MCCIP ARC Science Review 2010-11
Coastal Flooding

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EXECUTIVE SUMMARY

Over the past century, natural variations in storm frequency and magnitude over 10-20 year cycles have been the most important climatic factor driving coastal flood risk. However, changes in land use and movement of people and key services to coastal areas over this time period has generally increased vulnerability to coastal flooding.

Extreme sea levels in the future are likely to be dominated by climate driven changes to the mean sea level, rather than waves or storm surges. There is a great deal of uncertainty surrounding the magnitude of changes in mean sea level and wind waves (thus extreme events), but not the direction of change for mean sea level. This will increase the likelihood of coastal flooding. Without adaptation this will lead to significant losses to economic, social and environmental assets by the end of this century and beyond. Since sea level rise is committed to continue beyond 2100, even with immediate stabilisation of greenhouse gas emissions, then policy and adaptation measures require a strategy over a much longer period.

The direct effect is to increase the probability of inundation, although another factor is the increased risk of coastal defence failure due to increased loading. Any changes in the direction of major storm events could also alter patterns of coastal morphology and erosion. It has been estimated that a 40cm sea-level rise, which is broadly in line with UKCP09 projections by 2100 under a medium emissions scenario, would increase the number of properties at risk in eastern England from around 270,000 to 400,000. In the absence of adaptation measures, economic damage due to coastal flooding could become 0.2% of GDP by the 2080's.

FULL REVIEW

1. What is already happening?

There are five key processes that drive flood risk at the coast:

- Relative sea level rise: the local change of sea level due to the combined changes in sea level and vertical land movement
- Storm surges: the temporary change in sea level resulting from meteorological forcing of the sea surface
- Waves: the wind induced disturbance of the sea that propagates across the surface

- Coastal morphology and sediment supply: changes in the form of the seabed, shoreline and adjacent coastal land, and estuaries
- Socio-economic change: changes to population, demographics and asset value will affect the impact of flooding as well as our ability to recover from it

Coastal morphology can be an important buffer against the first three drivers, but sediment starvation (in part a result of coastal defences) and climate change means that erosion is dominant around much of the UK coastline.

There is a long history of human intervention to control coastal processes and reduce coastal flooding. As intervention has increased, man has become an important influence on how the coast behaves. The management of coastal erosion and flooding have become ever more interlinked, with low-lying flood prone land often fronted by gravel barriers or sand dunes (Hinton *et al.*, 2007). This interaction between coastal erosion and flood risk means that we cannot only think of changes to coastal water levels increasing the likelihood of flooding. We need to also consider changes to flood pathways, the vulnerability of those flooded and our future responses.

Long term management of the coastal zone has implications for the UK's food, energy and water security. Changes to mean and extreme coastal water levels, coastal storminess and incident wave energy will lead to an increase in the likelihood of coastal flooding both by overwhelming or overtopping sea defences or inundating undefended land, and also by increasing the rate of failure of sea defences or other coastal measures. Changes to coastal erosion rates could potentially expose new pathways for coastal inundation. As well as directly increasing the likelihood of flooding, changes to flood risk could lead to a greater maintenance requirement. This in turn would strain flood and coastal investment provision and direct resources away from other activities.

Vulnerability to coastal flooding is related to the number of people, property and key services that are located at risk in the coastal zone. Any change in flood frequency and magnitude has to be considered alongside increasing vulnerability in order to properly assess flood risk (see for example National Trust, 2005). Population growth, demographic changes and increasing asset values will potentially have as large an impact as climate change

Regional extreme sea levels including waves

Extreme sea levels around the UK arise from some combination of high tide, extreme waves and storm surge (the effect of wind stress and atmospheric pressure on sea level). Therefore, changes in extreme water level can result from changes in the local mean sea level or changes in the atmospheric storminess driven components of water level, namely waves and surges. In a global study of tide gauge data since 1975, Woodworth and Blackman (2004) concluded that almost all the trends in extreme high water levels are dominated by changes to mean sea level. For the UK over recent decades there is no compelling observational evidence for trends in either storm surge frequency or magnitude.

Changes in coastal wave climate may have an effect on susceptible coastal regions, especially in conjunction with the effects of storm surges and sea level rise. Wind waves and swell can damage the coastline, including natural and man-made sea defences. It is therefore important to understand the natural variability of wave climate, and also to estimate how it might alter in climate change scenarios of the 21st century. The primary variable for waves is wave height, represented by the significant wave height (SWH), but other wave parameters may also be important (e.g. the overtopping of coastal structures is sensitive to wave period; the wave direction will have an impact on the alongshore transport of sediment and so any persistent future change in wave direction is of relevance).

Trends in extreme wave heights for the North Atlantic have been the subject of much study (e.g. Wolf and Woolf, 2006). The last 20 years of the 20th century saw rises in extreme wave heights of up to 0.5m to the west of the UK. However, detailed cataloguing and analysis of storm patterns over the British Isles (Allen *et al.*, 2008) concluded that changes in storm frequency over the last several decades of the 20th century are likely to be due to large-scale natural climatic variability. These changes are significantly correlated with the Iceland-Azores North Atlantic Oscillation (NAO). Numerous modelling studies (e.g. WASA, 1998) have been directed at the hypothesis of a worsening North Atlantic wave climate: increases in mean and extreme wave heights are all consistent with decadal variability in the storms which drive the waves. Preliminary data from the Irish Marine Weather Buoy Network (http://www.marine.ie/home/publicationsdata/data/buoys/DataBuoyHome.htm) confirm increases in SWH over the latter part of the last century and do not suggest any significant subsequent decrease, but further analysis of the data is required before any conclusions can be drawn from this.

Flood risk in England and Wales

There is at least £150 billion worth of property and 430,000ha of agricultural land at risk from coastal flooding and towards 100,000 properties in areas that, without protection, could be eroded (Defra, 2001). The area at risk of coastal flooding equates to a coastline of 3500km, of which 3200km is defended. The remaining coastline, 2500 km, is high ground including cliffs and may be subject to erosion.

Most of the undefended coastal zone is made up of salt marsh or other land that benefits from flooding and provides a buffer for coastal processes. Around 55% of sea defences are maintained by the Environment Agency and the remainder are maintained by third parties (made up of Local Authorities and private individuals). There is of the order of 2500km of coastline and £10bn of property at risk of erosion 20% of which have some form of coastal erosion intervention. Defra have estimated that approximately one third of the coastal defences in England and Wales could not be justifiably improved under current economic rules on investment (Defra, 2001).

Within coastal lowlands, such as the Norfolk Broads, Lancashire coastal plain and the Fens, draining and consolidation along with oxidation and subsequent peat loss have produced substantial declines in land elevation. Most of the Fens now lie below high-tide and significant areas are below mean sea level. The extent and rate of future localised changes are hard to predict. The result of this localised land level change is that if coastal defences were overtopped or breached, inundation would occur over a wide area and persist for some time, significantly damaging often protected freshwater habitats and potentially threatening policy deliverables such as the Water Framework Directive.

Flood risk in Scotland

Coastal flooding has had a significant impact in Scotland throughout history, in both economic and social terms. Some 304 coastal floods have been recorded since 1849 (Ball et al., 2009). The 1953 floods had significant impact in Scotland in the North, East (including the Forth Estuary), Orkney and Shetland (Hickey, 2001). In 1991, a major storm caused around £10.5m damage in the Clyde Estuary, resulting in the commissioning of the Clyde Estuary Flood Warning system, operated by the Scottish Environment Protection Agency (SEPA) since 2001 (Kaya et al., 2005). In 2005, a storm caused major flooding across a swath of the North and West coast and

Islands. Present annualised assessments of damage from coastal flooding are around £19 million, compared with £34.5 m from fluvial flooding (Werritty with Chatterton, 2004). Around 27,000 properties are thought to be at risk of a 0.5% annual probability coastal flood (Kemeling, 2007).

Flood risk in Ireland

In the Republic of Ireland, there has been much recent activity attempting to identify knowledge gaps prior to a full assessment of baseline coastal water levels and an assessment of regional implications. This work has focussed on increasing monitoring capacity, as well as numerical terrain and ocean modelling. Operational systems have been established to provide surge warnings, and there has also been investment in monitoring infrastructure. The Irish Marine Climate Change program has led to the establishment of two sentinel water level and temperature monitoring stations at Malin Head (Co. Donegal) and Ballycotton (Co. Cork). The west coast of Ireland is made up of a predominantly rugged granite and limestone littoral zone substrate, so the impact of storms is naturally limited. The eastern coast is made up of more fragile material so is more susceptible to erosion during relatively short period events.

2. What could happen in the future?

The results of UKCP09 (Lowe *et al.*, 2009) suggest that extreme sea levels are likely to be dominated by climate driven changes to the mean sea level, rather than waves or storm surges. This topic is addressed thoroughly in the companion MCCIP submission for sea level. As noted in that document, projections of 21st century sea level rise for the UK give a range of 12-76cm for the year 2095.When vertical land movement is taken into account then larger sea level rises are projected for southern parts of the UK with smaller increases in relative sea level for the north. Projected relative sea level increases for 1990–2095 for London are approximately 21–68cm based on a medium greenhouse gas emissions scenario. The upper limit increases to 83cm in a high emissions scenario. In the UKCP09 work, a low probability sea level range (denoted H++) has been defined for contingency planning purposes only. This extreme estimate of sea level rise ranges from 93 cm to 1.9 m by 2100.

Changes to the frequency and magnitude of storm surges were also considered. Based on an 11 member ensemble of climate models coupled to storm surge models, the surge expected to occur once every 50 years (the so-called 50-year return level) was not found to change significantly around the majority of the coastline. In the southwest of the UK there was a small but significant trend in the 50-year return level, which implies a change to large storm surges of less than 10 cm over the 21st century. A complementary analysis, based on statistical downscaling, confirmed the absence of any trend in storm surge over the period 1961-2100. However, this projection of a relatively constant storm surge climate contains some uncertainty. One member of the IPCC (2007) multi-model ensemble predicts increasing storm intensity over Europe: despite this model being unique in making those projections it cannot be completely ruled out. Predicting changes to storm tracks over long timescales remains a challenge for weather prediction models (Brayshaw *et al.*, 2009) and it cannot be assumed that the present generation of IPCC climate models represents the full range of storm track variability over northern Europe.

In a limited analysis of possible future wave climates, Lowe *et al.* (2009) used the predicted winds from three regional climate model members of the Met Office ensemble that contributed to UKCP09. These winds were used to force a well-established third-generation wave model, PROWAM (Monbaliu *et al.*, 2000). The climate model ensemble members represented low, medium and high climate sensitivity. All results were for the medium emissions scenario (SRES A1B). It should be noted that a more thorough analysis of all 11 ensemble members is needed in order to provide a better estimate of uncertainty in future wave conditions.

The resulting changes in seasonal mean SWH are shown in Lowe *et al.* (2009), Chapter 5. When the regional model is run into the future (to the 2070-2100 period) using the medium sensitivity ensemble member, the change in winter mean SWH shows a distinctive north-south pattern (see Figure 1). To the south of the UK, there is generally a small increase: this includes the English Channel and the southern North Sea. To the north, there is a larger reduction in SWH. This spatial pattern may suggest an intensification of westerly winds and a reduction in northerly winds, which could be related to a change in storm tracks (Wolf and Woolf, 2006). The autumn pattern is quite different with an increase in wave height to the north west of Scotland. In spring, any increase is limited mainly to the west coast.

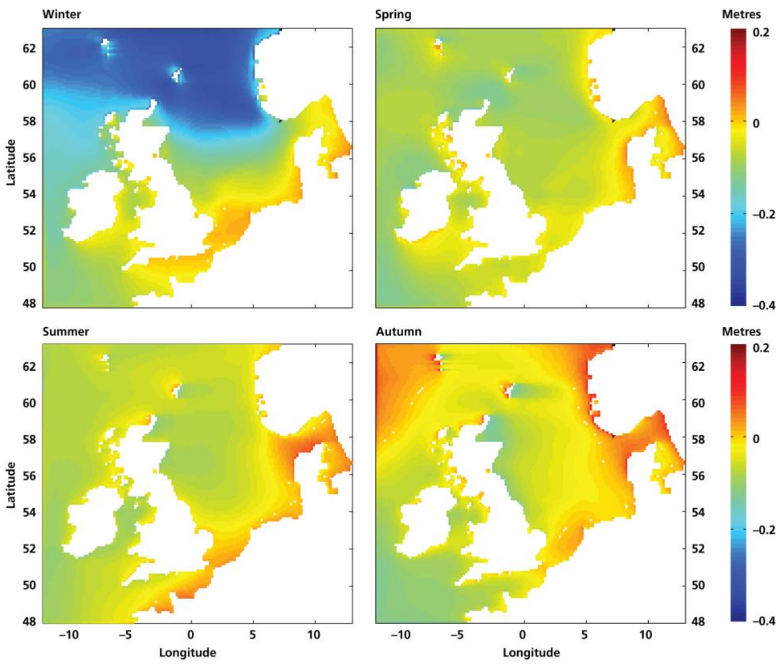


Figure 1. *UKCP09 projected changes in seasonal means of Significant Wave Height (m) from 1960-1990 to 2070-2100. Winter = DJF., Spring = MAM, Summer = JJA, Autumn = SON.*

However, very large uncertainties are evident when the three ensemble members are considered, especially with the projected extreme values. Changes in the winter mean SWH are projected to be between –35 cm and + 5 cm; changes in the annual maxima are projected to be between -1.5 m and +1 m. Only one wave model simulation was carried out for the whole 140-yr simulation period. This showed that the use of two 30-yr time slices can produce misleading trends because of the large inter-annual variability in wave parameters, especially extreme values.

A major gap in understanding present and future risks from wave action is the linkages between offshore and inshore wave heights. In this regard, the WaveNet network of wave buoys has recently been extended by Cefas and SEPA to include the Moray Firth, Firth of Forth and Western Isles (see www.cefas.co.uk/data/wavenet.aspx). The data will be valuable for both enhanced flood warning and more detailed assessments of flood risk from waves to verify the models.

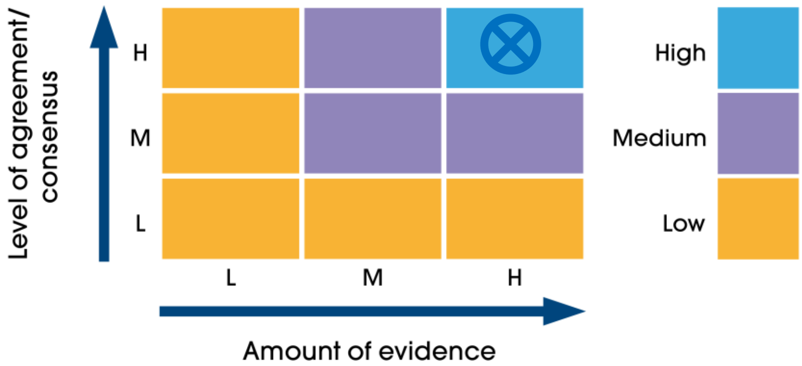
The best analyses of changes in wave climate and storm surge climate point to mean sea level change being the most important driver for extreme water levels and therefore coastal flooding.

Rising sea levels elevate all the coastal sources of flooding, such as storm surge and extreme waves. For example, a 70cm increase in relative sea level for East Anglia would result in the extreme water level that is currently experienced on average every 100 years being observed every 2-8 years, depending on local conditions. So the most immediate effect is to increase the probability of inundation. But, it also effects coastal morphology particularly beach erosion and salt-marsh decline. Such erosional changes would exacerbate the increased probability of flooding by increasing the risk of coastal defence failure among other mechanisms. Changes in the direction of major storm events also has the potential to alter coastal morphology and hence alter the pattern of erosion and accretion around the coast further affecting locations that are presently protected from offshore conditions.

No fully integrated assessment has yet been undertaken of the potential flood losses arising from the UKCP09 projections. However, previous studies indicate the scale of the change. The Association of British Insurers (ABI, 2006) estimated that a 0.4m sea level rise would increase the number of properties at risk in eastern England from 270,000 to 404,000. The OST Foresight Future Flooding project reported that if a "business as usual scenario" is assumed (i.e. no adaptation to the increasing coastal flood risk) then the expected annual damage in England and Wales due to coastal flooding would increase from the current £0.5 billion to between £1.0 and £13.5 billion, depending on the scenario of climate and socio-economic change. In the absence of adaptation measures, economic damage due to coastal flooding could become 0.2% of GDP by the 2080s (OST, 2004).

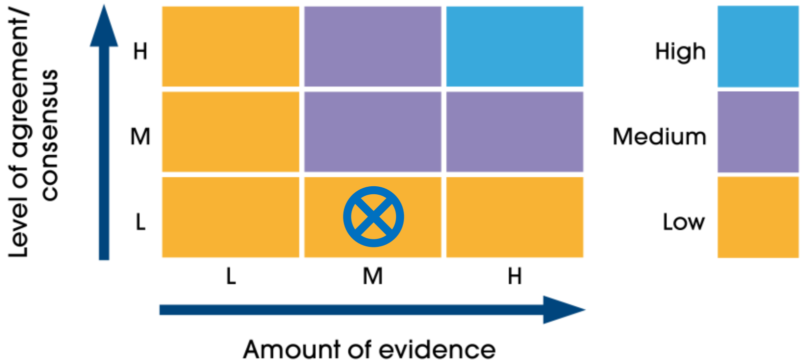
3. Confidence in the science

What is already happening: ***High***



Observational evidence for present day sea level (including land movement from GPS), storm surge and waves processes is of the highest quality. Present day flood risk (including exposure) is also quantified to a high degree of precision helped by numerical flood mapping and precision LIDAR shoreline data, so our understanding of what is already happening is high.

What could happen: ***Low***



Projections of the future rely on the accuracy of (i) our projections of mean sea level combined with the uncertainty surrounding future surge and wave climates and (ii) estimates of coastal development and land use. Both of these are known poorly so our level of confidence for what may happen in the future is low. The projected trend in mean sea level has no uncertainty about its direction (despite a range of values for its rate) so an increased risk of coastal flooding has high certainty.

4. Knowledge gaps

The top priority knowledge gaps that need to be addressed in the short term to provide better advice to be given to policy makers are:

1. A more complete examination of the future wave climate projected by the UKCP09 perturbed parameter ensemble, and that which may result from other climate models in the IPCC (2007) multi-model set
2. A reliable prediction of new coastal development, the siting of new infrastructure and the required level of protection
3. An integrated assessment of the potential flood losses arising from these projections, including ecosystem goods and services
4. Detailed scientific understanding of sediment transport processes and coastal morphology over long (decadal-centennial) timescales

There is wide agreement on these key challenges.

5. Socio-economic impacts

With the implementation of Marine Bills at both a UK and Scotland level, terrestrial and marine spatial planning will require co-ordination which may be assisted by existing non-statutory local coastal partnerships (established under principles of Integrated Coastal Zone Management – ICZM). Established in the early 1990s, these local voluntary partnerships have proved very successful in promoting multi-sector planning.

England and Wales

Evidence of increasing costs of coastal flood protection was provided by Burgess & Townend (2004), who estimated that by the 2080s the annual cost of new coastal defence structures will be between 150 and 400% of the current levels (depending on the emissions scenario). Costs were less sensitive to geographic location than to emissions scenario. The costs were predicted to increase because structures were found to be very vulnerable to increases in water depth. Non-structural measures, such as land use planning and flood warning, could also make a considerable contribution to reducing this risk though no attempt has been made to estimate the cost of these measures.

The Environment Agency's Long Term Investment Strategy (http://www.environment-agency.gov.uk/research/library/publications/108673.aspx) does not provide separate analysis for coastal flooding, but the findings illustrate the increasing investment required to fully respond to climate change. Modelling of both river and coastal flood risk suggests that to sustain current levels of protection in the face of climate change requires an increase in investment from current levels of £570 million to more than £1 billion a year, plus inflation, by 2035. Conversely, keeping investment in building and maintaining defences at current (2010/2011) levels could increase the number of properties at significant risk by 350,000 (from 490,000 now to 830,000 in 2035).

At many coastal sites (including major industrial and infrastructure facilities) there is limited scope to retreat inland without major economic and/or social implications. The frequency and severity of loading of defences means that they will be increasingly costly to repair or replace. A reduction in sediment supply to the coasts will be reflected in a narrowing of beaches and deterioration in amenity and ecological value of coasts. Avoidance of these losses requires a long-term strategic approach to coastal zone management.

Shoreline Management Plans (SMPs) are the backbone of coastal management in England and Wales. They contain flood and coastal erosion risk management policies for 20, 50 and 100 years into the future. Currently, local authorities are revising 18 SMPs and the Environment Agency the remaining four, ready for 2010. The new SMPs will provide a 'route map' for local authorities and other decision makers to move from the present situation towards meeting future needs, and will identify the most sustainable approaches to managing the risks to the coast in the short term (0-20 years), medium term (20-50 years) and long term (50-100 years).

The broad objective of the Draft Flood and Water Management Bill, put before Parliament on 19th November 2009, is the management of water in ways that address future climate change risks. It responds to key recommendations from the Pitt Review (http://archive.cabinetoffice.gov.uk/pittreview/thepittreview.html) and is the primary means of implementing the objectives set out in the Defra Making Space for Water Programme (http://www.defra.gov.uk/environment/flooding/policy/strategy/index.htm) and the EU Directive on flood risk. The Bill also aims to embody the principles of Integrated Coastal Zone Management (ICZM), a process that seeks to join up the different policies, and increase "stakeholder" influence in coastal management through effective dialogue. ICZM is currently being promoted throughout the European Union.

Examples of adaptation for coastal flood and erosion management can be found at: http://www.environment-agency.gov.uk/research/planning/108361.aspx

Scotland

Coastal flooding management policy in Scotland will be heavily influenced by the recent implementation of the EC Directive on Assessment and Management of Floods (the Floods Directive). This was put into law in 2009 by the Flood Risk Management (Scotland) Act. The Act expands the role of the Scottish Environment Protection Agency (SEPA) in risk assessment and planning, making it the lead authority for assessments of flood hazard and potentially vulnerable areas, and for drawing up flood risk management plans. Implementation of the Floods Directive is likely to be challenging at the coast, as hazard assessment requires quantification of the risk of extreme water heights, wave action, and the role of defences. A database of grant aided flood defence assets in Scotland has been compiled on a national level. However, there is still a general lack of data on flood defences and condition particularly those protecting infrastructure. Local databases will be established under the 2009 Act, which will be the responsibility of local authorities.

On Scotland's 'softer' coasts, susceptibility to erosion has often justified public funding for coastal protection. The resulting defences often provide ancillary flood management benefits (Ball et al., 2008). As in England and Wales, increasing rates of sea level rise and budget limitations call into question the future viability of defences, and lack of knowledge of sediment erosion and accretion rates along many parts of the coastline remains a key problem in planning for the future. SMPs in Scotland have regional coverage on coastlines where erosion is a management issue, and are valued in this respect by local authorities. They have identified some limited scope for targeted managed realignment which may have local flood risk management benefits in some locations. ICZM has been very effective in Scotland in bringing together voluntary stakeholder partnerships.

Ireland

A lack of underpinning knowledge is presently a compromising factor in developing socio-economic responses, and is a strengthening driver to further study. As a larger database of high quality observations becomes available, an improved understanding of the storm and wave climate around Ireland will enable demarcation of regions susceptible to projected changes.

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World wide web resources

Investing for the future. Flood and coastal risk management in England - a long term investment strategy:

http://www.environment-agency.gov.uk/research/library/publications/108673.aspx

The Pitt Review: Lessons learned from the 2007 floods

http://archive.cabinetoffice.gov.uk/pittreview/thepittreview.html

Defra Flood Management's Making Space for Water pages

http://www.defra.gov.uk/environment/flooding/policy/strategy/index.htm