Impacts of climate change on coastal flooding, relevant to the coastal and marine environment around the UK

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EXECUTIVE SUMMARY

Coastal floods are amongst the most dangerous natural hazards and are one of the most significant risks that the UK faces. Coastal flood risk is growing with climate change (especially mean sea-level rise) and other changes (mainly, population growth and development in low-lying coastal areas). The frequency with which extreme high-water levels are exceeded has increased over the last 150 years, driven primarily by the observed rise in relative mean sea level. Furthermore, saltmarshes, shingle and sand dunes, which provide important buffering against floods, are in decline. Population growth, changes in land use and increasing asset values in floodplain areas have also enhanced exposure to coastal flooding. However, overall, the consequences of flooding have reduced over time due to improvements in flood defences, together with advances in flood forecasting, warning and emergency response and spatial planning. Extreme water levels are very likely to increase during the 21st century and beyond, and evidence suggests this will be driven primarily by the changes in relative mean sea level, rather than any significant changes in the wave- or storm surge-patterns. Without adaption (e.g. raising flood defences, managed retreat), the projected increases in extreme water levels will significantly increase coastal flood risk. Population growth and accompanying development is likely to continue, particularly in areas that are current defended. Therefore, significant populations and assets will remain located in low-lying coastal areas and will be threatened in the event of a defence failure (e.g. overtopping or a breach).

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1. WHAT IS HAPPENING?

1.1 Introduction

Coastal floods are amongst the most dangerous natural hazards. Coastal flooding is one of the top priority risks for the UK (Cabinet Office, 2015). Recent flood events (e.g. over the winter of 2013/14) have demonstrated the ever-present threat of serious flood impacts in coastal regions, despite improved flood-protection measures and technology that has provided tools to forecast and mitigate risks. While flood-defence standards are among the highest in the world in the UK (e.g. Hallegatte *et al*., 2013), the significant populations and assets located in the coastal flood plain are threatened in the event of defence failure (e.g. major overtopping or a breach). In England, it is estimated that 520,000 properties are located in areas with a 0.5% or greater annual risk from coastal flooding (Committee on Climate Change, 2018). About £35 billion worth of assets in London would currently to be exposed to a 1% annual chance of flooding without the Thames Barrier and associated defences (Hallegatte *et al*., 2013) and preserving Foreign Direct Investment to the London economy (by alleviating concern of flood risk) is valued at £2 billion per annum. Annual average economic damages from coastal flooding in the UK are estimated to be £540 million (Sayers *et al*., 2015). Furthermore, coastal flooding is a growing threat due to accelerating mean sea-level rise and possible changes in tides and storminess associated with climate change (Church *et al*., 2013; Horsburgh *et al*., 2018; Palmer *et al*., 2018), as well as continued population growth, urbanisation and development in low-lying coastal areas (Sayers *et al*., 2015; Stevens *et al*., 2016).

Throughout history, many severe flooding events have affected the UK coast, with major social, economic and environmental consequences (Haigh *et al*., 2015; 2017). Large numbers of people (perhaps as many as 10,000 people per event) may have been killed on the east coast during events in 1099, 1421 and 1446 (Gönnert *et al*., 2001). In 1607, a major coastal flood impacted the west coast, resulting in the deaths of around 2000 people (Horsburgh and Horritt, 2006). This flood caused the greatest loss of life from any sudden-onset natural catastrophe in the UK during the last 500 years (RMS, 2007). There was extensive flooding along the south-west and south UK coasts during the great storm of 1703 (Le Pard, 1999). In the last century, central London was flooded on 10 January 1928, as a results of a large storm surge combined with high river flows, drowning 14 people (Haigh *et al*., 2017). The ‘Big Flood’ of 31 January–1 February 1953, killed about 300 people in eastern England and about 30 people in Scotland, 24,000 people fled their homes and the event caused damage costing £1.2 billion, at 2014 values (McRobie *et al*., 2005; Wadey *et al*., 2015). This event was the driving force for the construction of the Thames Storm Surge Barrier (completed in 1982) and associated defences for London (Gilbert and Horner, 1986) and the establishment of the UK Coastal Monitoring and Forecasting Service (Flather, 2000).

During the recent winter of 2013/14, the UK experienced an unusual (but not unprecedented) sequence of extreme storms and some of the most significant coastal floods in the last 60 years (Thorne, 2014; Kendon and McCarthy, 2015; Haigh *et al*., 2016). However, due to better defences and forecasting and warning systems, the damages were much lower than in 1953 (Spencer *et al*., 2014; Wadey *et al*., 2015); nevertheless floods (from both coastal and fluvial sources) over that winter season still resulted in ~£1.2 billion in damages in England and £28 million in Wales (Environment Agency, 2016). Key events included: 5-6 December 2013, where over 800 properties were flooded in Boston, Lincolnshire (Wadey *et al*., 2015); 5 February 2014, where the railway line was destroyed at Dawlish, Devon (due to severe coastal erosion from large waves) and the sea front at Aberystwyth, Wales was damaged by large waves which caused £0.5 million in damages and 250 people were evacuated from their homes (BBC, 2014); 14 February 2014, where there was considerable flooding along the south coast of the UK and significant erosion and damage to sea defences at Hurst Spit (Hampshire) and Chesil Beach (Dorset) (Haigh *et al*., 2017).

The multiple drivers of coastal flood risk are demonstrated by the Source–Pathway–Receptor–Consequence (SPRC) conceptual model (Figure 1), introduced to flood analysis by Sayers *et al*. (2002) and applied widely in the Foresight and subsequent assessments (Evans *et al*., 2004a, b; Thorne *et al*., 2007). The 'source' describes the origin of a hazard, which in the case of coastal floods, is extreme water levels. The 'pathway' is the route that a hazard takes to reach the 'receptors', and for coastal flooding describes how seawater makes its way onto normally dry land. The 'receptor' is the entity (e.g. people, property, environment) that may be harmed by the hazard (e.g. seawater inundation). 'Consequences' entail the social, economic and environmental effects of the coastal flooding on the receptors.

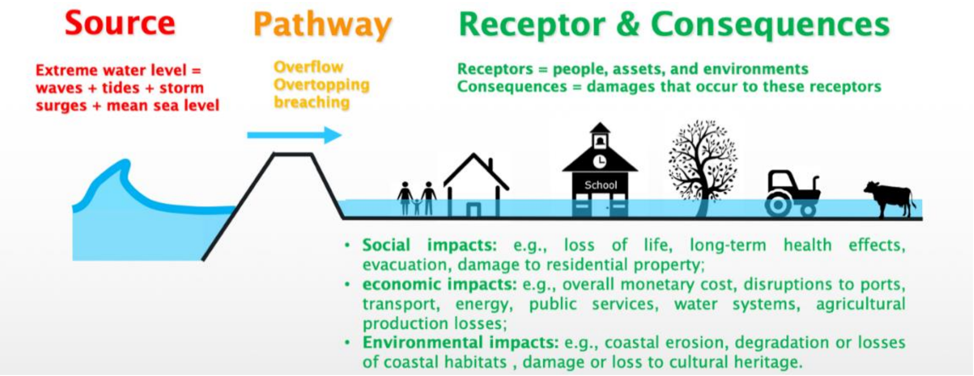


Figure 1: Source-Pathway-Receptor-Consequence (SPRC) conceptual model (after Sayers et al.*, 2002).*

This MCCIP report card is structured around the SPRC framework, and updates the previous report card on coastal flooding in 2013 (Donovan *et al*., 2013) and the 10-year report card in 2017 (Haigh and Nicholls, 2017). We describe current (this section) and future (Section 2) trends in coastal flood risk in each of the SPRC components in turn (note, as receptors and consequences are linked, we deal with them together), showing how a range of changes can increase flood risk, and equally how interventions can reduce flood risk. We then state what qualitative level of confidence we can place in the science for 'what is already happening' and 'what could happen in the future'. Finally, we briefly highlight key challenges and emerging issues.

1.2 Current trends in the source of coastal flood risk

Coastal floods are driven by extreme water levels, which arise as combinations of four main factors: (1) waves (especially setup and runup); (2) tides; (3) storm surges; and (4) relative mean sea level (Pugh and Woodworth, 2014). The term 'still water levels' refers to the average water surface elevation at any instant, excluding local variation due to waves. The additional influence of rainfall and river discharge may also be significant in some estuaries (Hawkes *et al*., 2002; Svensson and Jones, 2002, 2004; Hawkes, 2005; Hendry *et al*., 2019; Robins and Lewis, 2019), showing the importance of considering compound events (i.e. flooding from both marine and fluvial/pluvial sources occurring concurrently or in close succession (Wahl *et al*., 2018; Zscheischler *et al*., 2018). It is the interaction between the four components that combine to result in extreme water levels. These four components exhibit considerable natural year-to-year variability. The variability in the wave, storm surge and mean sea-level components is stochastic and linked to regional climate modes, such as the North Atlantic Oscillation (Hurrell, 1995). Whereas, the tidal component is deterministic, with predictable modulations at 4.4-year and 18.6-year timescales, respectively (Haigh *et al*., 2011). The year-to-year variability in each of the four components influences the potential frequency and magnitude of flooding (Wadey *et al*., 2014). Longer-term changes in any, or all**,** of the four components can also lead to variations in the frequency and magnitude of extreme sea levels (Pugh and Woodworth, 2014). Extreme water levels are affected both directly (e.g. with mean sea-level rise a lower storm surge elevation at high tide is necessary to produce a sea level high enough to cause flooding; Haigh *et al*., 2011) and indirectly (e.g. changes in mean sea level alter water depths and therefore modify the propagation and dissipation of the tide and storm surge components; Lyddon *et al*., 2018a; Lewis *et al*., 2019; or alter wave processes in shallow water, such as refraction; Dombusch, 2017), by changes in relative mean sea level, without any change in the frequency of occurrence of extreme events. In addition, extreme water levels may change with variations in the tracks and strengths of weather systems, which alter the frequency, intensity, and/or duration, of waves and storm surges (Palmer *et al*., 2018).

Current trends in still water levels, and storms and waves, are detailed in two companion report cards by Horsburgh *et al*. (2020) and Wolf *et al*. (2020), respectively. In brief, Horsburgh *et al*. (2020) highlight that a growing number of studies, at both global and national scale, have found evidence for increases in extreme still water levels over the late 19th, 20th and early part of the 21st century. The overwhelming scientific consensus is that these observed changes in extreme still water levels around the UK and worldwide have been driven primarily by the observed rise in relative mean sea level (as illustrated for the UK's longest high-frequency tidal gauge record Newlyn in Cornwall, Figure 2). As a result, extreme sea levels that previously had a long return period (>100 years) near the beginning of the 20th century now have much lower (~10 year) return periods (Haigh *et al*., 2011; Wahl *et al*., 2017). There is little evidence for long-term systematic changes in storminess or storm surge magnitude over the last 100 years above natural variability (Seneviratne *et al*., 2012; Marcos *et al*., 2015; Mawdsley and Haigh, 2016). However, there is some observational evidence for both positive and negative small changes in tidal high and low water, and therefore tidal range, at select sites around the UK and elsewhere worldwide (Woodworth *et al*., 1991; Mawdsley *et al*., 2015). This has slightly increased or decreased extreme high sea levels. The drivers of these changes remain unclear, although it is likely that they relate to changes in local bathymetry (mainly dredging for navigation) and/or climate-change related variations (Haigh *et al*., 2020). It has proved difficult to accurately assess current and historical changes in the wave climate due to the lack of long-term wave measurements and due to the fact that trends are obscured by large natural variability (Wolf *et al*., 2020). However, positive regional trends in extreme wave heights have been reported at several locations in the North-East Atlantic since the late 1970s (Wolf *et al*., 2020).

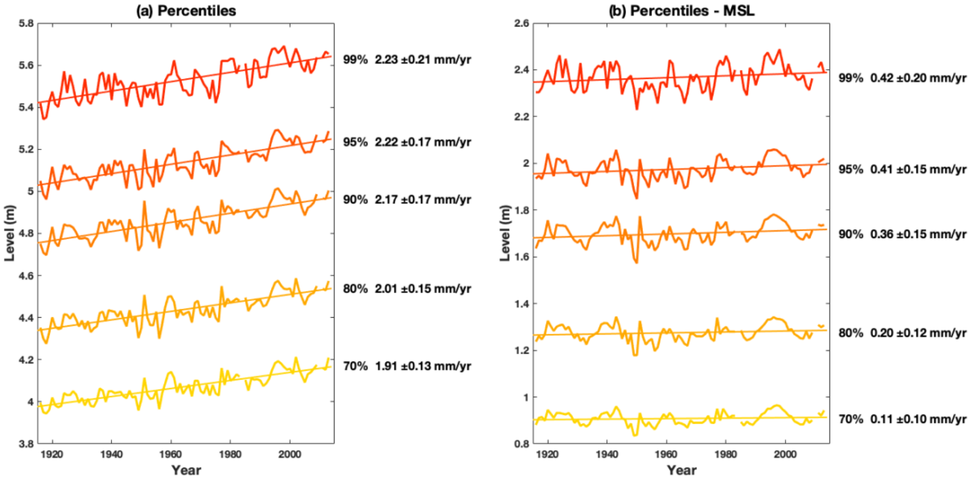


Figure 2: Trends in high water level percentiles at Newlyn, Cornwall (a) before; and (b) after, removing the influence of relative mean sea-level rise. The magnitude of the trend is given in mm/yr with a standard error. Trends in the different high water levels time–series are all statistically significantly at 95% confidence (i.e. two standard errors), but after removing mean sea level none of the trends in the percentile time-series are statistically significant. This highlights that extreme water levels have increased at Newlyn and that the increase has primarily been driven by the rise in relative mean sea-level.

1.3 Current trends in the pathway of coastal flood risk

The nature of flood pathways varies around the coast and is influenced by natural features, although in many places engineered defences have been constructed and also must be considered. Seawater can inundate normally dry land via several different pathways. First, by overflow, where the sea height exceeds the elevation of the land and there is no barrier. Second, by overtopping of a natural (e.g. barrier beaches) or artificial (e.g. sea wall) barrier by waves (Brown *et al*., 2016a; EurOtop, 2018). Third, by breaching of a natural or artificial barrier, which is lowered by flood forces, allowing more water to flow landward. Overtopping and overflow can be a precursor to breaching. Decline in natural defences, and deterioration in artificial ones over time impact flood pathways and can increase flood risk. In contrast, nourishment of beaches, building of new sea walls, or managed re-alignment can alter flood pathways and reduce flood risk (Brown *et al*., 2016b). Within estuaries in particular, changes in coastal morphology can influence flood pathways and alter flood risk (Philips *et al*., 2017; Lyddon *et al*., 2018b).

Determining historical and current trends in flood pathways is more difficult, than in flood sources, due to the combined natural and human elements at play and the lack of appropriate long-term datasets in the relevant parameters (e.g. full history of flood defences, saltmarsh extents, etc.). It is increasingly recognized that natural systems, such as saltmarshes, shingle and sand dunes, provide important buffering against floods and are in decline, which has increased flood risk (Committee on Climate Change, 2018). Current flood risk would be far higher without the many decades of investment that have developed extensive flood and coastal erosion risk management infrastructure (Environment Agency, 2014). However, it is important to recognise that defences deteriorate with time and this process leads to a steady increase in flood risk over time (Environmental Agency, 2012). In contrast, improvements in flood defences over time, including soft measures, such as beach nourishment or managed re-alignment, have resulted in reduced flood risk (Haigh *et al*., 2017). Data on flood defences over time is not well developed, but it is clear that massive investments in defences have occurred over the 20th and early 21st century. Events such as the 1953 flood were an important trigger, but more-proactive planning is now apparent. Nearly a quarter of England’s 4500 km of coast is now defended (Sayers *et al*., 2015) and several new schemes are currently being built or are planned, such as the North Portsea defences around Portsmouth. The UK has two of the World’s 18 storm surge barriers, the Thames Barrier, which became operational 1982, and a smaller barrier across the River Hull, which became operational in 1980. Both of these barriers protect low-lying land, and the associated communities, properties and assets, from coastal flooding. The Thames and Hull barriers close on average two and 12 times per year, respectively (Mooyaart and Jonkman, 2017). Two smaller barriers are currently being built at Ipswich, Suffolk and Boston, Lincolnshire.

The sustained period of coastal flooding over the winter of 2013/14 provided a recent impetus for further defence improvements and new schemes. Despite the 5–6 December 2013 event producing higher sea levels along the UK east coast than in 1953 in many places, damages were much less in 2013 due to improvements in flood defences, and flood forecasting and warnings prevented loss of life (Wadey *et al*., 2015). It is estimated that about 720,000 properties were protected from the high sea levels during the 5–6 December 2013 event because of flood defences (Environment Agency, 2016). However, flood defences were damaged during the 2013/14 season and the cost of repair (including fluvial defences) has been estimated to be approximately £147 million (Environment Agency, 2016). The Thames Barrier was closed an ‘exceptional’ 50 times in the winter of 2013/14, the maximum recommended number, but this was predominantly due to high river flow. No statistically significant trend in past closures has been detected (Environment Agency, 2016).

1.4 Current trends in the receptors and consequences of coastal flood risk

Receptors and consequences are linked, and so we deal with them together here. Receptors are the people, assets, and environments in the coastal floodplain. Consequences are the damages that occur to these receptors as a result of the seawater inundation, be it injury or death, property damage and/or environment destruction. For past coastal flood events, Haigh *et al*. (2017) record 15 types of consequences, broadly grouped into social (e.g. loss of life, number of people evacuated, damage to residential property), economic (e.g. overall monetary cost, disruptions to ports, transport, energy, public services, water systems, agricultural production losses) and environmental (e.g. coastal erosion, degradation or losses of coastal habitats, damage or loss to cultural heritage) impacts. The consequences of a flood can be long lasting (e.g. injury or long-term health effects; Jackson and Devadason, 2019). For example, it is thought that anxiety and disruption of the evacuation and loss of belongings during the 26 February 1990 coastal floods in Towyn in Wales contributed to the premature death of about fifty people (Wales Audit Office, 2009). The consequences of a flood can also extend outside of the area of coastline directly impacted, as a result of, for example, disruption to transport or supply chains. The destruction of the Dawlish railway in February 2014 (due to severe coastal erosion from large waves) and its subsequent closure for two months (Dawson *et al*., 2016) is estimated to have cost the south-west English economy more than one hundred million pounds in losses.

Determining historical and current trends in the receptors and consequences of coastal flooding is again more difficult than for flood sources. Just as rising mean sea levels increase flood risk, so does growth in the number of receptors in flood-prone areas. Stevens *et al*. (2015) assessed changes in the incidents of flooding across the UK, from all sources (e.g. including fluvial) and found that the increase in the total number of reported flood events in the 20th century is dominantly controlled by growth in the number of receptors. From 2005 to 2014, the National Trust (2015) found this trend continued in coastal areas, with 15,000 new buildings built in areas subject to flooding and erosion. Changes in land use and increasing asset values in floodplain areas have also enhanced exposure to coastal flooding. Despite this growing loss potential, evidence from Haigh *et al*. (2017) suggests that the number and consequences of coastal floods appears to have declined since 1915 in the UK, reflecting better defences and improvements in flood forecasting, warning and emergency response and planning. Wider efforts at improved adaptation should also be noted, particularly in recent decades, which has also resulted in a reduction in flood risk. Spatial planning and building codes are already very effective at reducing the risk to new build properties within coastal flood plains (Sayers *et al*., 2015). For example, new properties in the coastal flood plain are generally raised above flood levels, including an allowance for mean sea-level rise, minimising flood damages.

The severe consequences that can arise during coastal flooding were strongly highlighted during the recent sequence of coastal flood events over the winter of 2013/14, and demonstrate why concerns about climate change are valid. What appears noteworthy about this period is the large spatial 'footprint' of some of the events (i.e. simultaneous flooding along extended coastline stretches during the same storm) and the temporal 'clustering' of the flood events (i.e. events occurring one after another in close succession) (Haigh *et al*., 2016; Dissanayake *et al*., 2015). The spatial extent of events can greatly influence the magnitude of inundation, as highlighted by Lewis *et al*. (2011). The events of the winter of 2013/14 included the previous mentioned 5–6 December 2013 storm, during which water levels exceeded the benchmark 'Big Flood' of 1953 at several sites along the east coast. This resulted in widespread flooding of property and infrastructure, including damage to the Port of Immingham, and significant coastal erosion (Spencer *et al.*, 2015 and Wadey *et al.*, 2015). Impacts in Boston in Lincolnshire were particularly notable, where 803 properties were flooded. A series of strong storms in January and February 2014 caused widespread damage to defences, property and infrastructure (most notably the collapse of the main railway line to Plymouth and Cornwall at Dawlish which was closed for six weeks; Dawson *et al.*, 2016) on the southern English coast and the west coast of Wales. The costs and impacts of the winter 2013/14 floods are summarised in Environment Agency (2016).

2. WHAT COULD HAPPEN IN THE FUTURE?

In this section, we explain how a range of changes in the different SPRC components could significantly increase flood risk in the future, and how interventions could reduce flood risk.

2.1 Future trends in the source of coastal flood risk

Future trends in still-water levels, and storms and waves for the UK are detailed in the two previously mentioned companion report cards (Horsburgh *et al*., 2020; Wolf *et al*. 2020). These draw significantly on the recent UKCP18 marine projections (Palmer *et al*., 2018). There is high confidence that regional mean sea-level will continue to rise around the UK, and the likely range (90% confidence) is between 0.27 and 1.12 m by 2100 (excluding vertical land motions). Larger rises are considered possible (up to 2.5 m), due to potential marine ice sheet instabilities (DeConto and Pollard, 2016), but assessing their likelihood is almost impossible. There is low confidence in regional projections of storminess and associated changes in storm surges and waves. Recently, a number of modelling studies (e.g. Pickering *et al*., 2012, 2017; Ward *et al*., 2012; Pelling *et al*., 2013a, b; Wilmes *et al*., 2017; Schindelegger *et al*., 2018) have predicted regional changes in tidal range resulting from future changes in mean sea level and stratification and ice-extent (Haigh *et al*., 2020). These studies suggest that changes in tidal range will typically be in the order of plus or minus 10% of any changes in mean sea level, which could slightly enhance or lessen coastal flooding at some locations. Extreme sea levels are therefore very likely to increase during the 21st century, driven primarily by the changes in relative mean sea level, rather than any changes in storminess, with some modifications at select sites due to changes in tides. Coastal flooding risk could also vary in the future as a result of changes in sediment pathways (e.g. longshore transport) and morphology (especially in estuaries; Lyddon *et al*., 2018a), that may result from mean sea-level rise or variations in the wave climate, or anthropogenic process (e.g. dredging).

Without appropriate adaption, the projected increases in extreme high water levels will increase coastal flood risk. Small increases in mean sea-level rise can lead to large decreases in the standard of projection, the frequency that a given defence is likely to be overtopped. For example, a 0.5 m rise in relative mean sea level (which would be expected around 2070 at the upper end of the UKCIP18 projects for RCP8.5), would result in a high sea level with a 1 in 100-year return level today, becoming a 1 in 3-year, 1 in 8-year, <1 in 1-year and 1 in 1-year return level by 2100, at London, Cardiff, Edinburgh and Belfast, respectively; while a 1 m rise would result in a high sea level with a 1 in 100-year return level today, becoming <1 in 1-year event at all four sites (Figure 3).

It is important to consider our long-term commitment to mean sea-level rise beyond 2100 (Nicholls *et al*., 2018). Reducing human emissions of greenhouse gases will stabilise temperature in about a century, but mean sea-level rise will continue for many centuries even if temperature is stabilised. This is because it takes many hundreds of years for the cryosphere and the deepest parts of the ocean to adjust to increased air temperatures. Several recent studies (e.g. Schaeffer *et al*., 2012; Horton *et al*., 2014; Mengel *et al*., 2018; Goodwin *et al*., 2018), including UKCIP18 (Palmer *et al*., 2018), have presented projections of mean sea-level rise out to 2300. Goodwin *et al*. (2018) estimates that if we limit temperature increases to 1.5°C, we will save up to 37 cm of global SLR by 2100, but up to 4.0 m by 2300 compared to unmitigated emissions. In combination, result from these studies imply that the UK coast will be subject to at least 1 m of mean sea-level rise, it is just a matter of when (Committee on Climate Change, 2018). As illustrated earlier, 1 m of mean sea-level rise will significantly increase coastal flood risk without adaptation (Figure 3).

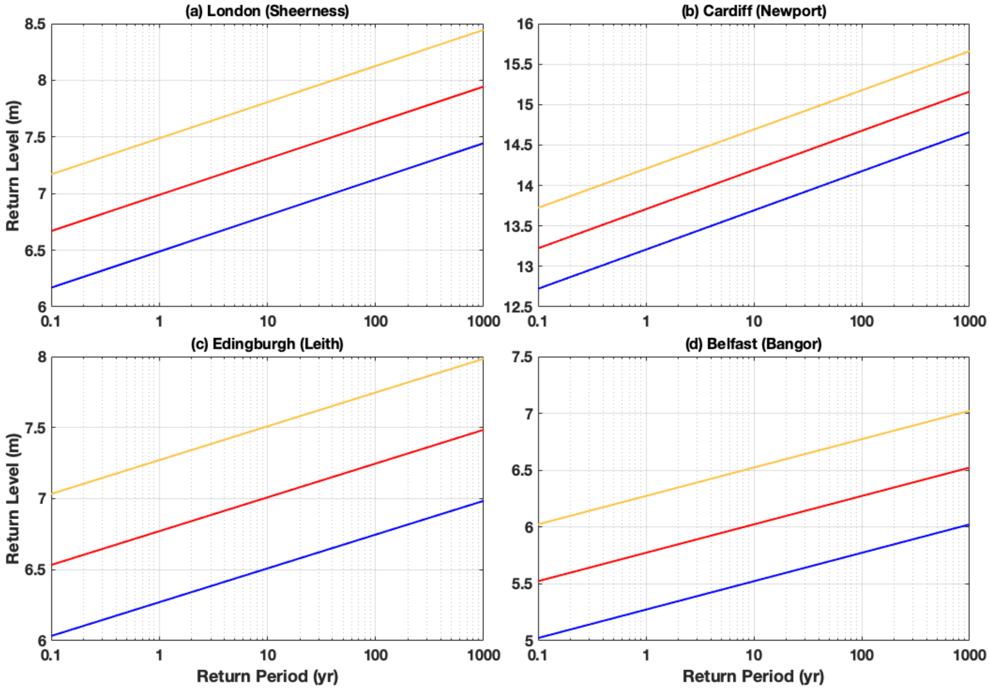


Figure 3: Return period curves for (a) London; (b) Cardiff; (c) Edinburgh; and (d) Belfast at the year 2000 (blue) and with 0.5 m (red) and 1.0 m (orange) mean sea-level rise.

2.2 Future trends in the pathway of coastal flood risk

Predicting future trends in coastal flood pathways is more difficult. With mean sea-level rise and coastal squeeze (and any future changes in sediment supply, wave action and water quality), there is likely to be a continued decline in saltmarshes, shingle and sand dunes over the coming century and beyond. This will likely lead to defence maintenance costs increasingly dramatically, in certain areas, as buffering effects are reduced. Changes in flood pathways will be closely linked to future policy decisions. Strategic shoreline management planning has been implemented since the 1990s which currently selects one of four options: (1) advance the line; (2) hold the line; (3) managed re-alignment and (4) no active intervention, over three-time epochs going to 100 years in the future (Hosking, 2006). The Committee on Climate Change (2018) argued that the proposed reduction in defences in the current strategy may not be enough and there is a great adaptation challenge in the coastal zone. The Committee on Climate Change (2018) calculated that implementing the current Shoreline Management Plans would cost £18–30 billion, depending on the rate of climate change. 1460 km of coastline designated as ‘hold the line’ to the end of the century, achieves a lower benefit-cost ratio than the flood and coastal erosion risk management interventions that the government fund today. Therefore, on this basis, funding to protect some of these coastal stretches is unlikely.

Sea defences themselves are at risk, including soft and hard shoreline structures (natural and engineered) and flood barriers. Sayers *et al*. (2015) presents an assessment of the relationship between mean sea-level rise and the length of existing coastal defences that will become very difficult to maintain as mean sea levels rise (Figure 4). The analysis suggests that the length of coastal defences ‘highly vulnerable’ to failure would almost double under 0.5 m mean sea-level rise, with the number of properties affected if these were lost rising disproportionately by around 160%. Under a more extreme scenario (2.5 m of global mean sea-level rise), the length of highly vulnerable defences is projected to treble and the number of properties affected by flooding if these defences where lost would increase by 490%. If the Thames Barrier continues to be used for managing both river flow and tidal flood events, future sea-level rise is predicted to make the number of closures unsustainable by around 2034; if used only for tidal flooding, this is predicted to extend to around 2070 (Environment Agency, 2016).

The Environment Agency established the Thames Estuary 2100 (TE2100) project with the aim of developing a strategic flood-risk management plan for London and the Thames estuary through to the end of the century (Environment Agency, 2012). This was instrumental in introducing a novel, cost-effective approach to manage increasing flood risk by defining adaptation pathways that can cope with large ranges of changes if needed. A possible ‘route’ of cheaper defence options could be initially followed, but decision makers could switch to more-expensive options (such as a new downstream barrage) if mean sea level was found to be increasing faster than predicted with climate change. In repsonse, the concepts and the assessment of adaptive pathways and approaches to valuing adpative capacity are increasingly moving mainstream (McGahey and Sayers, 2008; Ranger *et al*., 2010; Brisely *et al*., 2016; Haasnoot *et al*., 2013, 2019).

2.3 Future trends in the receptors and consequences of coastal flood risk

Predicting future trends in the receptors and consequences of coastal flood risk is again difficult. Population growth and accompanying development is likely to continue, particularly in areas that are current defended (e.g. London) and have a ‘hold the line’ management policy (Sayers et al., 2015). Therefore, significant populations and assets will remain located in the coastal flood plain and will be threatened in the event of a defence failure (e.g. a breach). Furthermore, compared to the national average, more socially vulnerable communities at the coast are disproportionally at risk and will see their risk increase more rapidly with climate change than elsewhere (Sayers et al., 2017). Other factors over time are likely to reduce (or slow the growth of) the number of receptors exposed to coastal flooding and therefore, lessen the growth of flood consequences. Massive investment in existing and new flood defence schemes are likely to continue, for heavily populated and developed regions. Land-use planning decisions in particular will play a large role in determining future trends. Avoiding inappropriate development in the floodplain will reduce future exposure to flood risk and decrease the consequences when they occur (Donovan *et al*., 2013). Insurance policies will also influence future trends. For example, if insurance policies are changed such that flooded properties are restored, but in more flood-resilient ways with property-level protection, this could reduce flood consequences over time. Continued improvements to the flood forecasting (particularly in regards to forecasting impacts) and warning service will also likely reduce flood consequences over time. Improvements in lead times will continue to allow evacuations and/or preventative measures to be appropriately installed prior to events, such as temporary flood barriers or pumping stations that reduce consequences of flooding. Note, however, that temporary barriers will not be effective in open-coast flooding scenarios (e.g. where there are large low-lying coastal flood plains, such as along the UK south-east coast).

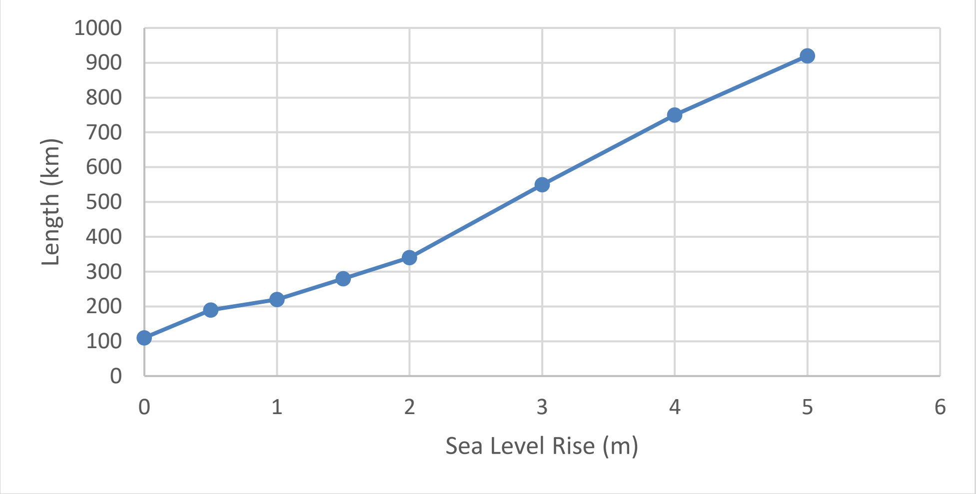
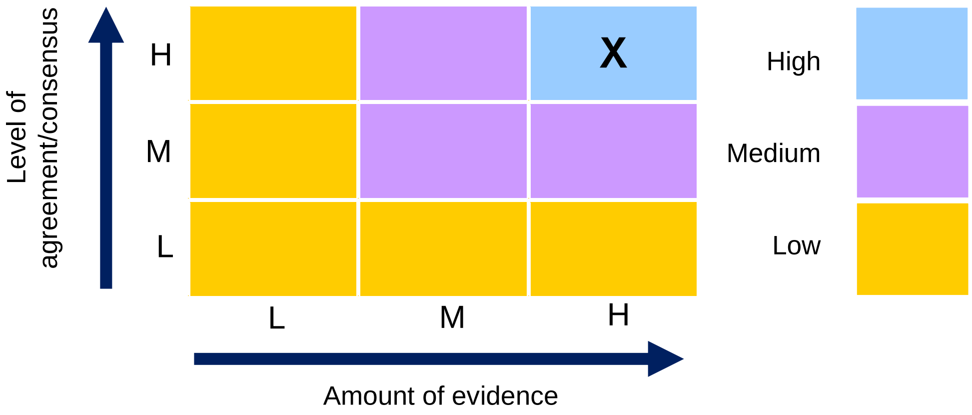


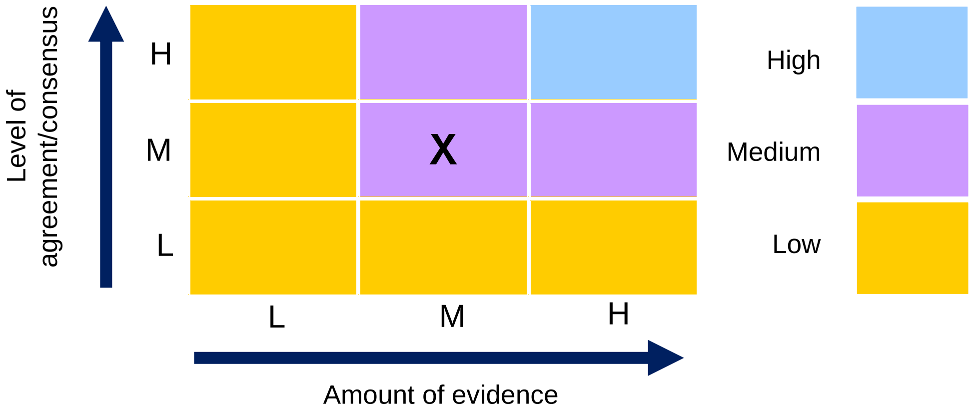
Figure 4: The length of coastal flood defences that may become highly vulnerable as mean sea levels rise (source: Sayers et al. *2015).*

Projections of potential future coastal flooding impacts to the 2080s have been made by Sayers *et al*. (2015) and are usefully summarised together with other coastal risk literature in Edwards (2017). The Sayers *et al*. analysis is based on three mean sea-level rise scenarios (1.2°C; 2.4°C; and 3.0°C a higher scenario based on H++) and considers three population growth (low, high and no growth), and six adaption, scenarios (including assumed enhanced and reduced adaptation levels when compared to present day). The analysis concludes that expected annual damages are estimated to more than double from £540m today to £1.2–1.7 billion by the 2080s in the high sea-level scenario and more than triple to £1.7–1.9 billion in a more extreme scenario. The Committee on Climate Change (2018) also recently made projections of potential future coastal flooding impacts. They concluded that around 520,000 properties are currently located in areas with a 0.5% (i.e. 1 in 200-year level) or greater annual risk from coastal flooding (not taking into account coastal defences) and by 2080s, this could increase to 1.5 million properties.

By the 2080s, they estimate that the number of people living in England in areas at 0.5% or greater chance of coastal flooding in a given year is projected to increase from 0.95 million people to 1.10 million (2°C world with ambitious adaptions scenarios) and 1.55 million (4°C world with low levels of adaption). In addition, they estimate approximately 1600 km of major roads, 650 km of railway, 92 railway stations and 55 historical landfill sites are likely to be at risk of coastal flooding or erosion by the end of the century. The critical Dawlish line is projected to suffer serious reliability issues due to flooding by 2040, with line restrictions increasing from 10 days per year to 30–40, and maintenance costs tripling or quadrupling (£6.9–£8.7m per year, including over £1m compensation; Dawson *et al*. 2016). Drawing on a vulnerability-led and decision-centric framework, Brown *et al*. (2018) developed a ‘Decision Support Tool’ which combined observations and modelling to explore the future vulnerability to mean sea-level rise and storms for nuclear energy sites in Britain.

3. CONFIDENCE ASSESSMENT





Confidence in what is already happening with coastal flooding has increased from ‘low’ (Lowe, 2006) to ‘high’ (Donovan *et al*., 2013), over the duration of the MCCIP report cards. It remains ‘high’ here as there is a high level of consensus that: (1) extreme water levels are rising, (2) that to date we managed this sufficiently to contain growth in flood risk, and (3) nonetheless losses in a major event – above defence design standards – are growing. Confidence in what could happened in the future remains the same as previous, ‘medium’ (Donovan *et al*., 2013). While it is very likely extreme water levels will increase in frequency with mean sea-level rise, possible changes in the wave- and storm surge-climate remain uncertain and there is considerable uncertainty in how flood pathways and receptors will change in the future.

4. KEY CHALLENGES AND EMERGING ISSUES

4.1 Top three challenges

1. A more-complete assessment of future changes in the wave- and storm surge-climate, based on improved atmospheric models, is required to improve understanding of natural variability and better isolate possible long-term trends.
2. A better and more-accurate analysis of historical storm events and their impacts is required, which will lead to improved understanding of natural variability, which would allow trends due to climate change to be isolated.
3. A better understanding of expected annual damages and event losses due to coastal sources, historically, today and into the future is also required to inform the national threat level.

4.2 Top three emerging issues

1. An emerging issue is the increased realisation that it is unrealistic to promote a ‘hold the line’ policy for much of the coastline. The Committee on Climate Change (2018) recently highlighted that 1460 km of coastline designated as ‘hold the line’ to the end of the century, achieves a much lower benefit-cost ratio than the flood and coastal erosion risk management interventions that are government-funded today. On this basis therefore, funding for these locations is unlikely and realistic plans to adapt to the inevitability of change are needed now. This raises the fundamental questions of how to: (i) plan our future shoreline on the open coast and along estuaries, and (ii) deliver practical portfolios of adaptation options that are technically feasible, balance costs and benefits, can attract appropriate finance, and are socially acceptable.
2. Another emerging issue is the increased realisation that there are major barriers to implementing the policy of ‘managed realignment’ or ‘no active intervention’ in Shoreline Management Plans (SMPs). For example, many historical coastal landfill sites for waste are located in low-lying coastal areas (Brand *et al*., 2017) and where landfills are present, the shoreline is usually defended to protect the environment and people from hazards that may be realised if the landfill is flooded or eroded. Therefore, coastal landfill sites need to be projected, but this may be at odds with SMPs that recommend ‘managed realignment’ or ‘no active intervention’ (Beaven *et al*., 2018).
3. A further emerging issue has been the selection of adaptation pathways to manage growing coastal flooding with climate change, which has embraced uncertainty in future changes. The adaptive pathways approach for managing flooding risk, introduced in the Thames Estuary 2100 project for London, has gained recognition and could be applied much more widely.

REFERENCES

BBC (2014) 250 evacuated over Aberystwyth flood fear. BBC News, http://www.bbc.co.uk/news/uk-wales-25626256

Beaven, R.P., Nicholls, R., Haigh, I.D., Kebede, A.S., Watts, J. and Stringfellow, A. (2018) *Coastal Landfill and Shoreline Management: Implications for coastal adaptation infrastructure.* Case Study: Lyme Regis, University of Southampton Report.

Brand, J.H., Spencer, K.L., O’Shea, F.T. and Lindsay, J.E. (2017) Potential pollution risks of historic landfills on low-lying coasts and estuaries. *WIREs Water*, **5**, e1264, doi:10.1002/wat2.1264

Brisley, R., Wylde, R., Lamb, R., Cooper, J., Sayers, P. and Hall, J. (2016) Techniques for valuing adaptive capacity in flood risk management. *Proceedings of the ICE – Water Management*, doi: http://dx.doi.org/10.1680/jwama.14.00070

Brown, J.M., Prime, T., Phelps, J.J.C., Barkwith, A., Hurst, M.D., Ellis, M.A., Masselink, G. and Plater, A.J. (2016a) Spatio-temporal variability in the tipping points of a coastal defence. *Journal of Coastal Research*, **SI**:75. 1042–1046, https://doi.org/10.2112/SI75-209.1.

Brown, J.M. Phelps, J.J.C., Barkwith, A., Hurst, M.D., Ellis, M.A., Plater, A.J. (2016b). The effectiveness of beach mega-nourishment, assessed over three management epochs. *Journal of Environmental Management*, **184**(2), 400–408, https://doi.org/10.1016/j.jenvman.2016.09.090.

Brown, J.M., Morrissey, K.; Knight,P., Prime, T.D., Almeida, L.P., Masselink, G.; Bird, C.O., Dodds, D.; Plater, A.J., (2018). A coastal vulnerability assessment for planning climate resilient infrastructure, *Ocean & Coastal Management*, 163. 101–112, https://doi.org/10.1016/j.ocecoaman.2018.06.007

Cabinet Office (2015) *National Risk Register of Civil Emergencies*, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/419549/20150331_2015-NRR-WA_Final.pdf

Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., Merrifield, M. A., Milne, G. A., Nerem, R. S., Nunn, P. D., Payne, A. J., Pfeffer, W. T., Stammer, D. and Unnikrishnan, A. S. (2013) Sea Level Change. *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, [Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P. M. (eds).], Cambridge University Press, Cambridge, UK and New York, NY, USA.

Committee on Climate Change (2018) Managing the coast in a changing climate, https://www.theccc.org.uk/wp-content/uploads/2018/10/Managing-the-coast-in-a-changing-climate-October-2018.pdf

Dawson, D., Shaw, J. and Gehrels, W. R. (2016) Sea-level rise impacts on transport infrastructure: The notorious case of the coastal railway line at Dawlish, England. *Journal of Transport Geography*, **51**, 97–109, http://dx.doi.org/10.1016/j.jtrangeo.2015.11.009

DeConto, R.M and Pollard, D. (2016) Contribution of Antarctica to past and future sea-level rise, *Nature*, **531**, 591–597.

Dissanayake, P. Brown, J., Wisse, P. and Karunarathna, H. (2015) Comparison of storm cluster vs isolated event impacts on beach/dune morphodynamics. *Estuarine, Coastal and Shelf Science*, **164**, 301–312, https://doi.org/10.1016/j.ecss.2015.07.040

Donovan, B., Horsburgh, K., Ball, T. and Westbrook, G. (2013) Impacts of climate change on coastal flooding. *MCCIP Science Review 2013*, 211–218, doi:10.14465/2013.arc22.211-218

Dornbusch, U. (2017) Design requirement for mixed sand and gravel beach defences under scenarios of sea level rise. *Coastal Engineering*, **124**, 12–24, https://doi.org/10.1016/j.coastaleng.2017.03.006

Edwards, T. (2017) *Future of the Sea: Current and future impacts of sea level rise on the UK*, Foresight, Government Office for Science, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/663885/Future_of_the_sea_-_sea_level_rise.pdf

Environment Agency (2012) *Thames Estuary 2100 Plan: Managing flood risk through London and the Thames estuary*, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/322061/LIT7540_43858f.pdf

Environment Agency (2014) *Flood and Coastal Erosion Risk Management. Long-term Investment Scenarios*, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/381939/FCRM_Long_term_investment_scenarios.pdf

Environment Agency (2016) *The Costs and Impacts of the Winter 2013 to 2014 Floods*, Non-Technical Report, SC140025/R2, http://evidence.environmentagency.gov.uk/FCERM/Libraries/FCERM_Project_Documents/Costs_and_impacts_of_winter_2013_to_2014_floods_-_Non-tech_report.sflb.ashx

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

Evans, E., Ashley, R., Hall, J., Penning-Rowsell, E., Sayers, P., Thorne, C. and Watkinson, A. (2004b) *Foresight. Future Flooding. Scientific Summary: Volume 2 – Managing future risks*. Office of Science and Technology, London.

EurOtop (2018) *Manual on Wave Overtopping of Sea Defences and Related Structures*. An overtopping manual largely based on European research, but for worldwide application, http://www.overtopping-manual.com/assets/downloads/EurOtop_II_2018_Final_version.pdf

Flather, R.A. (2000) Existing operational oceanography. *Coastal Engineering*, **41**, 13-40. http://dx.doi.org/10.1016/S0378-3839(00)00025-9

Gilbert, S. and Horner, R. (1986) *The Thames Barrier*, Thomas Telford Ltd, 216pp.

Gönnert, G., Dube, S.K., Murty, T.S. and Siefert, W. (2001) *Global Storm Surges: Theory Observation and Applications*. Heide in Holstein: Westholsteinische Verlagsanstalt Boyens & Co, 623 pp.

Goodwin, P., Brown, S., Haigh, I.D., Nicholls, R.J., Matter, J.M. (2018) Adjusting Mitigation Pathways to stabilize climate at 1.5 and 2.0 °C rise in global temperatures to year 2300. *Earth's Future*, **6**(3), 601–615, https://doi.org/10.1002/2017EF000732

Haasnoot, M., Kwakkel, J.H., Walker, W.E. and ter Maat, J. (2013) Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*, **23** (2), 485–498, http://dx.doi.org/10.1016/j.gloenvcha.2012.12.006.

Haasnoot, M., Brown, S., Scussolini, P. Jimenez, J. Vafeidis, T.A. and Nicholls, R. (2019) Generic adaptation pathways for coastal archetypes under uncertain sea-level rise. *Environmental Research Communications*. https://doi.org/10.1088/2515-7620/ab1871.

Haigh, I.D., and Nicholls, R.J. (2017) Coastal Flooding. *MCCIP Science Review 2017*, pp. 98–104, doi:10.14465/2017. arc10.009-cof, http://www.mccip.org.uk/media/1769/2017arc_sciencereview_009_cof.pdf.

Haigh, I.D, Nicholls, R.J and Wells, N.C. (2010) Assessing changes in extreme sea levels: application to the English Channel, 1900–2006. *Continental Shelf Research*, **30**, 1042–1055, http://dx.doi.org/10.1016/j.csr.2010.02.002

Haigh, I.D., Eliot, M. and Pattiaratchi, C. (2011) Global influences of the 18.6-year nodal cycle and quasi-4.4 year cycle on high tidal levels. *Journal of Geophysical Research*, **116**, C06025, doi:10.1029/2010JC006645

Haigh, I.D., Wadey, M.P., Gallo, S.L, Loehr, H., Nicholls, R.J., Horsburgh, K., Brown, J.M and Bradshaw, E. (2015) A user-friendly database of coastal flooding in the United Kingdom 1915–2014. *Scientific Data*, **2**, 150021, doi:10.1038/sdata.2015.21

Haigh, I.D., Wadey, M.P., Wahl, T., Brown, J.M, Horsburgh, K. and Nicholls, R.J. (2016) Spatial footprint and temporal clustering analysis of extreme sea level and storm surge events around the coastline of the UK. *Scientific Data*, **3**, 160107.

Haigh, I.D., Ozsoy, O., Wadey, M.P., Nicholls, R.J., Gallop, S.L., Wahl, T. and Brown, J.M. (2017) An improved database of coastal flooding in the United Kingdom from 1915 to 2016. *Scientific Data*, **4**, 170100.

Haigh et al. (2020). The Tides They Are a-Changin': A comprehensive review of past and future non-astronomical changes in tides, their driving mechanisms and future implications. Reviews of Geophysics, https://doi.org/10.1029/2018RG000636

Hallegatte, S, Green, C., Nicholls, R.J., Corfee-Morlot, J. **(**2013) Future flood loses in major coastal cities, Nature Climate Change, **3**, 802-806.

Hawkes, P.J., Gouldby, B.P., Tawn, J.A. and Owen, M.W. (2002) The joint probability of waves and water levels in coastal engineering design. *Journal of Hydraulic Research*, **40**(3), 241–251, doi: 10.1080/00221680209499940

Hawkes, P.J. (2005) *Use of Joint Probability Methods in Flood Management: A Guide to Best Practice*, Flood and Coastal Defence R&D Programme, HR Wallingford.

Hendry, A., Haigh I.D., Nicholls R.J., Winter, H., Neal, R., Wahl T., Joly-Laugel, A. and Darby, S.E. (2019) Assessing the Characteristics and drivers of Compound Flooding Events around the UK Coast, *Hydrology and Earth System Sciences*, 23, 3117–3139.

Horsburgh, K. and Horritt, M. (2006) The Bristol Channel floods of 1607 – reconstruction and analysis. *Weather*, **61**, 272–277.

Horsburgh, K., Rennie, A. and Palmer, M. (2020) Impacts of climate change on sea-level rise relevant to coastal and marine environment around the UK. *MCCIP Science Review*, 116–131

Horton, B.P., Rahmstorf, S., Engelhart, S.E. and Kemp, A.C. (2014) Expert assessment of sea-level rise by AD 2100 and AD 2300, *Quaternary Science Reviews*, **84**, 1-6.

Hosking, A. (2006) *Shoreline Management Plan Guidance Volume 1: Aims and requirements*, Defra report.

Huntingford, C., Marsh, T.J., Scaife, A.A., Kendon, E.J., Hannaford, J. *et al*. (2014) Potential influences on the United Kingdom's floods of winter 2013/14. *Nature Climate Change*, **4,** 769–777.

Hurrell, J.W. (1995) Decadal Trends in the North Atlantic Oscillation: Regional Temperatures and Precipitation. *Science*, **269**, 676 (1995), doi: 10.1126/science.269.5224.676

Jackson, L. and Devadason, C.A. (2019) *Climate Change, Flooding and Mental Health*. Report from the Secretariat of the Rockefeller Foundation Economic Council on Planetary Health. https://www.planetaryhealth.ox.ac.uk/wp-content/uploads/sites/7/2019/04/Climate-Change-Flooding-and-Mental-Health-2019.pdf

Kendon, M. and McCarthy, M. (2015) The UK's wet and stormy winter of 2013/14. *Weather*, **70** (2), 40-47, doi:10.1002/wea.2465

Le Pard, G. (1999) The great storm of 1824. *Proceedings of Dorset Natural History and Archaeological Society*, **121**, 23–36.

Lewis, M., Horsburgh, K., Bates, P. and Smith, R. (2011) Quantifying the uncertainty in future coastal flood risk estimates for the UK. *Journal of Coastal Research*, **27**(5), 870–881.

Lewis, M.J., Palmer, T., Hashemi, R., Robins, P., Saulter, A., Brown, J., Lewis, H. and Neill, S. (2019) Wave-tide interaction modulates nearshore wave height. *Ocean Dynamics*, 1–18.

Lowe, J. (2006) Impacts of climate change on coastal flooding in Marine Climate Change Impacts Annual Report Card 2006. [Buckley, P.J., Dye, S.R. and Baxter, J.M. (eds.)], *Online Summary Reports*, MCCIP, Lowestoft, www.mccip.ork.uk

Lyddon, C., Brown, J.M, Leonardi, N. and Plater, A.J. (2018a) Flood hazard assessment for a hyper-tidal estuary as a function of tide-surge-morphology interaction. *Estuaries and Coasts*, **41**(6). 1565–1586, https://doi.org/10.1007/s12237-018-0384-9

Lyddon, C., Brown, J.M., Leonardi, N. and Plater, A.J. (2018b) Uncertainty in estuarine extreme water level predictions due to surge-tide interaction. *PLoS ONE*, **13**(10), e0206200. https://doi.org/10.1371/journal.pone.0206200.

Marcos, M., Calafat, F.M., Berihuete, Á. and Dangendorf, S. (2015) Long-term variations in global sea level extremes. *Journal of Geophysical Research: Oceans*, **120**, 8115–8134, doi: 10.1002/2015JC011173.

Mawdsley, R.J., Haigh, I.D. and Wells, N.C. (2015) Global secular changes in different tidal high water, low water and range levels. *Earth Future*, **3**, 66–81, doi:10.1002/2014EF000282

Mawdsley, R.J. and Haigh, I.D. (2016) Spatial and Temporal Variability and Long-Term Trends in Skew Surges Globally. *Frontiers in Marine Science*, **3**, 277, http://dx.doi.org/10.3389/fmars.2016.00029

McGahey, C. and Sayers, P.B (2008) Long term planning – robust strategic decision making in the face of gross uncertainty. In: *FLOODrisk 2008*, 30 September –2 October 2008, Keble College, Oxford, UK.

McRobie, A., Spencer, T. and Gerritsen, H. (2005) The big flood: north sea storm surge. *Philosophical Transaction of the Royal Society* A, **363**, 1263–1270, doi: 10.1098/rsta.2005.1567

Mengel, M. Nauels, A., Rogeli, J. and Schleussner, C-F. (2018) Committed sea-level rise under the Paris Agreement and the legacy of delayed mitigation action *Nature Communications*, **9**, 601.

Mooyaart, L.F. and Jonkman, S.N. (2017). Overview and Design Considerations of Storm Surge Barriers. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, **143**(2).

National Trust (2015) *Shifting Shores*, https://www.nationaltrust.org.uk/documents/shifting-shores-report-2015.pdf

Nicholls, R.J., Townend, I.H., Bradbury, A., Ramsbottom, D. and Day, S. (2013) Planning for long-term coastal change: experiences from England and Wales. *Ocean Engineering*, **71**, 3–16, doi: 10.1016/j.oceaneng.2013.01.025

Nicholls, R.J., Brown, S., Goodwin, P., Wahl, T., Lowe, J, Solan, M., Godbold, J., Haigh, I.D., Lincke, D., Hinkel, J., Wolff, C. and Merkens, J-L. (2018) Stabilisation of global temperature at 1.5°C and 2.0°C: Implications for coastal areas. *Philosophical Transactions of The Royal Society A*, **376**(2119), 20160448.

Palmer, M., Howard, T., Tinker, J., Lowe. J., Bricheno, L., Calvert, D., Edwards, T., Gregory, J., Harris, G., Krijnen, J., Pickering, M., Roberts, C. and Wolf, J. (2018) UKCP18 *Marine Report*, https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Marine-report.pdf

Pelling, H. and Green, J.A.M. (2013a) Sea-level rise, tidal power, and tides in the Bay of Fundy. *Journal of Geophysical Research*, **118**, 1–11, doi:10.1002/JGRC.20221

Pelling, H.E., Green, J.A.M. and Ward S.L. (2013b). Modelling tides and sea-level rise: To flood or not to flood. *Ocean Modell*ing **63**, 21–29, doi:10.1016/j.ocemod.2012.12.004

Penning-Rowsell, E.C. (2015) A realistic assessment of fluvial and coastal flood risk in England and Wales. *Transactions of the Institute of British Geographers*, **40**, 44–61.

Phillips, B., Brown, J., Bidlot, J. and Plater, A. (2017) Role of beach morphology in wave overtopping hazard assessment. *Journal of Marine Science and Engineering*, **5**(1), 5010001, https://doi.org/10.3390/jmse5010001

Pickering, M.D., Wells, N.C. Horsburgh, K.J. and Green, J.A.M. (2012) The impact of future sea-level rise on the European Shelf tides. *Continental Shelf Research*, **35**, 1–15, doi:10.1016/j.csr.2011.11.011

Pickering, M.D., Horsburgh, K.J. Blundell, J.R. Hirschi, J.J.-M. Nicholls, R.J. Verlaan, M. and Wells N.C. (2017) The impact of future sea-level rise on the global tides. *Continental Shelf Research*, **142**, 50–68, doi:10.1016/j.csr.2017.02.004

Pugh, D. and Woodworth, P. (2014). *Sea-Level Science: Understanding Tides, Surges, Tsunamis and Mean Sea-Level Changes*, Cambridge University Press.

Ranger, N., Millner, A., Dietz, S, Fankhauser, S., Lopez, A. and Ruta, G. (2010) *Adaptation in the UK: A Decision-making Process*. Grantham Research Institute on Climate Change and the Environment and Center for Climate Change Economics and Policy, http://www.lse.ac.uk/GranthamInstitute/wp-content/uploads/2014/03/PB-Ranger-adaptation-UK.pdf

RMS (2007) *1607 Bristol Channel Floods: 400-year Retrospective. Risk Management Solutions Report*, http://static.rms.com/email/ documents/fl_1607_bristol_channel_floods.pdf

Robins, P.E. and Lewis, M.J. (2019) Changing Hydrology: A UK Perspective. In *Coasts and Estuaries*, Elsevier, pp. 611–617.

Robins, P.E., Lewis, M.J., Freer, J., Cooper, D.M., Skinner, C.J. and Coulthard, T.J. (2018) Improving estuary models by reducing uncertainties associated with river flows. *Estuarine, Coastal and Shelf Science*, **207**, 63–73.

Sayers, P.B., Hall, J.W. and Meadowcroft, I.C. (2002) Towards risk-based flood hazard management in the UK. *Civil Engineering*, **150**(5), 36–42.

Sayers, P.B., Horritt, M. S., Penning-Rowsell, E., and Mckenzie, A. (2015) *Climate Change Risk Assessment 2017: Projections of future flood risk in the UK*. Sayers and Partners LLP report for the Committee on Climate Change, 125 pp, https://www.theccc.org.uk/wp-content/uploads/2015/10/CCRA-Future-Flooding-Main-Report-Final-06Oct2015.pdf

Sayers, P.B., Horritt, M., Penning Rowsell, E., and Fieth, J. (2017) *Present and Future Flood Vulnerability, Risk and Disadvantage: A UK assessment.* A report for the Joseph Rowntree Foundation. Sayers and Partners LLP, http://www.sayersandpartners.co.uk/uploads/6/2/0/9/6209349/sayers_2017_-_present_and_future_flood_vulnerability_risk_and_disadvantage_-_final_report_-_uploaded_05june2017_printed_-_high_quality.pdf

Schaeffer, M., Hare, W., Rahmstorf, S. and Vermeer, M. (2012) Long-term sea-level rise implied by 1.5 °C and 2 °C warming levels. *Nature Climate Change*, **2**, 867–87.

Schindelegger, M., Green, J.A.M. Wilmes, S.-B. and Haigh I.D. (2018) Can we model the effect of observed sea level rise on tides? *Journal of Geophysical Research: Oceans*, **123**, doi:10.1029/2018JC013959

Seneviratne, S. I. *et al*. (2012) A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC) [Field, C. B. *et al.* (eds)] Cambridge University Press, pp. 109–230.

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

Stevens, A.J., Clarke, D. and Nicholls, R.J. (2016) Trends in reported flooding in the UK: 1884-2013. *Hydrological Sciences*, **61**, 50-63, doi:10.1080/02626667.2014.950581

Svensson, C. and Jones, D.A. (2002) Dependence between extreme sea surge, river flow and precipitation in eastern Britain. *International Journal of Climatology*, **22**(10), 1149–1168, doi: 10.1002/joc.794

Svensson, C. and Jones, D. A. (2004) Dependence between sea surge, river flow and precipitation in south and west Britain. *Hydrology and Earth System Sciences Discussions European Geosciences Union*, **8**(5), 973–992.

Thorne, C.R., Evans, E.P. and Penning-Roswell, E.C. (2007) *Future Flooding and Coastal Erosion Risks*, Thomas Telford.

Thorne, C. (2014) Geographies of UK flooding in 2013/4. *The Geographical Journal*, **180**, 297–309, doi:10.1111/geoj.12122

Wadey, M.P., Haigh, I.D. and Brown, J.M. (2014) A century of sea level data and the UK's 2013/14 storm surges: an assessment of extremes and clustering using the Newlyn tide gauge record. *Ocean Science*, **10**, 1031−1045, doi:10.5194/os-10-1031-2014

Wadey, M., Haigh, I.D., Nicholls, R.J., Brown, J.M., Horsburgh, K., Carrol, B., Gallop, S L., Mason, T. and Bradshaw, E. (2015) A comparison of the 31 January–1 February 1953 and 5–6 December 2013 coastal flood events around the UK. *Frontiers in Marine Science*, **2**, 793, http://dx.doi.org/10.3389/fmars.2015.00084

Wahl, T., Haigh, I.D., Nicholls, R.J., Arns, A., Dangendorf, S., Hinkel, J. and Slangen, A.B.A. (2017) Understanding extreme sea levels for broad-scale coastal impact and adaptation analysis. *Nature Communications*, 16075.

Wahl, T., Ward, P.J. Winsemius, H.C. AghaKouchak, A. Bender J. Haigh, I.D. Jain, S. Leonard, M. Veldkamp, T.I.E. and Westra, S. (2018) Hydrologic compound events: unappreciated hazards, *Eos, Transactions American Geophysical Union*.

Wales Audit Office (2009) *Coastal Erosion and Tidal Flooding Risks in Wales. Report prepared by Jeremy Colman and team for the National Assembly under the Government of Wales Act 2006, 29 October 2009*, http://www.assembly.wales/Laid Documents/AGR-LD7767 – Coastal Erosion and Tidal Flooding Risks in Wales, 29102009-149678/agr-ld7767-e-English.pdf

Ward, S., Green J.A.M. and Pelling, H. (2012) Tides, sea-level rise and tidal power extraction on the European shelf. *Ocean Dynamics*, **62**(8), 1153–1167, doi:10.1007/s10236-012-0552-6

Wilmes, S.-B., Green, J.A.M. Gomez, N. Rippeth, T.P. and Lau H. (2017) Global tidal impacts of large-scale ice-sheet collapses. *Journal of Geophysical Research: Oceans*, **122**, 8354–8370, doi:10.1002/2017JC013109

Woodworth, P. L., Shaw, S.M. and Blackman D.L. (1991) Secular trends in mean tidal range around the British Isles and along the adjacent European coastline. *Geophysical Journal International*, **104**(3), 593–609, doi:10.1111/j.1365-246X.1991.tb05704.x

Wolf, J., Woolf, D. and Bricheno, L. (2020) Impacts of climate change on storms and waves relevant to the coastal and marine environment around the UK. *MCCIP Science Review 2020*, 132–157.

Zscheischler, J., Westra, S., Bart, J.J.M., Van Den Hurk, S.I., Seneviratne, P.J.W., Pitman, A., Aghakouchak, A, Bresch, D.N., Leonard, M., Wahl, T. and Zhang, X. (2018) Future climate risk from compound events. *Nature Climate Change*, **8**, 469–477.