Office for Nuclear Regulation

ONR Expert Panel on Natural Hazards

Annex 3

Expert Panel Paper No: GEN-MCFH-EP-2021-2:

Submitted to ONR August 2021

August 2021

ONR Expert Panel on Natural Hazards

NS-TAST-GD-013 Annex 3 Reference Paper:

Analysis of Meteorological Hazards for Nuclear Sites

Expert Panel Paper No: GEN-MCFH-EP-2021-2

Sub-Panel on Meteorological & Coastal Flood Hazards

Cm9 Ref. 2021/62118

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

This document was drafted by members of the ONR Expert Panel on Natural Hazards - Sub-Panel on Meteorological and Coastal Flood Hazards (Kevin Horsburgh of the National Oceanography Centre with significant contributions from Stephan Harrison and David Smith of Climate Change Risk Management and Paul Sayers of Sayers and Partners LLP provided additional engineering input). Ben Gouldby of HR Wallingford also provided significant contributions on aspects related to overtopping and methods for deriving extreme sea conditions. Significant assistance was also provided by the Environment Agency in the production of this document. The document was also reviewed and additional input provided by several staff members of the Office for Nuclear Regulation, by Alice B Walker, who serves as Technical Secretary to the ONR Expert Panel, and the Defence Nuclear Safety Regulator. The document was reviewed at an earlier stage in its production, by Hamish Hall and Mike Walkden, both of WSP.

Comments were also received from various external stakeholders through an organised stakeholder event in 2017. All these comments are gratefully acknowledged.

1 INTRODUCTION

1. A key element of developing a safety case for nuclear plant at a nuclear licensed site is the demonstration that the plant is adequately protected against external hazards, including those related to meteorological and geological processes. An indispensable component of this process is the characterisation and quantification of the external hazards that can credibly challenge nuclear safety at the site. Guidance for inspectors on the assessment of site-specific studies to quantify the threat from external hazards at nuclear sites is provided in *Nuclear Safety Technical Assessment Guide NS-TAST-GD-013* (ONR, 2020), generally referred to as TAG 13.

2. Annex 3 of TAG 13 (ONR, 2018a) is focused specifically on the hazards of coastal flooding, coastal erosion and tsunami and their analysis for nuclear sites in the UK. The purpose of this document is to provide additional detail on the analysis of coastal flooding and erosion hazards. The present document is intended to provide guidance to inspectors as well as experts or consultants called upon to assist inspectors with assessments of tsunami and coastal flooding hazard studies for nuclear sites in the UK. It also builds upon the overview of climate change provided in Annex 2 (ONR, 2018b) specific for coastal flooding hazards along with the methods by which this is incorporated into the hazard analysis process.

2 OVERVIEW OF COASTAL FLOODING, INCLUDING EROSION AND TSUNAMI IN THE UK

3. Coastal flooding is one of the most significant risks that the UK infrastructure faces, with wide-ranging social, economic and environmental impacts. It is also one of the risks most impacted by the consequences of climate change. Nationally, it is estimated that £150 billion of assets and 4 million people are currently at risk from coastal flooding in the UK (Environment Agency, 2009). Coastal flooding is identified as one of the key risks that have the potential to cause significant disruption in the UK, in the National Risk Register of Civil Emergencies (Cabinet Office, 2017). It is a growing threat due to long-term mean sea-level rise and possible future changes in storminess (Church et al., 2013) as well as continued population growth and development in flood-exposed areas (Hallegatte et al., 2013). Irrespective of any future change in storm climate (which would affect storm surges and waves), mean sea-level rise will result in more instances of extreme sea-level thresholds being reached.

4. Coastal flooding occurs when some combination of high tide, storm surge and wave conditions is sufficiently severe to overtop or breach coastal defences and cause inundation of low-lying areas (Figure 1). Extreme high waters around the UK are normally caused by a combination of exceptionally high tides and severe weather events. Extra-tropical cyclones (the prevailing weather systems for the UK) produce storm surges that can increase tidal levels by 3-4 m in exceptional cases. The still water level (defined as the sea level before short period waves are taken into account) can be further elevated at the coast by wave setup caused by wave breaking. Storms then also produce large wind and swell waves, which can overtop coastal defences/beaches and cause flooding and erosion.

5. The combination of high-water levels and severe weather can also result in changes to beaches and nearshore bed features; which in turn can expose man-made or natural defences to greater threat. These increased pressures, such as deeper water at the toe of the defence or localised failure of defences can then increase the potential for coastal flooding.

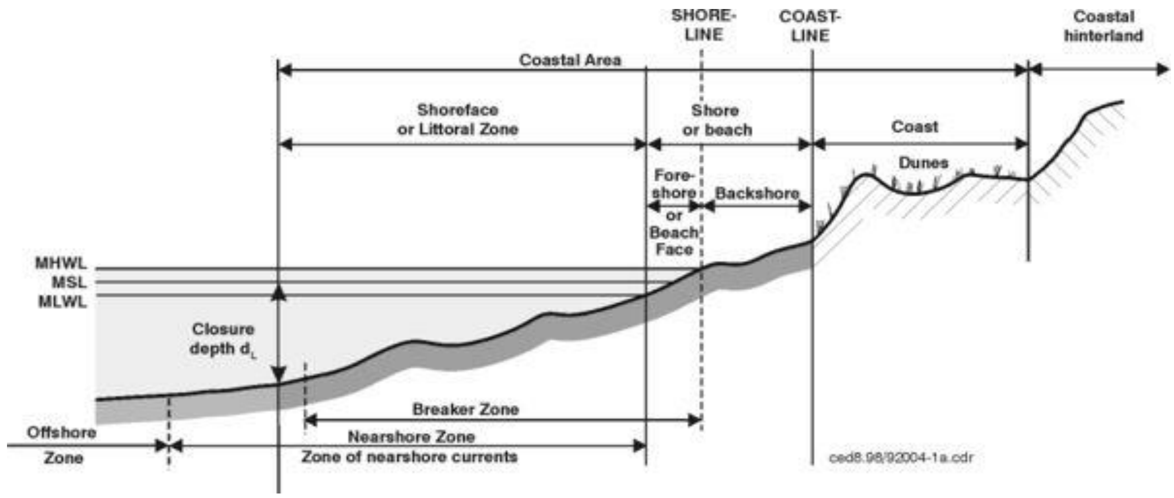

Figure 1

Definition of coastal terms, mainly from Shore Protection Manual (Coastal Engineering Research Center, 1984).

6. A further factor that drives coastal flood risk is socio-economic change (Thorne et al., 2007). Changes in land use and increasing asset values in floodplain areas have led to enhanced exposure to flooding (Horsburgh et al., 2010). This has, and is likely to lead to the provision of more forms of coastal protection that can cause changes in coastal morphology. Changes in coastal morphology can also influence flood pathways and thus flood risk (Thorne et al., 2007; Nicholls et al., 2015). As erosion is expected to dominate coastal morphological change in the future because of mean sea-level rise, this will add to the overall flood risk.

7. All components of sea level display considerable natural variability, which influences the frequency of flooding on inter-annual and multi-decadal time scales. 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 (eg the quasi-decadal cycle known as the North Atlantic Oscillation; NAO). 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 very unusual (although not unprecedented). On 5th December 2013, extreme sea levels in the North Sea exceeded those of the 1953 floods at several sites (Wadey et al., 2015) resulting in damage to property and infrastructure. The subsequent storms in January and February 2014 caused widespread damage to defences, property and infrastructure on the south-western coastlines of England and Wales (most notably the collapse of the main railway line at Dawlish in Devon; Dawson et al., 2016).

8. This report also considers the risk to the UK posed by tsunami, based on reports that were published by the Department for Environment, Food and Rural Affairs (Defra) (Defra, 2005; 2006), and the literature therein, following the Indian Ocean tsunami of 26th December 2004.

2.1 Mean sea level

9. Sea level change at any particular location depends on many regional and local physical processes as well as global climate drivers, so regional sea level change will differ from the global average. The fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2013) concluded that it is very likely that the average rate of global averaged sea-level rise was 1.7 mm per year between 1901 and 2010. For the more recent 1993 to 2010 period, the average rate of change was 3.2 mm per year, with a consistency between tide-gauge and satellite altimeter data. There is high confidence that the rate of observed 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 slow long-term acceleration in the rate of sea-level rise throughout the 20th century (Church and White, 2011). Whether the faster rate of increase in sea level during the period from the mid-1990s reflects an increase in the longer-term trend or decadal variability is still not clear.

10. Although there is a great deal of local variability in the measured values, mean sea levels around the UK (from tide gauge records) mostly exhibit 20th century rises that

are consistent with the global mean value, although the central estimate around the UK is slightly lower than that of the global value (Woodworth et al., 2009). Other regional studies based on analysis of tide gauge data (Haigh et al., 2009; Wahl et al., 2013) find similar values of around 1.4 ± 0.2 mm per year for sea-level rise around the UK.

2.2 Vertical land movement and gravitational effects

11. For planning and engineering purposes, it is sea level with respect to the local land level that is of primary interest and the solid Earth itself is also moving as it recovers from ice loading during the most recent ice age. A key process that affects vertical land motion is the viscoelastic response of the solid Earth to deglaciation, termed glacial isostatic adjustment (GIA). The most recent analysis of GIA effects for the British Isles is provided by Shennan et al. (2018). An accurate understanding of regional sea level change is a particular area, which involves combining the global models of eustatic sea level change (ie sea-level rise due to volume changes as well as geological changes to ocean basins) with local models of GIA, modified by localised effects at the coast (eg Smith et al., 2012).

12. A further complication is that sea level change is affected by large scale gravitational adjustment in response to polar ice melt. Mitrovica et al. (2001; 2009) showed how rapid melting of major ice sources gives rise to spatial changes in the Earth's gravity field (as well as to the volume of water in the oceans); their model predicts a fall in relative sea level close to the source of melting as the gravitational interaction between ice and ocean is reduced whereas there is a correspondingly larger rise in sea level further from the melt source.

2.3 Storm surges

13. Storm surges are the large-scale increase in sea level due to a storm. They can increase sea levels by 3-4 m in European coastal seas and they last from hours to days and span hundreds of square kilometres. They are caused by wind stress at the sea surface and the horizontal gradient of atmospheric pressure (Pugh and Woodworth, 2014), although the magnitude of any particular storm surge is influenced by many factors including the intensity and track of the weather system, bathymetry, and coastal topography. The same physics controls storm surges caused by mid-latitude weather systems (extra-tropical cyclones) and tropical cyclones (hurricanes). In regions of high tidal range, storm surges represent the greatest threat when they coincide with tidal high water: most operational forecasting centres now systematically refer to the combination of a storm surge and tidal high water as the storm tide.

14. In a strongly tidal nation like the UK, it is important to understand the interaction between storm surges and tides. Such interactions have been extensively studied (eg Rossiter, 1961; Prandle and Wolf, 1978). The dominant mechanism for tide-surge interaction is that increased water levels due to meteorological forcing induce a phase shift in the tidal signal (Horsburgh and Wilson, 2007); many properties of a non-tidal residual time series (ie the time series of sea-level observations minus tidal predictions) are simply an artefact of small changes to the timing of predicted high water. The most useful measure of storm surges is the skew surge, which is the difference between the maximum observed sea level and the maximum predicted

tidal level, regardless of their timing during the tidal cycle (de Vries et al.,1995). Hence each tidal cycle has one predicted high-water value and one associated skew surge value. The advantage of using the skew surge is that it is a simple and unambiguous measure of the storm surge.

15. Williams et al. (2016) showed that the magnitude of high water exerts no influence on the size of the most extreme skew surges, confirming previous observations (Environment Agency, 2011; Batstone et al., 2013). This provides a statistically robust proof that any storm surge can occur on any tide and this is essential for understanding worst-case scenarios. The lack of any observed storm surge dependency on water depth emphasises the dominant natural variability of weather systems. There are however seasonal relationships between skew surges and tidal high waters, and the inclusion of these in future statistical methods will improve the estimates of extreme sea levels (see Section 6).

2.4 Waves

16. Waves are smaller scale disturbances on the sea surface caused by the wind. Whilst waves do not affect the average height of the sea surface, they cause overtopping (intermittent pulses of water or spray over the top of a coastal defence); waves also possess considerable energy and can change nearshore bed and beach morphology. This energy, either in isolation or in combination with an altered nearshore, can weaken coastal defences leading to an eventual breach. The largest waves in UK waters are found on the Atlantic boundaries of the coastline where waves can propagate over large fetches from the ocean, especially in autumn and winter when strong winds are more intense and persistent. Instrumental wave records are available from the 20th century onwards and inter-annual variability in the wave climate is known to be strongest in the winter and can be related to atmospheric modes of variability, most notably the NAO. Swell waves are relatively long waves (periods typically 10-12 seconds) that travel long distances and are often observed a long distance from their region of generation. Swell waves and locally-formed wind waves can have different directions of propagation, and swell waves carry more energy than shorter wind waves of equivalent wave height.

17. Wave setup is a temporary increase in mean sea level due to the presence of breaking waves. As waves break, the wave energy flux decreases (due to energy dissipation) and the mean surface adjusts to balance the decreased wave radiation stress. Large waves during storm events can add up to 30 cm to mean sea level through wave setup. Wave setup and storm surges cannot be separated from a tide gauge record – they both add to the predicted tidal level.

18. All wind and wave time series show a great deal of variability including inter-annual and inter-decadal fluctuations. Increases in average wave heights occurred between 1960 and 1990, but these are now seen as just one feature within a longer history of variability (Woolf and Wolf, 2013). For example, Alexander et al. (2005) showed that wave heights increased significantly between 1950 and 1990, yet during this same period trends in wind speed around the UK were significantly weaker than for wave heights, and, therefore, the increase in wave heights is attributed to Atlantic waves propagating as swell. There is no clear pattern in results since 1990.

19. Many of the changes over the last 50 years can be understood in terms of the behaviour of the NAO (Woolf and Wolf, 2013). The trend towards stormier conditions in the NAO from the 1960s to early 1990s is unique in the record of this climate index but there is no clear connection to other aspects of climate such as global warming (Osborn, 2004). There is currently no consensus and large uncertainty surrounding the influence of climate change on extratropical storm track positions and intensities (eg Shaw et al., 2016). This is because different elements of climate forcing can have opposing effects on the locations of strong atmospheric temperature gradients.

2.5 Tides

20. Tides are periodic variations in the surface water level that result from the mutual gravitational attraction of the Earth, Moon and Sun. Most places around the UK experience two high tides and two low tides each day. Several recent studies have detected measurable changes in tidal range during the 20th century and early part of the 21st century at a number of locations (see Mawdsley et al., 2015 for a review). In addition, there have been several studies that predict changes in tidal range around the UK resulting from future changes in mean sea level (Pickering et al., 2012; Ward et al., 2012; Pelling et al., 2013). Whilst further research is needed to explain the observed global changes in tides, the likely mechanisms for change are adjustments to the resonant systems of shallow seas, combined with changes in energy dissipation due to increased average water depths. Typically, all these modelling studies suggest that changes in tidal range will be in the order of plus or minus 10% of the changes in mean sea level. Although small in comparison to the mean sea level changes, altered tidal ranges could enhance coastal flooding at some locations. Changes in tides, therefore, need to be considered in future assessments of extreme sea level change and coastal flooding.

2.6 Extreme sea levels

21. IPCC (2013) states that, at most locations, mean sea level is the dominant driver of observed changes to sea level extremes, although large-scale modes of variability such as the NAO may also be important. There is evidence of increases in extreme water levels over the past 100-200 years around many parts of the global coastline, including around the UK (eg Menendez and Woodworth, 2010). While changes in storminess could contribute to changes in sea level extremes, there is little or no evidence for either systematic long-term changes in storminess or any detectable change in storm surges (IPCC, 2012). Future changes to storminess for the UK and Europe cannot be ruled out and some model studies do give projections of changed storm activity over Europe, either due to global temperature changes or changes to Atlantic oceanic processes (eg Oltmanns et al., 2020). A recent report (Met Office and CEH, 2014) suggests that, while strong extra-tropical cyclones affecting the UK in the winter have not increased since the late nineteenth century, the mean intensity has. However, a systematic review of storminess over the North Atlantic and northwest Europe (Feser et al., 2015) concluded that trends in storm activity depend strongly on the period analysed; studies based on measurements or reanalyses generally do not show any changes in storminess. Allen et al. (2008) show that changes in UK storm frequency over the second half of the 20th century were dominated by the natural variability of our weather systems. The scientific consensus is that any changes in extreme sea levels at most locations worldwide have been driven by the observed rise in mean sea level (eg Woodworth and Blackman, 2004;

Haigh et al., 2010; Menendez and Woodworth, 2010; Marcos et al., 2015; Wahl and Chambers, 2016). Storm surge simulations carried out under the UK Climate Projections 2018 (UKCP18) (see Section 4) for the 21st century suggest a best estimate of no significant changes to storm surges.

2.7 Tsunamis

22. Following the Sumatra earthquake of 26th December 2004 and the devastating tsunami that followed, the UK government conducted a full review of tsunami risk. Tsunami hazard to the UK was assessed by gathering evidence on past events, considering possible source regions, and modelling the propagation of tsunami waves from plausible source locations to the coast. Studies (Defra 2005; Defra, 2006) concluded that a tsunami reaching the UK from the Azores-Gibraltar fault zone (which was responsible for the earthquake and tsunami causing the destruction of Lisbon in 1755) is the most likely event to affect the UK coastline. Long (2015) found three additional small tsunami events since 1941, all emanating for the Azores-Gibraltar fault zone, and an additional small tsunami caused by coastal collapse in 1911.

23. In the modelling carried out for these studies, the projected heights of tsunami waves arriving close to the shore were comparable to those seen in typical storm surges. All areas potentially affected by the plausible range of tsunami wave heights have flood defence infrastructure designed to protect against waves of those sizes. However, certain characteristics of tsunami events (the number of waves, the range of typically longer wavelengths) are likely to create sea conditions different to those during a storm surge. The momentum associated with longer wavelength tsunami waves, and volume of water within a wave crest, result in incident wave energy that is significantly greater than for wind waves of the same height. Therefore, it should not be assumed that the impact of a tsunami would be comparable to that of a storm surge simply on the basis of similar wave heights and water levels. Also, tsunami events could occur at any time. They are not associated with adverse meteorological conditions so cannot be predicted in advance, although relatively expensive monitoring systems could give some degree of early warning.

24. There is geological evidence for a major tsunami affecting the coasts of Scotland and northeast England following a submarine landslide on the Norwegian continental shelf approximately 8150 years ago - the so-called Storegga slide (Bondevik et al., 2019). Analysis of sediment cores (eg Smith et al., 2007; Soulsby et al., 2007) shows that the run up of the tsunami may have reached more than 7 metres above high-water spring tides at that time. However, whilst there is clear localised sedimentary evidence, changes to bathymetry, past sea levels and lack of knowledge of the tidal state at the time makes an accurate estimate of wave height in the nearshore environment across the area as a whole difficult. Geological data suggest that large submarine landslides (submarine mass failures) in the critical region have occurred before although no others have been shown to affect the UK. The Defra (2005; 2006) reports remain the most authoritative guides to tsunami hazard to the UK.

2.8 Meteorological tsunamis

25. Around the UK the sea level variability largely occurs over periods from hours to days and is associated with extra-tropical storms (our weather systems). However,

there is an increasing recognition that higher-frequency sea level variations in the order of minutes to hours can also raise sea levels. Often referred to as ‘meteorological tsunamis’ or ‘meteotsunamis’ these are generated by traveling atmospheric disturbances such as thunderstorms or squall lines (Vilibić et al., 2016). They have similar spatial and temporal scales as ordinary tsunami waves and can affect some coastal areas causing extreme resonant conditions in bays and harbours, although they are normally far less hazardous than tsunamis caused by earthquakes. Whilst they are a genuine hazard elsewhere (eg Japan, the Mediterranean and Adriatic Seas) they typically have small amplitudes in other European coastal waters. Meteotsunamis affecting UK coasts have been catalogued by Long (2015). Meteotsunamis around the UK typically involve a wave of 20-30 cm (Tappin et al., 2013; Sibley et al., 2016; Ozsoy et al., 2016) - far smaller than typical storm surges - although occasionally they can cause nuisance flooding of low-lying areas.

3 IMPACT ON COASTAL INFRASTRUCTURE OF CLIMATE CHANGE

26. The UK Government has a vision to provide '…*an infrastructure network that is resilient to today's natural hazards and prepared for the future changing climate*… *by ensuring that an asset is located, designed, built and operated with the current and future climate in mind'* (HM Government, 2011). This goal applies equally to a wide variety of infrastructure associated with coastal risk management (natural and built) that act to 'control' flood waters, manage erosion and reduce the probability of flooding in most (if not all) of the UK floodplains that contain significant assets and the performance of coastal infrastructure used to ensure the safety of the nuclear facilities.

27. Climate change has the potential to impact the standard of protection they provide as well as their condition and reliability on demand. Impacts may include increasing:

- the rate of material degradation (eg spalling of concrete, corrosion of steel, soil desiccation, surface cover erosion etc.);
- the rate of wear and tear of mechanical components (eg through increased 'on-demand' use); or,
- the severity of loads, including increased wave overtopping and flow velocities leading episodic erosion and damage to structural elements (eg removal of rock armouring, toe scour, loss of surface cover).

28. Reliability of infrastructure may be reduced in response to these changes, and new designs and management approaches may be needed. Infrastructure providers are starting to establish a better understanding of these impacts and how to reflect the severe uncertainties associated with climate change within infrastructure investment plans, including the development of adaptative asset management (eg Tarrant and Sayers, 2012, Vonk et al., 2020) and greater consideration of impact of climate change on deterioration (eg Burgess, 2020). For many infrastructure providers however, climate change continues to be dealt with in a rudimentary fashion within the infrastructure design process (largely through the consideration of narrowly defined precautionary allowances applied to basic descriptions of coastal loads). Little consideration is given to changes in extreme values, storm sequencing and spatial coherence or the more subtle impacts of temperature, solar radiation or events occurring in combination is develop appropriate adaptive capacity within designs or maintenance activities. This should be considered in more detail in the future.

3.1 Sensitivity of infrastructure to climate change

29. The performance of coastal (and other flood) infrastructure is often represented using a fragility function derived from structural reliability analysis (Dawson & Hall, 2006; van Gelder et al., 2008, Sayers et al., 2012). Such analysis typically provides a 'snapshot' of performance given particular material properties, failure modes and loading conditions. Although the evidence on time-dependent deterioration processes remains extremely limited (eg Buijs et al., 2009; Environment Agency, 2013), it is widely accepted, with a high degree of confidence, that the performance will be sensitive to climate change.

3.2 Impact on coastal and estuarine infrastructure

30. Infrastructure at the coast has perhaps the greatest sensitivity to climate change. Sea-level rise (the strongest of climate change signals) acts to reduce the depth-limiting effect of near shore waves (Sutherland and Woolf, 2002). This leads to increased overtopping and the potential for larger wave impact forces (and subsequent structural damage and increased breach potential). Larger waves (or more persistent storms) are also likely to drive coastal morphology change and, particularly where backshores are constrained, lower beach levels; further exacerbating the impact of sea-level rise. Over the medium to long term any growth in offshore wave heights is therefore likely to be expressed at the coast (Hall et al., 2006). Other issues include:

- Mean sea level – increases in sea-level rise (and/or beach lowering) have many knock-on impacts; it can undermine the backshore structures (increasing the chance of collapse), lead to significant increases in overtopping or the loss of saltmarsh buffers; or an increased chance of liquefaction (Sutherland et al., 2007). Outfall may become tide locked and drainage difficult.

- Wave climate and joint waves and surge – The incident wave angle, height and period and the coincident tidal conditions all influence impact pressures, overtopping rates (Pullen et al., 2007) and sediment transport rates both longshore and cross-shore. Evidence for changes of wave angle is limited and any offshore changes are likely to be mitigated by refraction. Toe scour is typically more responsive to incident wave height and period alone, both of which are highly sensitive to changes that relax the depth limiting effect; including increases in mean sea level and surge heights.

- Storm sequencing – Beaches undergo continuous and on-going morphodynamical changes as a result of waves, tides and wind at a range of time scales. Significant erosion is typically episodic and takes place in response to a combination of the wave conditions, water levels, groundwater as well as geology and presence or absence of structures (local or remote to the site). Any future change in storm sequences has the potential to significantly influence the performance of coastal infrastructure (eg Karunarathna et al., 2014).

3.3 Problematic invasions and biological attacks

31. Although often overlooked, the vegetation, microbes and nutrients present within marine and fresh water systems are important components of infrastructure. Vegetation within watercourses needs to be managed to maintain conveyance and avoid blockage; marine vegetation can provide important buffers against erosion at the coast, and; nutrients and microbes can attack concrete and steel structures. For example, accelerated low water corrosion (the attack of concrete and steel structures by nutrients and microbes in the marine and estuarial environment) is an important influence on the performance of flood defence structures. Infrastructure in tidal and brackish water, such as the Thames Estuary are particular susceptible and can

experience rates of corrosion exceeding 1mm/side/year (CIRIA, 2005); a rate that is expected to increase with higher temperatures.

32. Conveyance of river channels, afflux at structures and the stability of flood defences can also be influenced by invasive species such as Japanese Knotweed (Defra, 2013). The preferential growth and survival of such species can be influenced by their adaption to conditions of high temperatures or drought. Internationally, climate change has been associated with the potential increase in more aggressive, non-native, animal burrowers that undermine the stability of flood defences, although there is currently no evidence to suggest this is occurring in the UK.

33. Timber degradation (or groynes, revetements or other control structures) can also be affected directly and indirectly by climate change through changes in water levels altering the exposure to wetting and drying, resulting in greater decay (rotting); changing temperatures that may alter the levels of marine borers found in the water; or larger waves/greater flows, which may change the dynamic regime and thus produce more aggressive and abrasive conditions (Burgess, 2020)

4 UK PROJECTION OF SEA LEVEL AND SEA LEVEL EXTREMES IN RESPONSE TO CLIMATE CHANGE

34. Sea level projections for the UK are set out in the UKCP18 Marine Report (Palmer et al., 2018) and the values provided in this section are taken from that report (or can be found on the UKCP18 website). 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 provide improvements over their predecessor 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 than were presented in the UK Climate Projections 2009 (UKCP09) (Lowe et al., 2009). For full technical details of the modelling carried out in UKCP18 see Palmer et al. (2018).

35. UKCP18 sea level projections include the spatial patterns of sea level change due to oceanographic processes, and also gravitational and other adjustments due to ice melt and changes to terrestrial water storage. 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. This is the main reason for spatial variations in projected mean sea level change around the UK for any given Representative Concentration Pathway (RCP) scenario (see paragraph 28). It is because of these complex interactions, the fact that the rate of sea-level rise changes over time, and that sea level will continue to rise long after temperatures have stabilised, that sea level changes cannot be simply equated to changes in global mean surface temperature (GMST).

36. UKCP18 marine projections used three of the RCPs (Meinshausen et al., 2011) that were the basis of the climate change projections in the IPCC AR5 (and these were RCP2.6, RCP4.5, and RCP8.5). These pathways refer to socioeconomic scenarios with differing greenhouse gas emissions. The RCP climate change scenarios span a greater range of climate forcing over the 21st century than the scenarios that were used previously in UKCP09.

37. For the UK, all RCP scenarios lead to significant sea-level rises over the 21st century. Projections for the year 2100 (relative to the 1981-2000 average) contain considerable uncertainty (eg for London, the central estimate sea level projection for the year 2100 ranges from 0.45-0.78 m, depending on the emissions scenario selected). Exploratory sea level projections beyond the year 2100 are discussed in paragraph 70 of this document.

38. All projections show spatial variation around the UK coastline due to differential rates of vertical land movement and the spatial pattern of sea level change due 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.

39. There is low confidence in future storm surge and wave height projections because of the lack of consistency between models, and limitations in the model capability to simulate extreme winds (IPCC, 2012). Whilst extreme sea levels might change in the future, as a result of (as yet unknown) changes in atmospheric storminess, mean

sea-level rise will continue to be the dominant control on trends in extreme future coastal water levels and coastal flooding.

4.1 Summary of UK national climate advice and guidelines

40. The recommended source of climate change information for the UK, including changes to sea level, are the UK Climate Projections 2018 (UKCP18) which provides climate projection tools designed to help decision-makers assess their risk exposure to climate.

41. The UKCP18 Marine Report (Palmer et al., 2018) provides a range of scenarios that may be used to assess and mitigate vulnerability of particular sites.

42. Further guidance for planners and developers in England, Scotland and Wales is issued by the responsible national agencies: Environment Agency (2020); Scottish Environment Protection Agency (2019); Natural Resources Wales (2018).

43. The Marine Climate Change Impacts Partnership (MCCIP) (www.mccip.org.uk) provides a co-ordinating framework for high quality evidence on UK marine climate change impacts, and guidance on adaptation and related advice, to policy advisors and decision-makers. The MCCIP 2020 Report Card provides a comprehensive understanding on current and future impacts of climate change on UK seas and coasts. The report is supported by a full scientific review of sea level changes (Horsburgh et al., 2020).)

5 DATA SOURCES FOR COASTAL FLOODING HAZARD ANALYSIS

5.1 Bathymetric and topographic data

44. Waves and water levels at the shore are normally influenced by the shape of the seabed, which may, in turn, be subject to processes of erosion and deposition. Even areas of hard rock may be occasionally covered by depositional features such as sandbanks. The availability of contemporary bathymetric data is, therefore, normally critical to the accurate assessment of coastal flood risk. Historic bathymetric data may also be needed to build understanding of how seabed features may be changing.

45. Charts are usually used to gain information on seabed form and development. Digital copies are usually acquired (emapsite.com is currently a leading supplier) and these may be in the form of vector datasets of bathymetric contours (isobaths) or raster charts where depth is indicated by pixel colour.

46. A Digital Elevation Model (DEM) of the seabed is needed to numerically model the effect of bathymetry on waves or surge. Such data (ideally from ‘multibeam’ sonar, see below) can often be freely sourced from online portals such as the Channel Coastal Observatory (CCO) and the UK Hydrographic Office Inspire portal.

47. Where a quality DEM is unavailable, or is out of date (perhaps due to the possible migration of seabed features), a bespoke bathymetric survey may be commissioned from a hydrographic surveying company. This may be one element of a larger study to capture broader meteorological and oceanographic (‘metocean’) data. High quality bathymetric data is normally recorded using sonar equipment in which sound waves are emitted from a moving vessel and their echo is recorded to calculate depth. Such sonar systems may be ‘single beam’ or the more detailed ‘multibeam’ (or ‘swathe’). Difficulties are typically encountered in inaccessible shallow waters and this may be important because of the strong transformations undergone by waves in the nearshore zone. Depths might be recorded in this area using airborne Light Detection and Ranging (LiDAR) equipment, which utilises a scanning laser to measure distance. However, this approach is hampered by the normally strong attenuation of the laser beam as it passes through (often turbid) seawater.

48. If flown at low tide, terrestrial LiDAR surveys can provide shore topographic data that can be joined to bathymetric data. LiDAR data is available for most (possibly all) of the UK coast, from portals such as the Environment Agency’s data.gov.uk or the CCO. Care is needed to avoid errors arising from differences in datum levels between datasets. Shore profile data recorded through ongoing strategic monitoring programmes can also be useful to extend bathymetric data. In many places this monitoring will include regular surveys of intertidal shore profiles, with less frequent ‘long’ profiles extending into deeper water. Such profile data may be obtained from the Environment Agency or online data portals such as the Coastal Explorer portal or the CCO.

49. Topographic LiDAR data is also typically utilised in assessments of coastal flooding for mapping of flood extents, and to support assessment of wave overtopping. This data is normally supplemented with ground-based topographic survey data to provide detail of coastal form and sea defence structures that cannot be reliably

obtained from LiDAR datasets. Other free (eg Ordnance Survey) and commercial sources of topographic data of varying resolution are also available.

5.2 Tide gauge and observed wave data

50. All sea level data from the UK Class A tide gauge network are available from the British Oceanographic Data Centre (bodc.ac.uk) which has a special responsibility for the remote monitoring and retrieval of sea level data from the network. Daily checks are kept on the performance of the gauges and the data is downloaded weekly. These are then processed and quality controlled prior to being made available for scientific use. The network includes 43 gauges, most of which are related through the national levelling network to Ordnance Datum Newlyn. Data is collected, processed and archived centrally to provide long time series of reliable and accurate sea levels which are then suitable for statistical analysis of extreme sea levels. Processed data from the tide gauge network from 1915 onwards are available free of charge. Other sea level datasets for certain locations are held by the Environment Agency and by various port authorities.

51. Since 2002, the WaveNet system has been operated by the Centre for Environment, Fisheries and Aquaculture Science (Cefas). WaveNet collects and processes data from the Cefas-operated Waverider buoys, tethered at strategic locations around the UK coastline. The WaveNet system also gathers wave data from a variety of third-party platforms and programmes (industry and public sector-funded), all of which are freely available for visualisation on the WaveNet website (WaveNet, 2018). The data is used to improve operational wave and storm surge models and, on a longer timescale, the data can provide coastal engineers and scientists with a better understanding of the wave climate when designing coastal flood defences and as evidence for climate change studies. Data is available for download from the WaveNet website (WaveNet, 2018).

52. Another source of wave data, albeit for a limited number of areas, is the National Network of Regional Coastal Monitoring Programmes of England. Real time wave data is available from their website.

5.3 Use of historical and geological (Palaeoceanographic) data

53. To provide additional context, or in the absence of lengthy observational records, historical records of high-water levels (eg Dawson et al., 2010) exist in scientific literature and are useful. However, care in interpretation is required as many are based on anecdotal observations rather than scientific instrumentation. Although such data is highly variable in quality, when taken with instrumental and coastal stratigraphic records, they can provide a useful longer-term context for identification of trends and changes in storminess. Geological evidence for the 2000 years prior to the advent of historical records and later instrumental records is also sometimes useful. Studies of geological evidence for storminess change have examined the record of sand dune movement (eg Gilbertson et al., 1999; Dawson et al., 2004). These studies consider the stratigraphic record of blown sand horizons within peat and / or episodes of sand movement associated with archaeological evidence. Recent work in Denmark (Goslin et al., 2018; 2020) maintains that in the North Atlantic millennial to centennial periodicities in storminess can be recognised. A second approach is to study cliff top storm deposits, notably in Shetland (eg Hansom

and Hall, 2009), but thus far only the most recent events have been recognised and longer-term frequency of storms not determined.

5.4 Coastal flooding databases

54. In order to better understand historical magnitudes and footprints of coastal flooding events, a UK wide systematic database of extreme sea level and coastal flooding has been compiled, covering the last 100 years (Haigh et al., 2015; SurgeWatch, 2018). Using records from the UK National tide gauge network, all sea levels that reached or exceed the 1 in 5 year return level were identified. These were attributed to 96 distinct storms, the dates of which were used as a chronological base from which to investigate whether historical documentation exists for a concurrent coastal flood. For each event the database contains information about: the storm that generated that event; the sea levels recorded during the event; and the occurrence and severity of coastal flooding that resulted. This database is continuously updated.

6 USE OF STATISTICAL METHODS IN ANALYSIS OF COASTAL FLOODING HAZARD

55. The need for consistent and improved national estimates of extreme sea levels, combined with the increase in available sea level data since previous national studies by Dixon and Tawn (1994; 1995; 1997), led to the production of an updated UK database of extreme sea levels (Batstone et al., 2013; Environment Agency, 2011; Environment Agency, 2018). A new method termed the Skew Surge Joint Probability Method (SSJPM) was used with the aim of correcting inadequacies associated with previous methods. Methods to derive extreme sea levels have evolved with advances in the understanding and modelling of tide and surge processes and improvements in recorded data quality and length (see Batstone et al., 2013, for a complete description).

56. Joint Probability Methods (JPM) produce probability distributions of two or more conditions occurring simultaneously. JPM is commonly used in flood management (eg Defra/Environment Agency, 2005) since many flood hazards depend on more than one variable. For coastal flooding, the distribution of extreme sea levels for a given location is obtained by combining statistically the separate distributions of tides1 and storm surges (and in some cases waves too). When storm surges are involved, JPMs are superior to other methods of sea level extreme estimation (Tawn, 1992) because they use all the storm surge data in a tide gauge record. JPMs are essential in environments where the tidal signal is of comparable magnitude to the storm surge (Haigh et al., 2010) and are also superior to threshold-driven methods (eg Tebaldi et al., 2012) which may not detect large storm surges on small tides. The first-order independence of skew surge and tidal high water (Williams et al., 2016) removes the need for artificial statistical functions or multivariate approaches to the estimation of extreme sea levels. However, the seasonal relationships that exist between tidal high water and skew surges could be represented by multivariate, or other more complex (Kergadallan et al., 2014) methods. The best known illustration of seasonal coincidence is that around the UK the biggest tides of any year occur at the equinoxes (in March and September) and there is more chance of stormy weather then than in the summer months.

57. In the SSJPM of Batstone et al. (2013), a parametric statistical model was used to estimate the upper tail of the skew surge distribution by fitting a generalised Pareto distribution (GPD) above a chosen threshold and using the empirical distribution of skew surges (from the observed tide gauge record) below this threshold. A high quantile (97.5%) was chosen as the threshold based on exploratory analysis of each dataset. For each tide gauge analysed, the two parameters of the GPD were estimated using the method of maximum likelihood. The probability distribution of extreme sea levels was evaluated by combining the deterministic tidal high waters with the statistically derived skew surge distribution, assuming the two to be independent to first order. This was proposed by Batstone et al. (2013) and confirmed in a wider analysis for the North Atlantic by Williams et al. (2016).

58. Extreme sea levels derived in this way are assigned a Return Period (RP) which describes the probability of a particular level being exceeded in any one year. For

[1] Whilst tides are deterministic one can still generate a probability distribution of a particular height occurring over a given period.

example, the 1 in 1000 year return level is the level whose probability of being exceeded in any year is 1/1000, or 0.1%. As with all probabilities, great care must be taken in interpreting RPs: the fact that a particularly elevated sea level has recently occurred does not preclude another happening the following week due to the nature of the weather and the tendency for higher than average tides to occur with known periodicity. So, a period of stormy weather around extreme high tides (eg during the equinoxes of March and September) could easily result in successive 10 or 50 year return levels.

59. For the SSJPM, uncertainties are expressed in terms of upper and lower 95% confidence limits. These can be calculated using a so-called boot-strapping technique, whereby thousands of synthetic time series of skew surges are created from the derived skew surge probability density function. Each of the synthetic time series is then used to derive a new skew surge probability distribution. For each return level, the 2.5 and 97.5 percentiles of the ensemble of generated values are used to define the 95% confidence interval. It should be noted that the range of uncertainty associated with the 10,000 year return period can be very high, typically 1-2 m. This is unavoidable with a data-driven method where tide gauge records are typically a few tens of years and seldom provide more than 100 years of data. The largest source of uncertainty is the calculation of the GPD parameters associated with the upper tail of the skew surge distribution; other sources of uncertainty for UK extreme sea level estimates are described in detail by Batstone et al. (2013).

60. Temporal sequences of extreme sea levels (eg clusters of several storms in a short period of time, or prolonged sequences over longer timescales) can have a cumulative effect, leading to amplified flood damages due to attritional effects on defences, and inadequate recovery time of natural (eg beaches) and human elements within the system (Wadey et al., 2014). At a single location, the statistical significance of storm clustering is accounted for by a parameter called the extremal index. This ensures that a single storm only contributes once to the statistical method, even if it spans more than one tidal cycle. Estimates of extreme sea levels may be improved further by the development and use of statistical methods that represent the combined spatial footprint (areal extent) and clustering of storm events. Recent research (Environment Agency, 2021) highlights statistical techniques that account for the risk of widespread flooding from multiple sources.

61. Tide gauges are the best source of sea level data that can be used in the statistical methods described. However, tide gauges are geographically sparse and hydrodynamic models can be used to simulate sea levels between gauged sites, in order to determine how extremes are likely to vary from one gauge to the next. In the most recent national evaluation of extreme sea levels (Environment Agency, 2018), the primary estimates were derived using tide gauge data and SSJPM and then coastal ocean models were used to interpolate estimates of extreme sea levels at intermediate locations.

62. A further consideration for extreme water levels is the combination of extreme still water level (ie the tide plus storm surge) with large waves and their subsequent overtopping of defences. There are generally two types of methods employed; deterministic design-storm approaches that use joint exceedance contours with a specified annual exceedance probability, and risk-based approaches. It is well-

established that design-storm approaches do not facilitate a direct estimate of the annual exceedance (return period) of wave overtopping rates and the associated flood hazard. This method tends to underestimate flood hazards unless correction factors are applied (HR Wallingford, 2000, Defra/EA, 2005, Gouldby et al., 2014; 2017). Risk-based methods provide a direct estimate of annual exceedance overtopping rates and related flood hazards.

63. Within extreme wave and sea level joint probability analyses, the statistical modelling is typically undertaken offshore in deep water. This minimises the potential for physically implausible extrapolations (which are likely in the nearshore region). When the analysis is conducted offshore, wave heights are often derived from numerical models (eg the Met. Office European Wave Model) or even offshore wave measurements. These offshore conditions must be transformed to the nearshore taking account of various physical processes, using an appropriate wave model such as Simulating WAves Nearshore (SWAN) (Booij et al., 1999), see Section 8 for more detail. The marginal extreme wave heights can be derived at specific offshore model locations by fitting a GPD to the model data.

7 ANALYSIS OF COASTAL FLOODING HAZARD - STILL WATER LEVEL

64. The most recent projections of sea level change for the UK are set out in the UKCP18 Marine Report (Palmer et al., 2018). For full details, see the Palmer et al. (2018) report and follow links to data from the UKCP18 web pages. All UKCP18 projections are presented in a probabilistic manner. Future sea-level rise for any given scenario is presented based on the 5th to 95th percentile range of the underlying model distribution (ie a 90% confidence interval). Central estimates presented in UKCP18 are the median (50th percentile) value from model distributions. As an illustration, Figure 2 below shows the range of projected sea-level rise over the 21st century for the three RCPs.

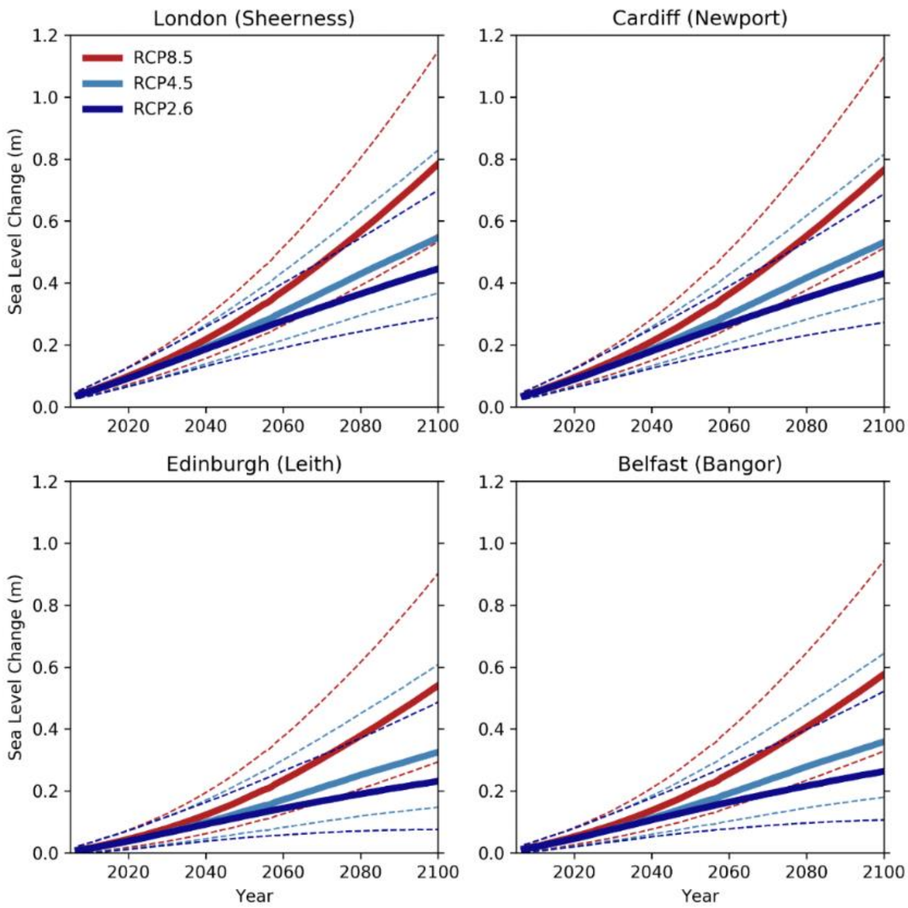

Figure 2.
21st century projections of mean sea level for the UK capital cities under three RCPs. Central estimates are shown by the solid lines and the dashed lines indicate the 5th and 95th percentiles. (Reproduced from UKCP18 Marine Report, with permission)

65. The sea-level rises shown in Figure 2 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 a 15-member ensemble of GIA estimates from the NERC BRITICE_CHRONO project (http://www.britice-chrono.group.shef.ac.uk/)

66. On the basis of the UKCP18 projections, the Environment Agency has updated its sector-specific flood and coastal risk guidance documents (Environment Agency, 2020), as has the Scottish Environment Protection Agency (2019). The Welsh

Government is currently reviewing its climate change guidance (Natural Resources Wales, 2018) to align with UKCP18 data.

67. UKCP18 does not contain the so-called H++ or “high-plus-plus” scenarios that were used in UKCP09 (Lowe et al., 2009) and which were designed to provide plausible but unlikely high-end sea-level rise scenarios for planning purposes. However, some guidance (eg Environment Agency, 2020) still refers to the use of the old H++ scenarios for sensitivity tests that apply to, “developments that are very sensitive to flood risk, and with lifetimes beyond the end of this century”. New high-end scenarios are being developed by current research which aims to provide an attributional approach to high-end sea levels (eg specifying the exact amount of sea-level rise that could result from a complete collapse of the Greenland ice sheet).

68. The IPCC Fifth Assessment Report of Working Group I (IPCC, 2013) recognises the possibility of future sea-level rises beyond the likely range of the process-based models. Only the collapse of large 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) assigned medium confidence to this additional contribution not exceeding 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 (eg Levermann et al., 2014). Since IPCC AR5, uncertainty around high-end sea-level rises due to the Antarctic component has increased (Bamber et al., 2019) due to divergent results of recent studies, and new hypotheses concerning potential ice sheet processes. In a study that relied on structured expert judgement, Bamber et al. (2019) obtained sea-level rise estimates exceeding 2m at the 95th percentile, for a 5°C temperature increase (ie unchecked emissions). Their findings support the use of scenarios of 21st century sea-level rise exceeding 2 m for planning purposes and are thus consistent with UKCP09 H++ scenarios.

69. 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 states that there is low confidence in region-specific projections of storminess and associated storm surges (due to limitations of current climate models to simulate extreme winds). UKCP18 carried out projections of storm surges that made use of CMIP5 simulations under scenario RCP8.5 that were then downscaled by regional atmospheric models (Jacob et al., 2014). UKCP18 only used the most severe climate scenario for extremes, in an attempt to maximise any climate change signal. Two of the downscaled simulations showed coherent signals but disagreed on the sign of any change to the skew surge, whilst the other three simulations showed weaker and less coherent trends. On the basis of these inconclusive results, UKCP18 proposed a best estimate of zero change in skew surge over the 21st century.

70. Substantial rises in mean sea level are likely to result in changes to the shelf sea tides. The change in mean sea level affects the phase speed of the tidal wave, which in turn modifies the tidal resonance in the European shelf seas. Any modification to the tide is highly spatially variable, but in places the change in tidal amplitude can be as much as 20% of assumed mean sea-level rise. This could lead to some local changes (increases or decrease) in the spring tidal range of over 0.2 m, if a mean

sea-level rise of 1 m were obtained. A recent Rapid Evidence Assessment (Environment Agency, 2020) acknowledges that coastal flood risk assessments currently fail to include changes in the astronomical tide, and recommends that new guidance includes consideration and better quantification of tides changing due to mean sea-level rise.

71. It is very likely that global mean sea-level rise will continue beyond the 21st century. The thermal expansion of the ocean to increased temperatures takes place over centuries to millennia; so thermal expansion will continue beyond 2100 even if greenhouse gas concentrations are stabilised immediately. UKCP18 presents exploratory projections of mean sea level out to 2300. This naturally involves more uncertainty than the projections out to 2100. The longer-term projections contained in recent literature are consistent for low to medium greenhouse gas concentration scenarios (RCP2.6, RCP4.5), but offer differing estimates under the high emissions scenario, with values at 2200 under RCP8.5 ranging from about 1 m (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 1.0 m (RCP2.6) to greater than 2.5 m (RCP8.5) with large spatial variations.

8 ANALYSIS METHODS FOR SHORELINE EVOLUTION, NEARSHORE WAVE TRANSFORMATION AND INTERACTION (FOR THE DESIGN OF FLOOD DEFENCES AND UNDERSTANDING COASTAL EROSION)

72. Analysis of the interaction between coastal sea levels (tides, storm surges, wave conditions) and the local shoreline for the purpose of designing flood defences is necessarily site-specific, and considers smaller scales and local processes. An overview of typical coastal defence structures found in the UK relevant to the analysis of coastal flooding and erosion at UK nuclear sites is given in Annex 3 of TAG 13 (ONR, 2018a). Understanding local transformational processes on waves and currents requires the best available local data for bathymetry, topography and sediment type. Significant changes to coastal geomorphology can occur over timescales of 10-100 years, and shoreline analysis uses coupled hydrodynamic and sediment transport models to assess plausible future bathymetric and topographic scenarios. For model simulations to be effective, they must be based on the best possible data for bathymetry and sea bed material, forced by realistic worse case scenarios of sea level and meteorological conditions. Different future geomorphologies can result in significantly different nearshore wave fields impinging on engineering structures.

73. Long term (order 100 years) coastal erosion rates for the coast of England and Wales have been provided by the Foresight Flood and Coastal Defence Project (Foresight, 2004) and results suggest that 28% of the coast is experiencing erosion rates in excess of 10 cm per year (Burgess et al., 2007). However, Burgess et al. (2002) argue that 67% of the coastline is under threat since a significant fraction of the coastline is held in position by engineering measures. Where a coastline is constrained by backshore structures, increases in sea level result in a steepening of the intertidal beach profile, known as coastal squeeze. The importance of coastal squeeze was recently reviewed by the Environment Agency, confirming the importance focus on habitat and ecosystem services that are being ‘squeezed’ and approaches to managing coastal squeeze (Ponte et al, 2019). The authors defined coastal squeeze as follows:

“Coastal squeeze is the loss of natural habitats or deterioration of their quality arising from anthropogenic structures, or actions, preventing the landward transgression of those habitats that would otherwise naturally occur in response to sea-level rise (SLR) in conjunction with other coastal processes. Coastal squeeze affects habitat on the seaward side of existing structures.”.

74. According to Taylor et al. (2004), almost two-thirds of intertidal profiles in England and Wales have steepened over the past hundred years. Shoreline Management Plans (SMPs) across England and Wales provide some recognition of this and promote a ‘Managed Realignment’ policy for around 9 percent of the coastline by 2030, rising to 14 percent by 2060 (CCC, 2013) but little realignment has been delivered to date. Analysis by Sayers (2018) for the CCC suggest that for some locations where ‘hold the line’ is the current policy, the economic case for longer term protection is low (of those that anticipate major investment in shoreline management - greater than £25m Present Value - between 130-150km may not be cost effective to implement, achieving a Benefit-Cost Ratio, BCR, less than 1). The inference from this is that significant areas currently operating under a ‘Hold the Line’ policy may need to be realigned. Any changes in the management of the adjacent

coast impacts the updrift and downdrift coast – both in sediment supply and possible outflanking. Understanding the future regional coastal setting is important for long term planning.

75. Several predictive models have been developed to improve our understanding of coastal erosional processes, and these models tend to focus on particular typologies of coastlines. A full review of coastal evolution models for different coastal types is given by Masselink and Russell (2013) and recently the Environment Agency published a review of morphological modelling approaches for decision makers, providing a high level but useful context (Blanco et al., 2019). The Soft Cliff and Platform Erosion (SCAPE) model (Walkden and Hall, 2005) was used to assess erosion in Essex and predicted that a tripling in sea-level rise (from 2 mm to 6 mm per year) resulted in a 15% increase in cliff recession. The same model has been used to develop climate change and management scenarios for the Norfolk coastline (Walkden et al., 2008). Brooks et al. (2012) applied SCAPE to the Suffolk coast and predicted that volumes of sediment released by erosion in the 21st century due to mean sea-level rise will increase by about an order of magnitude above the sediment release estimates for the early 20th century. All these results convey the physical fact that increased sea levels will expose increased areas of soft cliff to wave action.

76. Different modelling approaches are applied to morphological change in estuaries. One widely used example is the ASMITA model (Aggregated Scale Morphological Interaction between Inlets and Adjacent coast; Stive et al., 1998) which represents the estuary as a series of morphological elements (tidal flat, channel, etc). This model has been applied to the Thames estuary where it predicted that over the next century the estuary will experience accretion less than the predicted rate of sea-level rise, resulting in a deepening of the estuary by up to 0.5 m (Rossington and Spearman, 2009).

77. Having defined any future, plausible coastline, evaluating the interaction of extreme nearshore wave conditions with coastal topography and defences requires offshore wave fields to be transformed using a suitable wave transformation model. As offshore waves enter shallower water they are modified by a number of physical processes (eg diffraction, refraction, shoaling, wave breaking) as well as influences of local winds and tidal currents. Consequently, the waves impinging on coastal structures can have very different properties to offshore waves. A recent and thorough review of wave transformation models has been provided by Lawless et al., (2016), as part of a wider review of best practice for coastal flood forecasting, commissioned by the Environment Agency. This guidance document also lays down required standards of accuracy for all elements of sea level forecasting (tide, surge, wave, overtopping) and is intended to maximise consistency in coastal flood forecasting across the spectrum of models used by coastal engineers. The role of these models is described briefly below, but refer to Lawless et al. (2016) for more details.

78. Phase-averaging spectral wave models such as SWAN, (Booij et al., 1999) compute the two-dimensional (2D) wave spectral energy in a similar way to offshore wave models by solving the action balance equation. They can be run on either a regular or irregular grid and they derive wave parameters such as significant wave height, wave period and wave direction. These models are forced at their seaward boundary

by offshore wave and wind conditions, and they represent the majority of wave transformation processes. Other models in this class include MIKE21-SW (MIKE, 2018), STWAVE (AQUAVEO, 2018) and TOMAWAC (open TELEMAC-MASCARET, 2018). These models typically resolve bathymetric features of ~100 m size but are not routinely used at finer resolution due to computational intensity. A common approach – so-called hybrid approach - is to combine a wide area 2D wave model with a series of one-dimensional (1D) wave models to transform waves from the tidal low water contour to specific beaches or structures.

79. More complex wave transformation models, so-called phase-resolving models, exist to account explicitly for diffraction and refraction by solving the mild slope equation. Explicit representation of individual waves is also possible but is computationally demanding. A full list of this type of model is provided by Lawless et al. (2016). Because these models simulate individual waves, their spatial resolution is typically a few metres. This renders them suitable for the analysis of specific sites (and the effect of specific waves), but not wide area forecasting.

80. Wave transformation models depend on accurate bathymetry. To model the transformation from offshore to a specific structure will normally require some combination of charted bathymetric data (eg from Admiralty or other surveys) and accurate beach profile data from LiDAR. For many parts of England and Wales, LiDAR data is held by the Environment Agency (see Section 5.1 of this document).

81. Wave transformation models require careful validation, based on a selection of storm events. Ideally, waves inshore will be measured with suitable devices (eg Waverider buoys). Measured wave data for the UK is available from WaveNet, the Met. Office and the Channel Coastal Observatory. Hindcast waves and atmospheric forcing can be derived from the operational Wavewatch III model run at the UK Met. Office.

82. A number of studies have shown that joint probability contouring approaches, that use a joint exceedance approach to define annual exceedance contours of waves and sea levels, do not facilitate a direct estimate of the annual exceedance of structural responses (eg wave overtopping rate) and the related flood hazard (HR Wallingford, 2000; Defra/EA, 2005; Gouldby et al., 2017). The joint probability contouring approach tends to underestimate flood risk unless correction factors are applied to account for this known discrepancy. To obtain an unbiased estimate of coastal flood hazards, it is necessary to adopt a risk-based approach. In this approach, the multivariate extreme value distribution is integrated over the outcome variable of interest (eg wave overtopping or floodplain flood depth). The JOIN-SEA software was developed to implement this approach (HR Wallingford, 2000). More recently, advances in the underlying statistical models (Heffernan and Tawn, 2004) have been applied to asses coastal flooding using a risk-based approach at a national scale. Offshore waves, winds and sea levels have been extrapolated to extremes, these have then been transformed to the nearshore and through to overtopping rates using the SWAN wave model combined with statistical emulators and an empirical wave overtopping model to directly estimate wave overtopping annual exceedance probabilities and the related flood risk. Gouldby et al. (2017)

used a statistical emulator and the SWAN model to derive a national set of extreme events at a 1 km resolution in the nearshore region.

83. Extreme combinations of waves and sea level lead to wave overtopping which occurs when waves run up the face of a seawall or dike and pass over the crest of the structure (so-called ‘green-water’). In cases where the structure is vertical, the wave may impact against the wall and send a plume of water over the crest. A different form of overtopping occurs when waves break on the seaward face of the structure and produce significant volumes of splash and spray, which may then be carried over the wall either under their own momentum or by an onshore wind. Whether overtopping discharges are by green-water, plume or splash, the consequences will tend to vary according to circumstances. Typically, green-water and plume overtopping will be associated with flood inundation and structural damage, whereas spray will be associated with personal safety and also incremental damage to buildings.

84. Analysis of wave overtopping of structures is complex and there are a range of prediction methods that are adopted in practice, all of which are complex and have associated uncertainties. These methods include structure-specific empirical formulae detailed within the EurOtop manual (Pullen et al., 2008; EurOtop, 2018), generic empirical metamodeling approaches involving neural networks (eg Van Gent et al., 2007; Kingston et al., 2008; Zanuttigh et al., 2016), numerical models (also referred to as Computational Fluid Dynamics or CFD models) that solve the full 3D Navier Stokes Equations (Hirt and Nichols, 1981; Chen et al., 2016; and Dimakopoulos et al., 2014), and finally laboratory based, scaled physical model experiments. All of the empirical approaches are based on functions fitted to data from physical model experiments. This is because measured overtopping rates are rare and laboratory data is generally considered the next most reliable source of data. The empirical EurOtop (2018) methods are generally applicable when the structures are of common geometry (eg a simple slope, recurved wall etc). Where structures deviate from these common geometries (to include complex features, for example multiple berms), the meta-modelling approaches are often employed as they facilitate interpolation to non-standard geometry. Numerical models that simulate the physical processes can be challenging to calibrate and these are often employed in parallel with physical models.

85. The rate of wave overtopping is generally presented as a mean discharge per metre run of seawall, averaged over approximately 1000 waves. Whilst mean discharge is convenient for analysis of flood volume, the instantaneous hazards to people or building damage are more closely correlated to individual wave volumes and / or velocities. For the analysis of individual wave overtopping volumes and velocities, CFD and physical models offer the most robust estimates

86. In response to external loads, coastal infrastructures exhibit a range of failure modes (ie processes that influence the integrity of the defence in a way that has the potential to lead to failure – for example a breach – during a storm). The relationship between the external load and the conditional probability of failure (given that load) is often referred to as a ‘fragility curve’. Wave overtopping, for example, is a primary consideration in determining the chance of failure at most coastal locations, as it may erode the grass cover of the rear face or scour rear toe and ultimately lead to

breach. Various documents provide advice on the relationship between different loading conditions and the failure modes they may influence. For example, ‘safe’ overtopping conditions and good practice design principles are set out in the ‘Rock Manual’ (CIRIA, 2007). It is however often the case, that ‘failure’ of sea defence is not caused by one single failure mechanism or loading condition but by several processes. Process-based failure analysis and failure trees all offer insights into the most important failure modes at a given location when used appropriately and supported by expert understanding and data (eg Kortenhaus, 2012)

9 ANALYSIS OF TSUNAMI HAZARD

87. For the UK and Europe there are records of several past events of significance, notably, in historical times, the earthquake of 1st November 1755 and the ensuing tsunami that, together, destroyed Lisbon. There is also firm geological evidence for the source region and the effects of a major tsunami impacting the coasts of Scotland and northeast England following a submarine landslide offshore Norway about 8150 years ago. The evidence that tsunamis have reached the UK in the past indicates that the possibility of significant future events cannot be dismissed. Also, there may be other potential sources of future tsunami.

88. The Defra (2005) study found that a tsunami reaching the UK from the Azores-Gibraltar region (the region responsible for the earthquake and tsunami causing the destruction of Lisbon in 1755) is a possible event. However, the likelihood of a future tsunami from this source being worse than that of 1755 is negligible since the consensus of literature concerning the Lisbon earthquake already ascribes it the largest possible magnitude (M8.7) outside of subduction zones. A tsunami resulting from a landslide on the Canary Islands would be heavily dependent on the nature of the collapse. Some reports (eg Ward and Day, 2001) have suggested that the western flank of La Palma, in the Canary Islands, is vulnerable to collapse, with devastating effects around much of the North Atlantic coastline. Whether a tsunami generated by a flank collapse was capable of crossing large distances or not would depend entirely on the nature of the event; a coherent large block entering the sea with high acceleration would produce such an effect, but if the slope failure were composite or less energetic, the effects produced would be local. Studies of the offshore turbidites created by landslides from the flanks of the Canary Islands suggest that these result from multiple landslides spread over periods of several days. Separate failures occurring over this time scale would each generate a discrete tsunami, but these successive failures are too widely spaced in time to have a cumulative effect on tsunami magnitude (Wynn and Masson, 2003). All the submarine landslides so far studied in detail around the Canary Islands indicate that they are multiple events, implying smaller scale tsunamis. The results of the tsunami propagation modelling carried out in Defra (2005) are summarised in Table 2 below.

89. Geologically, an earthquake in the North Sea sufficiently large to cause a tsunami is possible although there is no record of any such event. A model of a credible North Sea event centred on the location of the 1931 earthquake gave wave heights along eastern UK coasts of 1-2 m.

90. To provide a more detailed assessment of the potential hazard, the Defra (2006) study focused on a near coastal North Sea event and a more detailed analysis of a Lisbon 1755 type event. The model studies of the Lisbon 1755 event explored the effects of a variety of plausible earthquake magnitudes and fault orientations. Larger magnitude earthquakes produced tsunami waves with typical wave amplitudes of 1-2 m around the south west of the UK, with 3-4 m waves in localised bays. Whilst the size of these tsunami waves is comparable to those in typical storm surges, certain characteristics of tsunamis are likely to create sea conditions different to those during a storm surge. The model study of the near-coast event in the North Sea was centred on the location of the 1931 earthquake (Versey, 1939), with an assumed magnitude of M6.0. The resulting tsunami was propagated through high resolution

storm surge and wave models in order to estimate the wave run up and inundation on a variety of beach slopes.

91. The model results were used to assess hazard at the coastline. As the tide did not interact with the tsunami wave, the analysis made the most conservative assumption that any tsunami could coincide with the highest possible tides. The tsunami elevations around the coast were compared against 50 year and 100 year return period extreme sea levels. Only the south west coast of the UK was found to incur sea level elevations slightly in excess of the 1 in 100 year extreme sea level predictions (and it should be noted that the default standard for coastal engineering is the 200 year return period). A further assessment of hazard reviewed the wave elevation and flow velocity at the still water level for the tsunami wave as it ran up and down typical beaches. The hazard for beaches for the hypothetical North Sea tsunami was classified as low, but the hazard for beaches in Cornwall and Devon was classified as dangerous for a M8.7 Lisbon 1755 type tsunami. Although only the most south-westerly coast of the UK might incur sea level elevations marginally in excess of the 1:100 year extreme sea level predictions, the inundation potential of any tsunami is greater due to its long wavelength. Furthermore, flow velocities on inundated areas are potentially higher during tsunami incidence.

Tsunami source	Height and propagation time of wave reaching the coast, regions affected and (assumed amplitude of wave at its origin)
Near field earthquake in North Sea (cf. Dogger Bank, 1931)	Height: 0.8-2 m Propagation time: 1-2 hours Regions Affected: Yorkshire and Humberside coasts (Assumed wave amplitude at origin: 1 m)
Passive margin earthquake in the western Celtic Sea	Height: 0.5-1 m Propagation time:3-6 hours Regions Affected: North Devon, Bristol Channel, South and West Wales (Assumed wave amplitude at origin: 1 m)
Plate boundary west of Gibraltar (Lisbon earthquake of 1755)	Height: 0.8-1 m Propagation time:5-8 hours Regions Affected: Cornwall, North Devon and Bristol Channel, South Wales(Assumed wave amplitude at origin: 1 m)
La Palma slide (Canary Islands)	Height: 1-2 m Propagation time:7-8 hours Regions Affected: Cornwall, North and South Devon (Assumed wave amplitude at origin: 2 m)

Table 2 Results from the tsunami modelling exercise in Defra (2005) with the most plausible tsunami sources for the UK

92. The importance of landslide generated tsunami on UK coasts is unclear. Much interest surrounds the tsunami generated by the Storegga Slide - a submarine landslide, or submarine mass failure, that occurred approximately 8150 years ago on the Norwegian continental shelf and slope. The portion of seafloor that fractured and moved downslope was approximately 200 miles wide, up to 3200 km^3 and affected an area of sea floor of 95,000 km^2.

93. Mapping of tsunami deposits show that this landslide generated a tsunami that reached the northern UK coastline. To date, evidence for the tsunami has been identified at over 30 sites from northern Scotland to north-eastern England (eg Smith et al., 2004). Measurements of the sediment run-up of the tsunami on the mainland Scottish coast range from 0-6 m locally above the contemporary shoreline, and up to tens of metres on Shetland, but actual water depths in which the sediments accumulated were several metres higher (eg Smith et al., 2007; Soulsby et al., 2007). Other possible tsunamis are registered on Shetland and dated at c. 5500 years ago and c.1500 years ago (Bondevik et al., 2005a; 2005b), but their singularity on Shetland alone renders them uncertain (Long and Wilson, 2007; Long, 2015; Tappin et al., 2015). Thus, so far, the Storegga Slide tsunami is the only landslide generated tsunami confirmed to have occurred on mainland UK coasts.

94. The Storegga slide is of course only one of several slides along the continental slope west of the UK and Norway, most of which occurred in glacial sediments, but the frequency of sliding is as yet unclear. Neither is it clear if any of the other slides generated tsunamis that reached the UK.

10 REFERENCES

Alexander, L.V., Tett, S.F.B. and Jonsson, T. (2005) Recent observed changes in severe storms over the United Kingdom and Iceland. *Geophysical Research Letters*, 32, L13704, pp.1-4, doi:10.1029/2005GL022371

Allen, R., Tett, S. and Alexander, L. (2008) Fluctuations in autumn-winter storms over the British Isles: 1920 to present, *International Journal of Climatology*, 29, pp. 357-371, doi: 10.1002/joc.1765

AQUAVEO (2018). STWAVE Nearshore Wave Modeling with SMS. https://www.aquaveo.com/software/sms-stwave

Bamber, J.L., Oppenheimer, M., Kopp, R.E., Aspinall, W.P., and Cooke, R.M. (2019) Ice sheet contributions to future sea-level rise from structured expert judgment. Proceedings of the National Academy of Sciences, 116 (23) 11195-11200; DOI: 10.1073/pnas.1817205116

Batstone, C., Lawless, M., Tawn, J., Horsburgh, K., Blackman, D., McMillan, A., Worth, D., Laeger, S. and Hunt, T. (2013) A UK best-practice approach for extreme sea level analysis along complex topographic coastlines. *Ocean Engineering*, 71, pp.28-39, http://dx.doi.org/10.1016/j.oceaneng.2013.02.003

Bindoff, N.L., Willebrand, J., Artale, V., Cazenave, A., Gregory, J.M., Gulev, S., Hanawa, K., Le Quéré, C., Levitus, S., Nojiri, Y., Shum, C.K., Talley, L.D. and Unnikrishnan, A. (2007) *Observations: Oceanic climate change and sea level. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (eds.)]. Cambridge University Press, Cambridge, UK, pp. 385-432.

Blanco, B.L.D.S.R., Woods Ballard, B., Simm, J., Brampton, A., Sutherland, J., Gouldby, B. and Rossington, K., (2019). Coastal morphological modelling for decision-makers. Report – SC090036/R. A report published by the Environment Agency. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/844082/Coastal_morphological_modelling_for_decision-makers_-_report.pdf

Bondevik, S., Mangerud, J., Dawson, S., Dawson, A.G. and Lohne, Ø. (2005a) Evidence for three North Sea tsunamis at the Shetland Islands between 8000 and 1500 years ago. *Quaternary Science Reviews,* 24 (14-15), pp.1757-1775, https://doi.org/10.1016/j.quascirev.2004.10.018

Bondevik, S., Løvholt, F., Hartbitz, C., Mangerud, J., Dawson, A.G. and Svendsen, J.I. (2005b). The Storegga Slide tsunami – comparing field observations with numerical solutions. *Marine and Petroleum Geology*, 22, pp.195-208, https://doi.org/10.1016/B978-0-08-044694-3.50021-4

Bondevik, G. 2019. Tsunami from the Storegga landslide. In: Meyers, R.A. (ed.) Encyclopaedia of Complexity and Systems Science.

Booij, N., Ris, R. C. and Holthuijsen, L. H. (1999), A third-generation wave model for coastal regions, Part I: Model description and validation, *Journal of Geophysical Research*, 104, C4, pp.7649-7666.

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

Buijs, F. A., Hall, J. W., Sayers, P. B. and Van Gelder, P. (2009). Time-dependent reliability analysis of flood defences. Reliability Engineering and System Safety, 94(12), pp. 1942-1953.

Burgess, K., (2020). Impact of climate change on asset deterioration. Report - SC120005/R1. Published by the Environment Agency.

Burgess, K., Orford, J.D., Dyer, K., Townend, I. and Balson, P. (2002) *FUTURECOAST - The integration of knowledge to assess future coastal evolution at a national scale*. Proceedings 28th International Conference on Coastal Engineering, ASCE, 3221-3233.

Burgess, K., Jay, H., Nicholls, R.J., Green, C. and Penning- Rowsell, E.C. (2007) *Assessment of future coastal erosion risk*. In: Future flooding and coastal erosion risks [Eds. Thorne, C., Green, C. and Penning-Rowsell, E.C.], Thomas Telford, London: 280-293.

Cabinet Office (2017) National Risk Register of Civil Emergencies. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/644968/UK_National_Risk_Register_2017.pdf

Coastal Engineering Research Center, Department of the Army, Waterways Experiment Station (1984) *Shore protection manual*. Available at: https://archive.org/details/shoreprotectionm01unit

Chen, Q., Kelly, D.M., Dimakopoulos, A.S. and Zang, J. (2016) Validation of the PICIN solver for 2D coastal flows, *Coastal Engineering*, 112, pp. 87-98, https://doi.org/10.1016/j.coastaleng.2016.03.005

Church, J.A. and White, N. (2011) Sea-level rise from the Late 19th to the Early 21st Century. *Surveys in Geophysics,* 32(4-5), pp. 585-602, doi:10.1007/s10712-011-9119-1

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.: 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, edited by: 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., Cambridge University Press, Cambridge, UK and New York, NY, USA, 2013.

CIRIA (2005). Management of accelerated low water corrosion. Published by CIRIA: Construction Industry Research and Information Association.

CIRIA (2007) Construction Industry Research, Information Association. The rock manual: the use of rock in hydraulic engineering. Vol. 683.

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

Dawson, A.G., Mcilvenny, J. and Warren, J. (2010) Winter gale day frequency in Scotland and the Faroes, AD 1866-1905: links to sea ice frequency and the North Atlantic Oscillation. *Scottish Geographical Journal,* 126(3), pp.141-152, https://doi.org/10.1080/14702541.2010.527857

Dawson, R. J. and Hall, J. W. (2006). Adaptive importance sampling for risk analysis of complex infrastructure systems. Proc. Royal. Society A, p. 462(2075): 3343–3362.

Dawson, S., Smith, D.E., Jordan, J. and Dawson, A.G. (2004) Late Holocene coastal sand movements in the Outer Hebrides, N.W. Scotland. *Marine Geology,* 210, pp.281-306, http://dx.doi.org/10.1016/j.margeo.2004.05.013

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

Defra (2013). Japanese knotweed, giant hogweed and other invasive plants. Published by Defra, London via https://www.gov.uk/japanese-knotweed-giant-hogweed-and-other-invasive-plants (accessed 20 March 2014).

Defra (2005) The threat posed by tsunami to the UK, Study commissioned by Defra Flood Management. http://webarchive.nationalarchives.gov.uk/20130123162956/http:/www.defra.gov.uk/environ/fcd/studies/tsunami/tsurpes.pdf

Defra (2006) Tsunamis – Assessing the Hazard for the UK and Irish Coasts, Study commissioned by the Defra Flood Management Division, the Health and Safety Executive and the Geological Survey of Ireland. http://webarchive.nationalarchives.gov.uk/20130123162956/http:/archive.defra.gov.uk/environment/flooding/documents/risk/tsunami06.pdf

Defra/Environment Agency (2005) Use of Joint Probability Methods in Flood Management. A Guide to Best Practice R&D Technical Report FD2308/TR2, March 2005, 77pp.

de Vries, H., Breton, M., de Mulder, T., Krestenitis, Y., Ozer, J., Proctor, R., Ruddick, K., Salomon, J. C. and Voorrips, A. (1995) A comparison of 2-D storm surge models applied to three shallow European seas, *Environmental Software*, 10(1), pp.23–42, https://doi.org/10.1016/0266-9838(95)00003-4

Dimakopoulos, A., Guercio, A. and Cuomo, G. (2014) Advanced numerical modelling of tsunami wave propagation, transformation and run-up. *Proceedings of the ICE - Engineering & Computational Mechanics*, 167(3), pp. 139-151

Dixon, M. and Tawn, J. (1994) Estimates of Extreme Sea Conditions. Extreme Sea levels at the UK A-Class Sites: Site-by-Site Analyses, Proudman Oceanographic Laboratory Report, 65, 228pp.

Dixon, M. and Tawn, J. (1995) Estimates of Extreme Sea Conditions. A Spatial Analysis of Extreme Sea levels, Proudman Oceanographic Laboratory Report, 72, 299pp.

Dixon, M. and Tawn, J. (1997) Spatial Analyses for the UK, Proudman Oceanographic Laboratory Report, 112, 200pp.

Environment Agency (2009) Flooding in England: A National Assessment of Flood Risk. Environment Agency report.

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/292928/geho0609bqds-e-e.pdf

Environment Agency (2011) Coastal Flood Boundary Conditions for UK Mainland and Islands. Project: SC060064/TR2: Design Sea levels. https://www.gov.uk/government/publications/coastal-flood-boundary-conditions-for-uk-mainland-and-islands-design-sea-levels

Environment Agency (2013). Assessment and Measurement of Asset Deterioration. Environment Agency, Bristol. Authors: Halcrow.

Environment Agency (2018) Coastal flood boundary conditions for the UK: update 2018, Technical summary report SC060064/TR6 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/827778/Coastal_flood_boundary_conditions_for_the_UK_2018_update_-_technical_report.pdf

Environment Agency (2020) Rapid Evidence Assessment of Non-Stationarity in Sources of UK Flooding. Report: FRS18087/REA/R1 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/935583/Rapid_evidence_assessment_of_non-stationarity_in_sources_of_UK_flooding_-_summary.pdf

Environment Agency (2020) Flood risk assessments: climate change allowances https://www.gov.uk/guidance/flood-risk-assessments-climate-change-allowances#what-climate-change-allowances-are

Environment Agency (2021) Spatial Coherence - Risk of Widespread Flooding (phase 1): Project SC060088/S. https://www.gov.uk/flood-and-coastal-erosion-risk-management-research-reports/spatial-coherence-risk-of-widespread-flooding

EurOtop (2018). Manual on wave overtopping of sea defences and related structures. An overtopping manual largely based on European research, but for worldwide application. Van der Meer, J.W., Allsop, N.W.H., Bruce, T., De Rouck, J., Kortenhaus, A., Pullen, T., Schüttrumpf, H., Troch, P. and Zanuttigh, B., www.overtopping-manual.com.

Feser, F., Barcikowska, M., Krueger, O., Schenk, F., Weisse, R. and Xia, L. (2015), Storminess over the North Atlantic and northwestern Europe—A review. Quarterly Journal of the Royal Meteorological Society, 141: 350-382. doi:10.1002/qj.2364

Foresight (2004) *Foresight Flood and Coastal Defence Project.* [online] Available at: http://webarchive.nationalarchives.gov.uk/20121206074428/http://www.bis.gov.uk/foresight/our-work/projects/published-projects/flood-and-coastal-defence

Gilbertson, D.D., Schwenninger, J.L., Kemp, R.A. and Rhodes, E.J. (1999). Sand-drift and soil formation along an exposed North Atlantic coastline: 14,000 years of diverse geomorphological, climatic and human impacts. *Journal of Archaeological Science*, 26(4), pp.439-469, https://doi.org/10.1006/jasc.1998.0360

Golledge, N. R., et al., (2015) The multi-millennial Antarctic commitment to future sea-level rise, *Nature*, 526, pp. 421–425.

Goslin, J., Fruergaard, M., Sander, L., Galka, M., Menviel, L., Monkenbusch, J., Thibault, N., Clemmensen, L.B. 2018. Holocene centennial to millennial shifts in North Atlantic storminess and ocean dynamics. Scientific Reports 8:12778, 12pp.

Goslin, J., Fruergaard, M.M., Sander, L., Galka, M., Manviel, L., Monkenbusch, J., Thibault, N., Clemmensen, L.B. 2020. Holocene centennial to millennial shifts in North Atlantic storminess and ocean dynamics. Scientific Reports 10:13529, 7pp.

Gouldby, B, Mendez, F.J., Guanche, Y., Rueda, A. and Minguez, R. (2014) A methodology for deriving extreme nearshore sea conditions for structural design and flood risk analysis, *Coastal Engineering*, 88, pp.15–26, https://doi.org/10.1016/j.coastaleng.2014.01.012

Gouldby, B., Wyncoll, D., Panzeri, M., Franklin, M., Hunt, T., Hames, D., Tozer, N., Hawkes, P., Dornbusch, U. and Pullen, T. (2017) Multivariate extreme value modelling of waves, winds and sea levels around the coast of England, Proceedings of the Institute of Civil Engineers – Maritime Engineering, 170(1), pp. 3-20.

Haigh, I., Nicholls, R. and Wells, N. (2009) Mean sea level trends around the English Channel over the 20th century and their wider context, *Continental Shelf Research*, 29(17), pp. 2083-2098.

Haigh, I., Nicholls, R. and Wells, N. (2010) Assessing changes in extreme sea levels: application to the English Channel, 1900–2006, *Continental Shelf Research*, 30(9), pp.1042–1055, https://doi.org/10.1016/j.csr.2010.02.002

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. http://dx.doi.org/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, doi:10.1038/sdata.2016.107

Hall, J., Sayers, P., Walkden, M. and Panzeri, M. (2006). Impacts of climate change on coastal flood risk in England and Wales: 2030–2100. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences.

Hallegatte, S., Green, C., Nicholls, R. J. and Corfee-Morlot, J. (2013) Future flood losses in major coastal cities, *Nature Climate Change*, 3, pp.802–806, http://dx.doi.org/10.1038/nclimate1979

Hansom, J.D. and Hall, A.M. 2009. Magnitude and frequency of extra-tropical North Atlantic cyclones: a chronology from Cliff-top storm deposits, *Quaternary International,* 195, pp. 45-52, https://doi.org/10.1016/j.quaint.2007.11.010

Heffernan, J. E. and Tawn, J. A. (2004) A conditional approach for multivariate extreme values (with discussion). Journal of the Royal Statistical Society: Series B (Statistical Methodology), 66, pp. 497–546, doi:10.1111/j.1467-9868.2004.02050.x

Hirt C.W. and Nichols B.D. (1981) Volume of Fluid (VOF) method for the dynamics of free boundaries. *Journal of Computational Physics,* 39(1), pp. 201-225, https://doi.org/10.1016/0021-9991(81)90145-5.

HM Government (2011). Climate Resilient Infrastructure: Preparing for a changing climate. Stationary Office Limited, London.

Horsburgh, K. J. and Wilson, C. (2007) Tide-surge interaction and its role in the distribution of surge residuals in the North Sea, Journal of Geophysical Research, 112, C08003, https://doi.org/10.1029/2006JC004033

Horsburgh, K., Ball, T., Donovan, B. and Westbrook, G. (2010). Coastal flooding in MCCIP Annual Report Card 2010-11, MCCIP Science Review, 10pp. www.mccip.org.uk/arc.

Horsburgh, K., Rennie, A. and Palmer, M. (2020) Impacts of climate change on sea-level rise relevant to the coastal and marine environment around the UK, MCCIP Science Review 2020, pp. 116–131. Doi: 10.14465/2020.arc06.slr

HR Wallingford (2000) The Joint Probability of Waves and Water Levels: JOIN-SEA – Version 1.0. Report TR 71 November 1998 (Re-issued with minor amendments May 2000)

IPCC (2013) 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, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2012) Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field, C.B., Barros, V., Stocker, T.F., Dahe, Q., Jon Dokken, D., Plattner, G-K., Ebi, K.L., Allen, S.K., Mastrandrea, M.D., Tignor, M., Mach, K.J. and Midgley, P.M. (Eds.)] Cambridge University Press, and New York, NY, USA, 582pp.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B., Bouwer, L. M., et al., (2014) EURO-CORDEX: new high-resolution climate change projections for European impact research. *Regional Environmental Change*, 14, pp. 563-578. https://doi.org/10.1007/s10113-013-0499-2

Karunarathna, H., Pender, D., Ranasinghed, O., Short, A. and Reeve, D. (2014). The effects of storm clustering on beach profile variability. Marine Geology.

Kergadallan, X., Bernardara, P., Benoit, M. and Daubord, C. (2014) Improving the estimation of extreme sea levels by a characterization of the dependence of skew surges on high tidal levels., *Coastal Engineering Proceedings*, 1(34), 48, pp.1-9.

Kingston, G., Robinson, D., Gouldby, B. and Pullen, T. (2008) Reliable prediction of wave overtopping volumes using Bayesian neural networks, Proc. FLOODrisk 2008: Flood Risk Management: Research and Practice, Oxford, Taylor & Francis Group, London, ISBN 978-0-415-48507-4

Kortenhaus, A., (2012). Performance of coastal flood defences. In Flood Risk: Planning, Design and Management of Flood Defence Infrastructure edited by P Sayers (pp. 103-123). ICE Publishing.

Lawless, M., Hird, M., Rodger, D., Gouldby, B., Tozer, N., Pullen, T., Saulter, A. and Horsburgh, K. (2016) Investigating coastal flood forecasting: good practice framework. Environment Agency report SC140007, Environment Agency, Bristol, UK, ISBN: 978-1-84911-385-4, 72pp.

Levermann, A., Winkelmann, R., Nowicki, S., Fastook, J. L., Frieler, K., Greve, R., Hellmer, H. H., Martin, M. A., Meinshausen, M., Mengel, M., Payne, A. J., Pollard, D., Sato, T., Timmermann, R., Wang, W. L., and Bindschadler, R. A. (2014) Projecting Antarctic ice discharge using response functions from SeaRISE ice-sheet models, *Earth System Dynamics*, 5, pp. 271-293. https://doi.org/10.5194/esd-5-271-2014

Long, D. and Wilson, C.K. (2007) Catalogue of tsunamis in the UK. British Geological Survey, Edinburgh.

Long, D. 2015. A catalogue of tsunamis reported in the UK. Energy and Marine Sciences programme, Internal Report IR/15/043. British Geological Survey, Edinburgh.

Lowe, J.A., Howard, T., Pardaens, A., Tinker, J., Jenkins, G., Ridley, J., Leake, J., Holt, J., Wakelin, S., Wolf, J., Horsburgh, K., Reeder, T., Milne, G., Bradley, S. and Dye, S. (2009) UK Climate Projections science report: Marine and coastal projections, Met Office Hadley Centre, UK, 99pp. http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=87905&

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, pp. 8115–8134. https://doi.org/10.1002/2015JC011173

Masselink, G. and Russell, P. (2013) Impacts of climate change on coastal erosion, MCCIP Science Review 2013, pp. 71-86, doi:10.14465/2013.arc09.071-086

Matthews, T., Murphy, C., Wilby, R. L. and Harrigan, S. (2014) Stormiest winter on record for Ireland and UK. *Nature Climate Change*, 4, pp.738–740.

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's Future,* 3, pp.66–81, https://doi.org/10.1002/2014EF000282

Meehl, G. A., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J.F., Stouffer, R.J., & Taylor, K.E., (2007) The WCRP CMIP3 multimodel dataset: A new era in climate change research, *Bulletin of the American Meteorological Society*, 88, pp.1383–1394, https://doi.org/10.1175/BAMS-88-9-1383

Meinshausen, M., Smith, S. J., Calvin, K. V., Daniel, J. S., Kainuma, M. L. T., Lamarque, J.-F., Matsumoto, K., Montzka, S. A., Raper, S. C. B., Riahi, K., Thomson, A. M., Velders. G. J. M., & van Vuuren, D., (2011) The RCP Greenhouse Gas Concentrations and their Extension from 1765 to 2300. *Climatic Change*,109(1-2), pp.213-241, https://doi.org/10.1007/s10584-011-0156-z

Menendez, M. and Woodworth, P.L. (2010) Changes in extreme high water levels based on a quasi-global tide-gauge dataset. *Journal of Geophysical Research*, 115, C10011, https://doi.org/10.1029/2009JC005997

Meteorological Office and Centre for Ecology and Hydrology. 2014. The Recent Storms and Floods in the UK. Natural Environment Research Council.

MIKE (2018). Wave modelling in oceans and coastal areas. https://www.mikepoweredbydhi.com/products/mike-21/waves

Mitrovica, J.X., Tamisea, M.E., Davis, J.L. and Milne, G.A. (2001) Recent mass balance of polar ice sheets inferred from patterns of global sea level change, *Nature*, 409(6823), pp. 1026-1029.

Mitrovica, J.X., Gomez, N. and Clark, P.U. (2009) The Sea level Fingerprint of West Antarctic Collapse, *Science*, 323(5915) pp.753.

Nicholls, R.J., French, J., Burningham, H., Van Maanen, B., Payo, A., Sutherland, J., Walkden, M., Thornhill, G., Brown, J., Luxford, F., Simm, J., Reeve, D.E., Hall, J. W., Souza, A., Stansby, P.K., Amoudry, L.O., Rogers, B.D., Ellis, M., Whitehouse, R., Horrillo-Caraballo, J.M., Karunarathna, H.U., Pan, S., Plater, A., Dix, J., Barnes, J. and Heron, E. (2015) Improving Decadal Coastal Geomorphic Predictions: An Overview of the ICOASST Project. Coastal Sediments 2015 (Proceedings of). ISBN: 978-981-4689-96-0

Natural Resources Wales (2018) Flood Consequence Assessments: Climate change allowances. www.gov.wales/sites/default/files/publications/2018-11/flood-consequence-assessments.pdf

Oltmanns, M., Karstenses, J., Moore, G.W.K., Josey, S.A. 2020. Rapid cooling and increased storminess triggered by freshwater in the North Atlantic. Geophysical Research Letters 47(14) 8pp.

ONR (2020). NS-TAST-GD-013 Rev. 8, Nuclear Safety Assessment Technical Guide: External Hazards.

ONR (2018a). NS-TAST-GD-013 Annex 3, Rev. 2: Coastal Flood Hazards.

ONR (2018b). NS-TAST-GD-013 Annex 2, Rev. 2: Meteorological Hazards.

Open TELEMAC-MASCARET (2018). TOMAWAC - Wave propagation in coastal areas. http://www.opentelemac.org/index.php/presentation?id=20

Osborn, T.J. (2004) Simulating the winter North Atlantic Oscillation: the roles of internal variability and greenhouse gas forcing. *Climate Dynamics*, 22, pp. 605-623. doi:10.1007/s00382- 004-0405-1

Ozsoy, O., Haigh, I.D., Wadey, M.P., Nicholls, R.J. and Wells, N.C. (2016) High-frequency sea level oscillations and implications for coastal flooding: a case study of the Solent, UK. *Continental Shelf Research*, 122, pp.1-13, https://doi.org/10.1016/j.csr.2016.03.021

Palmer, M., Howard, T., Tinker, J., Lowe, J., Bricheno, L., Calvert, D., Edwards, T., Gregory, J., Harris, G., Krijnen, J., and Roberts, C. (2018) UKCP18 Marine Report, Met Office Hadley Centre, Exeter, 175pp.

Pelling, H. E., Green, J.A.M. and Ward, S.L. (2013) Modelling tides and sea-level rise: To flood or not to flood, Ocean Modell., 63(0), 21–29, doi:10.1016/j.ocemod.2012.12.004.

Pickering, M., Horsburgh, K., Wells, N. and Green, 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.

Pontee, N., Pye, K., Tempest, J. and Blott, S., (2019). What is coastal squeeze? Project FRS17187. Published by the Environment agency. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/955318/FRS17187_What_is_coastal_squeeze_-_report.pdf

Prandle, D. and Wolf, J. (1978) The interaction of surge and tide in the North Sea and River Thames, *Geophysical Journal of the Royal Astronomical Society,* 55, 203–216, https://doi.org/10.1111/j.1365-246X.1978.tb04758.x

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

Pullen, T., Allsop, N.W.H., Bruce, T., Kortenhaus, A., Schüttrumpf, H. and Van Der Meer, J.W. (2007) EurOtop: Wave Overtopping of Sea Defences and Related Structures: Assessment Manual.

Rossington, K. and Spearman, J. (2009) Past and future evolution in the Thames Estuary. *Ocean Dynamics*, 59(5), pp.709-718, doi: 10.1007/s10236-009-0207-4

Rossiter, J. R. (1961), Interaction between tide and surge in the Thames, *Geophysical Journal of the Royal Astronomical Society*, 6(1), pp.29–53, https://doi.org/10.1111/j.1365-246X.1961.tb02960.x

Sayers PB (2018) Managing future coastal flood and erosion - Supporting analysis risk. Research undertaken by Sayers and Partners on behalf of the Committee on Climate Change. Published by Committee on Climate Change, London

Sayers, P. (2014) LWEC infrastructure Report card: https://nerc.ukri.org/research/partnerships/ride/lwec/report-cards/infrastructure-source06/

Sayers, P., Flickwert, J. and Kortenhaus, A. (2012). Supporting flood risk management through better infrastructure design and management. In: Flood Risk: Planning, design and management of flood defence infrastructure. Thomas Telford, London. ISBN 978 07277 4156 1

Scottish Environment Protection Agency (2019) Climate change allowances for flood risk assessment in land use planning, LUPS-CC1, Version 1, 2019. https://www.sepa.org.uk/media/426913/lups_cc1.pdf

Shaw, T.A., Baldwin, M., Barnes, E.A., Caballero, R., Garfinkel, C.I, Hwang, Y.-T., Li, C., O'Gorman, P.A., Rivière, G., Simpson, I.R. and Voigt, A. (2016) Storm track processes and the opposing influences of climate change, *Nature Geoscience*, 9(9), pp.656–664.

Shennan, I. and Bradley, S.L. and Edwards, R. (2018) Relative sea-level changes and crustal movements in Britain and Ireland since the Last Glacial Maximum, *Quaternary Science Reviews*, 188, pp.143-159.

Sibley, A., Cox, D., Long, D., Tappin, D. and Horsburgh, K. (2016) Meteorologically generated tsunami-like waves in the North Sea on 1/2 July 2015 and 28 May 2008. *Weather*, 71(3), pp.68–74, https://doi.org/10.1002/wea.2696

Smith, D.E., Shi, S., Brooks, C.L., Cullingford, R.A., Dawson, A.G., Dawson, S., Firth, C.R., Foster, I.D.L., Fretwell, P.T., Haggart, B.A., Holloway, L.K. and Long, D. (2004) The Holocene Storegga Slide tsunami in the United Kingdom. *Quaternary Science Reviews*, 23(23-24), pp. 2291-2321, https://doi.org/10.1016/j.quascirev.2004.04.001.

Smith, D.E., Foster, I.D.L., Long, D. and Shi, S. (2007) Reconstructing the pattern and flow onshore in a palaeotsunami from associated deposits. *Sedimentary Geology*, 200(3-4), pp. 362-371, https://doi.org/10.1016/j.sedgeo.2007.01.014

Smith, D.E., Hunt, N., Firth, C.R., Jordan, J.T., Fretwell, P.T., Harman, M., Murdy, J., Orford, J.D. and Burnside, N.G. (2012) Patterns of Holocene relative sea level change in the North of Britain and Ireland. *Quaternary Science Reviews*, 54, pp. 58-76, https://doi.org/10.1016/j.quascirev.2012.02.007

Soulsby, R.J., Smith, D.E., Ruffman, A. 2007. Reconstructing tsunami run-up from sedimentary characteristics – a simple mathematical model. In: Coastal Sediments ’07. American Society of Civil Engineers, 1075-1088.

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

SurgeWatch (2018). www.surgewatch.org

Sutherland, J. and Wolf, J., (2002). Coastal defence vulnerability 2075 (pp. 1-8). Wallingford: HR Wallingford Limited.

Sutherland, J., Brampton, A.H., Obhrai, C., Dunn, S. and Whitehouse, R. (2007). Understanding the Lowering of Beaches in Front of Coastal Defence Structures, Stage 2. Defra R&D Technical Report FD1927/TR, London

Tappin, D., Sibley, A., Horsburgh, K., Daubord, C., Cox, D. and Long, D. (2013). The English Channel ‘tsunami’ of 27 June 2011 – a probable meteorological source. *Weather,* 68(6), pp.144-152, https://doi.org/10.1002/wea.2061

Tappin, D.R., Long, D.L. and Carter, G.D.O. (2015) Shetlands Islands field trip May 2014 : summary of results. Nottingham, UK, British Geological Survey, 48pp. (OR/15/017) (Unpublished) http://nora.nerc.ac.uk/id/eprint/510756/

Tarrant, O. and Sayers, P. (2012). Managing flood risk in the Thames Estuary: The development of a long term robust and flexible strategy. Thomas Telford, London.

Tawn, J. (1992) Estimating probabilities of extreme sea levels. *Applied Statistics*, 41(1), pp. 77-93, doi: 10.2307/2347619

Taylor, R. G., Scanlon, B., Döll, P., Rodell, M. and Van Beek, R. et al. (2013). Ground water and climate change. Nature Climate Change, 3(4), pp. 322-329.

Taylor, K. E., Stouffer, R.J., & Meehl, G.A. (2012) An Overview of CMIP5 and the experiment design, *Bulletin of the American Meteorological Society*, 93, pp. 485-498 https://doi.org/10.1175/BAMS-D-11-00094.1

Taylor, J.A., Murdock, A.P. and Pontee, N.I. (2004) A macro-scale analysis of coastal steepening around the coast of England and Wales. *The Geographical Journal*, 170(3), pp.179-188, https://doi.org/10.1111/j.0016-7398.2004.00119.x

Tebaldi, C., Strauss, B.H., and Zervas, C.E. (2012) Modelling sea-level rise impacts on storm surges along US coasts, *Environmental Research Letters*, 7, 014032, doi:10.1088/1748-9326/7/1/014032

Thorne, C.R., Evans, E.P. and Penning-Roswell, E.C. (2007). Future Flooding and Coastal Erosion risks. Thomas Telford, London, 514pp.

UK Climate Projections 2018 (UKCP18) https://www.metoffice.gov.uk/research/approach/collaboration/ukcp/about

Van Gelder, P., Buijs, F.; Van, C. M., Wouter, H., Kanning, W., Mejad, M.; Gupta, S., Shams, R., van Erp, N., Gouldby, B., Kingston, G., Sayers, P., Wills, M., Kortenhaus, A., Lambrecht, H-J. (2008). Reliability Analysis of Flood Sea Defence Structures and Systems FloodSite Report T07-0.

Van Gent, M.R.A., Van den Boogaard, H.F.P., Pozueta, B. and Medina, J.R. (2007) Neural network modelling of wave overtopping at coastal structures. *Coastal Engineering*, 54(8), pp. 586–593, https://doi.org/10.1016/j.coastaleng.2006.12.001

Versey, H.C. (1939) The North Sea Earthquake of 1931 June 7. Geophysical Supplements to the Monthly Notices of the Royal Astronomical Society, Volume 4, Issue 6, Pages 416–423, https://doi.org/10.1111/j.1365-246X.1939.tb02906.x

Vilibić, I., Šepić, J., Rabinovich, A. B. and Monserrat, S. (2016) Modern Approaches in Meteotsunami Research and Early Warning. Frontiers in Marine Sciences, 3(57), pp.1-7, doi: 10.3389/fmars.2016.00057

Vonk, B., Klerk, W.J., Fröhle, P., Gersonius, B., den Heijer, F., Jordan, P., Radu Ciocan, U., Rijke, J., Sayers, P. and Ashley, R., 2020. Adaptive asset management for flood protection: The FAIR framework in action. *Infrastructures*, 5(12), p.109.

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(6), pp.1031–1045, http://dx.doi.org/10.5194/os-10-1031-2014

Wadey, M., Haigh, I.D., Nicholls , R.J., Brown, J., Horsburgh, K., Carroll, B., Gallop, S., 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, pp.84. http://dx.doi.org/10.3389/fmars.2015.00084

Wahl, T., Haigh, I.D., Woodworth, P.L., Albrecht, F., Dillingh, D., Jensen, J., Nicholls, R.J., Weisse, R. and Wöppelmann, G. (2013) Observed mean sea level changes around the North Sea coastline from 1800 to present, *Earth Science Reviews*, 124, pp.51-67.

Wahl, T. and Chambers, D. P. (2016) Climate controls multidecadal variability in U. S. extreme sea level records. *Journal of Geophysical Research: Oceans,* 121, pp.1274–1290, doi: 10.1002/2015JC011057

Walkden, M. and Hall, J. (2005) A predictive meso-scale model of the erosion and profile development of soft rock shores. *Coastal Engineering*, 52(6), pp. 535-563, https://doi.org/10.1016/j.coastaleng.2005.02.005

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

Ward, S.N. and Day, S.J. (2001) Cumbre Vieja volcano – potential collapse and tsunami at La Palma, Canary Islands. *Geophysical Research Letters*, 28, pp.3397-3400, https://doi.org/10.1029/2001GL013110

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),pp.1153–1167, http://dx.doi.org/10.1007/s10236-012-0552-6

WaveNet (2018). https://www.cefas.co.uk/cefas-data-hub/wavenet/data-download-procedure/

Williams, J., Horsburgh, K.J., Williams, J.A. and Proctor, R.N.F. (2016), Tide and skew surge independence: New insights for flood risk, Geophysical Research Letters., 43, 6410–6417, doi:10.1002/2016GL069522.

Woolf, D. and Wolf, J. (2013) Impacts of climate change on storms and waves, MCCIP Science Review 2013, 20-26, doi:10.14465/2013.arc03.020-026

Woodworth P.L. and Blackman D.L. (2004) Evidence for systematic changes in extreme high waters since the mid-1970s. *Journal of Climate*, 17(6), pp.1190–1197, https://doi.org/10.1175/1520-0442(2004)017<1190:EFSCIE>2.0.CO;2

Woodworth, P.L., Teferle, F.N., Bingley, R.M., Shennan, I. and Williams, S.D. (2009) Trends in UK mean sea level revisited, *Geophysical Journal International*, 176(1), pp. 19-30, https://doi.org/10.1111/j.1365-246X.2008.03942.x

Woodworth, P.L., Menendez, M., and Gehrels, W.R. (2011) Evidence for century-timescale acceleration in mean sea levels and for recent changes in extreme sea levels. *Surveys in Geophysics*, 32(4), pp. 603-618, doi: 10.1007/s10712-011-9112-8

Wynn, R.B. and Masson, D.G. (2003) Canary Islands landslides and tsunami generation: can we use turbidite deposits to interpret landslide processes? In: Locat, J. and Mienert, J., Editors, Submarine Mass Movements and their Consequences, Advances in Natural and Technological Hazards Research vol. 19, Kluwer Academic Publishers, Dordrecht: pp. 325–332.

Zanuttigh, B., Formentin, S.M. and Van der Meer, J.W. (2016) Prediction of extreme and tolerable wave overtopping discharges through an advanced neural network, *Ocean Engineering*, 127, pp. 7-22, https://doi.org/10.1016/j.oceaneng.2016.09.032

LIST OF ABBREVIATIONS[2]

AR5	Fifth IPCC Assessment Report
ASMITA	Aggregated Scale Morphological Interaction between Inlets and Adjacent Coast Model
CCO	Channel Coastal Observatory
Cefas	Centre for Environment, Fisheries and Aquaculture Science
CFD	Computational Fluid Dynamics
Defra	Department for Environment, Food and Rural Affairs
DEM	Digital Elevation Model
EA	Environment Agency
GIA	Glacial Isostatic Adjustment
GPD	Generalised Pareto Distribution
H++	Plausible high-end climate change scenarios, typically more extreme climate change scenarios on the margins or outside of the 10th to 90th percentile range presented in the UKCP09 projections
IPCC	Intergovernmental Panel on Climate Change
JPM	Joint Probability Method
LiDAR	Light Detection and Ranging.
M	Moment magnitude
MCCIP	Marine Climate Change Impacts Partnership
MHWL	Mean High Water Level
MLWL	Mean Low Water Level
MSL	Mean Sea Level
NAO	North Atlantic Oscillation
NERC	Natural Environment Research Council
ONR	Office for Nuclear Regulation
RCP	Representative Concentration Pathway
RP	Return Period
SCAPE	Soft Cliff and Platform Erosion model
SSJPM	Skew Surge Joint Probability Method
SWAN	Simulating WAves Nearshore
TAG	Technical Assessment Guide

[1] Several additional numerical model packages are described in Section 8. Their names and functions are fully explained therein and for further detail please refer to Lawless et al. (2016).

UKCP09	UK Climate Projections 2009
UKCP18	UK Climate Projections 2018

For more information contact:
Office for Nuclear Regulation
Building 4, Redgrave Court
Merton Road
Bootle L20 7HS
Email: contact@onr.gov.uk