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Impacts of climate change on sea level

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EXECUTIVE SUMMARY

Mean sea-level rise measured at tide gauges around the UK (1901-present) is estimated at 1.4 ± 0.5 mm per year, which is consistent with the globally averaged figure from tide gauge records (of 1.8 ± 0.5 mm per year). Vertical land motion will modify this by -1.2 to +0.7 mm per year. The rate of sea-level increase was greater in the 20th century than the 19th century.

The projections of sea-level rise for the UK, set out in UK Climate Projections 2009 (UKCP09), remain valid but should be updated in due course using the newer global and regional values from the IPCC Fifth Assessment Report.

Projected sea-level rises including the effect of vertical land movement for London over the interval 1990–2095 are estimated to be in the range 21–68cm. Due to the spatial pattern of crustal movement, slightly larger sea-level rises are projected for southern parts of the UK with smaller increases for the north.

Sea-level rise will continue beyond 2100, with the amount of sea-level rise dependent on greenhouse gas emissions

Observational evidence shows that patterns in extreme sea levels are controlled by changes to mean sea level, rather than changes in storminess.

There is no significant evidence for future changes in storm-related extreme sea levels for the UK, due to low confidence in the simulation of extreme winds in climate models. Therefore one may assume that future changes in extreme sea level will be governed by mean sea-level rise.

1. WHAT IS ALREADY HAPPENING?

Global and regional sea level

Global mean sea level has risen (IPCC, 2007) at a rate of 1.7 mm (1.2 to 2.2) per year over the 20th century, with 1.8 mm (1.3 to 2.3) per year over the period 1961 to 2003, and a rate of 3.2 mm (2.4 to 3.8) per year observed by satellite altimetry between 1993 to 2003. Recent studies bring the time series of sea level observations nearer to the present day, for instance Church and White (2011) estimate a rate of 3.2±0.4 mm per year for the period 1993-2009 from satellite measurements. Sea-level change at any particular location depends on a number of regional and local physical processes as well as global climate drivers; consequently regional sea-level change will usually differ from the global average. As far as impact is concerned, it is the sea level with respect to the local land level that is of primary interest and the solid Earth itself is also moving. 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.* (2012).

The recently released IPCC 5th assessment report (IPCC, 2013) concludes that it is very likely that the mean 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 it was 3.2 mm per year, with a consistency between tide-gauge and satellite altimeter data. It is also likely that similarly high rates occurred between 1920 and 1950.

A significant recent development is that by considering together the causes of sea-level rise and the energy budget of the earth it is now possible to explain a large fraction of the observed global sea-level rise over recent decades (Church *et al.*, 2011). Between 1972 and 2008 around 45% of the rise measured by tide gauges was due to thermal expansion of the oceans, 40% due to melting of glaciers and ice caps, with the remainder coming from ice sheet and other terrestrial water storage. There is now evidence that mass loss contributions from Greenland and Antarctica (which will contribute to sea-level rise) are accelerating (e.g. Rignot *et al.*, 2011; Sørensen *et al.*, 2011; Shepherd *et al.*, 2012).

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.

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 of 1.8 mm per year, although the central estimate around the UK is slightly lower than that of the global value (Woodworth *et al*., 2009).

Extreme sea levels

Extreme coastal high waters around the UK are caused by the combination of exceptionally high tides and severe weather events. Extra-tropical cyclones (the prevailing weather systems at UK latitudes) produce storm surges at the coast which can raise sea level by 2-3m in exceptional cases. The still water level (defined as that level before waves are taken into account) can be further elevated at the coast by wave setup caused by the onshore flux of momentum due to wave breaking. These – along with mean sea level – are the components of extreme sea level around the UK coastline.

There is evidence of an increase in extreme water levels around many parts of the global coastline, including around the UK (e.g Menendez and Woodworth, 2010). However, while changes in storminess can contribute to changes in sea level extremes, there is no evidence for either systematic long-term changes in storminess or detectable change in storm surges (IPCC, 2012). Allen *et al*. (2008) show that changes in UK storm frequency over the second half of the 20th century were dominated by natural variability. Conversely, several studies subsequent to the IPCC Fourth Assessment Report (henceforth 4AR, 2007) do provide evidence that trends in extreme coastal high water across the globe reflect the increases in mean sea level, suggesting that mean sea-level rise rather than changes in storminess has controlled the observed increase in extreme water levels. Menendez and Woodworth (2010), using data from 258 tide gauges across the globe, have confirmed the earlier conclusions of Woodworth and Blackman (2004) that there has been an increasing trend in extreme sea levels globally, more pronounced since the 1970s, but that this trend is consistent with trends in mean sea level (see also Lowe *et al*., 2010). Additional studies at particular locations, including tide gauge records around the UK, support this finding (e.g. Araujo and Pugh, 2008; Marcos *et al*., 2009; Haigh *et al*., 2010).

The IPCC fifth assessment report (AR5) highlights the local nature of water level extremes and confirms that at most locations mean sea level is the dominant driver of observed changes to extremes. In some locations, large-scale modes of variability, such as the NAO may be important.

2. WHAT COULD HAPPEN?

Global and regional sea level

The recent IPCC AR5 has projected global sea-level rise for the period 2081 to 2100, compared to 1986 to 2005, of 0.29 to 0.82m. The precise range varies with the assumed Representative Concentration Pathway (RCP) scenario. Unlike in the AR4, these projections include a contribution from changes in ice-sheet outflow, for which the central projection is 0.11m. Nevertheless, these new projections are broadly similar to those in the earlier AR4 assessment upon which UKCP09 is based. IPCC AR5 assigns only medium confidence in these ranges of global mean sea level rise because there is only medium confidence in the range of projected contributions from models of ice sheet dynamics. It is very likely that the rate of global mean sea level rise during the 21st century will exceed the rate observed during 1971–2010 for all RCP scenarios.

During the 21st century and beyond there will be strong regional patterns to sea level changes. The regional response will depend on global changes in the ocean, local heating and cooling, and gravitational adjustment in response to polar ice melt. Mitrovica *et al*. (2001) showed how rapid melting of major ice sources gives rise to spatial changes in 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; there is a correspondingly larger rise in sea level further from the melt source. Locally, the vertical land motion is relevant to the sea level experienced at the coastline. Following the last ice age, melting of ice sheets over geological timescales has allowed the Earth's crust to rebound. This viscoelastic response of the solid Earth is referred to as glacial isostatic adjustment (GIA). Comprehensive estimates of GIA effects on the coastline of the British Isles are provided by Shennan *et al*., (2009, 2012).

The most recent published projections of sea-level change for the UK are set out in the UK Climate Projections 2009 (Lowe *et al*., 2009). The methods used to generate sea-level projections for the UK use ensemble projections from the IPCC AR4 models (IPCC, 2007). Table 1 shows the sea-level change, excluding vertical land movements, for the UK for three emission scenarios over the 21st century.

Combining vertical land movements with the projected sea level changes gives an estimate of the local sea-level rise for the low, medium and high emissions scenarios. The vertical velocities of Earth's crust that were used in UKCP09 were taken from Bradley *et al*. (2008) and were treated as constant for the 21st century projections. Vertical land movement was calculated for four sample locations (London, Cardiff, Edinburgh and Belfast). Once land movement is included, slightly larger sea-level rise projections are obtained in southern parts of the UK where land is subsiding, and somewhat lower increases in sea level for the north. UKCP09 gives sea level increases (including vertical land movement) for 1990–2095 of approximately 21–68 cm for London and 7–54 cm for Edinburgh. The ranges refer to the most likely spread of values (5th to 95th percentiles) from the medium emissions scenario. The full spread of results can be found in Lowe *et al*. (2009). (Updated values for vertical crustal motions are now available (Shennan *et al*., 2012) but differ negligibly from those used in the UKCP09 arithmetic.)

Table 1. UK mean sea level change (cm) over the 21st century including ice melt, under three different scenarios, with 5th to 95th percentile confidence intervals. The changes relate to the periods 1980–1999 to 2090–2099.

Emissions scenario	5th Percentile	Central estimate	95th Percentile
High	15.4	45.6	75.8
Medium	13.1	36.9	60.7
Low	11.6	29.8	48.0

A complete description of the GIA process also contains terms which affect sea level through changes to the shape of ocean basins and also gravitational effects (e.g. Shennan *et al*., 2012). Including these components, the relative sea-level rise due to transition from the last ice age would be increased by 0.1-0.3mm per year at some locations around the British coast. These minor terms were not included in UKCP09. Their contribution (a maximum of 3cm per century) is relatively small compared to the explicit uncertainty in the sea level projections.

Several studies use simple statistical (so called semi-empirical) models that relate 20th-century (e.g. Rahmstorf, 2007) or longer (e.g. Vermeer and Rahmstorf, 2009; Grinsted *et al*., 2010) temperature or radiative forcing (Jevrejeva *et al*., 2010) with sea-level rise, in order to extrapolate future global mean sea level. These models are motivated by evidence in the paeleo record of a connection between global mean sea level and temperature over glacial/interglacial timescales. Assumptions regarding parameters and calibration data of these semi-empirical models result in a wider range, and typically larger, projections of sea-level rise than those obtained from process-based models. For example, Rahmstorf (2007) projected sea-level rise by 2100 under a range of climate scenarios as 0.50 to 1.40 m, and Vermeer and Rahmstorf (2009) suggested the range 0.75 to 1.90 m. For the A1B climate emissions scenario, Grinsted *et al*. (2010) projected sea-level rise of 0.90 to 1.30 m. There are several reasons why these methods may not accurately predict future sea levels for a given emissions pathway. For instance, the balance of processes from the period over which the model parameters are derived may not be the same in the future. Church *et al*. (2011) note that these models may overestimate future sea levels because of the exclusion of key non-linear processes and climate feedback mechanisms. Also, future rates of sea level rise may correlate less well with global mean temperature if ice sheet dynamics play an increased role in the future (Cazenave and Llovel, 2010).

The UK Climate Projections 2009 (Lowe *et al*., 2009) provided a high-end scenario (so-called 'H++') to aid contingency planning. Whilst such estimates contain numerous assumptions, they are nevertheless required by some agencies. This low probability, high impact, value was estimated at 1.9 m, consistent with physical constraints on glacier movement (Pfeffer *et al*. 2008); this value also encompasses the majority of semi-empirical model projections. For comparison, Katsman *et al*. (2011) used an alternative method to develop a high-end scenario of 0.40 to 1.05 m sea level rise (excluding land subsidence) on the coast of the Netherlands by 2100.

There has been some recent focus on the rise in 21st century sea level that would occur if the rise in global mean temperatures were to be limited to no more than 2°C of warming above pre-industrial levels (the stated goal of many nations and the United National Framework Convention on Climate Change). Pardaens *et al*. (2011) compared a scenario that limits global warming to around 2°C with a business-as-usual scenario (with no policy curbs on emissions growth) and showed that around a third of the 21st century projected sea-level rise (0.29-0.51m) was offset by the mitigation efforts.

The IPCC Fifth Assessment Report uses a new set of future pathways of greenhouse gas forcing, which were not available at the time of producing UKCP09. Furthermore the precise method of calculating sea-level changes, and the baseline period were different compared to the previous IPCC report. The greenhouse gas forcing associated with the SRES A1B scenario reaches a level late in the 21st century similar to that of the newer RCP6.0 pathway used in the IPCC 5th assessment report.

The central estimate for 21st century global sea-level rise for SRES A1B using the IPCC 4th assessment approach is around 35cm between a reference period of 1980-1999 and a future period of 2080-2099. When the 5th assessment approach is used with this scenario a higher central value is projected for the period between 1986-2005 to 2081-2100. Using the 5th assessment approach and reporting periods the SRES A1B is projected to cause a global mean sea-level rise between the results for the RCP6.0 (47cm) and higher RCP8.5 (62cm) central estimates.

The regional patterns of sea-level change in the 21st century still differ between models. However, about 70% of the global coastlines are projected to experience a sea-level change within 20% of the global mean sea-level change.

The fifth assessment did not report a 'H++' case but did consider the possibility of larger sea level increases during the 21st century. Such a contribution could come from the collapse of marine-based sectors of the Antarctic Ice Sheet and may reach several tenths of a meter of sea-level rise during the 21st century. With current understanding, it is not possible to put a probability on this occurring.

Extreme sea levels

Extreme sea levels could change in the future both as a result of changes in atmospheric storminess and of mean sea level rise. It is very likely that mean sea-level rise will continue to contribute to positive trends in extreme coastal high water levels in the future. 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).

Debernard and Roed (2008) used hydrodynamic models to investigate storm surge changes over Europe in four regionally downscaled climate models including two runs with B2, one with A2, and one with the A1B emission scenario. They report large inter-model differences with decreases (between 1961-1990 and 2071-2100) in the 99th percentile surge heights south of Iceland, yet an 8 to 10% increase along the coastlines of the eastern North Sea and the north-west British Isles in the winter season. Wang *et al.* (2008) reported a significant increase in wintertime storm surges around Ireland except the south Irish coast (2031-2060 relative to 1961-1990) using a downscaled GCM under an A1B scenario. Sterl *et al.* (2009) joined the output from an ensemble of 17 climate model runs into a single longer time series so as to estimate 10,000-year return values of storm surge heights along the Dutch coastline: they found no statistically significant change in this value for the 21st century because any wind speed changes were not associated with the surge-generating wind directions.

The United Kingdom Climate Projections (UKCP09; Murphy *et al.*, 2009) are regarded as the most comprehensive approach to date for quantifying uncertainties in regional projections (IPCC, 2012). A Bayesian framework was used to combine a perturbed physics ensemble exploring uncertainties in atmosphere and ocean processes, and the carbon and sulphur cycles, with structural uncertainty. An 11-member RCM perturbed physics ensemble then downscaled the projections to a storm surge model (Lowe *et al.*, 2009). The storm surge which statistically is expected to occur, on average, once every 50 years is defined as the 50-year return level. Lowe *et al.* (2009) reported that for the majority of the UK coastline there were no significant changes to return levels. In the southwest of the UK there was a small, but significant, trend in the 50-year return level, implying changes to large storm surges of less than 10cm over the 21st century. This is less significant than either observed or projected rises in mean sea level rise.

Lowe *et al.* (2009) also developed a low probability, high impact, H++ scenario in order to supply a plausible upper limit for contingency planning. Forcing winds from climate models were scaled up based on the most extreme winds derived from the global climate models in the IPCC 4AR (2007). Using this method, Lowe *et al.* (2009) estimated that this could hypothetically add up to 0.7m to the 5-year return period skew surge in 2100. However, the most recent IPCC special report into extremes (IPCC, 2012) states that there is generally low confidence in projections of changes in extreme winds because of the shortcomings in the simulation of these events (e.g. weather systems are not resolved by the current generation of climate models).

A further potential contribution to extreme sea levels around the UK is reported by Pickering *et al.* (2012). 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 amphidromic system in basins such as the North Sea. Any modification to the tide is spatially variable, but in places the change in M2 amplitude can be as much as 25% of assumed mean sea-level rise. This could lead to local changes in spring tidal range of over 0.25m, if a mean sea-level rise of 1m is obtained.

The IPCC 5th assessment report considers 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, This is consistent with are earlier analysis. The report also concludes that there is low confidence in region-specific projections of storminess and associated storm surges.

Updating UKCP09

It is important to review the UKCP09 projections now that the IPCC Fifth Assessment Report is available. This review should include the global mean sea-level rise component, regional mean sea-level change, and changes in surge that result from changes in storminess. Both central estimates and uncertainty ranges should be considered. There is some evidence than developments in climate modelling, such as a better treatment of the stratosphere (e.g. Scaife *et al.*, 2012) may impact on the position and future movement of the storm tracks, which could alter the projections of future storm surges. However, these new climate models have not yet been used to drive surge models for the UK shelf region and so the impact on surges is not reported directly in the IPCC fifth assessment report. Further analysis is needed.

Increases in sea level beyond 2100

It is very likely that global mean sea-level rise will continue beyond the 21st century. The thermosteric response 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 stabilized immediately (which is unlikely). Contributions to sea-level rise from ice sheets are expected to continue beyond 2100, but glacier contributions will decrease as the amount of glacial ice diminishes. The eventual amount of future sea-level rise is closely linked to projections of the future global surface temperatures, or to the concentration of carbon dioxide in the atmosphere. Some models suggest sea-level rises of between 1-3m in response to CO_2 concentrations above 700ppm. Studies of the last interglacial period (e.g. Kopp *et al.*, 2009) indicate a very high probability of a sea-level rise of 2m over 1000 years, and possibly values in excess of 4m.

The IPCC fifth assessment reports very high confidence that the maximum global mean sea level was at least 5 m higher than present and high confidence that it did not exceed 10 m above present during the last interglacial period. This sea level is higher than reported in the previous IPCC assessment because of more widespread and comprehensive paleoclimate reconstructions.

Simulations in the IPCC fifth assessment that go beyond 2100 show the expected continuation of sea-level rise seen in earlier reports.

3. KNOWLEDGE GAPS

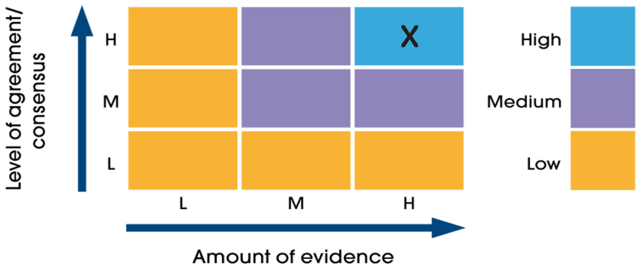
The top priority knowledge gaps that need to be addressed in the short term to provide better advice to policy makers are:

a. An improved understanding of the processes controlling time mean regional sea-level rise, in order to provide accurate regional projections. This implies more sophisticated combination of the ocean and solid Earth models, as well as sustained and careful monitoring of sea level

b. Improved modelling of physical processes that couple the ocean and the cryosphere. Coupled ocean ice sheet models require further development and validation in order to explore the plausibility of rates of sea-level rise outside that suggested by the current models

c. Improved modelling of mid-latitude weather systems with the ambition of seamless model configurations that span operational weather, seasonal forecasting and climate modelling. The future impact of waves and storm surges demands a more reliable projection of extreme wind conditions

There is strong consensus in the scientific community regarding these priorities.



4. SOCIO-ECONOMIC IMPACTS

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. The area at risk of coastal flooding equates to a coastline of 3500km, of which 3200km is defended. For complete details of the risk across the whole UK coastline, see the 2013 MCCIP report on coastal flooding (Donovan *et al.*, 2013).

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 need 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 over the same period.

There has been considerable progress in quantifying the socio-economic impacts of sea-level rise for London, where a significant proportion of UK GDP is focused. The Thames Estuary project, reported in the UKCP09 report (Chapter 7), combined climate projection information with socio-economic scenarios for the future of London to assess the impact of flooding on the capital city.

5. CONFIDENCE ASSESSMENT

What is already happening?

The observational evidence (for "what is already happening") is of the highest quality and has the benefit of international peer review. Scientific analysis of the past records of sea-level rise has improved since 2010; specifically more is known about centennial changes in sea-level rise, and the minimum length of records required to separate trends from variability on all time scales.

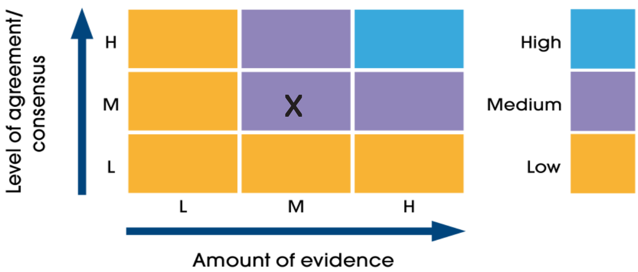
What could happen?

The largest challenge for future projections of sea level, or sea level extremes, is the inherent uncertainty in climate model predictions. For mean sea level, several processes are still not explicitly represented (e.g. coupling between ocean and melt water input). At the present time there is no single model of sea-level change due to heat uptake in the ocean, and the gravitational and GIA responses of the solid Earth. There are still significant uncertainties associated with the simulation and downscaling of winds, particularly extreme winds. Consequently, there is low confidence in the future simulations of storm surges and waves.

Ensemble simulations (both multi-model and perturbed parameter) have proven valuable in quantifying uncertainty. Advances in ensemble generation techniques and computing power have, since 2010, improved confidence in the results of ensembles. Increasingly, ensemble model simulations are combined with observations, however, there is no single agreed approach to this at present.

There is no scientific consensus on the validity of semi-empirical models. Although they tend towards higher estimates of sea-level rise it is impossible to assign significance to the results, and therefore they should be treated with caution. Synthetic, high-end scenarios contain very large uncertainty and cannot be assigned a probability.

The IPCC fifth assessment report further highlighted that there is low agreement in semi-empirical model projections, and no consensus about their reliability.



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