and relative sea levels appropriate for each region.

The first step of the modelling process was to divide the coast into discrete units, referred to here as regions.

3.1 Regionalisation

In regionalising the coast, account was initially taken of the following factors:

- tidal range
- wave climate
- shoreline angle

The effects of spatial variation in the first two were found to be relatively small, and so the last (shoreline angle) governed the regional boundaries.

Regions were sought where a single shoreline angle (in plan) might reasonably approximate most of the coast contained within it. The approach was more satisfactory in some areas, such as the gently varying coasts of East Anglia and Cardigan Bay than in more irregular coasts, such as the Gower, Pembrokeshire, Anglesey (Ynys Môn) and North Devon/Cornwall. Although far from ideal, issues arising from this simplification are mitigated, to a degree, by the fact that more irregular locations tend to be associated with harder geologies, where average recession rates are lowest, and overall errors will be smallest. No regions extended into estuaries, which were beyond the scope of this study.

Issues encountered during the regionalisation process, and the approaches through which they were managed, are presented in 3.1.1 to 3.1.6.

3.1.1 Location 1: Flamborough Head (south shore) to Hornsea

Issues: large change in shore orientation across a short distance.

Approach: the plan shape angle of the shore was chosen to be more representative of the southern part of this bay (where the coast erodes more rapidly) than the north (which has more resistant rock).

Implications: errors are expected to increase in the northern part of this region where recession rates are lower.

3.1.2 Location 2: the Dungeness cuspate foreland

Issues: large change in shore orientation across a short distance.

Approach: these changes were not accounted for in setting a shoreline angle for this region.

Implications: none; no cliffs exist in this area.

3.1.3 Location 3: the Solent

Issues: lack of reliable wave data.

Approach: the Solent was not represented.

Implication: lack of representation in this area.

3.1.4 Location 4: Isle of Portland

Issues: large change in shore orientation across a short distance.

Approach: these changes were not accounted for in setting a shoreline angle for this region.

Implications: errors are expected to increase close to the Isle of Portland, however recession rates are relatively low in this area.

3.1.5 Location 5: the inner Severn Estuary

Issues: Lack of suitable wave input data.

Approach: Analysis curtailed at Avonmouth and Newport.

Implication: Lack of output for the inner Severn Estuary (treatment of estuaries was beyond the scope of the study).

3.1.6 **Location 6: South-western section of the Llŷn Peninsula**

Issues: High local changes in shoreline angle.

Approach: A short region was introduced (number 71), with a shoreline angle assumed to be similar to that of Porth Neigwl (Hell's Mouth).

Implication: Small, the outputs will be most accurate for the section of this region where recession rates are highest.

The resulting 82 regions are shown in Figure 3-1.

Figure 3-1: Map illustrating the model regions for the English and Welsh coast

The regions shown in Figure 3-1 are numbered in a clockwise direction starting from the Berwick-upon-Tweed area, around the whole coastline of England and Wales and finishing on the south of the Solway Firth (Cumbria) – they are numbered from 1 through to 82. Note that the study avoided reviewing the distribution of cliffs around the coast and, instead, all regions were included. Also, regions 14, 24, 32, 36 and 56 are not labelled, but exist in clockwise sequence.

3.2 Simulation timeframes

As discussed in section 2, SCAPE modelling normally involves long-term simulations to allow the emergence of dynamic equilibrium in the profile shape. This means that inputs must represent long periods of time.

The end year of the simulations was set to 2300; the last year for which (UKCP18) sea level rise projections were available. The first year of the simulations had to be set far enough in the past to allow a sufficient spin-up (to erase the effect of the arbitrarily-chosen initial profile shape). A starting point of 8,000 years BC was considered more than sufficient, and had the advantage of approximately coinciding with the time at which Holocene relative sea levels were at their lowest.

This implied a total period of 10,300 years for each simulation, so that the computational resource would have been: (1) prohibitively demanding and (2) disproportionally weighted towards the past. It was, therefore, decided to reduce the number of simulations of past conditions, and to run the models in 2 stages in the following way:

- hindcasts, 8010 BC to 1990 AD (20 per region)
- forecasts, 1790 AD to 2300 AD (900 per region)

The hindcasts were continued past the start date of the forecasts so that they would provide information on shore recession through the 20th century, although this was not ultimately used. The hindcasts were used to provide the initial shore profile for the forecasts. The start date of the forecasts was set relatively early (that is, significantly before the present day) to allow time for any initialisation perturbations to decay.

3.3 Variability

Each model was used to explore the implications of uncertainty in future sea levels by running them under each of the 9 UKCP18 sea level trajectories (as described in section 3.6.4).

It was recognised that stochastic fluctuations in wave and tide conditions drive random fluctuations in the modelled profile (as in reality). These were accounted for by running multiple variants for each sea level rise trajectory and for each region as follows:

- hindcasts, 20 variants
- forecasts, 100 variants

Each variant was run using a different sequence of wave and tide conditions. The smaller number of hindcasts meant that each of their output (final shore profile shape) was used to initiate multiple forecasts. In total, 2,540 simulations were run, describing over 16 million years of shore erosion.

3.4 Model parameters

The parameters used to control SCAPE simulations are described in the SCAPE user guide (Walkden and Barnes, 2016). In this study, the coast was modelled in a generalised, 2-dimensional way, for reasons discussed above. Consequently, most of the parameters were unvarying across all models.

3.4.1 Unvarying parameters

Most parameters were kept at their default settings, and information on these can be found in the SCAPE user guide (Walkden and Barnes, 2016). Parameter settings that differed from the default, but were held constant for all simulations, are listed in Table 3-1

Table 3-1: Universal parameter settings

Parameter	Hindcast setting	Forecast setting	Notes
Start year	-8010	1790	The first year of the simulation.
End year	1990	2300	The last year of the simulation.
Profile output time step	100	10	Interval (in years) at which shore profiles are saved.
First year profile output	-8010	1790	Year in which the first profile is saved.
Last year profile output	1990	2300	Year in which the last profile is saved.
N sections	1	1	The coast was represented with a single 2-dimensional profile.
Section height	30	30	Height (in metres) of the coastal profile. This was large enough to represent the greatest variation in relative sea level and was applied uniformly to all units.
Element height	0.01	0.01	Height (in metres) of each element of the coastal profile.
Rock strength	1.3×10^6	1.3×10^6	Determined during the scoping stage of this study (see below).
Wave tide file start	Random	Random	The first condition read from the input timeseries of waves and tides.
MSLM	20	20	Mean sea level (in metres) relative to the base of the model profile.
MSL offset	0	Variable	The height of mean sea level up the model element that it is adjoining; obtained from the hindcasts for the forecasts.

Parameter	Hindcast setting	Forecast setting	Notes
QPMAX boundary right in	0	0	Controls (prevents) ingress of beach sediment.
QPMAX boundary left in	0	0	Controls (prevents) ingress of beach sediment.
Modify wave period	N/A	N/A	Array input to represent growth in wave conditions due to climate change; see section 3.5.2.
Modify wave height	N/A	N/A	Array input to represent growth in wave conditions due to climate change; see section 3.5.2.

As noted in the introduction, geological strength is represented in this study in the simplest terms, to avoid the results being tied to specific geological units. For this reason, the value of the rock strength parameter was relatively unimportant, and any value within a wide range would have been acceptable (this was explored during the scoping stage of this study, Environment Agency, 2025e). It seemed preferable to select a value that had been derived during a previous study and so the value used by Walkden and Hall (2005) was chosen.

3.4.2 Region-specific parameters

Four parameters were specific to each region. These are:

- baseline angle – the shoreline angle estimated from mapping
- depth OSCMSL - the depth of the bathymetric contour used to represent the nearshore slope - the origin was estimated from bathymetric data
- OSC angles - the angle of the representative contour, whose origin was estimated from bathymetric data
- wave point depth - the water depth, in metres, at the location represented by the wave timeseries - the origin was from the Met Office WAVEWATCH III wave model - more details in section 3.5

The region-specific parameter values can be found in Appendix B.

3.5 Wave and water level timeseries inputs

Each SCAPE simulation requires a timeseries input file, with a time step of one tidal period, of ‘offshore’ significant wave heights, periods and directions and (synchronised) ‘shoreline’ high tide levels. Each time step is, therefore, driven by a singular wave height, period and direction. SCAPE calculates the transformation of the waves to the shoreline.

To represent the very long periods of the simulations, an assumption was made that the wave and tide conditions that have occurred in recent decades (described below as the ‘baseline’ conditions) are reasonably representative of those that have occurred over recent millennia. This assumption becomes increasingly unrealistic as the time horizon extends further into the past, but the importance of the associated errors should be expected to decrease at the same time. This assumption allowed the wave and water level timeseries input to be recycled such that, when the end of the file was reached, it was rewound and read back into the model to allow the simulation to continue.

The baseline waves and tides were also used to describe future conditions, although the waves were modified to account for growth due to climate change.

Following sensitivity testing during the first stage of this project (Environment Agency, 2025d), surge was considered a relatively unimportant influence and was not represented.

3.5.1 Baseline wave conditions

Baseline wave data were drawn from outputs of the Met Office’s WAVEWATCH III model. This data is available for locations around the UK on a grid with a spacing of approximately 9 kilometres. This source had the following advantages:

- an industry-leading modelling tool
- national scale coverage
- relatively high resolution
- long time series
- forced by observed winds
- extensive calibration, validation and quality assurance
- free availability (under the Environment Agency’s licence)

The record covered the period from 1 January 1980 to 31 December 2017 (38 complete years). The data had a 3-hourly time step before 2001, followed by an hourly time step. SCAPE requires wave inputs once per tide, and so the data were filtered to provide results that coincided with high tide.

One point was chosen to represent the offshore wave climate in each region. These were normally chosen to be close to the centre of the region, and points close to the shore were generally avoided (deeper water locations were expected to be more reliable). In some cases, such as within the Bristol Channel, high angle waves were expected and here the locations were selected to be skewed towards the direction of wave approach.

Wave severity has been represented with the average of the highest one-third values (of significant wave height at high tide) throughout each 38-year time series (Figure 3-2).

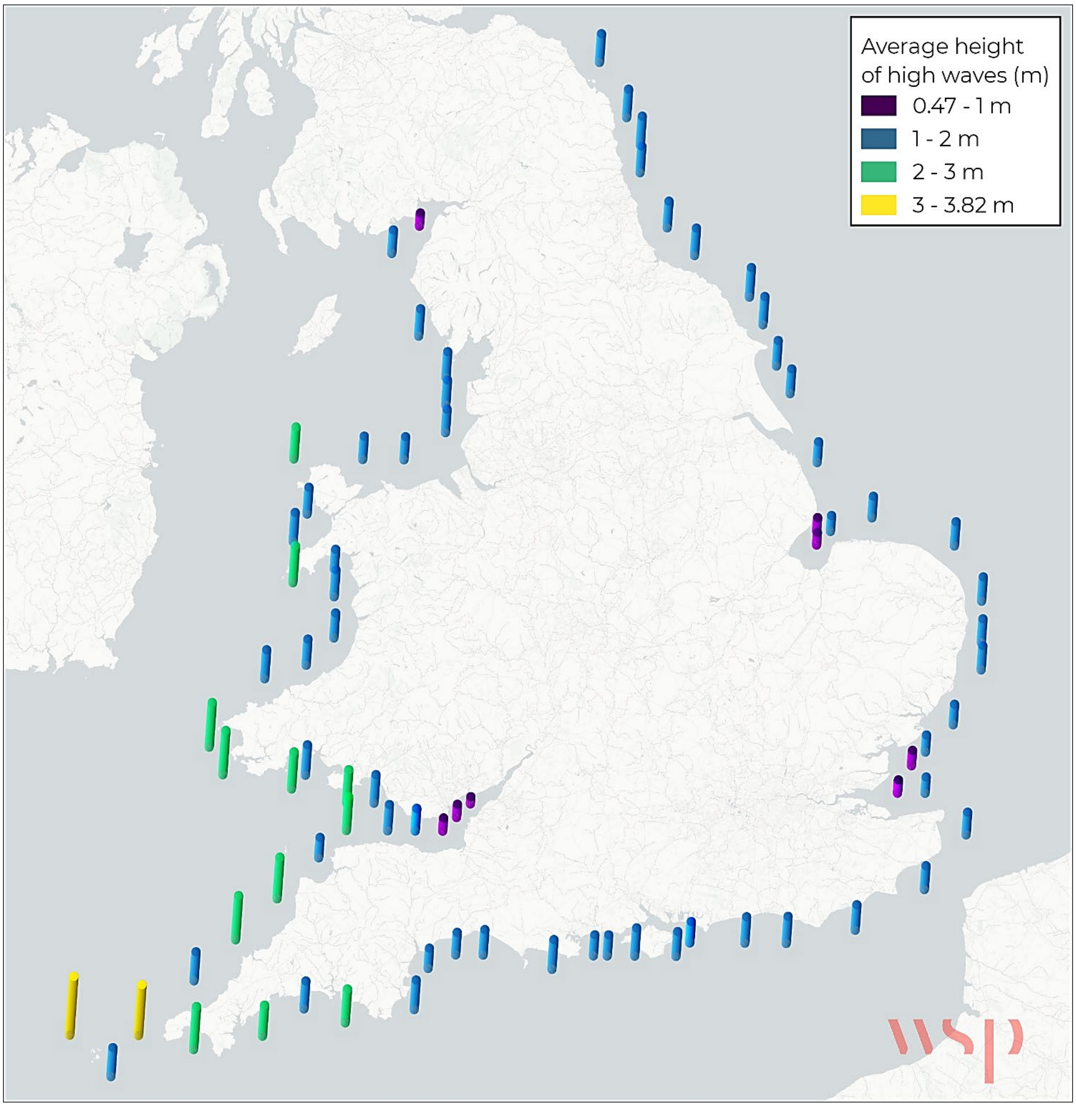

Figure 3-2: Map describing the variation in wave height across the model regions around the coastline of England and Wales

Figure 3-2 shows the average of the highest third of the high tide significant wave heights throughout the 38-year record; all directions are included and the severity is indicated by column height and colour. The average height of high waves is less than 2 m for large parts of the east and south coasts of England. The largest waves are found in the south-west of England and western coasts of Wales. More sheltered conditions can be seen in the Wash, the Thames Estuary, the Bristol Channel and the Solway Firth.

No attempt was made to represent extreme wave conditions not present within the record because earlier sensitivity testing had demonstrated that this was not critical (Environment Agency, 2025e). However, wave height and periods were increased to represent the effects of climate change.

3.5.2 Wave climate change

Growth in the wave conditions around the UK since the middle of the 20th century has been reported by many researchers (see, for example, Environment Agency, 2019). Further changes are expected through the 21st century, but they are highly uncertain and challenging to model. In line with the other aspects of this study, this uncertainty has been managed by adopting a ‘broad-brush’ and conservative approach to define an upper limit of potential change; that is, one that is unlikely to result in an underestimation of sensitivity.

Wave change was considered within the UKCP18 project (Palmer and others, 2018), which found:

> “… projections of average wave height suggest changes of the order 10 to 20% and a general tendency towards **lower** wave heights. Changes in extreme waves are also of the order 10 to 20%, but there is **no agreement in the sign of change** among the model projections…”

These findings are not definitive and are subject to caveats, including (Palmer and others, 2018):

> “… wave projections are based upon relatively small CMIP5 model ensembles. It is unlikely that these simulations span the full range of CMIP5 model responses under climate change. These projections should be viewed as **indicative of the overall magnitude** of changes we might see over the 21st century. … we cannot be sure of the relative influence of the climate change signal versus natural variability.”

In other words, the projections are indicative of an overall magnitude of change of 10% to 20%, but the sign of change (growth or decay) is not clear.

The Environment Agency project ‘Exploratory sea level projections for the UK to 2300’ (Environment Agency, 2019) reviewed studies of wave changes during the 20th and 21st centuries. The findings accord with those of Palmer and others (2018) and help to identify significant areas of uncertainty. These were found in the sign of change (growth or decay), spatial variations around the UK, the dependence on seasonality, and the relative growth of mean and extreme wave conditions. They also note that not all the studies reviewed accounted for wave generation processes in shallow waters.

Given the non-definitive nature of these findings and the need for appropriate conservatism, an assumption was made that wave heights (both ‘average’ and ‘extreme’) will increase linearly to 20% through to the end of the 21st century. This happens to be broadly in line with Environment Agency guidance for flood risk assessment (Environment Agency, 2020). To avoid an increase in wave steepness, the wave periods were also assumed to grow. For reasons of resource, no attempt was made to account for regional variations in the relationship between wave height and period, and instead a heuristic rule was used in which periods were assumed to grow by the square root of the wave height increase.

The date at which wave growth should be assumed to start is not clear cut, factors that were considered include the following:

- Environment Agency (2019) found that wave growth occurred from around the middle of the 20th century - the resulting growth in cliff toe recession is not captured in this study because it uses WAVEWATCH III data (1980 to 2017) for all time periods (in this respect, cliff toe recession will be underestimated)

- the current Environment Agency guidance for flood risk assessment (FRA) specifies that wave growth be assumed from the year 2000 (Environment Agency, 2020)
- UKCP18 assumes a baseline year of 1990

It was decided to implement growth from 1990. Although earlier than the Environment Agency FRA guidance, it is consistent with the UKCP baseline year, and will counter (by some degree) the lack of conservatism arising from the first point, above.

It may be noted that SCAPE explicitly captures effects of the increase in water depth on nearshore wave heights. As the sea level rises, the point of wave breaking moves inshore, so that the breaker zone becomes more energetic, driving a response in profile form and cliff retreat. This happens in addition to growth in the offshore waves.

Environment Agency (2019) note that:

> “Different emissions scenarios will give rise to different wave climate projections…”

But found that when the results from different climate model ensembles were compared:

> “…all the studies agreed that the modelling uncertainty was greater (than) the emissions scenario uncertainty…”

It is not, therefore, possible to distinguish different wave change scenarios for different representative concentration pathways (RCPs) and so the same pattern of growth was applied to all.

3.5.3 Baseline tide conditions

The baseline waves were synchronised with the high tide values found for each region. A unique time series of high tides was derived for each using the MIKE by DHI Global Tide Model. This calculates tidal conditions using harmonics obtained from satellite altimetry and generates results on a 0.125 degree grid (MIKE by DHI, 2017).

Although the model includes the largest shallow-water constituent around the UK (the M4 constituent), checking revealed significant differences between the results and inshore conditions published in the Admiralty tide tables (UK Hydrographic Office, 2019). Each time series was, therefore, corrected, point by point, using linear transfer functions derived from the Admiralty tide tables.

To explore the spatial variability in tide conditions, the spring tidal range was estimated as twice the elevation difference between mean sea level and mean high water spring, and the results are mapped in Figure 3-3.

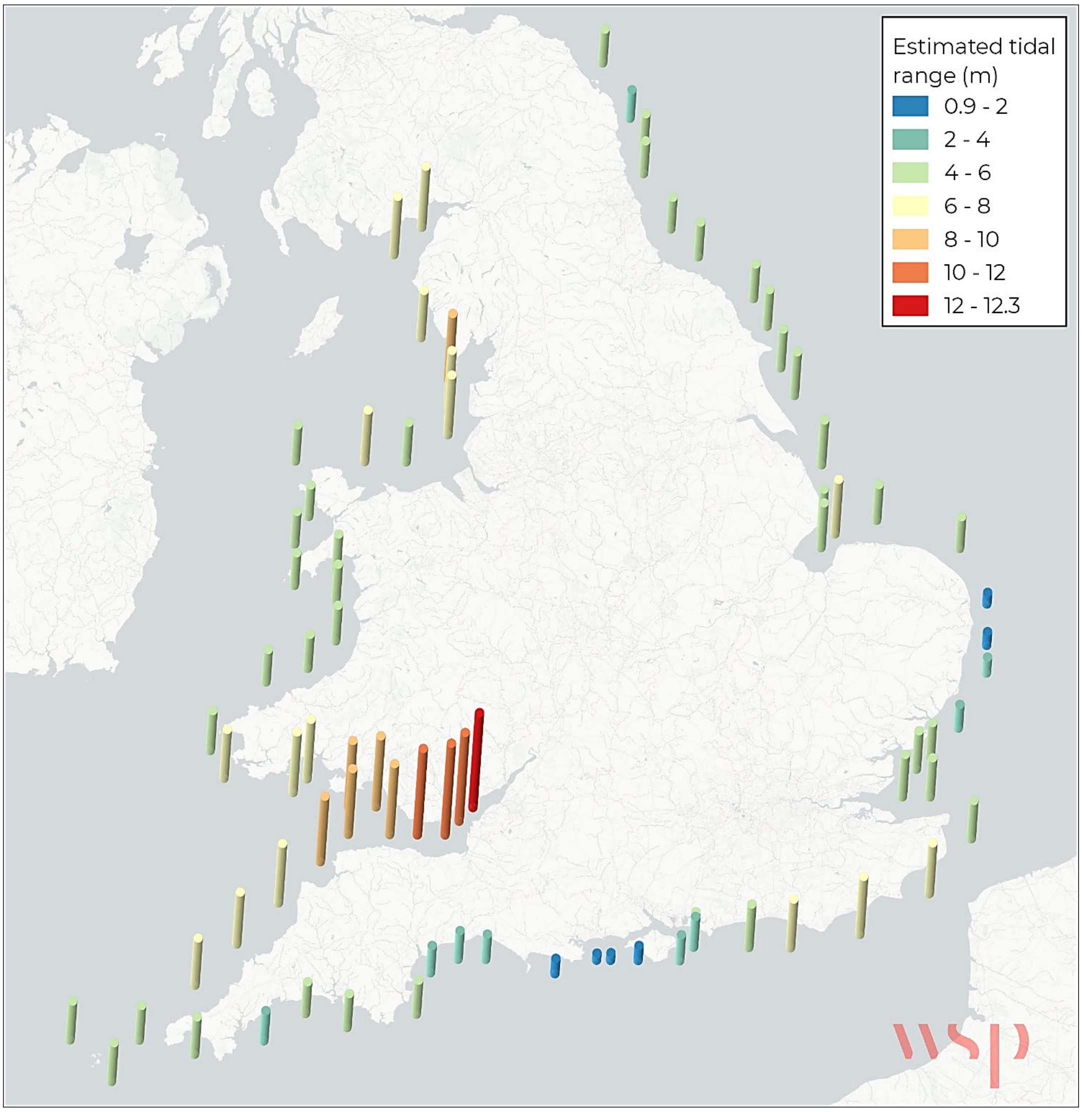

Figure 3-3: Map describing the estimated spring tidal ranges around the coastline of England and Wales (range indicated by column height and colour)

Figure 3-3 shows that around the coastline of England and Wales the tidal range varies based on local geography and other factors. The spring tidal range is generally 2 to 6 m, with some coastlines on the west coast and the Severn Estuary showing a spring tidal range greater than 8 m.

To simplify the modelling process, surge was not added to the astronomical component of the tides. In this respect, the total tidal range (that is, the range of the sea surface excursion at the shore) is underestimated.

The scoping stage of this study (Environment Agency, 2025d) showed that modest underestimations of tidal range resulted in a small increase in estimated sensitivity. It was therefore decided that this underestimation would be unlikely to have a strong influence on results.

It may seem counter-intuitive to neglect surge, because it is an important influence on cliff recession in some areas; particularly along some eastern coasts. Sea level rise will allow some surge events, that would otherwise be too small, to attack the cliff toe. In this way, it will trigger surge-related erosion events that would not otherwise have occurred. However, although surge may influence the rate of retreat, and the timing of retreat events, it does not necessarily influence the way a shore profile responds on average over the long term, to a progressive accelerated rate of sea level rise. Figure 5-15 and Figure 5-16 illustrate recession sensitivity against estimated tidal range. The trend seen supports the view that a modest underestimation of tidal excursion would not have a strong effect on sensitivity.

3.6 Relative sea level change

The study required consistent trajectories of relative sea level change extending from 10,000 years BP (before the present day) to the end of the available sea level rise projections (2300). Given these long timeframes and the need for greater detail for ‘near’ timeframes, it was necessary to draw on different sources of information for: (1) the Holocene, (2) the twentieth century and (3) for the future. These all had to account for glacial isostatic adjustment (GIA).

3.6.1 Glacial isostatic adjustment

GIA is the ongoing response of the earth’s crust to the last deglaciation. Some understanding of the resulting vertical movement of the British Isles in the current epoch can be seen in Figure 3-4, which is reproduced from the UKCP18 Marine report (Palmer and others, 2018).

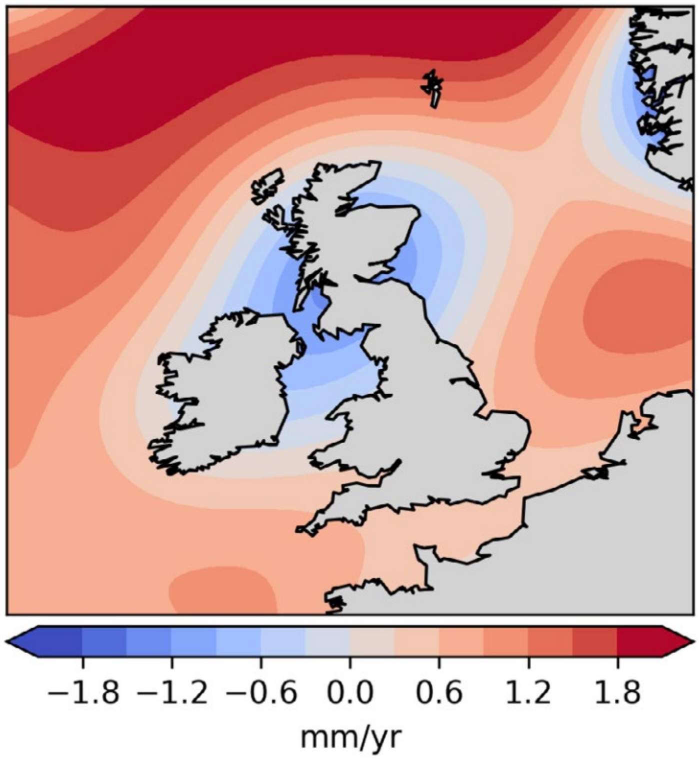

Figure 3-4: Illustration of the effect of glacial isostatic adjustment (GIA) on sea level (Palmer and others, 2018)

The map in Figure 3-4 shows the mean of 15 estimates of the ongoing regional relative sea level change associated with GIA, in mm/yr ranging from -1.8 to 1.8. Data was provided from the NERC BRITICE_CHRONO project by Dr Sarah Bradley (personal communciation 7 June 2019). This figure reveals the rise of central Scotland (due to ice sheet loss) and a corresponding lowering of southern Wales and southern England. The line of approximate (current) stasis has a roughly south-west to north-east alignment, and passes through the north of Wales and England. The cumulative effects of GIA through the Holocene have resulted in large changes in relative sea level.

3.6.2 Holocene relative sea levels

This study used the output of GIA simulations provided by Sarah Bradley (pers. comm. 7 June 2019) to represent relative sea levels through the Holocene for each model region. Those data were produced with the support of the NERC BRITICE_CHRONO project, and were provided as time series, 20,000 years in length in 1,000-year time steps. This time step represented valuable trends, but did not allow for the representation of short-term pulses of accelerated/decelerated relative sea level change. The results of several GIA models were provided and so a choice had to be made between them.

The outputs of 6 models (named D1, D2, D3, and C1, C2, C3) were provided because understanding of sea levels is, of course, subject to uncertainty. This is particularly true for those that occurred during the Holocene. The scoping stage of this study (Environment Agency, 2025e) demonstrated the importance of Holocene levels, and, as a result, the possibility of expanding the scope of this study to account for their associated uncertainties was discussed. However, this was found to be beyond the available resources and, therefore, it was decided, instead, to adopt a conservative bias in the representation of Holocene changes (in other words, to adopt a reasonable ‘worst case’ to minimise the likelihood that future sensitivity would be underestimated).

Following the equation of Walkden and Dickson (2008), sites with a history of rapid sea level rise can be expected to be least sensitive to future increase. Also, the later stages of the Holocene can be expected to be more significant to this study than the early stages. An approach was, therefore, followed in which, for each region, the Holocene data sets were interrogated to identify the time series that showed the highest sea level 1,000 years BP (these levels are shown in Figure 3-5). This was assumed to identify the most conservative of the GIA model simulations, which were then adopted for this study.

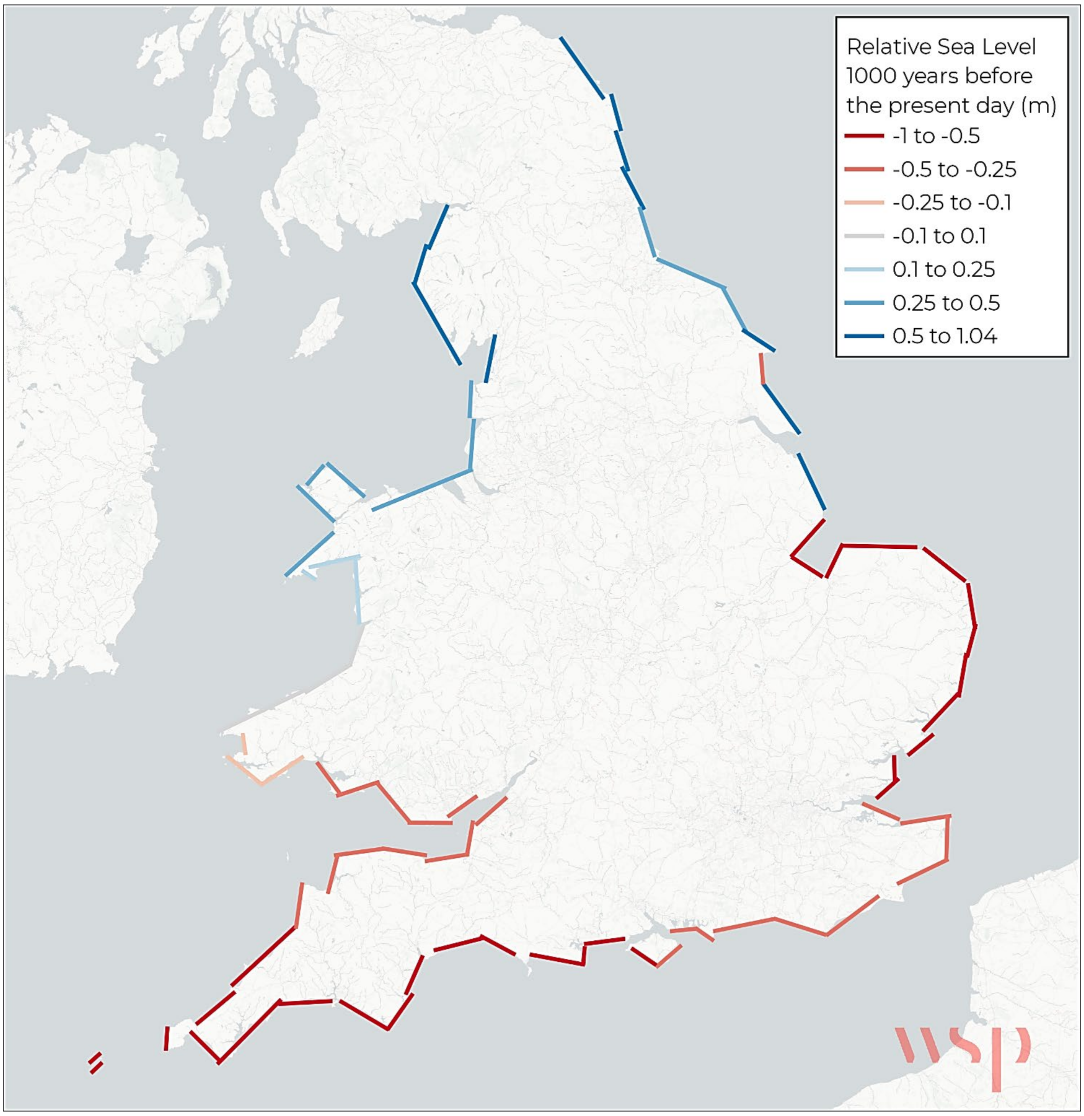

Figure 3-5: Map describing relative sea levels (in metres) 1,000 years BP assumed for this study around the coastline of England and Wales

Figure 3-5 shows that the relative sea level 1,000 years ago was different to the present day. The coastline levels are shown to be within a range of -1 m to + 1.04 m relative sea level 1000 years before the present day. The levels were generally lower than present day levels around southern coasts of England and Wales and higher to the north of England and Wales.

3.6.3 Twentieth century relative sea levels

Rates of sea level rise for (approximately) the twentieth century were adopted from the Environment Agency's revision of its coastal flood boundary condition data set (Environment Agency, 2018).

This had several important advantages, including:

- being recent

- being more spatially continuous than other data sets based solely on tide gauge observations such as Woodworth and others (2009)
- avoiding problems arising from interpolation across large areas where tide gauges are missing
- promoting consistency with other Environment Agency related studies

The Environment Agency data are linear trends in relative sea level (recent accelerations were found to be statistically insignificant). Their derivation is described as from:

> "… a combination of tide gauge data, GPS derived estimates of vertical land movement, late Holocene derived sea level estimates, and models for GIA …" (Environment Agency, 2018)

The full set of trends is included as Appendix A (Table A-1).

The results were tied to specific locations, which necessitated a stage of interpolation to derive rates for each model region. This was based on the distance between the centre of each model region and the 2 neighbouring Environment Agency trend reference locations. Appendix A (Table A-2) records the reference points used for each region and the derived trend in relative sea level.

3.6.4 Future changes in relative sea level

The most authoritative and recent projections of future sea levels around the UK were derived by the UK Meteorological Office, through the United Kingdom Climate Projections project (UKCP18).

All are based on RCP climate change scenarios (RCP2.6, RCP 4.5 and RCP 8.5) and are provided at different levels of probability on a yearly time step, across a spatially-continuous grid (approximately 12 km square). They can be downloaded from the UKCP18 User Interface.

Two sets of results are given, one that extends to 2100, and a second ('exploratory') set that reaches 2300. These were funded by the Joint Flood and Coastal Erosion Risk Management Research and Development Programme of Defra, the Environment Agency, Natural Resources Wales and the Welsh Government and the flood research programme of the Scottish Environment Protection Agency (see Environment Agency, 2019, for a more complete description). Both sets are rooted in CMIP5 climate model simulations (see Meehl and others, 2009 for CMIP5 objectives and strategy), however, methodological differences mean that the sets are not identical and have different strengths.

The projections account for a range of geophysical processes, including thermal expansion, addition of water to the ocean and gravitational effects. The projections also incorporate glacial isostatic adjustment, using data provided by Dr Sarah Bradley, which lends consistency with this study. A full description of the derivation of these projections can be found in the UKCP18 Marine report (Palmer and others, 2018).

3.6.4.1 Projections to 2100

The UKCP18 Marine report provides a summary graphic of the projected variation in relative sea level change at UK capital cities, and this is reproduced below as Figure 3-6.

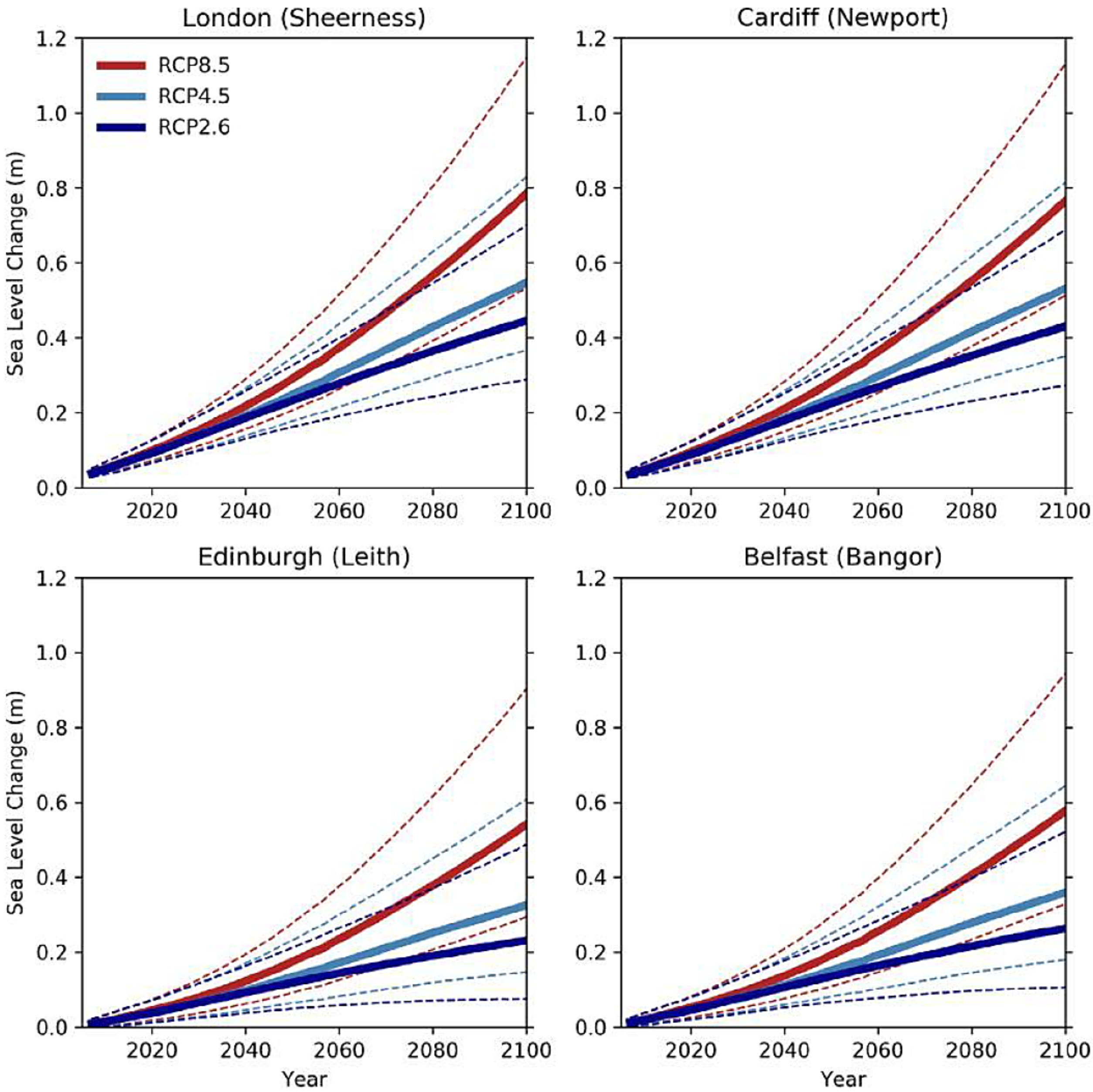

Figure 3-6: Graphs explaining the 21st century projections of time-mean sea level under change for UK capital cities

The 4 graphs in Figure 3-6 show projections of mean sea level for London, Cardiff, Edinburgh and Belfast, based on the nearest class A tide gauge location (Sheerness, Newport, Leith and Bangor). The solid lines indicate the central estimate, and the dashed lines indicate the range for each RCP (red line RCP8.5, royal-blue line RCP4.5, navy-blue line RCP2.6). All projections are presented relative to a baseline period of 1981 to 2000 (Reproduced from Palmer and others, 2018).

As may be expected from Figure 3-4, the projections show greater relative sea level rise in the south of the UK due to isostatic rebound. The ranges of change are summarised in Table 3-2, which is also reproduced from the UKCP18 Marine report.

Table 3-2: The projected ranges of sea level rise at UK capital cities under RCP2.6, RCP4.5 and RCP8.5 relative to a baseline period of 1981 to 2000 (this table is reproduced from the study of Palmer and others, 2018).

UK capital city	RCP 2.6	RCP 4.5	RCP 8.5
London	0.29-0.70	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

3.6.4.2 Exploratory projections to 2300

The exploratory projections, which extend to 2300, show significantly higher relative sea level changes. The upper limits of the RCP8.5 scenario for both London and Cardiff exceed 4 metres above a 1981 to 2000 baseline. The equivalent value for Edinburgh and Belfast is around 3.5 metres (see Figure 3-7).

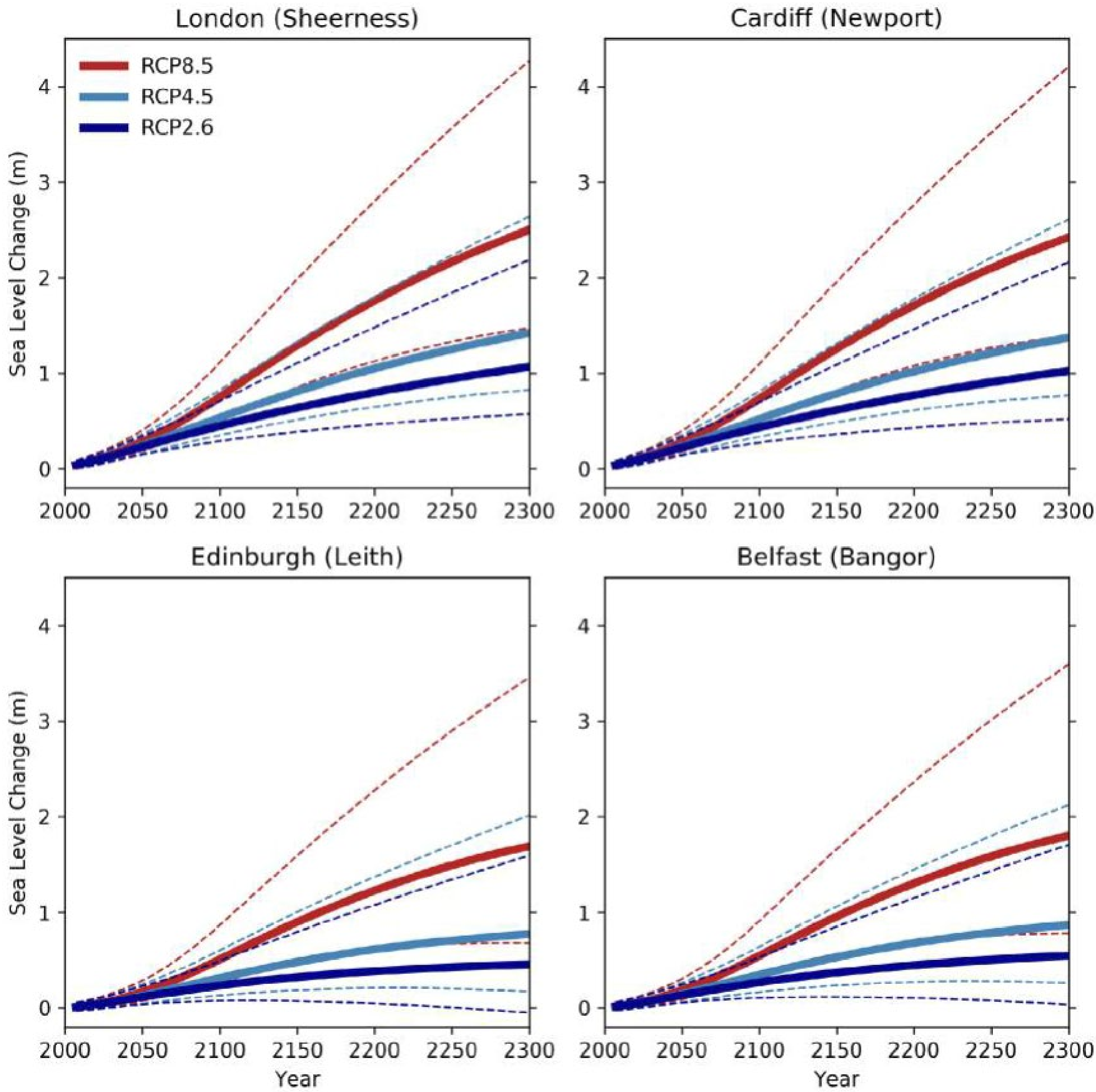

Figure 3-7: Four graphs explaining the time series of the time-mean sea level change to 2300 for each of the UK capital cities

In Figure 3-7 the 4 cities are London, Cardiff, Edinburgh and Belfast, based on the nearest class A tide gauge location (Sheerness, Newport, Leith and Bangor). The solid lines indicate the central estimate, and the dashed lines indicate the range for each RCP (red line RCP8.5, royal-blue line RCP4.5, navy-blue line RCP2.6). All projections are presented relative to a baseline period of 1981 to 2000. Image is reproduced from Palmer and others, 2018.

It should be noted that the method through which the exploratory projections were made was different to that used for the projections to 2100. As a result, they do not precisely agree, as illustrated for one region in Figure 3-8 and Figure 3-9.

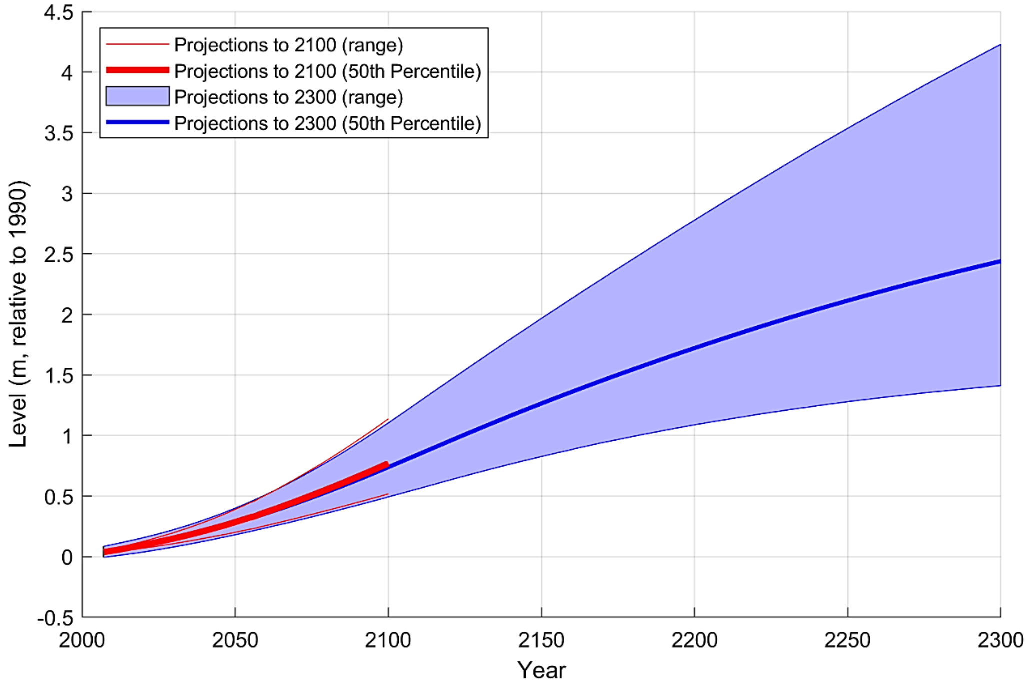

Figure 3-8: Graph illustrating the UKCP18 projections to 2300 for region 55 (Blue Anchor to Burnham-on-Sea), with small discrepancy between projections at 2100 due to the different methods being used

Figure 3-8 graph shows the UKCP18 sea level rise projections to 2300 for region 55. The y-axis represents the mean sea level (metres relative to 1990), ranging from -0.5 to 4.5, and the x-axis shows the time in years from 2000 to 2300. A line shows the 50^{th} percentile projection to 2100 (red line) and to 2300 (blue line). The 50th percentile projection indicates sea level rise, relative to 1990, of c.0.75m and 2.25m by 2300.

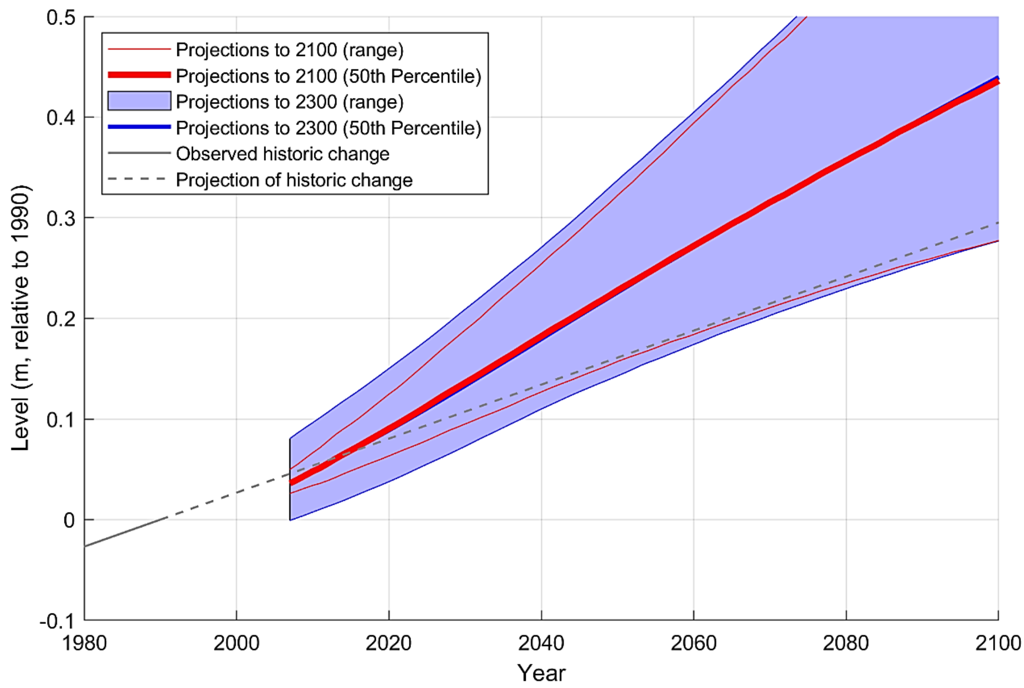

Figure 3-9: Graph showing the UKCP18 projections to 2100 for region 55 (Blue Anchor to Burnham-on-Sea)

In Figure 3-9, the y-axis represents the mean sea level, ranging from -0.1 to 0.5, and the x-axis shows the time in years from 1980 to 2100. Projections up to 2100 are depicted in red, and exploratory projections are shown in blue. The data pertains to region 55 (Blue Anchor to Burnham-on-Sea). The result, illustrated in cyan, aligns with the upper limit of the 2100 projections.

It can also be seen that neither set of projections precisely agrees with the recent historic data on relative sea level change (shown in grey). Work was, therefore, necessary to align each of the data sets, and this is described in the following section.

3.6.5 Time series alignment

Data from the different sources were put together as a connected series to make each of the 738 trajectories of relative sea level change needed for this study. All were derived as relative sea level change to a 1990 datum. Attention was given to the transitions between data sets, as described in the following sections.

3.6.5.1 UKCP18 projections

As noted above, the UKCP18 projections to 2100 and exploratory projections to 2300 do not precisely agree. The exploratory projections begin in 2007 and provide the only data for conditions beyond 2100. However, it was not considered appropriate to entirely rely on them because the projections to 2100 can be expected to be more reliable in the early part of the 21st century.

An algorithm was, therefore, developed to transition linearly from the ‘2100’ projections at the start of the 20th century to the exploratory projections at 2100. An example result, showing the derivation of an upper limit sea level trajectory, can be seen as a dashed cyan line in Figure 3-10.

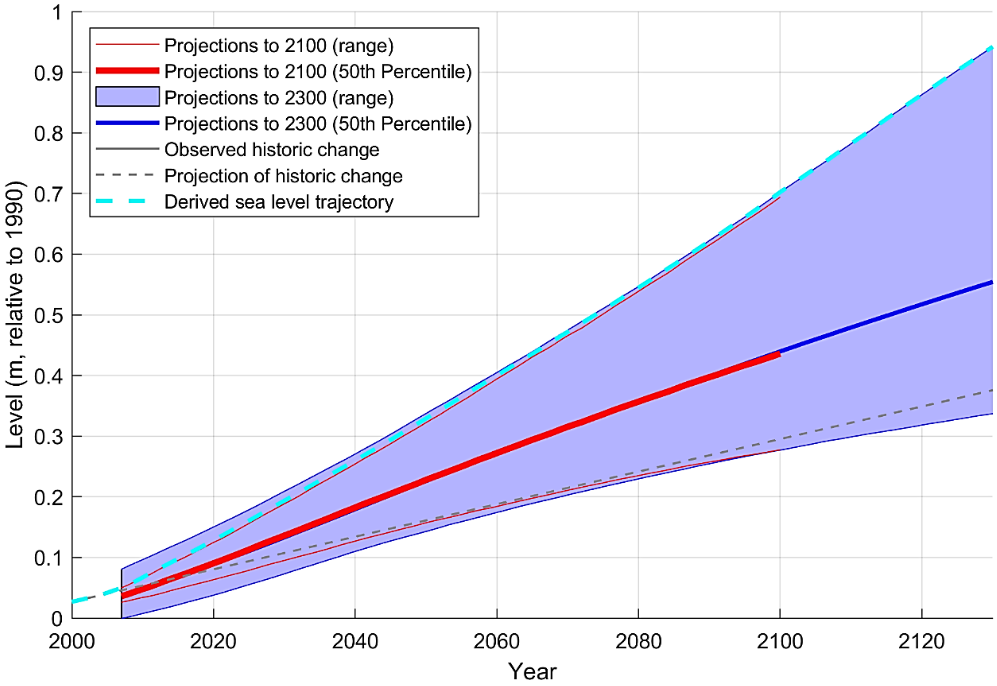

Figure 3-10: Graph illustrating the example transition shown as a dashed cyan line

In Figure 3-10 the y-axis shows mean sea level (in metres relative to 1990) from 0 to 1, and time on the x-axis, in years from 2000 to 2120. Between the projections to 2100 is shown in red and exploratory projections are in blue. Data for region 55 (Blue Anchor to Burnham-on-Sea). The result (shown in cyan) initially tracks the upper limit of the 2100 projection before smoothly migrating to follow the 2300 projection.

3.6.5.2 Environment Agency Coastal Flood Boundary (CFBC) data and UKCP18

A transition algorithm was also needed between the Environment Agency Coastal Flood Boundary Condition data and the UKCP18 projections. This was achieved by curve-fitting between the 2 data sets as illustrated in Figure 3-11.

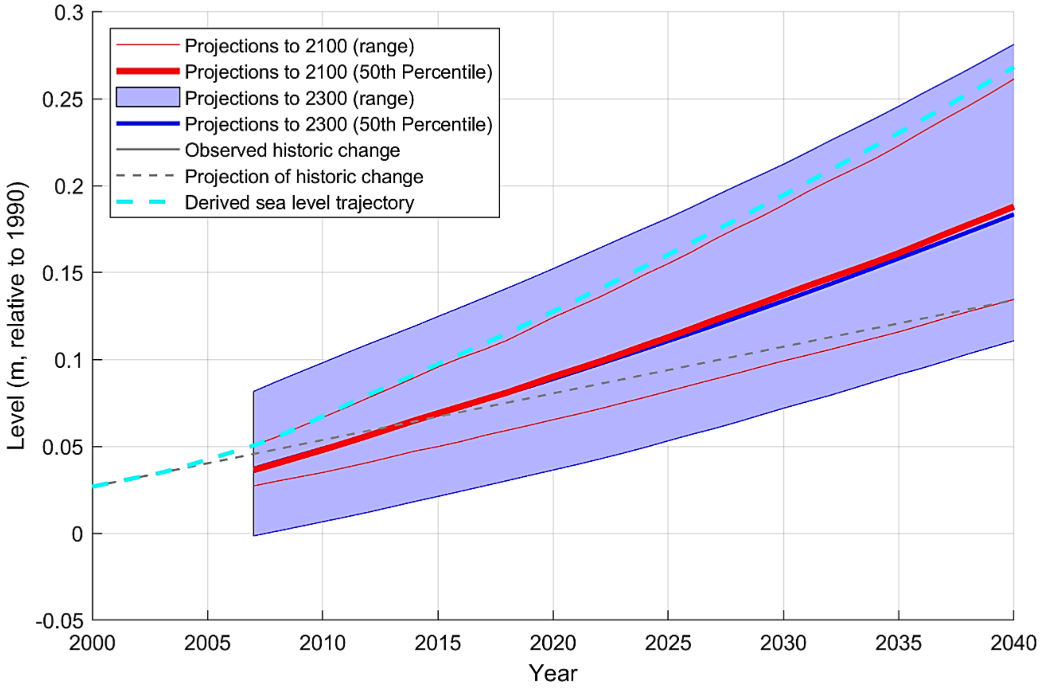

Figure 3-11: Graph presenting the transition between historic rate of change

In Figure 3-11 the y-axis shows level (in metres relative to 1990) from -0.05 to 0.3, and time on the x-axis, in years from 2000 to 2040. Between the projections to 2007 is shown in red and exploratory projections are in blue. The graph is adapted from Environment Agency Coastal Flood Boundary Condition data and UKCP18 projections.

3.6.5.3 GIA model output to Environment Agency CFBC data set

The GIA data extended to the present day but clearly could not be expected to be as realistic as Environment Agency data across the 20th century. A period of transition between these data sets was set (1870 to 1890) to approximate the period at which modern rates of sea level rise are understood to have first accelerated (see, for example, Jevrejeva and others, 2008). A parabolic curve was fitted across this 20-year period to allow a smooth transition, and a linear interpolation was then adopted to join with the adjacent GIA data point (at 1,000 years before present).

Other rules were included to overcome compatibility issues and a general summary is recorded below, which also notes implications of the approaches used.

Period/date: 10,000 years BP to late 19th century

Source: Six GIA models.

Chosen representation: Selected based on the highest relative sea level at 1,000 years BP (linear representation between data points).

Implications: Conservatism: this will tend to increase shore recession predicted with the results.

Period/date: Late 19th century to late 20th century

Source: Central, lower and upper estimates provided by the Environment Agency CFBC study.

Chosen representation: Central estimate.

Implications: Neutral (neither conservative nor non-conservative).

Period/date: Late 20th century to 2007

Source: Central, lower and upper estimates provided by the Environment Agency CFBC study and UKCP18 projections (from 1990).

Chosen representation is:

- adopt UKCP18 projections
- where these fall below the historic trends (represented by the Environment Agency CFBC data), the historic trends are preferred
- interpolation used to smooth transition from the (straight) historic trend to the (curved) projection

Implications: Prevents an unrealistic decrease in relative sea level rise during the start of the 21st century.

Period/date: 2007 to 2099

Source: Central, lower and upper estimates provided by (a) the Environment Agency CFBC study; (b) UKCP18 projections (from 1990); (c) UKCP18 (exploratory) projections to 2299.

Chosen representation:

- a (weighted average) transition was imposed between the UKCP18 projections and the UKCP18 exploratory projections - weighted towards the UKCP18 projections at the start of the 21st century and the UKCP18 exploratory projections at the end of the 21st century
- where these fall below the historic trends (represented by the Environment Agency CFBC data) the historic trends are preferred

Implications are:

- the effect of large uncertainties associated with the exploratory projections during the early 21st century are reduced
- avoids a step discontinuity in sea level that would otherwise occur at the end of the 21st century if no transition stage was used - in effect, it is assumed that climate change will not result in a ‘fall’ in rates of sea level rise

Period/date: 22nd and 23rd century

Source is:

- central, lower and upper estimates provided by the Environment Agency CFBC study
- UKCP18 (exploratory) projections to 2299

Chosen representation: Where the UKCP18 exploratory projections fall below the historic trends (represented by the Environment Agency CFBC data), the UKCP18 exploratory projections are preferred (and a transition stage is imposed).

Implications: Post 21st century representation is entirely based on the UKCP18 exploratory projections.

4 Post processing

The shoreline positions output by each model were processed to provide indicators of cliff toe sensitivity to sea level rise. These indicators were recorded as continuous time series and decadal indicators, beginning in the 2030s.

The latter results were provided to support the most rapid and high-level quantification of future recession; the former allows for more detailed application.

These were derived through a process of normalisation of model output against change during a chosen period. Essentially, the modelled future cliff toe retreat was divided by the modelled historic cliff toe retreat during a chosen baseline period.

4.1 The baseline period

A baseline period of 1920 to 2020 was chosen because:

- reasonably good information on historic shore change can normally be expected for this period
- the end date allows results to be aligned with the most recent data on shore position (that is, those recorded in 2020)
- it represents 100 years of change, which may simplify the interpretation of the results

It is expected that some end users will prefer a different baseline period, better aligned to the data available for a particular application. This adaptation can be made, and this is described in the method report (Environment Agency, 2025f).

4.2 Example simulation profiles

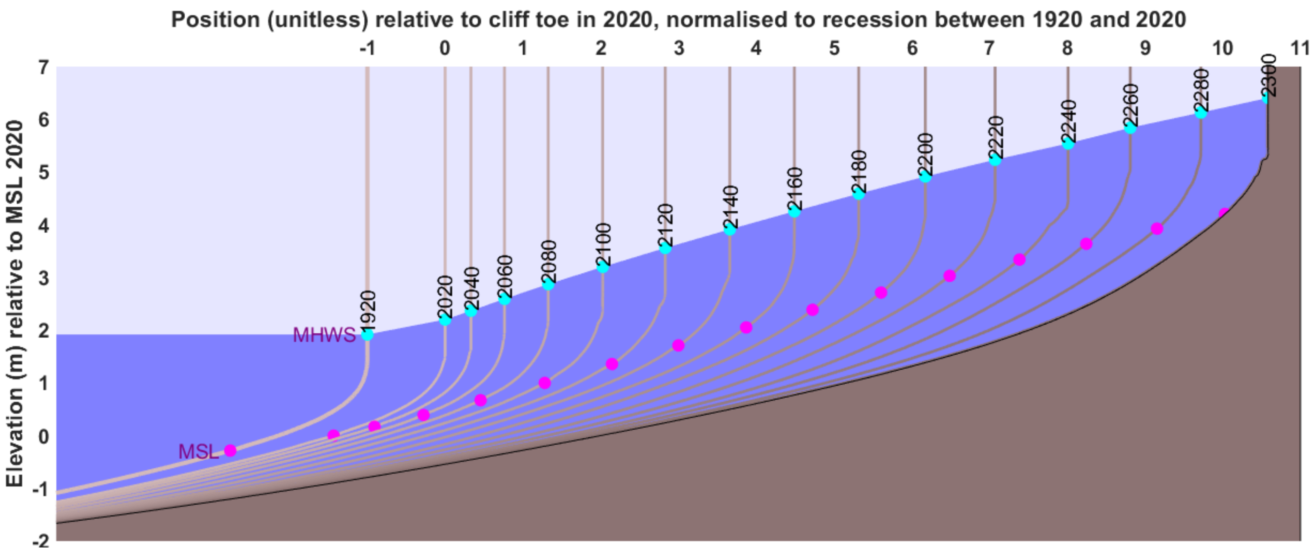

Figure 4-1: Graph illustrating the selected outputs from an example simulation

In Figure 4-1 the y-axis is elevation (in metres) relative to mean sea level in 2020. The x-axis is position (unitless) relative to cliff toe in 2020, normalised to recession between 1920 and 2020. The figure shows selected results from an example simulation for region 41 (east of start point). These are region 41, east of start point, RCP8.5, 95th percentile of RCP 8.5, including profiles in 1920, 2020, and then every 20 years to 2300; sea level rise after 1920 can be seen in the elevation of mean sea level and mean high water spring. This is shown as magenta and cyan dots, respectively.

A sequence of shore profiles is shown progressing from left to right. These include 1920, 2020, and then every 20 years to 2300. The horizontal axis represents the cross-shore distance from the cliff toe in 2020 normalised to the cliff recession during the preceding 100 years. It follows that the top of the 1920 profile is aligned with '-1' (indicating one unit of recession between 1920 and 2020).

As the sea rises, the rate of cliff recession grows, indicated by the increasing gap between the profiles after 2020. It may be noted that by 2120 (100 years after 2020) the cliff face has retreated by almost 3 units, that is, almost 3 times as quickly as the change over the previous 100 years.

It is also interesting to note that the profile shape has changed, becoming steeper overall. This can be recognised by the fact that the dots indicating MHWS and MSL are closer in the last profile, than they are in the first.

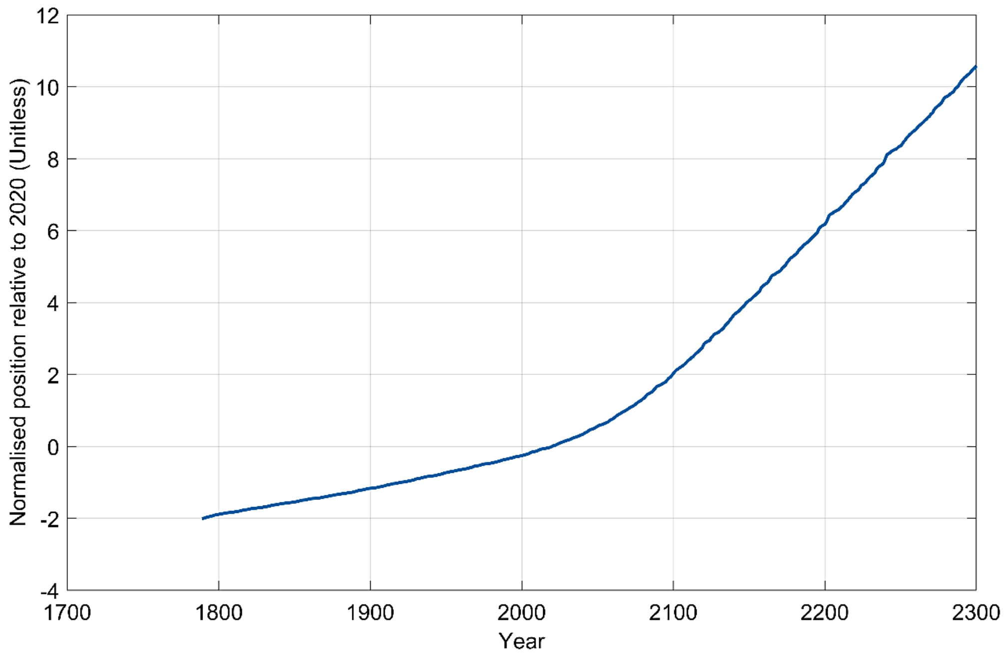

Figure 4-2: Graph shows the year-by-year retreat of the cliff toe

In Figure 4-2 the y-axis is the normalised position relative to 2020 (unitless) and is equivalent to the horizontal axis shown in Figure 4-1. The x-axis is year from 1700 to 2300. The plotted line passes through -1 in 1920, 0 in 2020 and approaches 3 in 2120.

Figure 4-2 represents one of 100 forecast variants that were run for one region (region 41) for one percentile (the 95th) for one RCP (8.5). A total of 73,800 such simulations were run to represent all 3 RCPs at each of the 82 regions. The cliff toe retreat output by each model was processed in the following steps:

- each was aligned so that the average of the (100) variants passed through zero in 2020
- each was normalised against the average change in position of all the variants between 1920 and 2020

Example results can be seen in Figure 4-3.

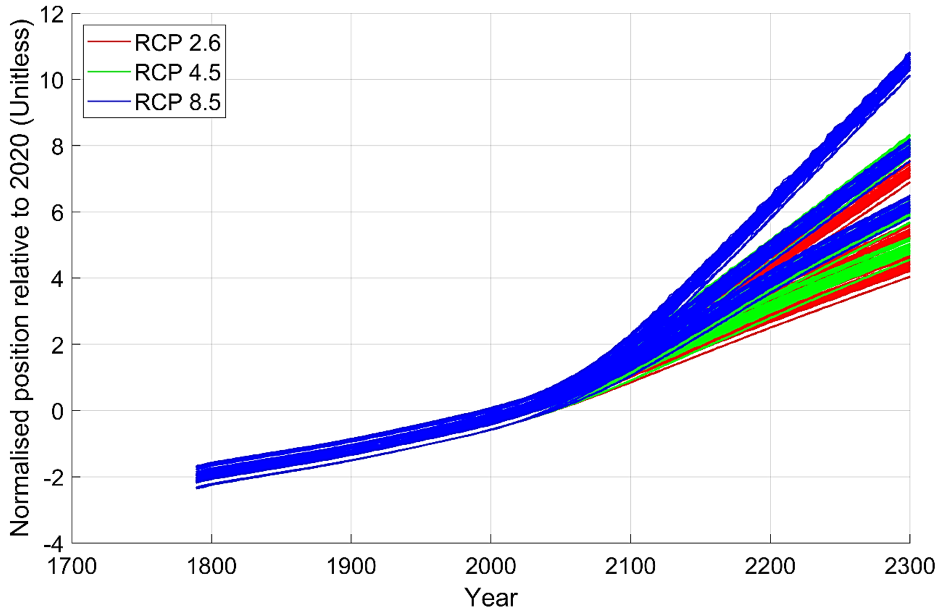

Figure 4-3: **Graph showing the normalised projections for region 41 (all RCPs and percentiles)**

Figure 4-3 includes all one hundred variants for all 3 percentiles of all 3 RCPs (that is, the outputs of 900 simulations), increasing over the years from just before 1800 through to 2300. RCP 8.5 was plotted last (in blue) and partially obscures the others: RCP 2.6 (red lines) and RCP 4.5 (green lines). The 3 percentile levels can be seen as diverging branches of each colour on the right-hand side of the figure, with the lowest representing the 5th percentile and the highest the 95th percentile.

Each set of 100 variants was then averaged, and Figure 4-4 shows the results (for region 41).

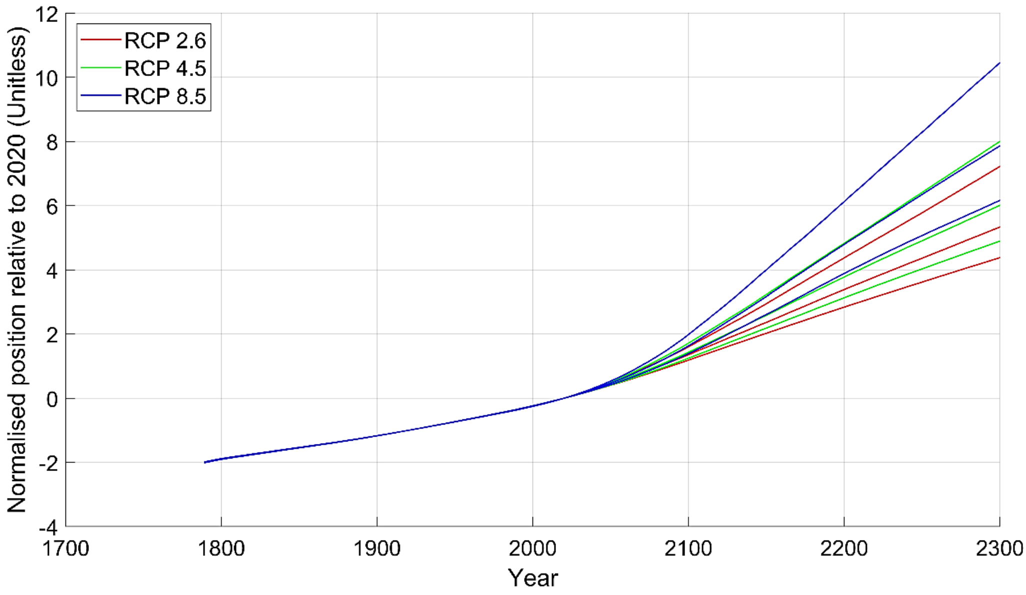

Figure 4-4: Graph presenting the mean of variants for region 41 (all RCPs and percentiles) increasing over the years from just before 1800 through to 2300

In Figure 4-4 the RCP 8.5 was plotted last (in blue), RCP 2.6 was plotted in red, and RCP 4.5 in green. The 3 percentile levels can be seen as diverging branches of each colour on the right-hand side of the figure, with the lowest representing the 5th percentile and the highest the 95th percentile.

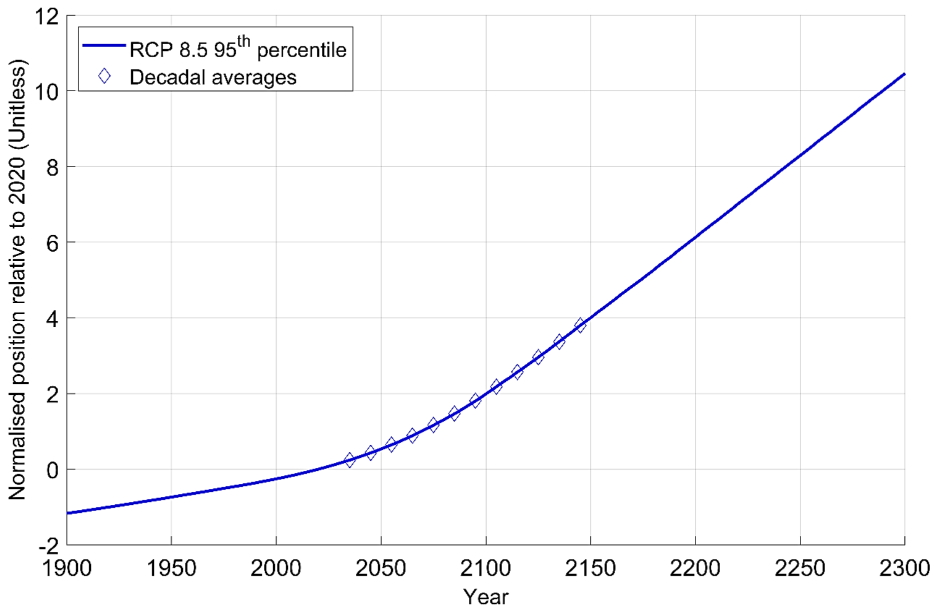

Figure 4-5: **Graph presenting the normalised results of the RCP 8.5, 95th percentile for region 20, 1900 to 2150**

In Figure 4-5 the y-axis is normalised position relative to 2020 (unitless) and the x-axis is years from 1900 to 2300. The result for the upper limit (95th percentile) of the RCP 8.5 scenario is shown (for simplicity) in isolation, increasing over time from below 0 to over 10 normalised position relative to 2020. The figure also indicates, with diamonds, 12 decadal averages between the 2030s and 2150s.

The contents of this figure represent the output of this study, which comprises decadal averages and the normalised curves from which they have been calculated, for each percentile, of each RCP scenario, for each region.

4.3 Encountered issue

Testing the post-processing algorithms revealed an unexpected periodic change in the variation of the cliff recession results. An example can be seen in Figure 4-6, which shows 100 simulations of cliff toe recession in one region. Around 1952, the spread of the results temporarily diminishes. This behaviour was not limited to this window of time, but extended along the timeseries, reoccurring every 38 years.

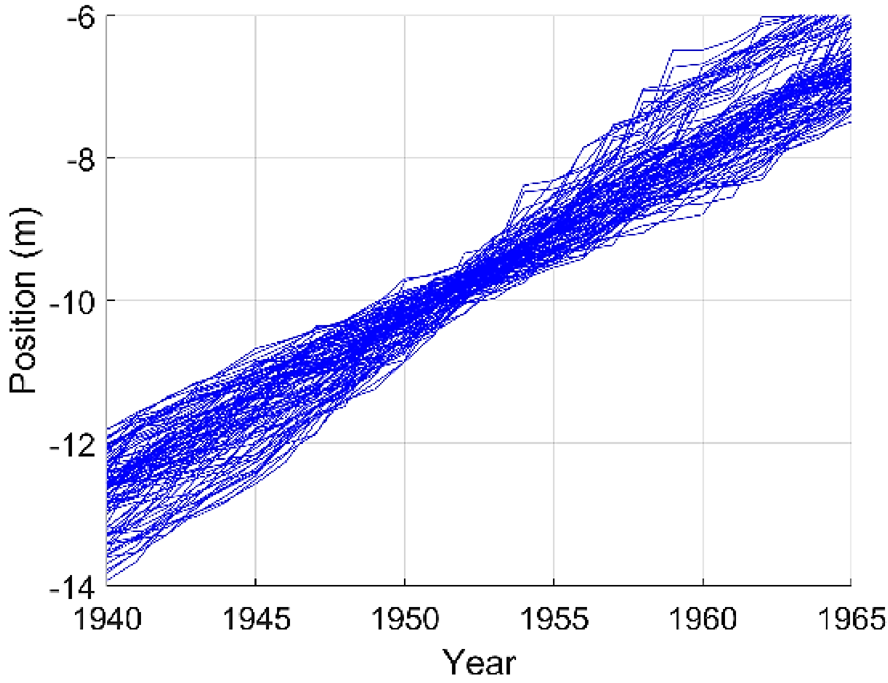

Figure 4-6a: Graph illustrating the example simulation set (100 variants) from -4 to 4 metres across the years 1940 to 1965. It shows the narrowing of variance in 1952

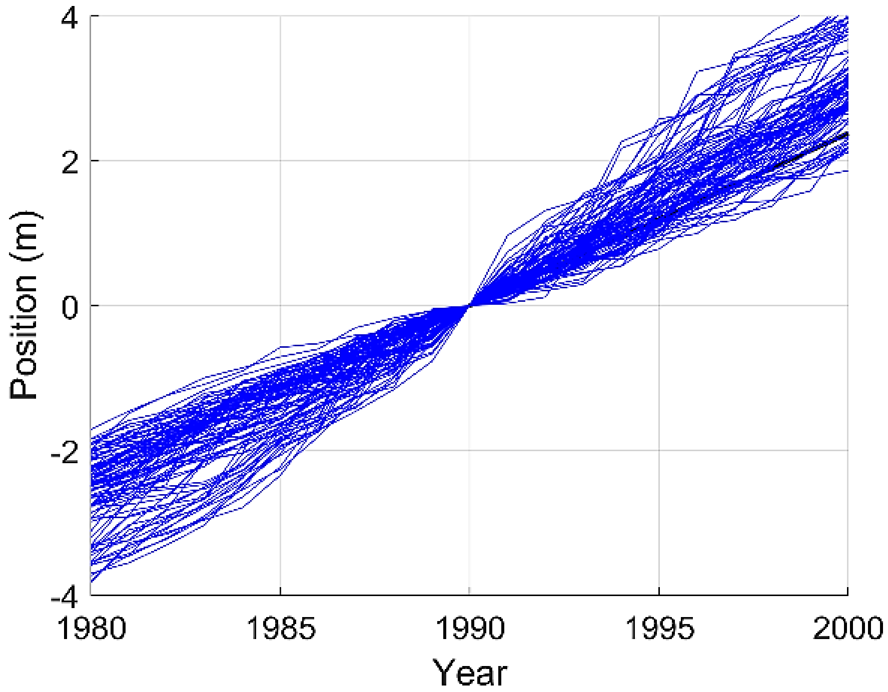

Figure 4-6b: Graph illustrating the example simulation set (100 variants) from -4 to 4 metres across the years 1980 to 2000

In Figure 4-6a and Figure 4-6b the alignment of results to zero occurs in 1990. The oscillation was only encountered when results were processed to pass through the same position in the baseline year.

This effect resulted from the process of recycling the wave and tide files ('rewinding' and reinputting this data as necessary to complete a model simulation, see section 3.5). This introduces a correlation between the variation at any moment in time, with the variation precisely 38 years later/earlier (the period represented by the input file). When the variation of the results is set to zero at a particular year (in this case, the baseline year), the variation at all correlated points is also reduced, appearing as an oscillation in variance.

The normalisation algorithm used for post-processing did not, ultimately, involve adjusting the results to pass through a singular point, and so this effect was avoided. In addition, the variance of the data was not output for the end user. This phenomenon was, therefore, considered unimportant.

4.4 Output format

The results have been saved as a set of 82 spreadsheets; one per region. Each contains one time series tab for each RCP. An example screenshot is shown as Figure 4-7.

	A	B	C	D
1		Cliff Toe Recession Under RCP 8.5 (Unitless)		
2		Normalised to recession between 1920 and 2020		
3				
4	Year	5th Percentile	50th Percentile	95th Percentile
291	2136	2.26	2.727	3.414
292	2137	2.286	2.759	3.456
293	2138	2.311	2.791	3.499
294	2139	2.337	2.822	3.542
295	2140	2.362	2.854	3.583
296	2141	2.386	2.884	3.624
297	2142	2.412	2.915	3.668
298	2143	2.439	2.949	3.715
299	2144	2.464	2.98	3.758
300	2145	2.489	3.012	3.801
301	2146	2.514	3.043	3.841
302	2147	2.539	3.077	3.884
303	2148	2.563	3.108	3.924
304	2149	2.586	3.139	3.963
305	2150	2.609	3.171	4.003

Figure 4-7: Example screenshot of timeseries output for region 41 for one RCP (8.5)

The screenshot in Figure 4-7 is from a spreadsheet and illustrates cliff toe recession between 1920 and 2020. Only a small number of rows are shown.

An additional tab in this spreadsheet contains tables of low, middle and high estimates for each decade between the 2030s and the 2140s, defined in the following way:

- ‘middle’ – the average of the time series values across the decade (as illustrated in Figure 4-5)
- ‘low’ – the value at the start of the decade
- ‘high’ – the value at the end of the decade

5 Results

The following results are presented to illustrate how cliff toe sensitivity may vary around the coastline of England and Wales, and to explore the influencing factors. It begins by reiterating the concept of normalised shore recession.

5.1 Example forecast and hindcast profiles

The outputs of the simulations have been normalised to allow their regional application, as was described in the previous section. The results are provided to the end user as indicators of change for each region, for sea level pathway and year. To understand the application of these indicators, it is useful to look at some of the modelled shore profiles from which the indicators were calculated. An example, representing part of the coast of Somerset, is shown in Figure 5-1.

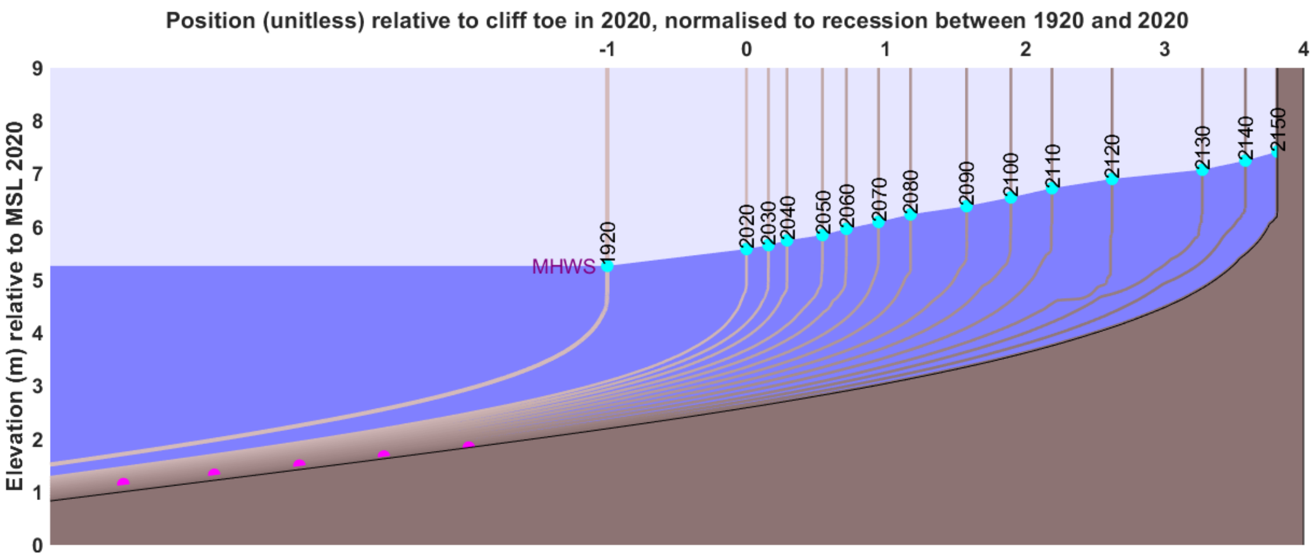

Figure 5-1: Graph describing shore profiles from one forecast simulation of the upper shore profile in region 55 (Blue Anchor to Burnham-on-Sea) under the 95th percentile of the UKCP18 RCP 8.5 projection

In Figure 5-1 the y-axis is elevation (m) relative to mean sea level 2020. The x-axis is the position (unitless) relative to cliff toe in 2020, normalised to recession between 1920 and 2020. The magenta dots represent the rising mean sea level (these are outside the axis range for the early profiles). Zero on the x-axis has been aligned to the cliff position in 2020. Horizontal distances have then been normalised to the cliff retreat over the previous 100 years (1920 to 2020) and so the cliff position in 1920 is located at -1.0. The cyan dots indicate rising MSL for each profile

This figure gives a good impression of acceleration in shore retreat as the sea level rises. For example, if future recession were similar to the historic recession, then the cliff in 2120 would be aligned with position 1.0 on the horizontal axis (that is, the same distance to the right of the 2020 position as the 1920 position is to its left). In fact, the 2120 position is located close to 2.6, showing that, over the next 100 years, the cliff face is projected to move around 2.6 times the distance it moved in the last 100 years. By 2150, this index of change (the Recession Sensitivity Indicator, or 'RSI') has increased to around 3.8.

It should be noted that SCAPE models recalculate profiles every tide, and that the forecast period was from 1790 to 2300, so the profiles in Figure 5-1 are only a few examples of those calculated.

Hindcast profiles for the same region, representing the 10,000 years to 1990, can be seen in Figure 5-2. The profile for the beginning of the year 1790 was captured from this hindcast and then adopted for use at the start of the forecast seen in Figure 5-1.

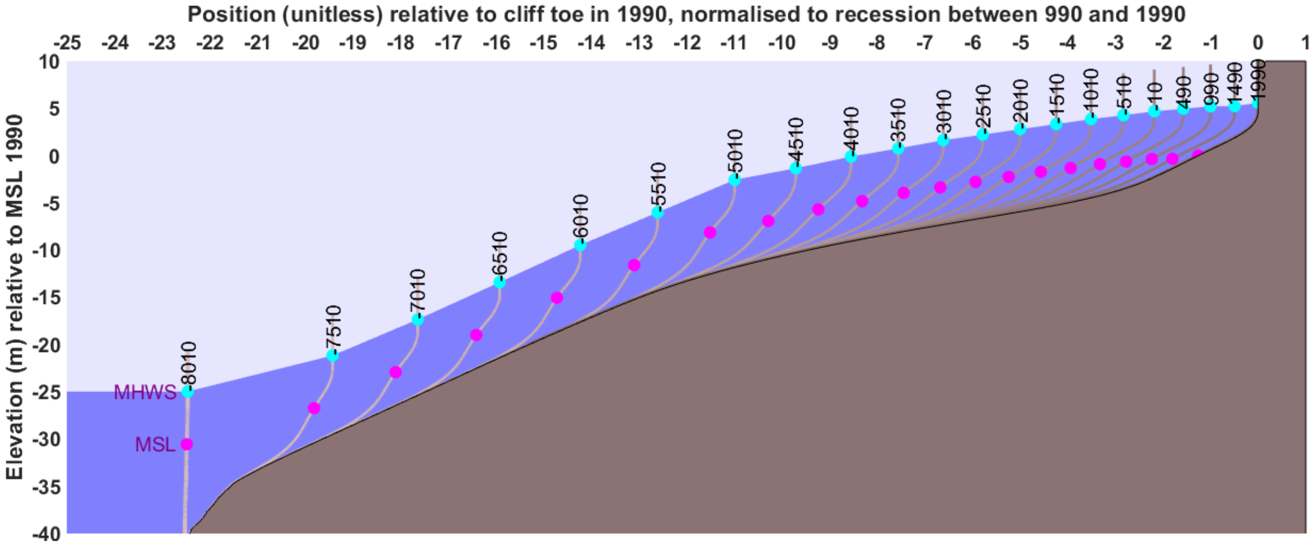

Figure 5-2: Graph describing the profiles from one hindcast simulation for region 55 (Blue Anchor to Burnham-on-Sea)

In Figure 5-2 the x-axis is position (unitless) relative to cliff toe in 1990, normalised to recession between 1920 and 2020 and the baseline period (990 to 1990) is different to that used in Figure 5-1. In this figure, the baseline period has been set (arbitrarily) to the last 1,000 years of the simulation. The magenta dots indicate the MHWS, and the cyan dots indicate rising MSL for each profile.

5.2 Recession sensitivity

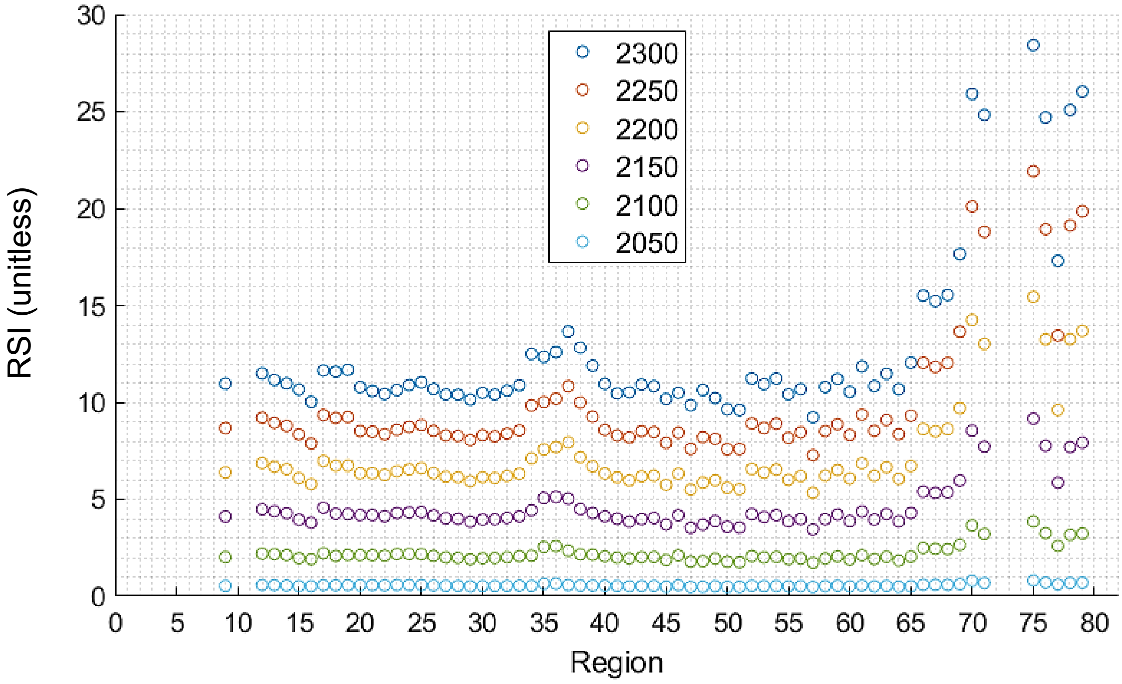

Figure 5-3: Graph showing the recession sensitivity indicators (RSI) every 50 years between 2050 and 2300, for the upper limit of the RCP 8.5 emissions scenario

Figure 5-3 shows RSI (unitless) on the y-axis (from 0 to 30) and region number on the x-axis from 0 to 80. The years are plotted as: 2050 (cyan), 2100 (green), 2150 (purple), 2200 (yellow), 2250 (red) and 2300 (blue). The graph illustrates how the indicators of recession sensitivity were found to vary through time, for the highest emissions scenario.

The analysis was not successful in all areas; no results are shown for some of the regions with low and high numbers (that is, those towards the north). The regions in the north-east (those with the highest section numbers) show the highest sensitivity.

Overall, the results range from less than one in the year 2050, through to approximately 30 in the year 2300. As time progresses, the alongshore differences increase. Figure 5-4 shows results for 2120, under the highest and lowest emissions scenarios.

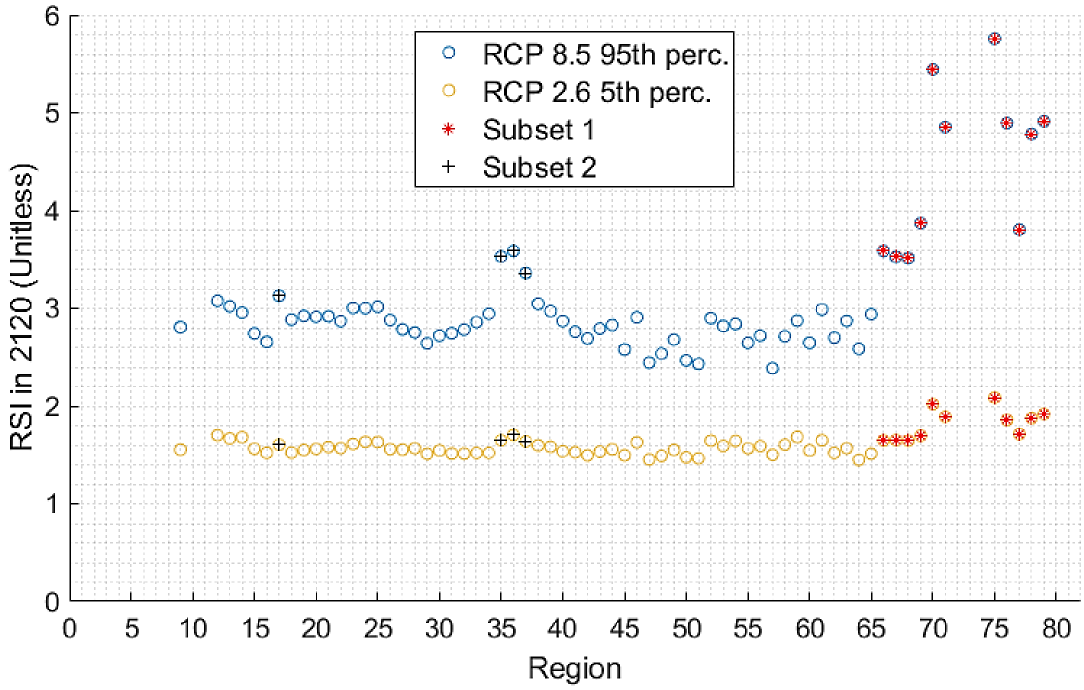

Figure 5-4: Graph illustrating the indicators of cliff toe sensitivity for the year 2120, for 2 sea level rise projections

Figure 5-4 shows RSI in 2120 (unitless) on the y-axis and region number on the x-axis. The 2 subsets identified are discussed in the text. RCP 2.6 is plotted with orange circles, RCP 8.5 in blue circles. The general pattern of the RCP 8.5 results is one of gradual fluctuation between around 2.4 and 3.6 for most of the coast, rising towards around 6 for the highest sections numbers (the north-west coast, identified with red asterisks in the figure as subset 1). A second subset (subset 2, identified with black crosses and discussed below) includes points with locally elevated sensitivity.

Most of the points show RSI below 4, indicating that for most of the coastline (where this form of analysis is applicable) cliff toe retreat over the next 100 years might be expected to be less than 4 times the recession seen over the last 100 years.

The variation from place to place is driven by, among other things, regional variations in:

- UKCP18 sea level projections
- tide gauge records
- long-term (Holocene) sea level change
- tidal conditions
- wave climate
- shoreline orientation

The relative importance of some of these influencing factors is considered below, beginning with an explanation of why the analysis was unsuccessful in some regions.

5.3 Unsuccessful regions

The rejection of some results in the north-east and north-west (specifically regions 1 to 8, 10, 11, 72 to 74, and 80 to 82) was based on an apparent lack of realism in the representation of isostatic rebound (and, therefore, late Holocene relative sea levels) in these areas.

An example is given through the following figures, which illustrate conditions in region 1 (the area around Berwick-upon-Tweed).

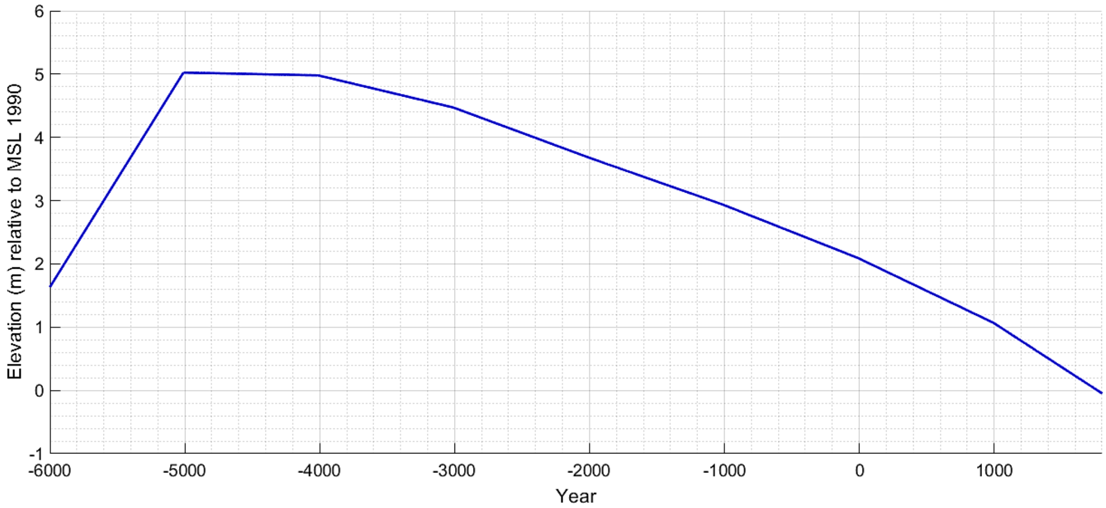

Figure 5-5: Graph showing the history of relative sea levels derived for region 1. Data provided by Dr Sarah Bradley and produced with the support of the NERC BRITICE_CHRONO project

Figure 5-5 shows elevation (in metres) relative to MSL 1990 on the y-axis and year from -6000 to 2000 on the x-axis. It shows the last 8,000 years of the relative sea level input to the region 1 model. A peak (highstand) of 5 m above present-day levels is seen around 7,000 years ago (at -5,000, or 5,000 BC). This reflects isostatic rebound; crustal uplift resulting from ice sheet loss.

As noted in Section 3.6.2, there are alternative interpretations of relative sea levels during this period, and of the relative strength of isostatic rebound. Exploring the consequences of this uncertainty was outside the scope of this study, and so the interpretation shown in Figure 5-5 was selected on the basis that it was conservative; it would be more likely to result in an overestimation than an underestimation of cliff toe sensitivity.

The effect that this time series had on the region 1 models is illustrated, in stages, in Figure 5-6a, Figure 5-6b and Figure 5-6c – these graphs show elevation (in metres) relative to MSL 1990 from -10 to 10 m on the y-axis, and on the x-axis position (unitless) relative to cliff toe in 1990 (normalised to recession between -8010 and -7910) from -10 to 1. The early stages of the simulation are similar to those seen in Figure 5-2, but the end is quite different.

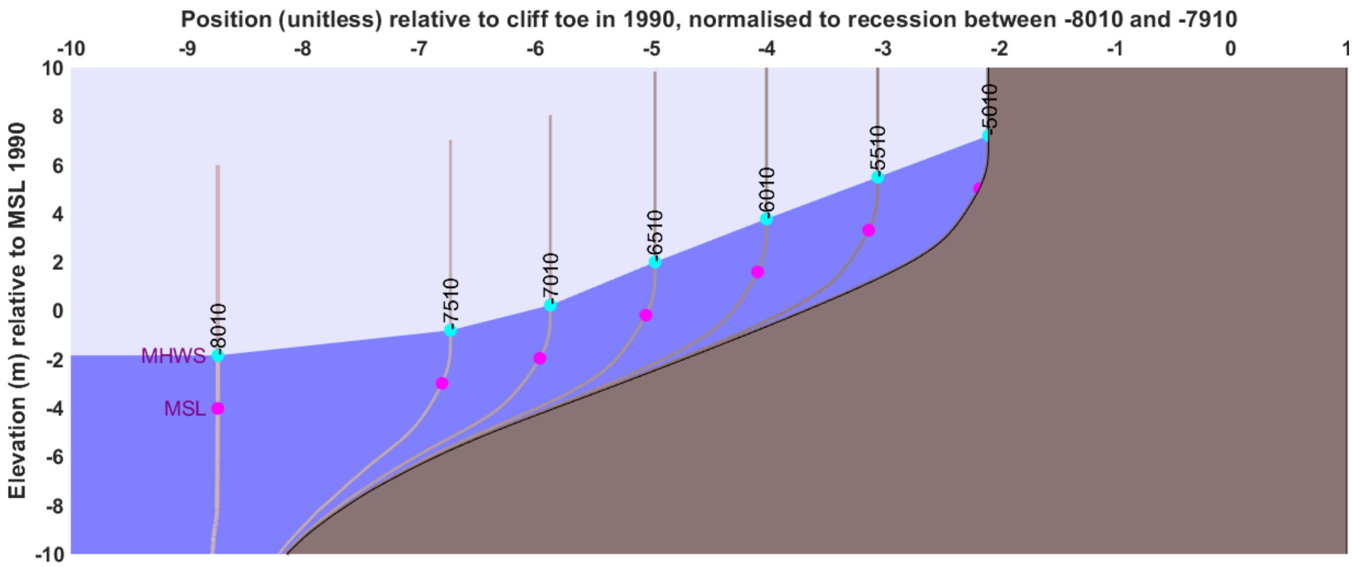

Figure 5-6a: Graph describing the hindcast simulation for region 1

In Figure 5-6a the area around Berwick-upon-Tweed is normalised to recession during the first 1,000 years of the simulation; date stamps are to the calendar year; circa 8,000 BC to 5,000 BC during relative sea level rise. The cyan dots indicate the mean high water spring level (MHWS) for each profile. They rise initially (top panel), are then fairly static for a period (middle panel), and then fall.

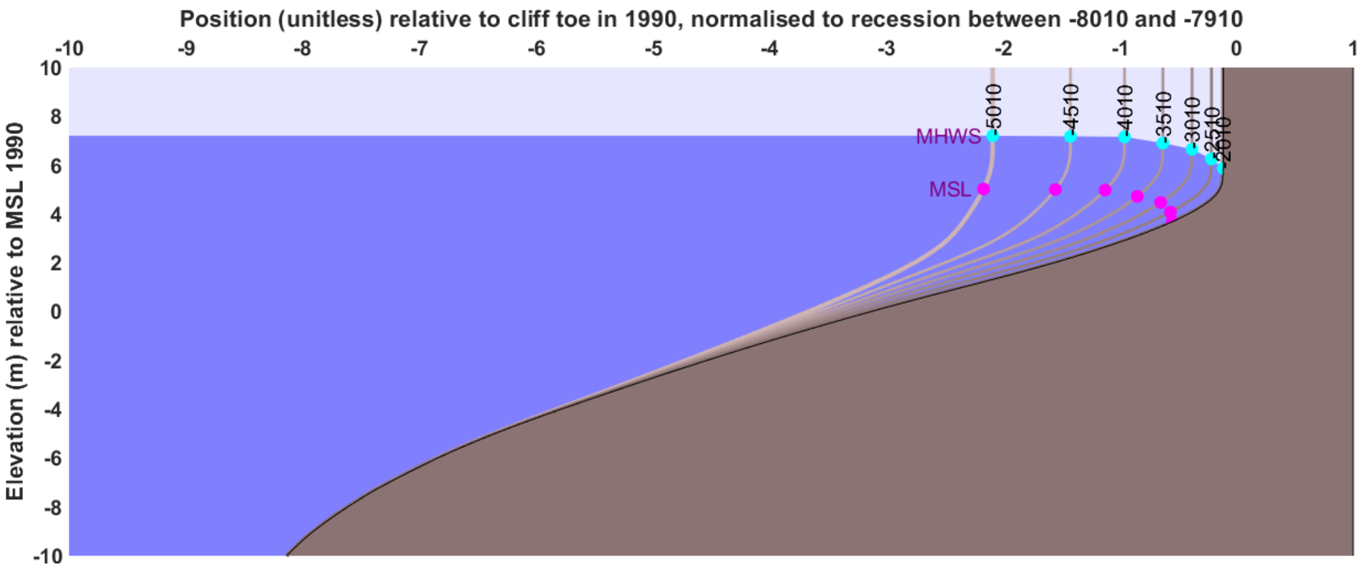

Figure 5-6b: Graph describing the hindcast simulation for region 1

In Figure 5-6b the area around Berwick-upon-Tweed is normalised to recession during the first 1,000 years of the simulation; date stamps are to the calendar year; circa 5,000 BC to circa 2,000 BC during relative sea level stasis/ fall. The cyan dots indicate the mean high water spring level (MHWS) for each profile. They rise initially (top panel), are then fairly static for a period (middle panel), and then fall.

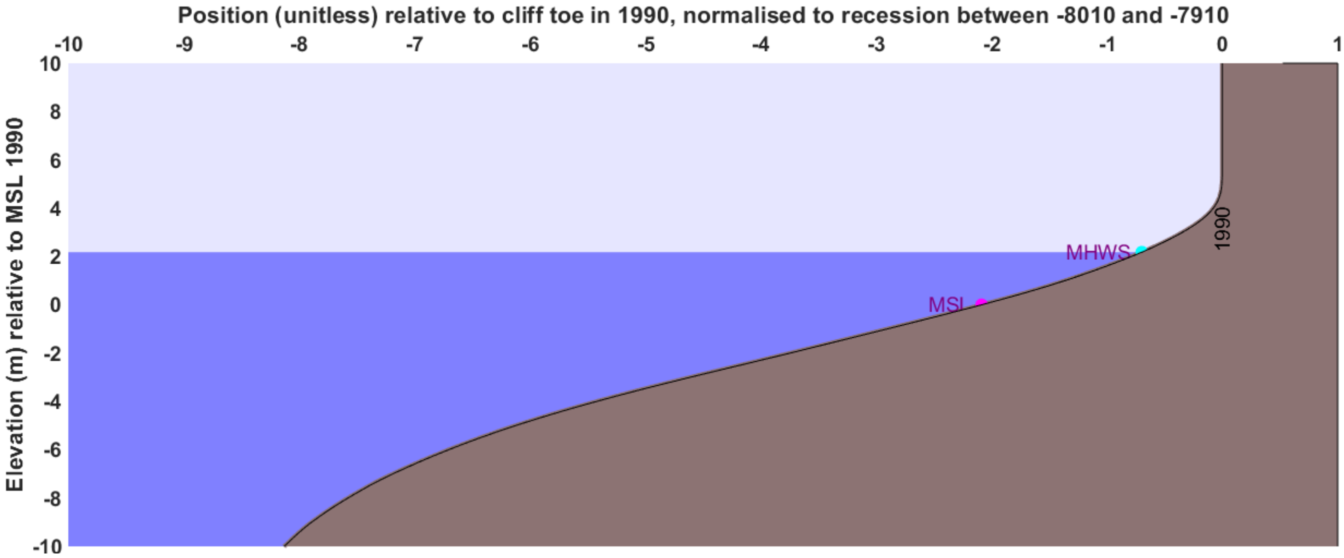

Figure 5-6c Graph describing the hindcast simulation for region 1

In Figure 5-6c the area around Berwick-upon-Tweed is normalised to recession during the first 1,000 years of the simulation; date stamps are to the calendar year; in 1990 AD, following recent sea level fall. The cyan dots indicate the mean high water spring level (MHWS) for each profile. They rise initially (top panel), are then fairly static for a period (middle panel), and then fall.

The decline begins around 7,000 years before the present day and results in a gradual reduction in the cliff recession (indicated by a narrowing of the gaps between profiles in the middle panel). By around 2,000 years before the present day, the MHWS level has fallen below the toe of the cliff, and cliff recession stops. From that point on, the intertidal zone advances down the shore platform, slowly eroding it. At the end of the simulation the cliff toe is more than 2 metres above the mean high water spring level, and so is unaffected by marine processes, and does not retreat.

Although this 'abandoned' state is a reasonable outcome of the input sea level data, it is not a realistic representation of conditions in region 1. For comparison, Figure 5-7 represents a cliff in the Berwick-upon-Tweed area, and it can be seen that the cliff toe is not above the MHWS line, or disconnected from marine processes.

Figure 5-7: Picture showing the cliffs north of Berwick-upon-Tweed (Mat Fascione, 2018, Creative Commons Licence through geograph.org.uk)

The representation of relative Holocene sea levels was, therefore, deemed to be overly conservative in region 1, and in others where this occurred, and no results were calculated.

It may be noted that, although raised shore platforms are present in some places around England and Wales, they generally predate the Holocene. Some examples of elevated coastal features can be found in the north-east region, including raised peat deposits and a small number of raised beaches (see, for example, Archaeological Research Services 2008., Royal Haskoning, 2009; and Natural England, 2015), but these do not tend to support the occurrence of a 5 metre highstand. Moreover, raised shore platforms of Holocene origin are not a recognised feature of this region of coast.

5.4 Sensitivity to wave growth

Sensitivity tests were run to assess the relative importance of the scenario of wave growth used in the simulations. Individual models were rerun under 2 new scenarios: (1) no growth in wave conditions and (2) the growth factors recommended by the Environment Agency for flood risk assessment (Environment Agency, 2020), which were applied to all waves. Results for region 71 (an area of high sensitivity) are compared in Figure 5-8.

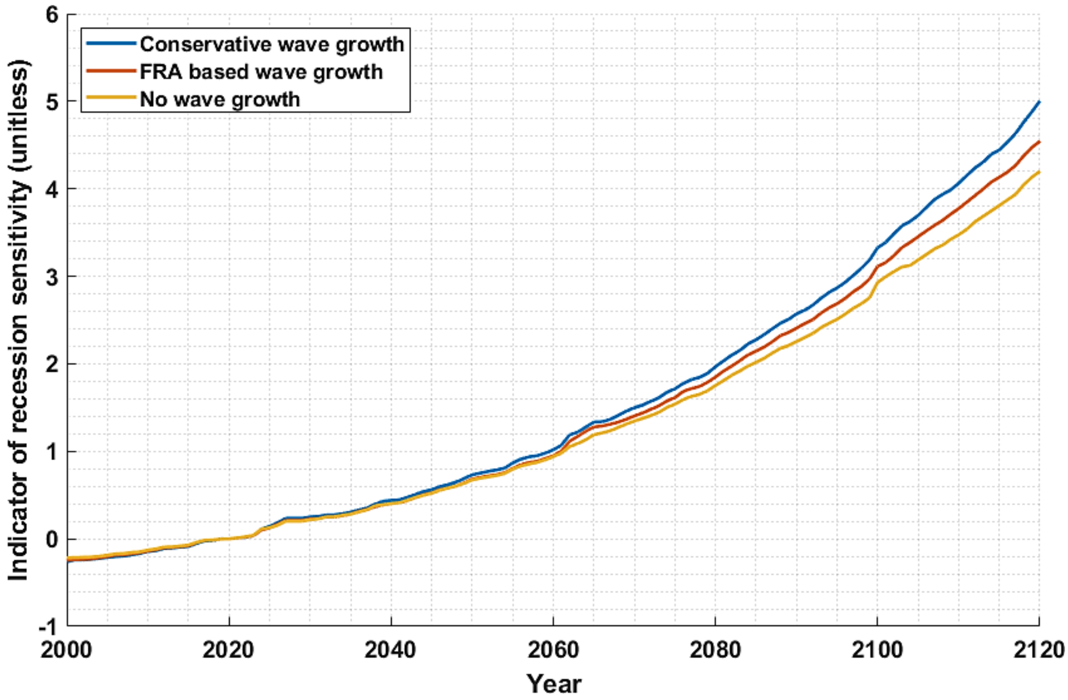

Figure 5-8: Graph illustrating the comparison of 3 scenarios of wave growth, region 71, upper limit of RCP 8.5 sea level rise

Figure 5-8 shows indicator of recession sensitivity (unitless) from -1 to 6 on the y-axis, and on the x-axis the year from 2000 to 2120. On the graph the effect of the scenario of wave growth used in this study is shown as a blue line (labelled as 'conservative wave growth'). The flood risk assessment (FRA)-based results are the red line and the yellow line indicates when there is no wave growth. The FRA-based results (in red) show lower sensitivity, and this is to be expected, because the scenario adopted for this study is intended to represent a conservative upper limit.

Comparison with the 'no wave growth' scenario shows that, by 2120, the wave increase accounts for 19% of the total sensitivity, and drives approximately twice the increase seen with the FRA-based scenario.

A similar comparison was made for region 55, which has a low overall sensitivity, and the results are shown in Figure 5-9.

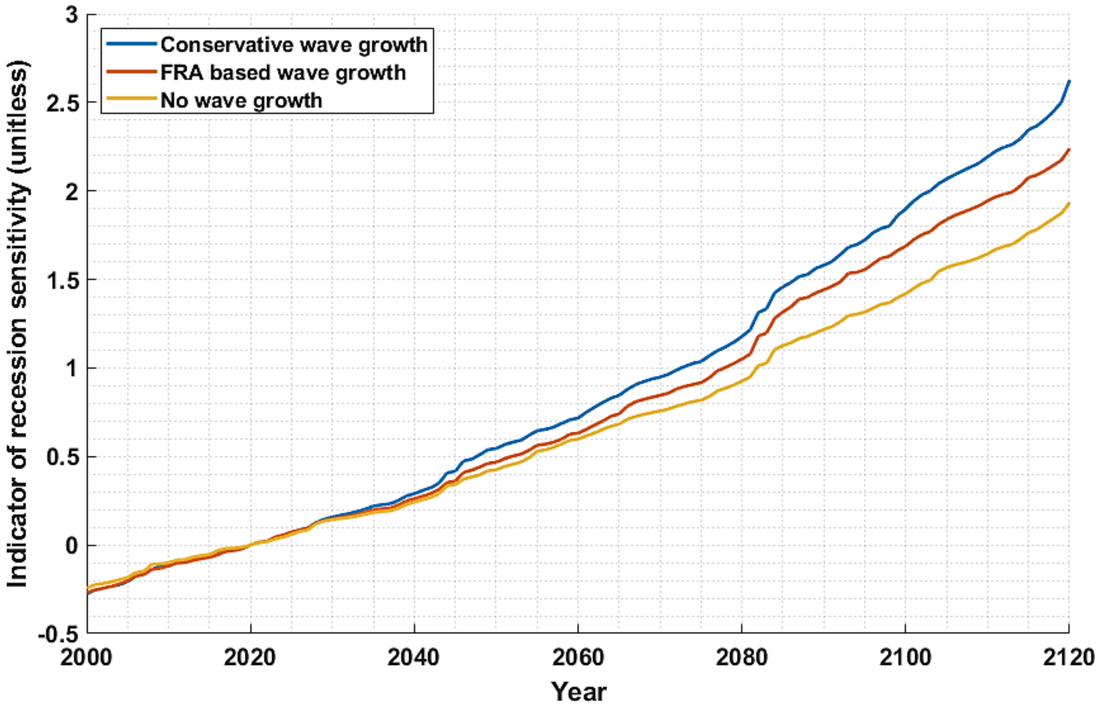

Figure 5-9: Graph presenting the comparison of 3 scenarios of wave growth, region 55, upper limit of RCP 8.5 sea level rise

Figure 5-9 shows indicator of recession sensitivity (unitless) from -0.5 to 3 on the y-axis and on the x-axis the year from 2000 to 2120. The FRA-based results are shown as a red line. The conservative wave growth is shown by the blue line, with the yellow line indicating when there is no wave growth.

In this case, by 2120, the contribution of the wave growth is 33% of the total sensitivity; as before it drives approximately twice the response of the FRA-based scenario. The implications of these sensitivity tests are discussed in section 6.

5.5 Subset 1 – results indicating high sensitivity

Figure 5-4 showed a group of regions with high sensitivity relative to most of the results; these were identified as ‘subset 1’. The behaviour of the models representing those regions is represented in the figures below, which show relative sea levels (Figure 5-10) and model profiles from region 70 (the south shore of the Llyn Peninsula) (Figure 5-11).

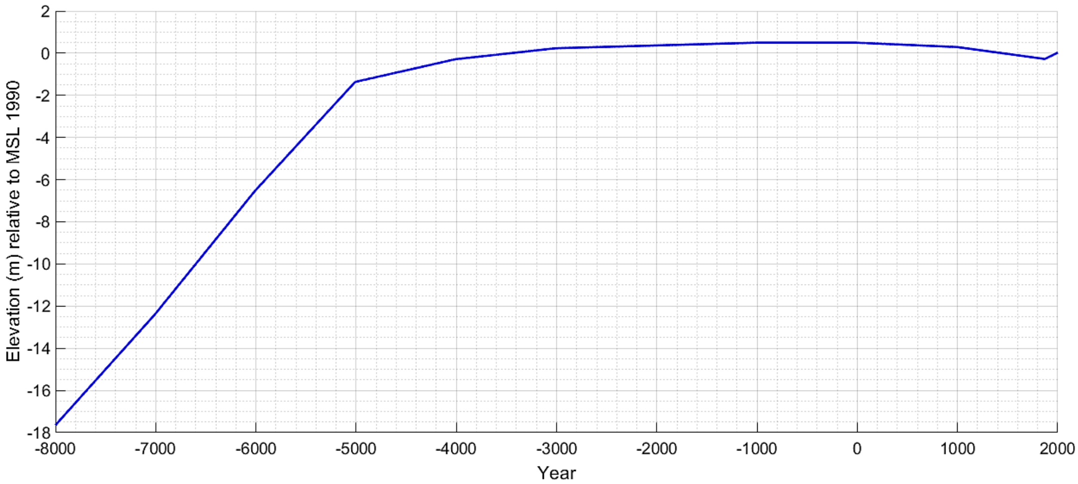

Figure 5-10: Graph showing the history of relative sea levels derived for region 70. Data is provided by Dr Sarah Bradley and produced with the support of the NERC BRITICE_CHRONO project

Figure 5-10 show elevation (in metres) relative to MSL 1909 on the y-axis from -18 to 2, and on the x-axis the year from -8000 to 2000. The graph shows the highstand (around 0.4 m) is lower than that seen in region 1; instead, relative sea levels are quite constant for around 7,000 years to the present day. The models representing this area do not show an abandoned cliff (as was the case with the unsuccessful regions), and toe recession is continuous. However, the rates of recession decrease through time, as shown in Figure 5-11.

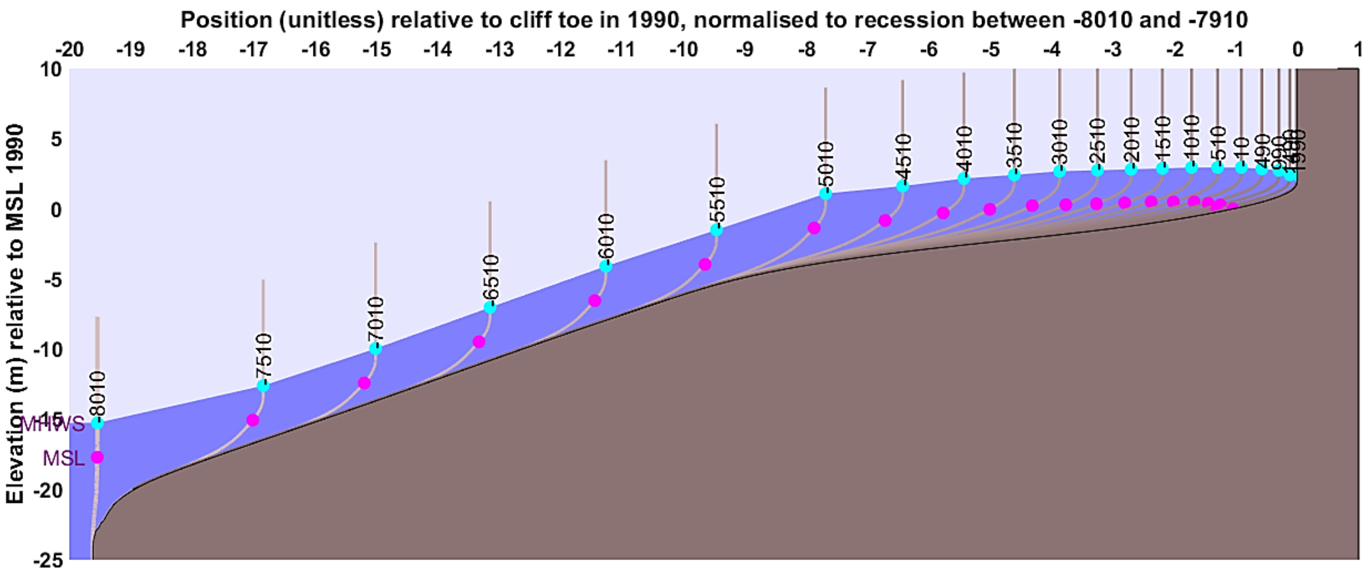

Figure 5-11: Graph illustrating a hindcast simulation to the year 1990 for region 70

In Figure 5-11 the y-axis is elevation (in metres) relative to MSL 1990, and on the x-axis position (unitless) relative to cliff toe in 1990, normalised to recession between -8010 and -7910. The south shore of the Llyn Peninsula is normalised to recession during the first 1,000 years of the simulation; date stamps are to the calendar year; profiles are shown in 500-year time steps. The cyan dots indicate the MHWS and the magenta dots indicates rising MSL for each profile.

This can be seen by the reducing space between the profiles, which are shown at regular 500-year time steps. This reduction is caused by the progressive shallowing of the profile, which has an important effect on the model behaviour when future changes are simulated (Figure 5-12).

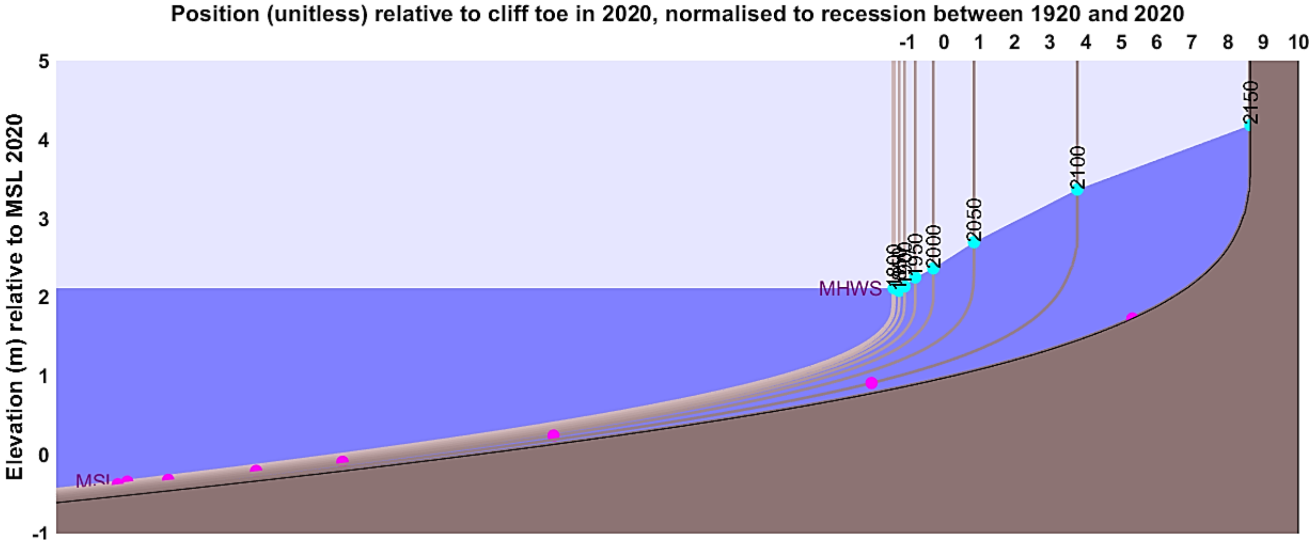

Figure 5-12: Graph showing the profiles from one forecast simulation of the upper shore profile in region 70

In Figure 5-12 the y-axis is elevation (in metres) relative to MSL 1990, and on the x-axis position (unitless) relative to cliff toe in 1990, normalised to recession between -8010 and -7910. It shows the south shore of the Llyn Peninsula between 1800 and 2150, in 50- year time steps, under the 95th percentile of the UKCP18 RCP 8.5 projection. Note that: (1) the normalisation period is different to that used in Figure 5-11, and (2) magenta dots represent MSL and cyan dots MHWS level.

An impression of the upper intertidal slope can be gained by examining the horizontal distance between the positions of mean sea level (magenta dots) and mean high water spring (cyan dots). The upper intertidal is gently sloping at the start of this simulation, for reasons explained above, but becomes much steeper through time. Consequently, the upper intertidal becomes progressively less effective at wave dissipation; the waves break more aggressively and become more erosive. The effect on recession rates is clear from the greatly increasing gap between the shore profiles.

These figures illustrate the importance of accounting for dynamic reshaping of the shore profile, and explain the high sensitivity found in the subset 1 regions. The models of these regions show the greatest sensitivity to historic relative sea levels (this is discussed in the following section), and so their output might benefit from improved representation of those levels.

5.6 Relative importance of regional factors

The indicators of recession sensitivity have been examined against various regional factors to understand what drives their variation.

5.6.1 Historic relative sea levels

As noted in the previous section (and as indicated by the equation of Walkden and Dickson, 2008), historical sea levels should be of some importance. The indicators of cliff toe sensitivity were, therefore, compared to relative sea levels in the year 1000 (that is, approximately 1,000 years before the present day); this is shown as Figure 5-13.

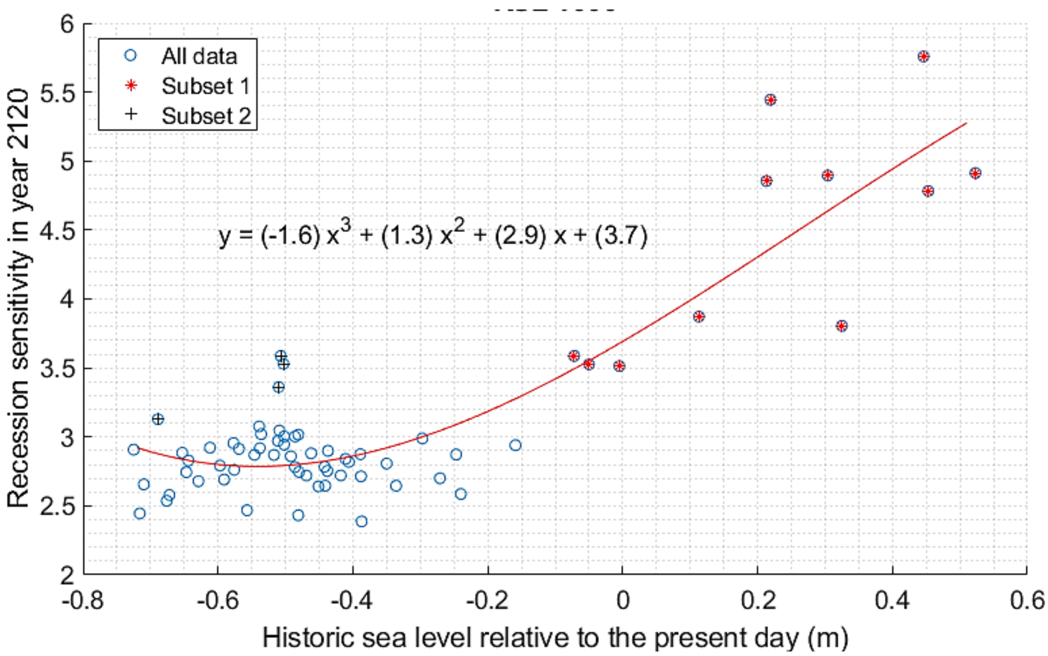

Figure 5-13: Graph describing the recession sensitivity in 2120, against historic relative sea levels 1,000 years before the present day (95th percentile of RCP 8.5)

In Figure 5-13 the y-axis is recession sensitivity in year 2120 from 2 to 6, and on the x-axis historic sea level relative to the present day (in metres) from -0.8 to 0.6 m. The subsets 1 and 2 correspond to those shown in Figure 5-4 - the line and equation represent a polynomial curve fitted to the data. A clear trend can be seen for historic relative sea levels greater than a threshold between -0.25 metres and -0.15 metres, in which higher levels are associated with higher sensitivity. Below this threshold, these properties appear independent.

The greatest sensitivities (shown by subset 1 of the data) are associated with the highest historic sea levels, for the reasons discussed in section 5.5.

Similar graphs for other years suggest that the level of correlation of this relationship increases with time, and that the threshold may decrease. When recession sensitivity for 2300 is plotted, the dependence is clearer (Figure 5-14).

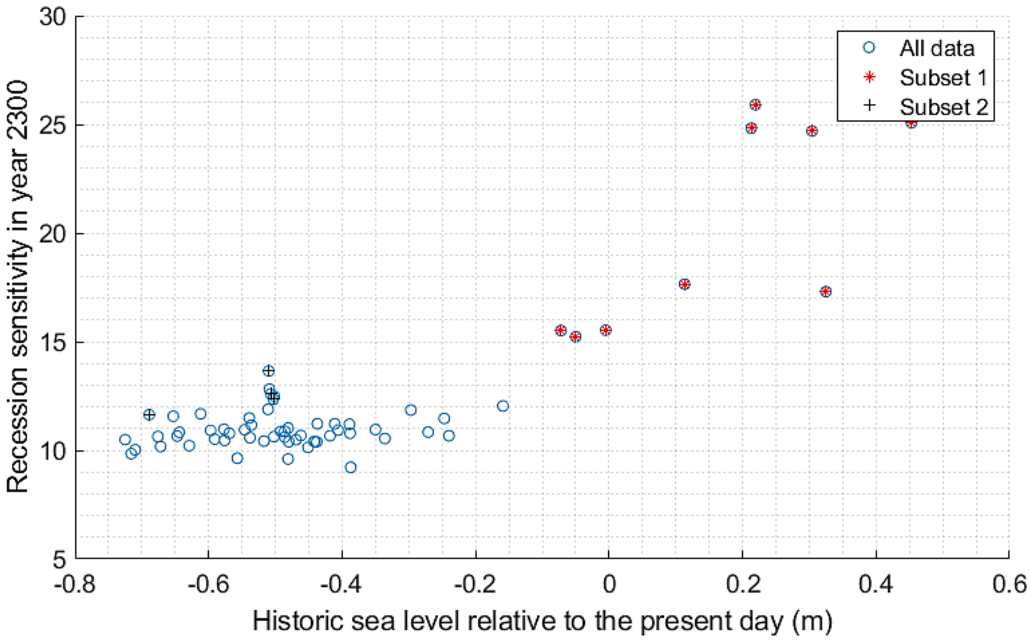

Figure 5-14: Graph showing the recession sensitivity in 2300 against historic relative sea levels 1,000 years before the present day (95th percentile of RCP 8.5)

In Figure 5-14 the y-axis is recession sensitivity in year 2300, and on the x-axis historic sea level relative to the present day (in metres) from -0.8 to 0.6 m. It shows that historic sea levels do not explain the (modest) peak in sensitivity seen in subset 2; this was explored by examining the effects of tidal range.

5.6.2 Tidal range

Spring tidal range was approximated as twice the elevation difference between mean sea level and mean high water spring level, and then plotted against recession sensitivity (Figure 5-15).

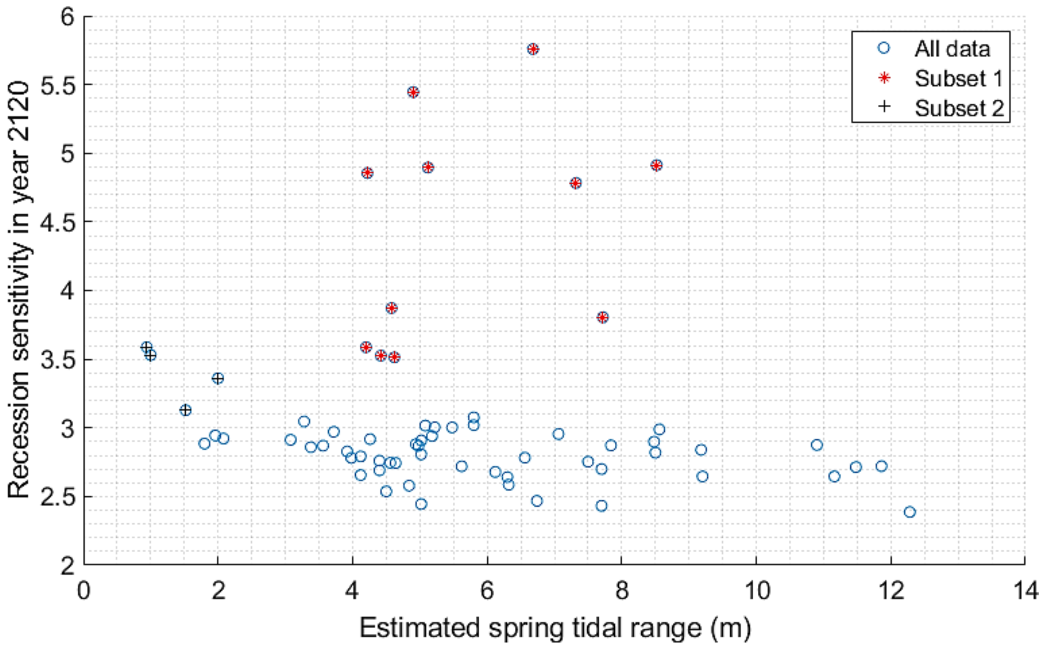

Figure 5-15: Graph presenting the recession sensitivity in 2120 against estimated spring tidal range (95th percentile of RCP 8.5)

In Figure 5-15 the y-axis is recession sensitivity in year 2120 from 2 to 6, and on the x-axis estimated spring tidal range (in metres) from 0 to 14 m. The subsets 1 (red asterisk) and subset 2 (black crosses) correspond to those shown in Figure 5-4. This graph suggests a dependence on tidal range in which higher tides result in lower sensitivity. This trend can be seen more clearly when subset 1, which was strongly influenced by historic sea levels, is disregarded. Low tidal range seems to explain the sensitivity found in subset 2.

To provide a clearer picture of the dependence on tidal range, the sensitivity data was filtered to reduce the influence of historic sea levels. This was achieved at each point by subtracting values from the polynomial function in Figure 5-13. These filtered values are plotted against tidal range in Figure 5-16.

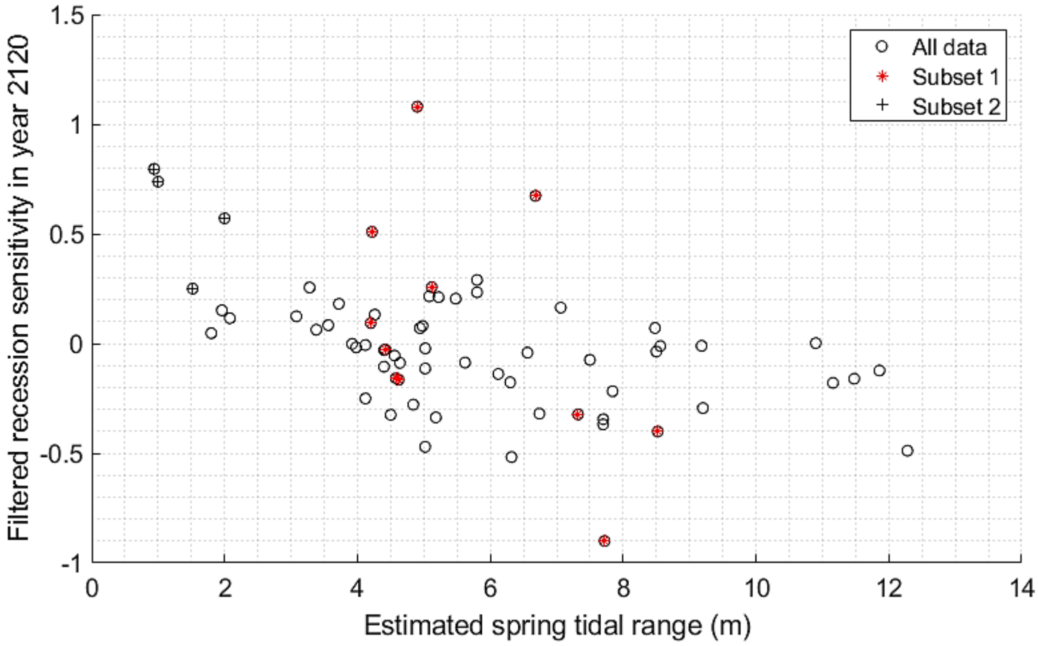

Figure 5-16: Graph showing the filtered measures of recession sensitivity in 2120 against estimated spring tidal range (as defined in section 3.5.3) 95th percentile of RCP 8.5)

Figure 5-16 shows on the y-axis filtered recession sensitivity in year 2120 from -1 to 1.5, and on the x-axis estimated spring tidal range (in metres) from 0 to 14. Subset 1 is indicated with red asterisk and subset 2 black crosses.

5.6.3 Wave height

The filtered data in Figure 5-16 were also used to map sensitivity to significant wave height; the average height of the highest one-third waves (including all directions). The unfiltered results are shown in Figure 5-17 and the filtered results in Figure 5-18.

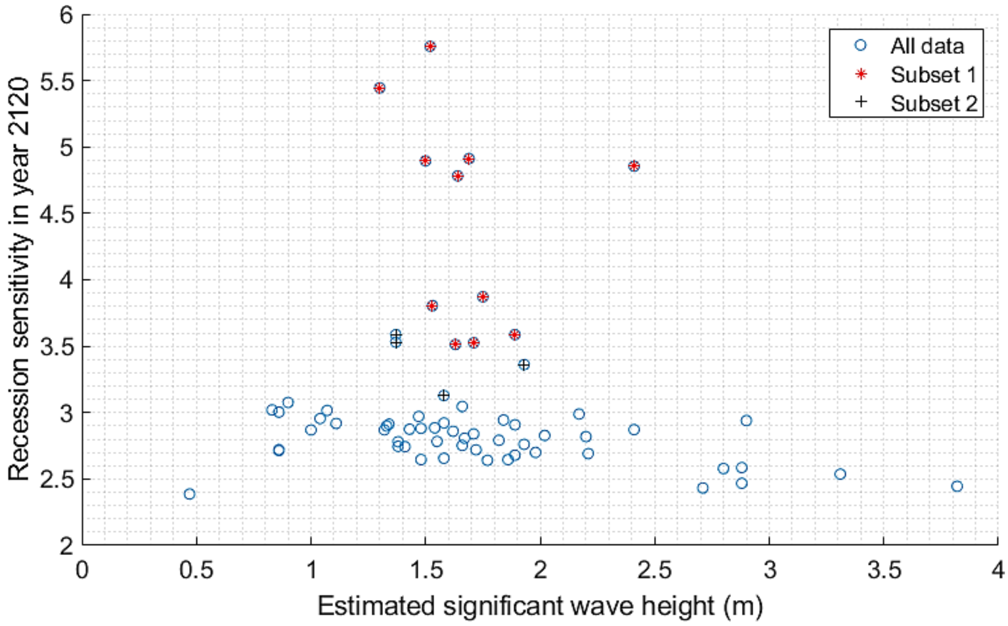

Figure 5-17: Graph showing the recession sensitivity in 2120 against significant wave height (95th percentile of RCP 8.5)

In Figure 5-17 the y-axis is recession sensitivity in year 2120 from -2 to 6, and on the x-axis estimated significant wave height (in metres) from 0 to 4. The graph shows results for all data (blue circles), subset 1 (red asterisk) and subset 2 (black crosses). The filtering illustrated in this figure suggests a potential trend in which areas with increased wave activity tend to display lower sensitivity. However, there is considerable scatter among the data points, resulting in a weak correlation between wave activity and sensitivity.

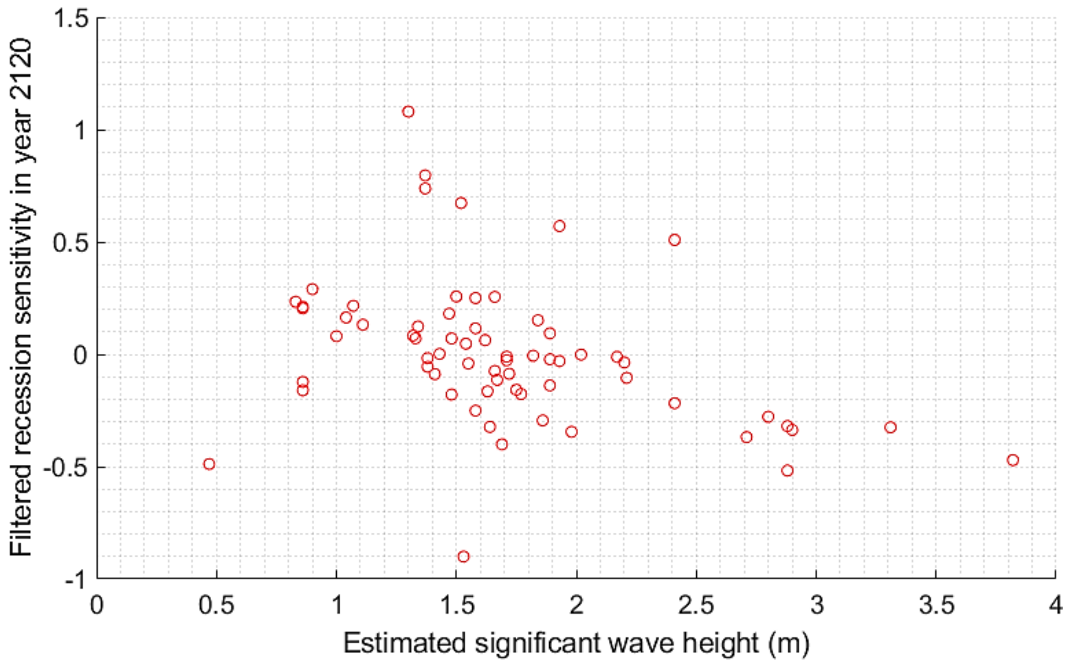

Figure 5-18: Graph showing the filtered measures of recession sensitivity in 2120 against significant wave height (95th percentile of RCP 8.5)

The graph in Figure 5-18 shows plots of the filtered results. The y-axis is filtered recession sensitivity in year 2120 from -1 to +1.5. The x-axis is estimated significant wave height, from 0 to 4 m.

The filtering shown in Figure 5-17 and Figure 5-18 appears to reveal a trend such that regions with higher waves have lower sensitivity. However, the scatter is large, and the relationship is weak. This variability implies that while certain areas align with this observed trend, others show significant deviations.

5.7 Spatial distribution of project outputs

Figure 5-19 and Figure 5-20 show the spatial distribution of recession sensitivity for the upper limit of the RCP emissions scenario in 2120 and 2300, respectively. The pattern of sensitivity, which is similar in both figures, can be interpreted from the trends graphed in section 5.6 - and the maps of marine conditions shown in section 3.5.

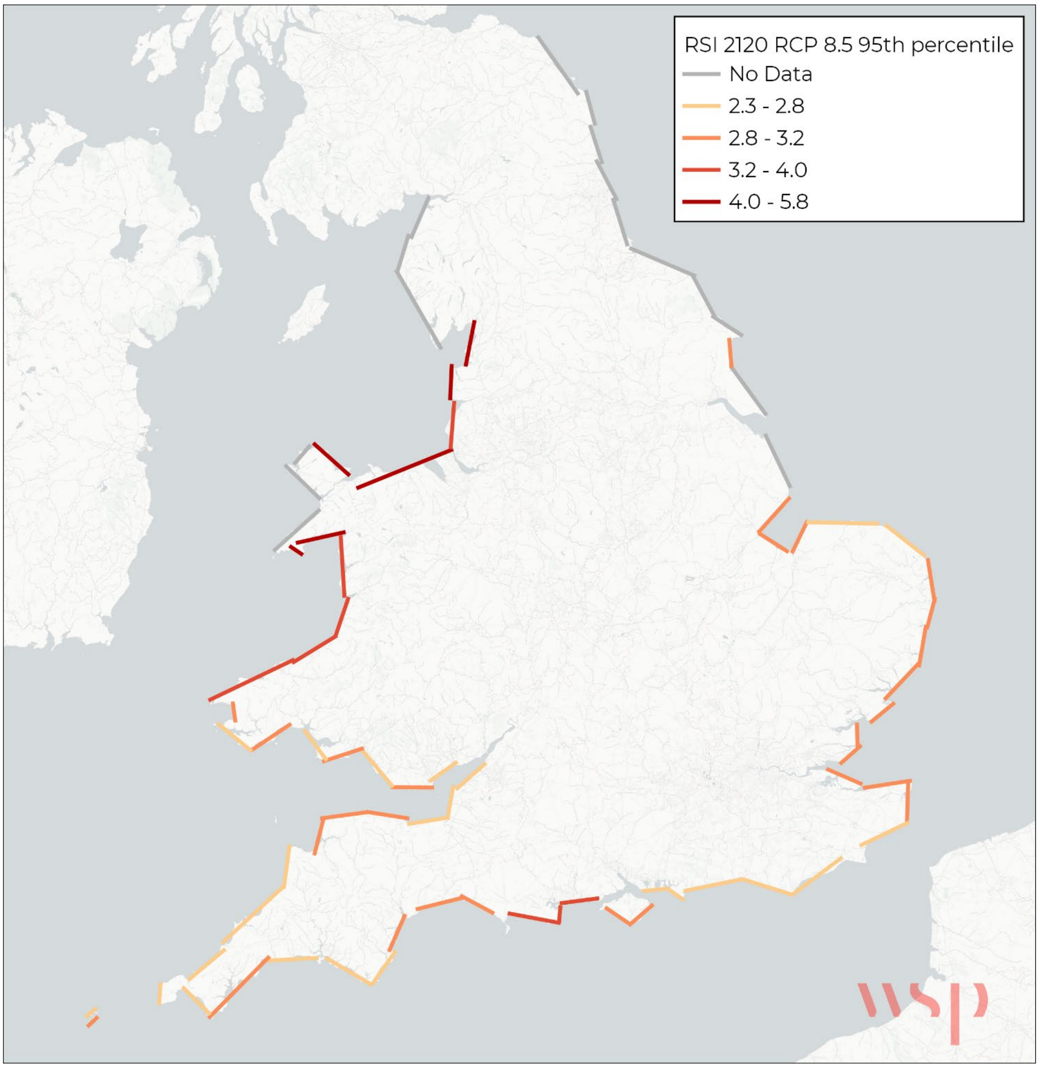

Figure 5-19: Map illustrating the spatial distribution of recession sensitivity in 2120 for the 95th percentile of the RCP 8.5 emissions scenario, around the coast of England and Wales

In Figure 5-19 each region around the coastline displays recession sensitivity for 2120 for the RCP 8.5 95th percentile scenario. The . The highest sensitivity is found in the north-west of Wales and England, due to the high Holocene relative sea levels in this area (Figure 3-5 and Figure 5-13). Sensitivities generally fall with distance south, but a localised increase can be found around the Isle of Purbeck on the south coast of England due to a low tidal range (Figure 3-3, Figure 5-15 and Figure 5-16). Low tidal range can also be found along the Suffolk shore (Figure 3-3) and this appears to elevate sensitivity, particularly over the longer term (Figure 5-20).

The south-west peninsula shows low sensitivity, which is associated with low relative sea levels during the Holocene (Figure 3-5). Those Holocene levels increase for points along the north coast of Devon and Somerset, but that trend is countered by growth in tidal range in the Bristol Channel; as a result, the sensitivity remains relatively constant.

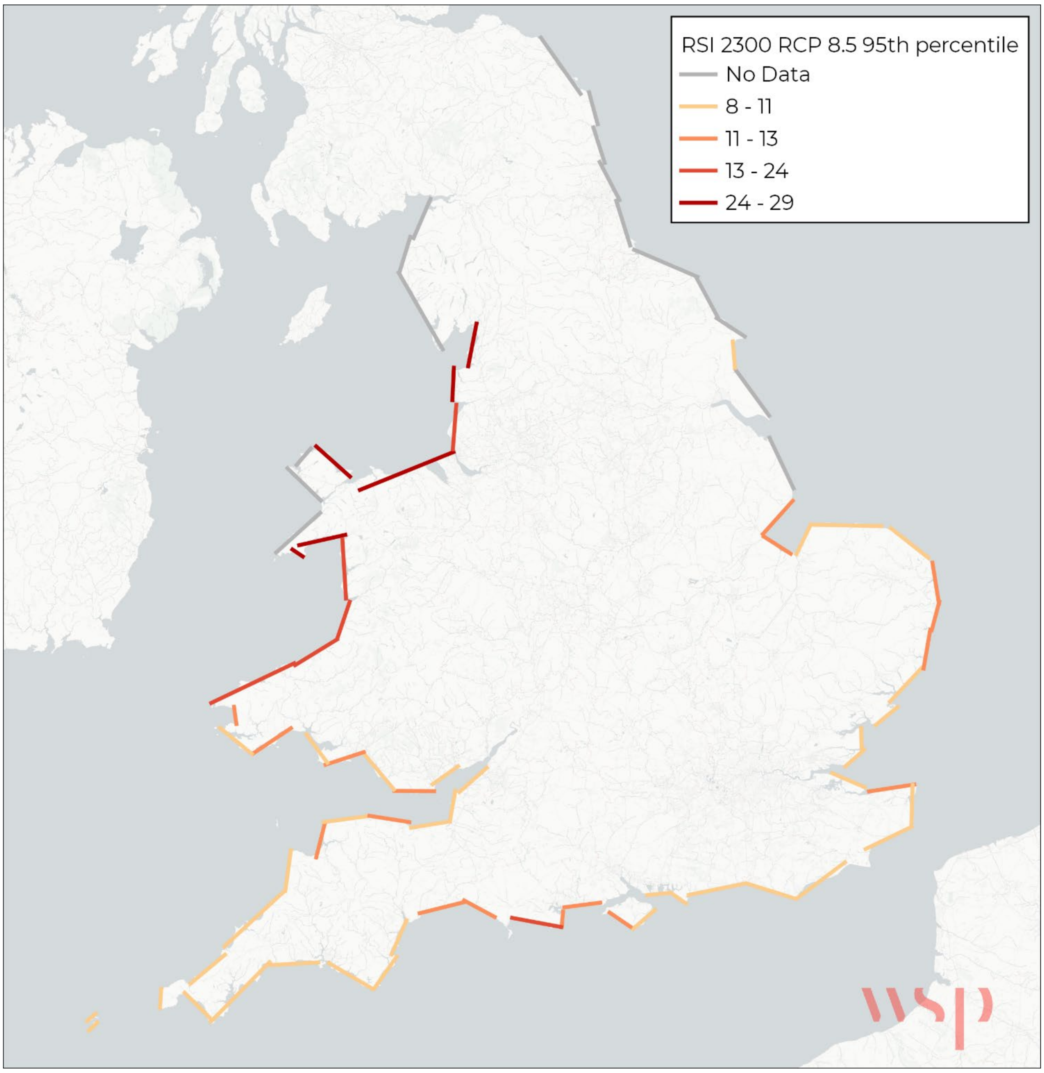

Figure 5-20: Map illustrating the spatial distribution of recession sensitivity in 2300, for the 95th percentile of the RCP 8.5 emissions scenario, around the coast of England and Wales

Figure 5-20 shows that the spatial pattern of recession sensitivity in 2300 shown is similar to that described 2120 in Figure 5-19. It should be noted that no data are presented for parts of northern England and north-west Wales, and this is discussed further in section 6.

6 Summary, discussion and further work

As noted in the introduction, the prediction of coastal cliff recession typically involves adopting the historic rate of change as a ‘baseline’ condition. This is then modified by factors that represent the effects of sea level rise and, if necessary, human interventions, and changes in the natural system. To support that process, this study provides quantified indicators of cliff toe recession sensitivity to sea level rise.

These indicators were derived from SCAPE numerical model simulations, which represented adjacent regions of the shoreline of England and Wales. The results (spatially and temporally varying indicators of cliff toe sensitivity) are intended to approximate the amplification of shore recession caused by sea level rise. They were calculated by dividing (modelled) future recession by (modelled) historic recession across a baseline period (1920 to 2020). The results do not apply to all cliffed locations, and should be interpreted as conservative indicators of future recession, not exact predictions.

The simulations were driven by UKCP18 sea level projections to 2300, for 3 percentiles (5^{th}, 50^{th} and 95^{th}) of 3 emissions scenarios (RCP2.6, RCP4.5 and RCP8.5). A scenario of wave growth was chosen to represent the upper boundary of possible future change.

At present, the approaches most widely used to account for sea level rise, when predicting cliff retreat, are based on the Bruun conceptualisation. These, for example, are recommended by most guidance documents (for example, Rogers and others, 2010; Lee and Clarke, 2002), and a variant was adopted for the first National Coastal Erosion Risk Maps, and many Shoreline Management Plans (SMPs) (Halcrow, 2007).

The new indicators of cliff toe retreat capture characteristics beyond those included in Bruun methods: variable closure depth, gradual (non-instantaneous) response, and a time-varying profile.

To support broad-scale application, a simplified conceptualisation of the shore system was developed, to capture its essential dynamics, but to avoid non-essential detail. Peer-reviewed work was used to inform this, but the outputs unavoidably reflect limitations in current understanding, and should only be applied after careful consideration. Simplifications in the conceptualisation and model inputs were selected to be more likely to result in an overestimation rather than an underestimation of sensitivity. Whether the final results are conservative, and how much they deviate from the ‘true’ answer cannot yet be known, but comparisons can be made with other methods. During the scoping stage of this study, the simplified method used here was tested against models built and calibrated to represent real sites. A comparison was also made, for one site, with the method used to inform the first NCERM published in 2012 (Environment Agency, 2025e). In that comparison, the new approach predicted lower sensitivity, despite its inherent conservatism, than the method used in the 2012 NCERM.

It is reiterated that the results should be interpreted as conservative indicators of future recession, not exact predictions. The indicators are intended to support broad-scale mapping, and recession projections (at suitable sites) where more detailed work is not economically justified. In that context, they might also be used in local or strategic studies. More detailed analysis or modelling should be preferred; SCAPE is freely available (see Walkden, 2019) for this purpose, where appropriate, and can be used to account for site-specific characteristics, such as the development of a beach, the effects of coastal structures/beach nourishment and local variations in geology (see, for example, Walkden and Hall, 2005; Walkden and Hall, 2011; Dickson and others, 2007; Walkden and others, 2016; and Carpenter and others, 2015).

The approach was developed to represent the behaviour of cliffed coasts, where cross-shore variations in geology are not significant, and where the beach is perched on a shore platform (or is absent). The study aimed to include the entire coastline, to avoid the need to review the prevalence of suitable cliffed shores in each region. Results are, therefore, provided regardless of whether suitable cliffs are present, and the insights they provide are not relevant to all locations.

Where the method used is suitable, the results indicate that sensitivity indicator will be below 4 by 2120 for much of the coastline (in other words, recession over the next 100 years may be less than 4 times larger than the recession seen over the last 100 years). Tidal range is a major influence, such that regions with a low tidal range tend to be more sensitive. Wave height appears to play a modest role, so that regions with larger waves are less sensitive. However, in areas of the north where isostatic uplift is relatively large, there is a strong dependence on historic sea levels, and this drives the highest overall sensitivity. These range up to around 6 by 2120 and approach 30 by 2300. These insights account for changes in the shore profile shape, and the time that this takes to occur.

A dependence on historic sea level (Figure 5-14) can be expected from the equation of Walkden and Dickson (2008); and Ashton, Walkden and Dickson (2011):

$$\varepsilon_2 = \varepsilon_1\sqrt{S_2/S_1}$$

Where S represents (unvarying) sea level rise rate, and ε represents equilibrium shore recession rate, and subscripts 1 and 2 represent past and future conditions, respectively. This equation suggests that areas of low historic sea level rise will tend to be more sensitive, and that the relationship will be non-linear.

However, this expression also appears to suggest that sensitivity should be independent of tidal range and wave height. This apparent anomaly can be understood by first noting that the equation relates conditions before, and after, the shore has transitioned from one equilibrium to another. Figure 6-1, which is reproduced in modified form from Ashton, Walkden and Dickson (2011) helps to illustrate the period of transition between the equilibrium states.

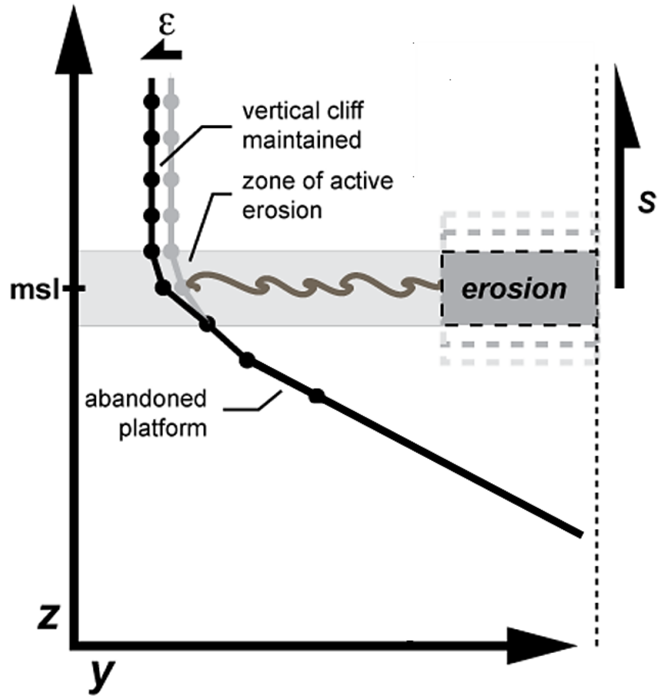

Figure 6-1 Schematic to illustrate the period of transition between the equilibrium states (reproduced in modified form from Ashton, Walkden and Dickson, 2011)

In Figure 6-1 the shore profile is represented by a series of discrete points (in black), and marine erosion as a zone rising with the sea level. Over time, each point on the retreating cliff face undergoes a transition as the erosion zone rises to it, past it and finally abandons it – resulting in the new profile (in grey). This suggests that the period of transition - that is the time taken to change from one equilibrium state to another - is governed by the rate of sea level rise and the height of the erosion zone.

The height of the erosion zone increases with the tidal range and the wave height. Sites where these are large can be expected to have a longer transition period; they will seem less sensitive. For the coastline of Great Britain, tidal range tends to have more influence on the height of the erosion zone than wave height, and so this is associated with greater sensitivity.

The dependence found in Figure 5-16 on tidal range, and the possible relationship with wave height (in Figure 5-18) are, therefore, plausible. These factors influence how fully each site has transitioned to the new rates of sea level rise.

Coastal cliffs in northern areas are estimated to be the most sensitive to future sea level rise, due to relative sea level stasis in recent millennia.

Areas with high tidal ranges will tend to be less sensitive, as will places where the wave climate is more energetic.

No results were generated for a set of northern regions (regions 1 to 8, 10, 11, 72 to 74, and 80 to 82) because the relative sea levels used appear to over-represent isostatic uplift. As a result, the models for these regions showed present day cliffs that were raised above high tide levels, and were, therefore, disconnected from marine erosion and not retreating (abandoned cliffs). Further work is recommended to explore the consequences of using less conservative (and more realistic) interpretations of isostatic uplift. Ideally, the uncertainty in historical sea levels should be explicitly modelled. This seems likely to increase the number of regions where results can be generated.

Strikingly high sensitivity was modelled in northern regions. The model behaviour from which this arises is physically plausible: (1) historic relative sea level stasis causing shallow, dissipative profiles and, therefore, low cliff recession, followed by (2) a rapid increase in cliff exposure to wave attack as the sea level rises. However, it is noted that this response is strongly non-linear, bringing a risk of increased conservatism. This should be recognised when the results of these regions (identified as subset 1 above) are considered for application. If further work on Holocene sea levels is carried out (as recommended above), then it should include these regions.

The scenario of wave growth, applied to all simulations, was chosen to represent an upper limit of change. As discussed in section 3.5.2, the uncertainties around the response of waves to climate change are large. Unlike sea level rise, UKCP18 was not able to identify specific patterns of change for different RCPs, and was only able to provide results that were “indicative of the overall magnitude of changes” “[of] the order 10 to 20 %” (Palmer and others, 2019).

Sensitivity testing showed that, for high rates of sea level rise, the scenario of wave growth accounted for 19% to 33% of the overall response. For smaller sea level rise trajectories, this proportion should be expected to be larger, and the use of this conservative scenario becomes less valid. It is, therefore, recommended that future work should revisit the wave growth scenario and seek ways to reduce the level of conservatism, particularly for the lower sea level rise scenarios, while still according with the change indicated by UKCP19.

The approach suggested for predicting cliff toe recession, where appropriate, is described in the method report that accompanies this technical report (Environment Agency, 2025f). It involves multiplying the indicator of cliff toe sensitivity by the recession at the study site during the baseline period. That historic recession is used as a proxy for the geological influence (its resistance or weakness), and, in this way, alongshore changes in geology can be accounted for. However, it is reiterated that variations in geology across the shore platform/cliff toe cannot be accounted for in this way.

Beaches were not included in the models, but nevertheless the results can be expected to represent the behaviour of sites with beaches of limited volume, and this is discussed further in the method report. This modelling simplification (the absence of a beach) was made to greatly reduce the number of necessary simulations, but it is far from ideal and is another reason why site-specific modelling should be preferred. The results do not, for example, capture feedback in which increased cliff recession can boost beach volumes. This is sacrificed to allow assessment at a national scale, and the effect will be to increase conservatism (in other words, it is expected to overestimate sensitivity).

It is worth noting that adaptations of the Bruun conceptualisation for cliffed shores are designed to account for this feedback, but neglect changes in the shore profile shape, and the time that this takes to occur. They also tend to assume a constant depth of closure. These contrasting limitations have implications for the settings in which it would be reasonable to apply the different approaches. Bruun-based methods might be preferred where the behaviour of a cliff/platform is governed by an overlying beach. The new work presented here has been developed for certain settings where shore behaviour is governed by the dynamics of the cliff and platform, and where the beach (if present) plays a subordinate role.

Clearly, these conditions lie on a continuum, and there is value in understanding the dependence of cliff sensitivity to this continuum. Previous work (Dickson and others, 2007; Walkden and Hall, 2011) has begun to explore this through 3-dimensional modelling. It is recommended that this work be continued, and potential approaches include: (1) further 2D modelling to explore cliff response to beaches of different sizes; (2) 3D modelling of idealised coastal settings; or (3) 3D modelling of coastal regions. Further generalised simulations could also be used to explore the sensitivity of cliff slopes to increased rainfall; early exploratory work carried out during the scoping stage of this project (Environment Agency, 2025e) could be expanded into a formal method for this.

The work presented here aims to extend current knowledge, but unavoidably reflects the limited nature of that knowledge. Further fundamental work is needed to better understand coastal systems and the way they respond to sea level change, together with ongoing monitoring and evaluation.

Developments to the SCAPE modelling tool are also recommended. SCAPE's tendency to under-represent the steepness of subtidal slopes should, in particular, be addressed. Observational data collected by the regional monitoring programme, which was not available when SCAPE was developed, could be used to achieve this.

Finally, it is recommended that new models of cliff/platform response to sea level change be developed that, like SCAPE, capture dynamic reshaping of the coastal profile. This study has demonstrated the strength of that capability.

7 Acknowledgements

The study gratefully acknowledges the support of the following people and organisations.

The work was funded by the Joint Flood and Coastal Erosion Risk Management Research and Development Programme.

Developers and adaptors of the version of SCAPE used here were Mike Walkden, Jim Hall, Mark Dickson, James Thomas and John Barnes. The modelling tool was made openly available by the Integrated Coastal Sediment Systems project (iCOASST), which was coordinated by the University of Southampton and funded by the Natural Environment Research Council.

Dr Sarah Bradley of Sheffield University provided Holocene relative sea level data, which were derived from a project supported by the Natural Environment Research Council consortium grant; BRITICE-CHRONO NE/J009768/1.

Projections of future sea levels to 2100 were provided by the United Kingdom Climate Projections project 2018 (UKCP18), which is part of the Met Office Hadley Centre Climate Programme funded by the Department for Business, Energy & Industrial Strategy (BEIS) and Defra.

Projections of future sea levels to 2300 were provided by the United Kingdom Climate Projections project 2018 (UKCP18) and funded by the Joint Flood and Coastal Erosion Risk Management Research and Development Programme of Defra, the Environment Agency, Natural Resources Wales and the Welsh Government and the flood research programme of the Scottish Environment Protection Agency.

Wave data were generated by the Met Office WAVEWATCH III model, under the Environment Agency licence.

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Appendix A - recent mean sea level trends

Table A-1: Recent Mean Sea Level trends from Environment Agency (2018)

Location	Trend (mm/year)
St Helier	2.07
Newlyn	1.73
St Mary's	2.24
Padstow	2.29
Ilfracombe	2.35
Hinkley Point	2.71
Portbury	2.09
Avonmouth	2.15
Newport	2.94
Mumbles	1.93
Milford Haven	3.14
Fishguard	1.76
Barmouth	2.42
Holyhead	1.82
Llandudno	1.47
Hilbre	1.61
Liverpool	1.83
Port Erin	1.15

Location	Trend (mm/year)
Heysham	1.52
Workington	0.23
Portpatrick	1.43
Millport	0.73
Port Ellen	2.35
Tobermory	1.12
Ullapool	1.19
Stornoway	1.81
Kinlochbervie	1.48
Lerwick	0.36
Wick	1.06
Moray Firth	0.49
Clachnaharry	0.47
Aberdeen	1.02
Leith	0.79
Grangemouth	0.48
North Shields	1.69
Whitby	2.88
Immingham	1.43

Location	Trend (mm/year)
Cromer	1.91
Lowestoft	2.27
Felixstowe	1.71
Harwich	1.89
Southend	2.01
Sheerness	1.81
Dover	2.03
Newhaven	2.2
Portsmouth	2.03
Bournemouth	2.07
Weymouth	1.11
Exmouth	2.21
Devonport	1.98
Belfast	0.92
Bangor	1.35
Portrush	0.7

Table A-2: Recent relative sea level trends applied to each region, and the reference points (in Table A-1) from which the trends were interpolated

Region	Left gauge	Right gauge	Trend (mm/yr)
1	Leith	North Shields	1.21
2	Leith	North Shields	1.39
3	Leith	North Shields	1.51
4	Leith	North Shields	1.65
5	North Shields	Whitby	2.03
6	North Shields	Whitby	2.60
7	Whitby	Immingham	2.63
8	Whitby	Immingham	2.28
9	Whitby	Immingham	2.03
10	Whitby	Immingham	1.70
11	Immingham	Cromer	1.59
12	Immingham	Cromer	1.67
13	Immingham	Cromer	1.69
14	Immingham	Cromer	1.73
15	Immingham	Cromer	1.81
16	Cromer	Lowestoft	2.01
17	Cromer	Lowestoft	2.19
18	Lowestoft	Felixstowe	2.19

Region	Left gauge	Right gauge	Trend (mm/yr)
19	Lowestoft	Felixstowe	1.99
20	Lowestoft	Felixstowe	1.76
21	Harwich	Southend	1.92
22	Harwich	Southend	1.96
23	Harwich	Southend	1.99
24	Sheerness	Dover	1.82
25	Sheerness	Dover	1.92
26	Sheerness	Dover	1.97
27	Dover	Newhaven	2.05
28	Dover	Newhaven	2.14
29	Newhaven	Portsmouth	2.20
30	Newhaven	Portsmouth	2.12
31	Newhaven	Portsmouth	2.07
32	Newhaven	Portsmouth	2.04
33	Portsmouth	Bournemouth	2.04
34	Portsmouth	Bournemouth	2.05
35	Portsmouth	Bournemouth	2.06
36	Bournemouth	Weymouth	1.85
37	Bournemouth	Weymouth	1.52

Region	Left gauge	Right gauge	Trend (mm/yr)
38	Weymouth	Exmouth	1.45
39	Weymouth	Exmouth	1.82
40	Exmouth	Devonport	2.17
41	Exmouth	Devonport	2.10
42	Exmouth	Devonport	2.05
43	Devonport	Newlyn	1.93
44	Devonport	Newlyn	1.83
45	Devonport	Newlyn	1.77
46	St Marys	St Marys	2.07
47	St Marys	St Marys	2.07
48	Newlyn	Padstow	1.80
49	Newlyn	Padstow	1.97
50	Padstow	Ilfracombe	2.30
51	Padstow	Ilfracombe	2.32
52	Padstow	Ilfracombe	2.34
53	Ilfracombe	Hinkley Point	2.39
54	Ilfracombe	Hinkley Point	2.54
55	Ilfracombe	Hinkley Point	2.68
56	Hinkley Point	Portbury	2.50

Region	Left gauge	Right gauge	Trend (mm/yr)
57	Hinkley Point	Portbury	2.19
58	Newport	Mumbles	2.83
59	Newport	Mumbles	2.54
60	Newport	Mumbles	2.23
61	Mumbles	Milford Haven	1.99
62	Mumbles	Milford Haven	2.31
63	Mumbles	Milford Haven	2.80
64	Milford Haven	Milford Haven	3.14
65	Milford Haven	Fishguard	2.64
66	Fishguard	Fishguard	1.76
67	Fishguard	Barmouth	2.06
68	Fishguard	Barmouth	2.22
69	Barmouth	Barmouth	2.42
70	Barmouth	Holyhead	2.29
71	Barmouth	Holyhead	2.22
72	Barmouth	Holyhead	2.05
73	Barmouth	Holyhead	1.89
74	Holyhead	Bangor	1.71
75	Holyhead	Bangor	1.53

Region	Left gauge	Right gauge	Trend (mm/yr)
76	Llandudno	Hillbre	1.54
77	Liverpool	Heysham	1.74
78	Liverpool	Heysham	1.62
79	Heysham	Workington	1.46
80	Heysham	Workington	0.89
81	Heysham	Workington	0.29
82	Workington	Portpatrick	0.44

Appendix B – Region specific model parameters

Region	BASELINEANGLE (degrees from north)	DEPTHOSCMSL (m)	OSCANGLES (Degrees from north)
1	144.8	18	145.7
2	164.9	15	165.5
3	162.3	14	171.8
4	152.5	11	153.1
5	162.8	15	167.4
6	113.2	16	114.2
7	151.7	15	150.3
8	123.2	17	140.8
9	175.3	13	190.5
10	143.9	17	147.7
11	154.7	10	154.1
12	221.9	6	223.7
13	122.7	7	126.2
14	25.8	7	30
15	91.2	11	106
16	128.3	11	127.5
17	170.9	9	172.4

Region	BASELINEANGLE (degrees from north)	DEPTHOSCMSL (m)	OSCANGLES (Degrees from north)
18	194.8	6	203.3
19	189.7	17	192.7
20	223.3	11	213
21	230.5	9	237.5
22	178.2	3	182.7
23	228.4	9	224.4
24	113.4	9	115.7
25	81.3	5	84.8
26	181.8	10	188.7
27	244.3	18	241.5
28	233	11	233.3
29	287.4	12	287.7
30	258.6	9	256.8
31	304.8	11	304.8
32	264.4	6	262.3
33	229.2	13	228
34	304.3	18	304
35	262.6	12	262.4

Region	BASELINEANGLE (degrees from north)	DEPTHOSCMSL (m)	OSCANGLES (Degrees from north)
36	185	11	194
37	280.6	11	279
38	298.3	10	298.1
39	256	18	256.4
40	203.8	12	202.8
41	215.2	14	205.5
42	300.5	17	300.1
43	266.9	17	266.8
44	224.6	17	224.6
45	314.9	17	315.1
46	226.3	10	225.7
47	48.4	10	48.6
48	3.9	17	3.7
49	50.1	16	50.1
50	47.3	19	47.5
51	7.9	18	8.1
52	14.2	12	14.3
53	82.3	14	82.4

Region	BASELINEANGLE (degrees from north)	DEPTHOSCMSL (m)	OSCANGLES (Degrees from north)
54	98.9	16	99
55	80.8	12	78.7
56	10	11	33.6
57	48.6	7	48.6
58	234.7	6	234.7
59	270.5	13	273.2
60	320.1	7	320.3
61	251.8	7	251.9
62	323.6	7	323.4
63	236.2	10	236.1
64	309.2	15	309.4
65	352.1	15	348
66	64.4	18	64.5
67	58.5	18	55.2
68	18.7	9	13.2
69	356.5	8	356.7
70	257.4	9	242.6
71	303.9	7	305

Region	BASELINEANGLE (degrees from north)	DEPTHOSCMSL (m)	OSCANGLES (Degrees from north)
72	48	19	44.6
73	314	5	314
74	40.8	17	41.2
75	131.8	11	131.7
76	67.9	11	66.2
77	4.4	11	12.6
78	2.7	11	2.6
79	11.1	6	11.1
80	330.1	11	334
81	17	10	11.3
82	23.2	7	23.2

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