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Coastal Flooding

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KEY HEADLINES

• Coastal flooding remains one of the most significant risks that the UK faces with wide-ranging social, economic and environmental impacts. These risks are growing with climate change and other changes (e.g. population growth), as shown by the Source-Pathway-Receptor model.

• Extreme sea levels have increased over the last 150 years, driven primarily by relative mean sea level rise due to climate change. On-going vertical land movement relating to glacial isostatic adjustment from the last ice age must also be considered increasing the rise in southern Britain and reducing it in northern Britain.

• Population growth, changes in land use and increasing asset values in floodplain areas have enhanced exposure to coastal flooding, but overall the consequences of flooding have reduced over time due to improvements in flood defences, together with advances in flood forecasting, warning and emergency planning.

• There is high certainty that relative mean sea level will continue to rise, and likely accelerate. As a result, high sea levels will be exceeded more frequently in the future with climate change, increasing the likelihood of coastal flooding. Without appropriate ongoing adaptation measures, such as defence upgrades, this will have significant impacts on the UK's coastal population, economy and infrastructure.

• Considerable uncertainty remains in regard to future changes in the frequency, magnitude and tracks of storms with climate change and thus there is low confidence about how the wave and storm surge climate around the UK may alter over time.

• The unusual, but not unprecedented sequence of extreme storms and coastal floods over the winter of 2013/14 are a recent and dramatic reminder of the ever-present risks facing coastal communities in the UK today requiring ongoing assessment and management.

1. INTRODUCTION

Coastal floods, driven by extreme sea levels, are a major hazard both nationally and globally, with wide-ranging social, economic and environmental impacts. Coastal flooding is one of the most significant risks the UK faces from 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 (Halcrow, 2001). Coastal flooding is rated as the second highest risk for causing civil emergency in the UK, after pandemic influenza (Cabinet Office, 2015). Combined with fluvial flooding, it is responsible for at least £0.25bn in annual economic damages in England and Wales (Penning-Rowsell, 2015). Coastal flooding is a growing threat due to accelerating mean sea-level rise and possible changes in storminess associated with climate change (Church *et al.*, 2013) as well as continued population growth and development in flood-exposed areas (Hallegatte *et al.*, 2013; Stevens *et al.*, 2016). The Source-Pathway-Receptor (SPR) Model introduction by the Foresight Study (Evans *et al.*, 2004a; 2004b; Thorne *et al.*, 2007) demonstrates the multiple drivers of coastal flood risk. As explained below, a range of changes can increase flood risk (though this paper focuses on climate changes), and equally appropriate interventions can reduce flood risk.

The UK has a long history of severe coastal flooding. Historical accounts suggest that large numbers (magnitudes up to 10^5) of people were drowned on the east coast during events in 1099, 1421 and 1446 (Gönnert *et al.*, 2001). In the last 500 years, major coastal flood events impacted the west coast in 1607, the west and south coasts in 1703 and the south coast in 1824, collectively resulting in the deaths of up to 2,000 people (Horsburgh and Horritt, 2006, 2003; RMS, 2007; Le Pard, 1999). The 1607 flood remains the event that has caused the greatest loss of life from any sudden-onset natural catastrophe in the UK during the last 500 years (RMS, 2007). In the last century, a storm surge combined with high river flows flooded central London on 10 January 1928, drowning 14 people. During the 'Big Flood' of 31 January–1 February 1953 (Figure 1), 307 people were killed in southeast England and 24,000 people fled their homes Almost 2,000 lives were also lost in the Netherlands and Belgium (McRobie *et al.*, 2005). This benchmark event was a pivotal driving force for advancements in sea level research, forecasting and warning, and flood risk management in the UK. It led to the construction of the Thames Storm Surge Barrier and associated defences for London (completed 1982) (Gilbert and Horner, 1986) and the establishment of the UK Coastal Monitoring and Forecasting Service (Flather, 2000). During the recent winter of 2013/14 the UK experienced an unusual (but not unprecedented) sequence of extreme storms and some of the most significant coastal floods in the last 60 years (Thorne, 2014; Kendon and McCarthy, 2015), but due to warning systems and better defences the damages were much lower than in 1953.

Figure 1: *A family evacuated in Whitstable, Kent, during the 'Great Storm' of 1953. These floods killed 307 people in eastern England and were the catalyst for the construction of the Thames Barrier. Photo credit - Canterbury City Council 2015.*

Coastal floods are driven by extreme sea levels, which arise as combinations of four main factors: waves, astronomical tides, storm surges and relative mean sea level (Pugh and Woodworth, 2014). The additional influence of river discharge may also be important in some estuaries (Wahl *et al.* 2015). A storm surge is a short-lived large-scale rise in water level, driven by low atmospheric pressure and strong winds associated with a storm, and enhanced locally by coastal topography. The worst coastal flooding occurs when the peak storm surge coincides with high spring tide. Local or remote storms can also produce large wind or swell waves, which can overtop coastal defences/beaches and causing flooding and erosion.

Each of the four main factors of extreme sea levels exhibit considerable natural variability, which influence the frequency of flooding on inter-annual and multi-decadal time scales, and makes isolating changes due to climate change difficult. Natural variability in the wave, storm surge and mean sea level components is stochastic and linked to regional climate, such as the North Atlantic Oscillation. In contrast the tidal component is deterministic, manifesting regular and predictable modulations at 4.4-year and 18.6-year time scales, relating to the perigean and nodal cycles of the Moon's orbit (Haigh *et al.*, 2011). Flood rich periods occur when the variability is in of phase and flood poor periods when it is in phase (Eliot, 2012).

Longer-term changes in any, or all, of the four components can lead to variations in extreme sea levels. Changes in relative mean sea level (due to changes in sea level associated with climate change and vertical land movement), affects extreme sea levels both directly and indirectly without any change in the occurrence of extreme events. The direct effect of a rise in mean sea level results in a lower storm surge elevation at high tide being necessary to produce a sea level high enough to cause flooding. The indirect effect occurs as changes in relative mean sea level alter water depths and hence modify the propagation and dissipation of the wave, tide and storm surge components of sea level. In addition, extreme sea levels may change as a result of variations in the strength and tracks of weather systems, related to climate change, which alter the intensity, and/or duration, of waves and storm surges (and river discharge), although this is less certain than rises in mean sea level.

There is a difference between risk, and the likelihood of extreme sea levels – which are explained by the four factors given above. An important contributor to coastal flood risk is the socio-economic changes (the receptors) that generally increase or reduce flood consequences (Thorne et al., 2007). Population growth, changes in land use and increasing asset values in floodplain areas have led to enhanced exposure to flooding (Horsburgh *et al.*, 2010). Historically this was the main contributor to increasing flood exposure and risk (Stevens *et al.*, 2016). To date improvements in flood defenses, together with advancements in flood forecasting and warning and emergency planning, have typically reduced flood consequences since the 1950s, but in the future mean sea-level rise is expected to become a much more important contributor to the risk of coastal flooding occurring.

Changes in coastal morphology can also influence flood pathways and thus flood risk (Thorne *et al.*, 2007; Nicholls *et al.*, 2015 a). Coastal erosion is expected to increase with accelerating sea level rise (Wong *et al.*, 2014), so flooding linked to erosion is of increasing concern.

2. TOPIC UPDATE

Our understanding of how coastal flood risk has altered due to climate change has not changed fundamentally since the last MCCIP review in 2013. However, in the intervening period the UK has experienced some of the most significant and wide spread coastal flooding in the last 60 years (Matthews *et al.*, 2014; Thorne, 2014; Kendon and McCarthy, 2015). These events are a reminder of the ever-present risks facing coastal communities in the UK today and show us why concerns about climate change are valid. They also bring the issue of natural variability into sharp focus. Understanding natural variability is important so that the longer-term effects due to climate change can be better understood, isolated and effectively managed.

The events of winter of 2013/14 included the 5-6 December 2013 storm, during which water levels exceeded the benchmark 'Big Flood' of 1953 at several sites along the east coast. This resulted in wide-spread flooding of property and infrastructure, including damage to the Port of Immingham, and significant coastal erosion. Detailed analyses of this event have been undertaken by Spencer *et al.* (2015) and Wadey *et al.* (2015). A series of strong storms in January and February 2014 caused widespread damage to defences, property and infrastructure (most notably the collapse of the main railway line to Plymouth and Cornwall at Dawlish which was closed for six weeks; Dawson *et al.*, 2016) on the southern English coast and the west coast of Wales. Collectively, these events caused an estimated £2.5 billion of damages[1], but much greater destruction was avoided due to well functioning defences, along with good forecasts, warnings and evacuations.

[1]http://floodlist.com/insurance/uk/cost-of-2013-2014-floods

3. HOW OUR UNDERSTANDING HAS DEVELOPED OVER THE PAST DECADE?

Over the last decade a growing number of studies, at both national and global scale, have found evidence for an increase in extreme sea levels over the last 150 years due to climate change (Figure 2). Increasingly there has been a consensus that the change has been primarily driven by the observed rise in relative mean sea level, with little or no evidence found for significant increases in the storm surge component of sea levels at most locations worldwide (e.g. Araújo and Pugh, 2008; Woodworth and Blackman, 2002, 2004; Haigh *et al.*, 2010; Menendez and Woodworth, 2010; Sweet and Park, 2014; Weisse *et al.*, 2014; Dangendorf *et al.*, 2014a; Marcos *et al.*, 2015; Wahl and Chambers 2016; Mawdsley and Haigh, 2016). Confidence in what is already happening has thus increased from 'low' (Lowe, 2006) to 'high' (Donovan *et al.*, 2013) over the duration of the MCCIP report cards. There has also been an improved understanding of the mechanisms driving inter-annual and multi-decadal variability in both mean and extreme sea levels around the UK coast (Woodworth *et al.*, 2009; Haigh *et al.*, 2010; Calafat *et al.*, 2012; Wahl *et al.*, 2013; Dangendorf *et al.*, 2014b). In addition, there has been an increasing focus on understanding much longer-term past (i.e. thousands to millions of years before present) sea level changes to inform the future (e.g. Kopp *et al.*, 2009; Woodworth *et al.*, 2011; Gehrels and Woodworth, 2013; Rohling *et al.,* 2013; Barlow *et al.*, 2014).

In the last ten years there has been a shift away from using the non-tidal residual component of sea level (i.e. the component that remains once the tide and mean sea level have been removed form the sea level record) to assess the characteristics, trends due to climate change and exceedence probabilities of storm surges, to using the skew surge parameter (Horsburgh and Wilson, 2007; Batstone *et al.*, 2013; Wadey *et al.*, 2014 , 2015; Haigh *et al.*, 2015; Mawdsley and Haigh, 2016). A skew surge is the difference between the maximum observed sea level and the maximum predicted (astronomical) tidal level regardless of their timing during the tidal cycle (de Vries *et al.*, 1995). Hence each tidal cycle has one 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 relevant to any predicted high water, and operationally it defines the parameter that may lead to flooding.

While there has been a steady increase in the frequency in which high waters have been exceeded due to climate change, there has been growing recognition, in the last decade, that this has not led to a corresponding increase in coastal flooding (Stevens *et al.,* 2016). This is because of continued improvements in flood defences, together with advances in flood forecasting and warning and emergency planning. The increased application of the Source-Pathway-Receptor-Consequence conceptual model, introduced in the last decade (Evans *et al.,* 2004a; 2004b; Thorne *et al.*, 2007), has helped to separate the different drivers of flood risk and thus has been useful in shedding light on the complex range of drivers that exist for coastal (and other) flooding.

The development of broad-scale assessment tools for examining coastal flooding in the context of climate change (e.g., Hall *et al.*, 2003; Gouldby *et al.*, 2008) has facilitated national (England and Wales) analyses which have focused strategic thinking and made the UK a world leader in this area. It has helped to define the scale of the problem and the potential mitigations. However, a recent assessment of expected annual losses by Penning-Rowsell (2015) suggests that the methods require further refinement as the model estimated annual losses of £1.1 bn, while analyses of actual losses are much lower (£0.25 bn).

Two especially noteworthy studies in the last 10 years are the Foresight Flooding (Evans *et al.*, 2004a; 2004b; Thorne *et al.*, 2007) and the Thames Estuary 2100 (TE2100; Environment

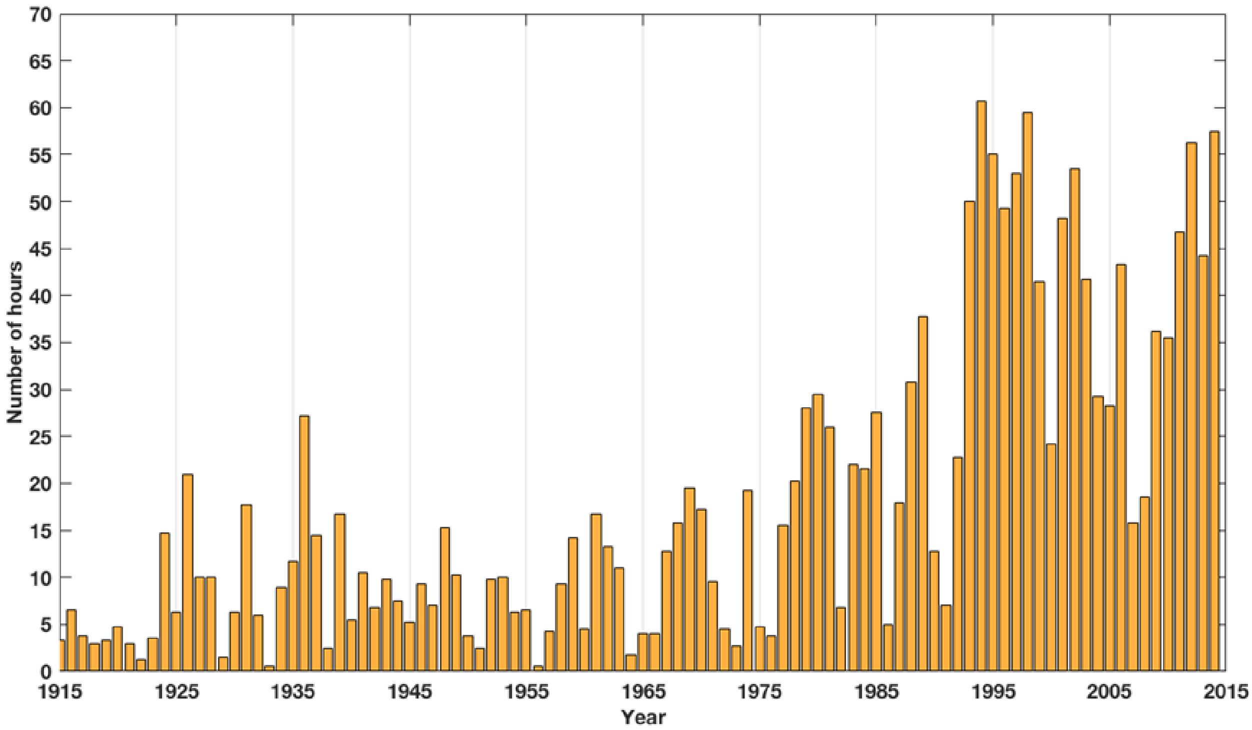

Figure 2: *Number of hours per year that water levels exceeded 5.75m CD at Newlyn, Cornwall.*

Agency, 2012) studies, which focused on better planning and mitigating for climate change. The Foresight Flood and Coastal Defence project addressed two key questions: How might the risks of flooding and coastal erosion change in the UK over the next 100 years? What are the best options for Government and the private sector for responding to the future challenges? The TE2100 project was established by the Environment Agency with the aim of developing a strategic flood risk management plan for London and the Thames estuary through to the end of the century. The TE2100 project was instrumental in introducing a novel, cost effective approach to manage increasing flood risk by defining adaptation pathways that can cope with large ranges of changes if needed. A possible 'route' of cheaper defense options could be initially followed, but decisions makers could switch to more expensive options (such as a new downstream barrage) if sea level was found to be increasing faster than predicted with climate change. The adaptive pathways approach is being developed into a tool for wider application (Ranger *et al.*, 2010; Haasnoot *et al.*, 2013). The TE2100 project also introduced and applied a low probability but high impact mean sea level rise scenario (known as H++), which it considered in its recommended adaptation planning. It has also been applied in coastal climate change impact assessments (Nicholls *et al.*, 2011).

Over the last decade, projections of future changes in mean sea level, storm surge and wave climate due to climate change have been presented globally by the Intergovernmental Panel on Climate Change (IPCC) in their Fourth (2007) and Fifth (2013) Assessment Reports. The UK has moved from using UKCP02 (UK Climate Projections) to UKCP09 projections and is now looking ahead to UKCP18. Over this ten-year period, Defra and the Environment Agency (EA) have produced various flood and coastal risk guidance documents, based on these projections, with the latest released in 2016 (Environment Agency, 2016). Projections of mean sea level rise have varied by a few 10's of cm in these assessments, but there is consensus that mean sea level will continue to rise and at an accelerated rate due to climate change. Confidence in what could happen in the future with regard to coastal flooding has thus increased from 'low' (Lowe, 2008) to 'medium' (Donovan *et al.*, 2013) over the duration of the MCCIP report cards. There was been increased focus on producing regional (rather than global) mean sea level projections (e.g. Slangen *et al.*, 2014; Grinsted *et al.*, 2015) and projections that better capture the low probability, but high impact end of the range (Rohling *et al.* 2013; Jevrejeva *et al.*, 2014; Kopp *et al.*, 2014; Goodwin *et al.*, 2017). Despite the use of a wide range of improved, higher-resolution models (which have incorporated an ensemble approach) and a community inter-comparison project for waves (Hemer *et al.*, 2012), considerable uncertainty remains in relation to future changes in the wave and storm surge climate due to climate change (Lowe *et al.*, 2010; Weisse *et al.*, 2014; Wolf *et al.*, 2015).

4. KNOWLEDGE GAPS AND KEY CHALLENGES

Key research requirements to improve our understanding of coastal flooding are:

- Monitoring of sea level around the UK coast should continue through on going investment in the national network of tide gauges and improved use of satellite altimetry in the coastal zone.
- A better and more accurate analysis of historical storm events, which will lead to improved understanding of natural variability, and ultimately trends due to climate change.
- A more complete assessment of future changes in the wave and storm surge climate (based on improved atmospheric models) is required, with efforts to improve understanding of natural variability.
- Continue to improve statistical methods for assessing present and changing future flood risk.
- While the Thames Estuary 2100 methods for long-term planning have been applied to London, it could be argued that similar analyses of flooding and sea-level rise might be useful for other areas at risk from coastal flooding in the UK.
- Better understanding of expected annual damages and event losses (cf. Penning-Rowsell, 2014).

5. EMERGING ISSUES(CURRENT AND FUTURE)

In terms of flood risk management, an emerging issue has been the selection of adaptation pathways to manage growing coastal flooding with climate change. The adaptive pathways approach for managing flooding risk, introduced in the Thames Estuary 2100 project for London, has gained recognition and could be applied much more widely (Nicholls *et al.*, 2015b). Another emerging issue has been the increased implementation of managed realignment (or managed retreat) as a 'soft engineering' solution for flood defence and inter-tidal habitat creation (Cooper, 2003). Recent managed realignment schemes include Medmerry in Sussex and Steart Marshes in Somerset.

There is a continued need to improve statistical methods for assessing present and changing future flood risk, and account for the emerging issues of spatial footprint and temporal clustering aspects of extreme events (Dissanayake *et al.*, 2015; Haigh *et al.*, 2016). What was especially noteworthy about the 2013/14 winter was the large spatial 'footprints' (i.e. simultaneous flooding in multiple locations during the same storm) and the temporal 'clustering' (i.e. events occurring one after another over a short period of time) of the coastal flooding events. These two issues have important implications for financial and practical aspects of risk management (in areas such as re-insurance, infrastructure reliability and emergency response), yet understanding and appreciation for them is lacking.

Another emerging issue relates to changes in tidal range, which could affect coastal flooding in the future. Tides have generally been considered to have undergone little change over the last century and it is often presumed that they will not change significantly over the next century. However, several studies have detected measurable changes in tides during the 20th century and early part of the 21st century at a number of locations (see Mawdsley *et al.*, 2015, for a review) and modeling studies have predicted changes in tidal range around the UK, with future changes in mean sea level (Pickering *et al* ., 2012; Ward *et al.*, 2012; Pelling *et al.*, 2013).

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