Impacts of climate change on sea-level rise relevant to the coastal and marine environment around the UK

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EXECUTIVE SUMMARY

- Increases in future extreme sea levels are expected to result in increases in flooding and erosion in the coming decades, although precise changes are highly location- and context-specific.
- Future extreme sea levels will be dominated by changes in mean sea level, not by the storm surge component, nor changes to tides.
- Several independent studies consistently estimate the rate of regional sea-level rise around the UK, attributable to climate change and observed by tide gauge records, to be between 1 and 2 mm per year. When vertical land movement (glacial isostatic adjustment since the last ice age) is also included, this rate is increased for the south of England and decreased for some parts of Scotland undergoing isostatic ‘rebound’.
- Future projections of sea-level rise around the UK (from climate models) are taken from the UKCP18 Marine Report (Palmer *et al*., 2018). These projections supersede those of UKCP09 (Lowe *et al*., 2009) used in previous MCCIP report cards.
- Projections for the year 2100 (relative to the 1981–2000 average) contain considerable uncertainty. For London, the central estimate sea-level projection for the year 2100 ranges from 0.45–0.78 m, depending on the emissions scenario. Similar ranges of the central estimate at 2100 for other cities are: Cardiff 0.43–0.76 m; Edinburgh 0.23–0.54 m; Belfast 0.26–0.58 m.
- All projections show spatial variation due to differential rates of vertical land movement and also the spatial pattern of sea-level change linked to polar ice melt. For the year 2100, sea levels for southern England are projected to be approximately 0.4 m higher than for parts of Scotland.
- Exploratory model results suggest that sea levels will continue to rise until the year 2300 and beyond. Upper estimates for London and Cardiff under the highest emissions scenario exceed 4 m. These estimates have much lower confidence than the projections to 2100.

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- There is no observational evidence for long-term trends in either storminess across the UK or resultant storm surges.
- Storm surge simulations for the 21st century suggest a best estimate of no significant changes to storm surges.

1. WHAT IS ALREADY HAPPENING?

1.1 Global and regional sea level

According to the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2013) it is very likely (with >90% probability) that the average rate of globally averaged sea-level rise was 1.7 mm per year between the years 1901 and 2010. For the 1993 to 2010 period, the average rate of change was 3.2 mm per year, with good agreement between tide-gauge and satellite altimeter data. There is a high confidence that the rate of observed global sea-level rise increased from the 19th to the 20th century (Bindoff *et al*., 2007; Woodworth *et al*., 2011) and there is evidence of a long-term acceleration in the rate of sea-level rise throughout the 20th century (Church and White, 2011). Whether the faster rates of sea-level rise during the period from the mid-1990s reflects an acceleration in the longer-term trend or natural variability is still not known.

Sea-level change at any particular location depends on many geophysical processes operating across a range of time and space scales. Regional variability is affected by ocean- and atmosphere-circulation processes, and local changes in seawater temperature and salinity. For many practical purposes, it is sea level with respect to the local land level that is of interest. The solid Earth is recovering from ice loading during the most recent ice age. This vertical land motion (and other effects) resulting from the viscoelastic response of the solid Earth to deglaciation is termed ‘Glacial Isostatic Adjustment’ (GIA). An additional consideration is that sea-level change is affected globally by gravitational adjustment of the World’s ocean in response to melting ice in Antarctica and Greenland. Mitrovica *et al*. (2009) showed how rapid melting of major ice sources can cause spatial changes in the Earth’s gravity field as well as to the volume of water in the oceans. There is a fall in sea level close to the source of any melting as the gravitational interaction between ice and ocean is reduced; conversely, there is a larger rise in sea level further away from the melt source. These complex interactions are explained in more detail in the UKCP18 Marine Report (Palmer *et al*., 2018).

The most-recent comprehensive observational study of mean sea level around the coast of the UK was by Woodworth *et al*. (2009). They found that spatial variations in the trends around the coastline were due to vertical land motions. After removing this factor using geological data (Shennan and Horton, 2002), the estimated rate of regional sea-level rise around the UK attributable to climate change was 1.4 ± 0.2 mm per year. Haigh *et al*. (2009) obtained similar estimates of sea-level changes in the English Channel after removing the effects of vertical land movement, and their analyses also considered complementary measurements of vertical land movement from GPS instruments (Bingley *et al*., 2007). Wahl *et al*. (2013) used a more-recent update (Shennan *et al*., 2012) to the geological corrections in their analysis of tide gauge records from around the North Sea, and obtained estimates of sea-level rise of 1.5 ± 0.1 mm per year with slight, but not significant, variations in different locations. All these studies found year-on-year variability in the sea-level changes, which were predominantly due to atmospheric effects on shorter timescales (i.e. a few years), with oceanic processes controlling a larger fraction of the variability over longer (decadal) timescales. Separating a long-term acceleration to European sea-level rise from these oscillations has been the focus of some recent work, with some work (e.g. Ezer *et al*., 2015) reporting small positive accelerations detectable in the longest European tide gauge records. The small values obtained (approximately 0.01 mm/year^2) agree with the global analysis of Church and White (2011). It should be noted that rigorous statistical analysis of European tide gauges shows any sea-level rise accelerations to be not statistically significant from zero (Watson, 2016), so clearly this is an area for ongoing research.

Any future comprehensive study of UK sea level rise needs to incorporate the ever-improving estimates of vertical land movement (e.g. Shennan *et al*., 2018; Hansen *et al*., 2012), but these modifications have not hitherto altered the headline UK figure for sea-level rise attributable to climate change.

Taking these studies into consideration, the overall picture is that mean sea levels around the UK largely exhibit 20th century rises consistent with the global mean values of IPCC (2013) although the central estimate around the UK is slightly lower than that of the global value (Woodworth *et al*., 2009). All shorelines of the UK are presently experiencing some sea-level rise and this is expected to continue into the future. When vertical land movement is included, then relative rates of sea level are lower in much of Scotland, Northern Ireland and the north of England, and up to 1 mm per year greater for the south of England, Channel Islands, Isles of Scilly, and the Shetland Isles.

1.2 Extreme sea levels around the UK

Extreme high waters around the UK are typically caused by a combination of exceptionally high tides and severe weather events. Extra-tropical cyclones, also called ‘mid-latitude depressions’, are the prevailing weather systems for the UK. These weather systems produce storm surges, which are large-scale increases in sea level due to the storm. They can increase sea levels by 3–4m with the highest levels around the UK along the east coast (Haigh *et al*., 2015). Storm surges persist for hours to days and affect hundreds of square kilometres. They represent the greatest threat when they coincide with tidal high water, a situation that many operational forecasting centres refer to as a ‘storm tide’. Extreme water levels can be elevated further by short-period wind waves and wave setup (which is caused by breaking waves); these factors are considered separately in an accompanying MCCIP report card (Wolf *et al*., 2020).

While changes in storminess could contribute to changes in sea-level extremes, there is little or no observational evidence for either systematic long-term changes in storminess or any detectable change in storm surge magnitude (IPCC, 2012). The findings of IPCC (2013) are that at most locations around the World, mean sea-level change is the main factor influencing observed changes to sea-level extremes (although large-scale modes of ocean variability, such as the North Atlantic Oscillation may also be important). Allen *et al*. (2008) showed that changes in UK storm frequency over the second half of the 20th century were dominated by the natural variability of our weather systems. Dawson *et al*. (2007) found the same for Scottish weather records. The scientific consensus is overwhelmingly that any changes in extreme sea levels for the UK and worldwide, and any observed increases in actual flooding, have been driven by the rise in mean sea level (Woodworth and Blackman, 2004; Ball *et al*., 2008; Haigh *et al*., 2010; Menendez and Woodworth, 2010; Marcos *et al*., 2015; Wahl and Chambers, 2016).

The natural variability in the wave-, storm surge- and mean sea level-components ranges from variability associated with stochastic (random) processes, to those displaying seasonal and longer-period changes associated with regional climate (e.g. the North Atlantic Oscillation). The UK recently experienced an unusual sequence of extreme storms over the winter of 2013–2014, resulting in some of the most significant coastal flooding since the North Sea storm surge of 1953 (Matthews *et al*., 2014; Haigh *et al*., 2016). Although no individual storm was exceptional, the persistence of storminess was unusual although not unprecedented.

2. WHAT COULD HAPPEN IN THE FUTURE?

2.1 Projected regional sea level around the UK

To ensure consistency of sea-level advice that informs UK policy and decision making, this section draws significantly from the UKCP18 Marine Report (Palmer *et al*., 2018) which provides updated marine projections, building on the models and methods presented in the IPCC Fifth Assessment Report (AR5) of Working Group 1 (IPCC, 2013). The scenarios and findings of UKCP18 supersede those of UKCP09, which was used to inform previous MCCIP scorecards. The UKCP18 sea-level projections are based on the climate model simulations of the Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor *et al*., 2012). These models formed the basis of the climate projections presented in the IPCC Fifth Assessment Report of Working Group I (IPCC, 2013) and deliver substantial improvements over their predecessor CMIP3 models (Meehl *et al*., 2007). The most significant methodological difference is the inclusion of ice dynamics in UKCP18 projections of future sea-level rise, resulting in systematically larger values for sea-level rise than were presented in UKCP09. For full technical details of the modelling carried out in UKCP18, see Palmer *et al*. (2018).

The UKCP18 sea-level projections used three of the Representative Concentration Pathways (RCPs, Meinshausen *et al*., 2011) that were the basis of the climate change projections in IPCC AR5. These pathways refer to socioeconomic scenarios with varying greenhouse gas emissions. They are named according to the radiative forcing on the climate system relative to pre-industrial values. The RCP climate change scenarios span a greater range of climate forcing over the 21st century than the scenarios used in UKCP09. In the diagrams and tables presented here, future sea-level rise for any given scenario is presented on the basis of the 5th to 95th percentile range of the underlying model distribution (i.e. a 90% confidence interval). Central estimates presented here are the median (50th percentile) value from model distributions, and therefore there is an equal chance of these under- or over-estimating future changes.

The UK sea-level projections presented both here and in UKCP18 incorporate the spatial patterns of sea-level rise due to oceanographic processes, and also gravitational and other adjustments following ice melt and changes to terrestrial water storage (e.g. Slangen *et al*., 2014). The projections contain the most-recent estimate of the pattern of sea-level change caused by the elastic response of the solid Earth to the last de-glaciation. UKCP18 used an ensemble of GIA estimates from the NERC BRITICE_CHRONO project (http://www.britice-chrono.group.shef.ac.uk/) and this mechanism is the primary reason for spatial variations in projected mean sea-level change around the UK for any given RCP scenario (see Figure 1).

Projected UK-average sea-level rise is slightly lower than global mean sea-level rise across all RCP scenarios. For example, under RCP4.5 the UK-average value at 2100 is 89% of the global value.

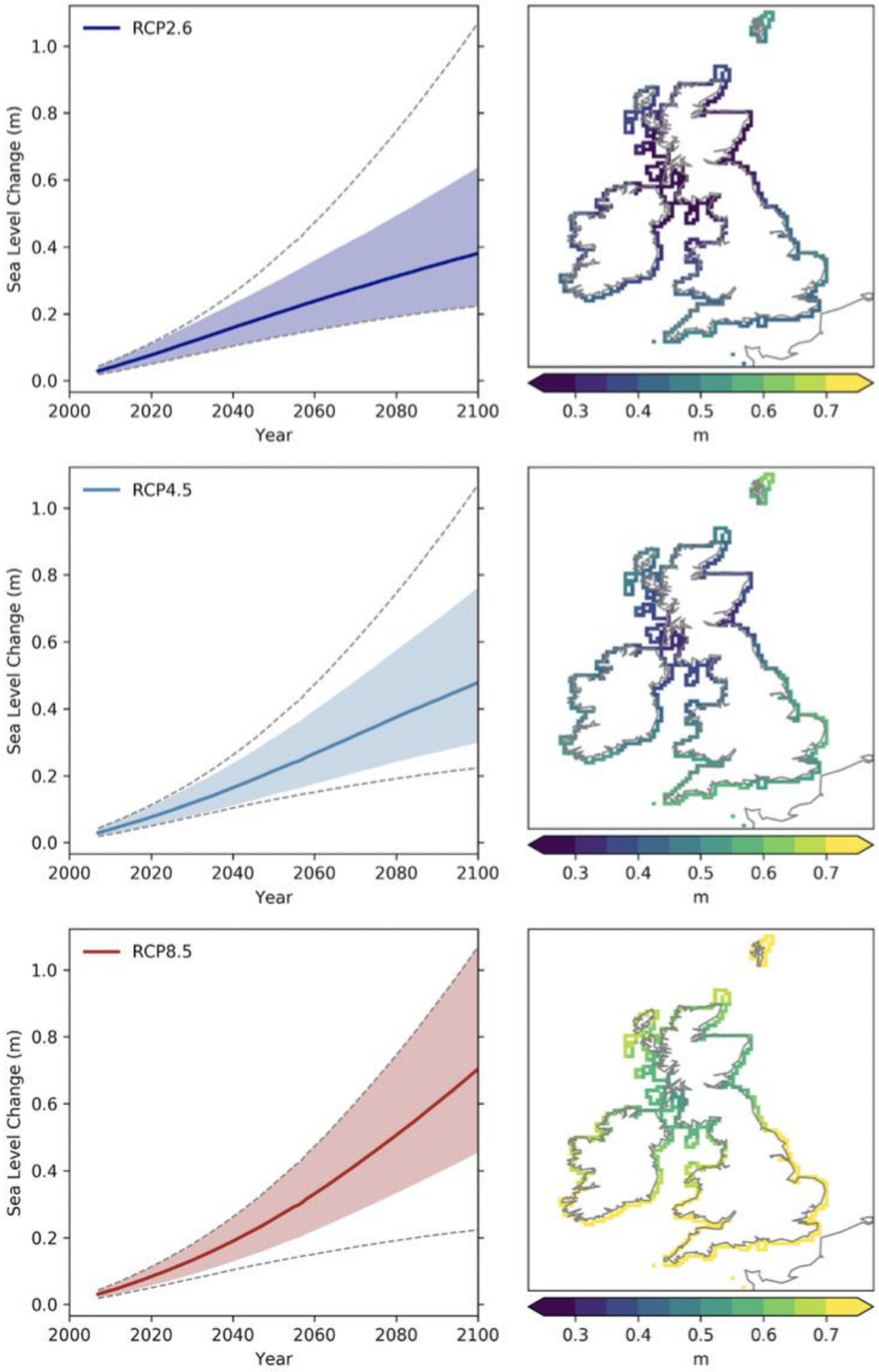


Figure 1: Time series of modelled UK-average sea level projections. The solid line is the central estimate and shaded regions represent the 5th to 95th percentile range (left). The range across all RCPs is indicated by the dashed lines. The spatial pattern of sea-level change for the UK at 2100 for three climate scenarios (RCPs) (right). All projections are relative to the 1981–2000 average values. The reason for the north–south gradient of sea level change is GIA and contribution from the Greenland ice sheet. (Reproduced from UKCP18 Marine Report, with permission.)

Due to spatial variations in the rate of sea-level rise around the UK (caused by different rates of land uplift, subsidence caused by GIA, and oceanic processes), some regions will experience a rise greater than the global mean. The projection ranges for UK capital cities over this century are summarised in Table 1.

Table 1: Projection ranges (5th to 95th percentile) of sea-level rise at 20-year intervals, relative to a baseline period of 1981–2000, for UK capital cities. (Reproduced from UKCP18 Marine Report, with permission.)

YEAR	**London**			**Cardiff**			**Edinburgh**			**Belfast**		
	R2.6	**R4.5**	**R8.5**	**R2.6**	**R4.5**	**R8.5**	**R2.6**	**R4.5**	**R8.5**	**R2.6**	**R4.5**	**R8.5**
2020	0.07 – 0.13	0.07 – 0.13	0.07 – 0.13	0.06 – 0.12	0.06 – 0.12	0.07 – 0.13	0.01 – 0.07	0.01 – 0.07	0.02 – 0.07	0.02 – 0.08	0.02 – 0.08	0.03 – 0.08
2040	0.13 – 0.26	0.14 – 0.27	0.16 – 0.29	0.12 – 0.25	0.13 – 0.26	0.15 – 0.28	0.04 – 0.16	0.05 – 0.17	0.06 – 0.20	0.05 – 0.18	0.06 – 0.18	0.08 – 0.21
2060	0.19 – 0.40	0.22 – 0.44	0.26 – 0.52	0.18 – 0.39	0.21 – 0.43	0.25 – 0.51	0.06 – 0.27	0.08 – 0.30	0.13 – 0.38	0.08 – 0.29	0.10 – 0.32	0.15 – 0.40
2080	0.24 – 0.55	0.30 – 0.63	0.39 – 0.80	0.23 – 0.53	0.28 – 0.62	0.38 – 0.79	0.07 – 0.37	0.12 – 0.45	0.21 – 0.62	0.10 – 0.40	0.15 – 0.48	0.23 – 0.65
2100	0.29 – 0.70	0.37 – 0.83	0.53 – 1.15	0.27 – 0.69	0.35 – 0.81	0.51 – 1.13	0.08 – 0.49	0.15 – 0.61	0.30 – 0.90	0.11 – 0.52	0.18 – 0.64	0.33 – 0.94

2.2 Likelihood of RCP2.6, RCP4.5 and RCP8.5

The likelihood of individual RCPs occurring is dependent on current and future greenhouse gas emissions and the implementation of mitigation strategies. At a UK-level, emissions are declining, but they are not currently on track to meet legally binding carbon budgets (Committee on Climate Change, 2018a). Globally, greenhouse gas emissions have reached record levels with no sign of a reversal of the upward trend (WMO Greenhouse Gas Bulletin, 2017). Substantial global greenhouse gas reductions are required to secure a global air temperature rise of only 1.6°C by 2100 which corresponds to the RCP2.6. A 2.4°C future aligns with RCP4.5. A 2.8°C future aligns with RCP6.0 and 4.3°C future aligns with RCP8.5 (Fung and Gawith, 2018). Given this context and to assist in the interpretation of this report, unless there is substantial progress in the coming decades as called for at COP24, the most likely scenario is RCP8.5.

The range of projected sea-level rises, at UK capital cities, for the three RCPs, including the range of uncertainty is shown in Figure 2.

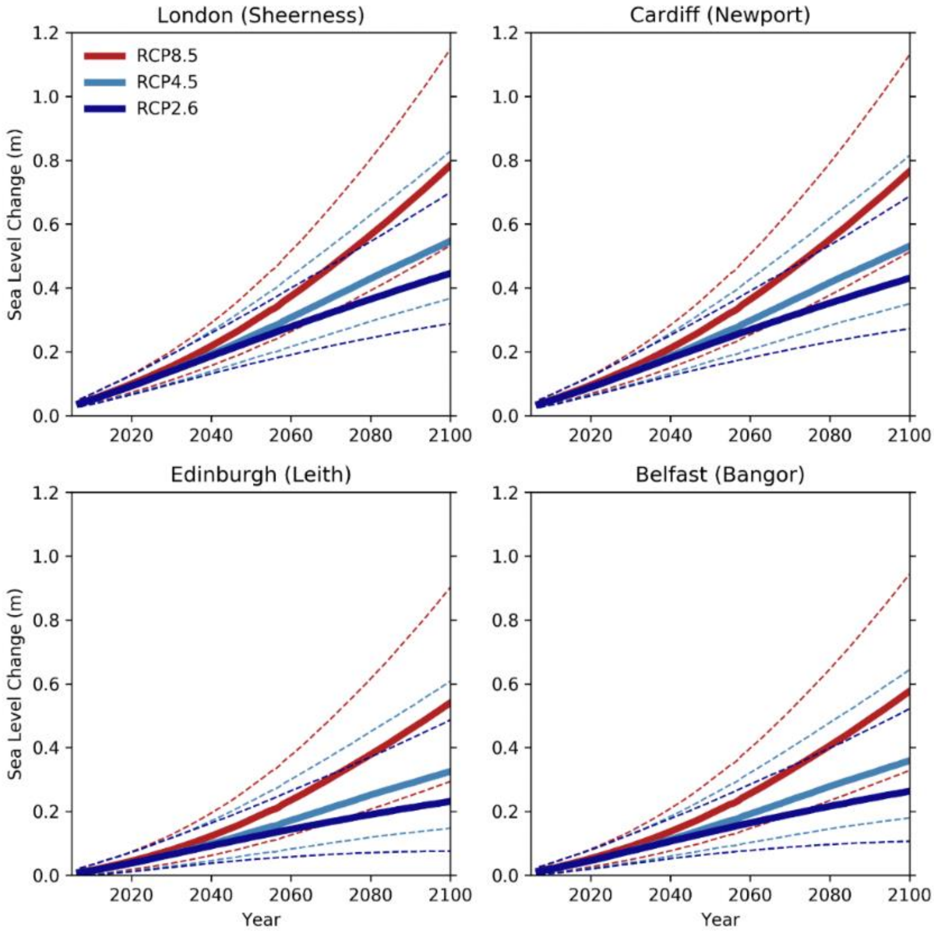


Figure 2: 21st century projections of mean sea level for the UK capital cities under three RCPs. Central estimates are shown by the solid lines and the dashed lines indicate the 5th and 95th percentiles. (Reproduced from UKCP18 Marine Report, with permission.)

2.2 Increases beyond the IPCC likely range

The IPCC Fifth Assessment Report of Working Group I (IPCC, 2013) did not rule out future sea level rise beyond the likely range of the process-based models. Only the collapse of sectors of the Antarctic ice sheet could cause global mean sea level to rise substantially above the likely range during the 21st century. IPCC (2013) attributes medium confidence that this additional contribution would not exceed several tenths of a metre by 2100. Most studies published since IPCC AR5 suggest maximum rates of about 0.4-0.5 m per century for the global sea level rise contribution from Antarctica (Levermann *et al.*, 2014; Ritz *et al.*, 2015; Ruckert *et al.*, 2017; Cornford *et al.*, 2016; Clark *et al.*, 2016). However, some recent studies have suggested instability feedback mechanisms that imply larger rises over this century (Rignot *et al*., 2014; Favier *et al*., 2014; Pollard *et al*., 2015; DeConto and Pollard, 2016). Whilst these mechanisms could give higher sea level rises than those stated by the IPCC, assessing their likelihood is difficult because these modelling studies depend on simple parameterisations of poorly understood processes (e.g. DeConto and Pollard, 2016).

UKCP18 does not contain the so-called H++ or ‘high-plus-plus’ scenarios that were used in UKCP09 and which were designed to provide plausible but unlikely high-end sea level rise scenarios for planning purpose. The Met Office is currently working with the wider research community on a new set of H++ scenarios of mean sea-level change for the UK.

2.3 Increases in sea level beyond 2100

UKCP18 presents exploratory projections of mean sea level for the period to 2300. Such a far-term view naturally involves more uncertainty than the projections to 2100. The results should be considered as illustrative of potential changes (e.g. for planning purposes) rather than values to which confidence limits can be attached. The longer-term projections among the wider literature remain consistent for low to medium greenhouse gas concentration scenarios (RCP2.6, RCP4.5), but diverge under the high emissions scenario, with values at 2200 under RCP8.5 ranging from about one metre (Golledge *et al*., 2015) to several metres (DeConto and Pollard, 2016). The average UK coastal sea-level rise at 2300 has central estimates ranging between less than 1.0 m (RCP2.6) to greater than 2.5 m (RCP8.5) with substantial spatial variations. For the RCP8.5 scenario, the 95th percentile exceeds 4.5 m at 2300 for some regions of southern England, the Channel Isles, Isles of Scilly and Shetland Isles.

2.4 Projected changes in extreme sea levels around the UK

Mean sea-level rise will continue to be the dominant control on trends in future extreme water levels and coastal flooding. The IPCC Fifth Assessment Report of Working Group I (IPCC, 2013) concludes that it is very likely that there will be a significant increase in the occurrence of future sea level extremes by 2050 and 2100, with the increase being primarily the result of an increase in mean sea level. The report also concludes that there is low confidence in region-specific projections of storminess and associated storm surges. The increase in extreme sea levels will result in critical flood defence thresholds being reached more frequently, and therefore the risk of flooding will increase. The implication for coastal engineers is that any given ‘return period’ (the annual probability of a specified water level occurring) will change due to mean sea-level rise.

The UKCP18 projections of storm surges make use of CMIP5 simulations under scenario RCP8.5 that have been dynamically downscaled by regional atmospheric models as part of the EURO-CORDEX experiment (Jacob *et al*., 2014). UKCP18 used only the most severe climate scenario for extremes, to maximise any climate change signal and therefore obtain the most significant statistics of any change. The five models used were chosen because of their realistic simulation of present-day climatology over north-west Europe. The quantity analysed was the skew surge – this being the difference between the highest water level obtained within a tidal cycle with and without atmospheric forcing (see Williams *et al*., 2016). Two of the UKCP18 downscaled simulations showed coherent signals, but disagreed on the sign of any change to the skew surge (Figure 3). The other three simulations showed weaker and less coherent trends in extreme sea levels. In UKCP18, skew surge trends ranged about –1 mm per year to about 0.7 mm per year. On the basis of these differing results, UKCP18 proposed a best estimate of zero change in skew surge over the 21st century. UKCP18 concludes that water-level extremes for the UK during the 21st century would come primarily from the change in the mean sea level rather than any changes in storminess. Population growth and land use further affect coastal risk and vulnerability. For the European coastline, annual cost of repair of damage due to coastal flooding are estimated to increase by two to three orders of magnitude (from €1.25 billion today) by 2100 (Vousdoukas *et al*., 2018). Recent work by Jevrejeva *et al*. (2018) warns that without additional adaptation the UK would be exposed to flood risk damage repair costs of 6.5% of UK GDP (£800 billion per year) by 2100 if the worst greenhouse gas emissions scenario is realised.

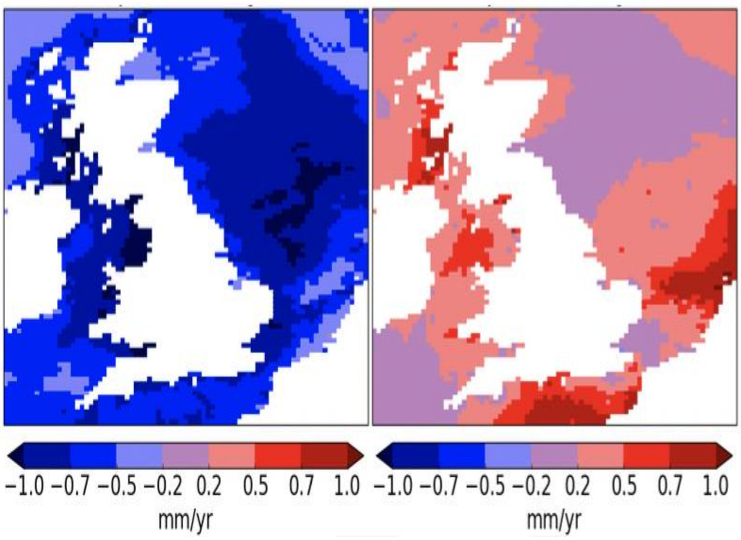


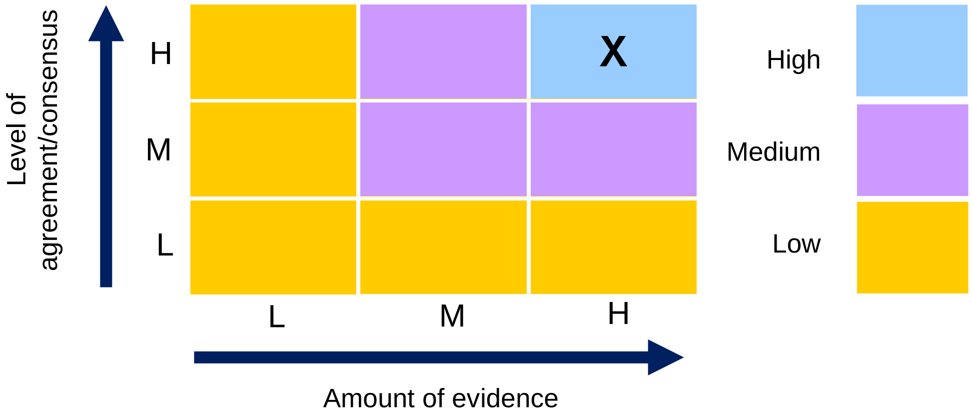
Figure 3: Projected 21st century change in skew surge extremes (the trend in the 1-year return period skew surge) from HadGEM2-ES-RCA4 (left), and MPI-ESM-LR-RCA4 (right). The contrast between these two results highlights the large uncertainty in projections of the future atmospheric storminess change contribution to storm surges. (Reproduced from UKCP18 Marine Report, with permission.)

The potential for changes to tides around the UK coastline adds a further component to total extreme sea-level change. A number of recent studies have suggested changes in tidal range resulting from future changes in mean sea level (Pickering *et al*., 2012; Ward *et al*., 2012; Pelling *et al*., 2013). These modelling studies all suggest that changes in tidal range will be of the order of plus or minus 10% of any changes in mean sea level, with large spatial variability. Although small in comparison to the mean sea level changes, altered tidal ranges could enhance (or reduce) coastal flooding at some locations. They would also have implications for the future erosion and accretion of salt marshes and other coastal ecosystems (e.g. Horton *et al*., 2018). Williams *et al*. (2016) have proven that the magnitude of high water exerts no influence on the size of the most extreme observed skew surges. This provides a statistically robust indication that any storm surge can occur on any tide – essential for understanding worst-case scenarios.

For contingency planning, UKCP18 produced an illustrative, high-end storm surge projection by focusing on one CMIP5 simulation that was not downscaled, but that exhibited larger changes in atmospheric storminess. This single global climate model was used to directly force the storm surge model and did produce larger trends in skew surges over the 21st century. Using this model, depending on the location around the UK, a trend of –0.5 to 1.3 mm per year was found for the 1-year return level; for the 200-year return level the trend was –1.1 to 2.7 mm per year. For comparison, typical projected rates of mean sea level rise over the 21st century are around twice this value (see above, Section 2). Therefore, even the largest illustrative changes in storm surges are considerably smaller than projected changes in mean sea level.

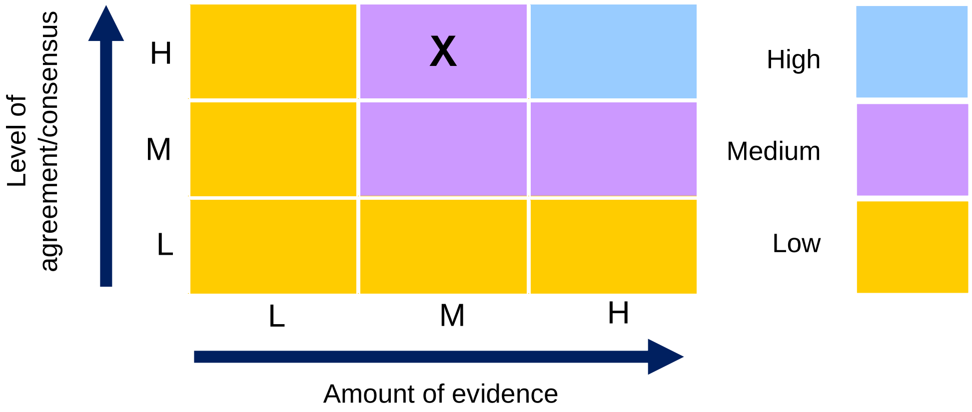
3. CONFIDENCE ASSESSMENT

3.1 What is already happening?



Current observational evidence for mean sea levels and sea-level extremes is of the highest scientific quality and arises from a broad selection of peer reviewed scientific papers, many of which contributed to the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2013). There is now firm evidence that the rate of sea level rise (both for the UK and globally) was higher overall in the 20th century than the 19th.

3.2 What could happen in the future?



The level of consensus has increased since the previous MCCIP report in 2013. This is due to considerable improvements in the underlying set of climate models used, particularly the inclusion of improved representations of ice sheet processes, and the nature of the downscaling for the UK (as described in the UKCP18 Marine Report; Palmer *et al*., 2018). The climate model simulations used were the Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor *et al*., 2012). These models were used to deliver the climate projections presented in the IPCC Fifth Assessment Report of Working Group I (IPCC, 2013) and represent a significant improvement over their predecessor CMIP3 (Meehl *et al*., 2007) models. This report also makes use of an improved estimate of the pattern of sea-level change caused by the elastic response of the solid Earth to the last de-glaciation. Where we have presented a 5th–95th percentile range, this can be interpreted as 90% of our modelled results lying between these bounds.

4. KEY CHALLENGES AND EMERGING ISSUES

4.1 Improved understanding of dynamic ice processes to better quantify and constrain high-end scenarios

Whilst 90% of modelled results fall within the values reported here, there may be a greater than 10% chance that the real-world response lies outside this range, and this likelihood cannot currently be accurately quantified. Only the collapse of sectors of the Antarctic ice sheet could cause sea level rises substantially above the values reported here. Further research into dynamic ice processes and their controlling factors is the highest priority for sea level research.

4.2 Future storm surges and the response of the Atlantic storm track under climate change

It is known that all projections of future storminess are limited by the lack of consistency between climate models and the capability of even regional climate models to accurately simulate extreme winds. Further research is needed to understand how extratropical cyclones in general might respond to climate change and how the North Atlantic storm track is affected by a warming climate (e.g. movement, intensification or weakening of the storm track). Higher resolution climate models simulations are now being performed in Coupled Model Intercomparison Project Phase 6 (CMIP6), and coupling these new climate models to storm surge and wave models is a priority.

4.3 Translating updated sea-level science into resilience planning

A large gap remains in the translation of our scientific knowledge of the consequences of sea-level changes into the necessary steps policy makers (government, society and businesses) need to take to remain resilient. The practical implications of even modest sea-level rises are significant: increased erosion and erosion-enhanced flooding, possible localised increased accretion, exposure of assets on shorelines. Across the UK, new development continues to be proposed in areas which are expected to become increasingly at risk as climate change continues. We must devise incentives and mechanisms to plan differently for sea-level changes. The UK’s Committee on Climate Change (CCC) (2018b) recently considered the English Shoreline Management Plans (SMPs) and found them to be not fit for purpose. The Committee has not commented if the same concerns exist for Welsh SMPs. In Scotland Shoreline Management Plans have been very limited in extent, though the CCC recently called for all inhabited areas to have an SMP by 2020 (Committee on Climate Change, 2019). Such long-term plans are absent in Northern Ireland. The challenge is to ensure plans to manage and adapt specific shorelines over the coming century should be realistic and sustainable in economic, social and environmental terms.

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