

KEVIN HORSBURGH¹ AND JASON LOWE²

¹National Oceanography Centre, Joseph Proudman Building, Liverpool. L3 5DA

²Met Office Hadley Centre (Reading Unit), Department of Meteorology, University of Reading, Reading, RG6 6BB.

Please cite this document as:

Horsburgh, K. and J. Lowe (2010) Mean Sea Level and Sea Level Extremes in MCCIP Annual Report Card 2010-11, MCCIP Science Review, 10pp. www.mccip.org.uk/arc

EXECUTIVE SUMMARY

- From tide gauge records, global mean sea level rise over the last 55 years is measured at 1.8 (\pm 0.2) mm per year. Satellite altimetry gives a rate of about 3 mm per year since 1992, but it is unclear if this is a permanent acceleration or natural variability in the rate.
- Mean sea level rise measured at sites around the UK is consistent with the globally averaged figure.
- Projections of 21st century sea level rise (excluding vertical land movement) 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 sea level increases (including vertical land movement) for 1990–2095 for London are approximately 21–68cm.
- A low probability sea level range, denoted H++, has been defined *for the purposes of contingency planning only*. This extreme estimate of sea level rise ranges from 93 cm to 1.9 m by 2100.
- There is no significant evidence for any recent observed trend in storm surge frequency or magnitude. This component of extreme sea level appears to be less important than changes in global mean sea level over the next 100 years.

FULL REVIEW

1. What is already happening?

Global and local mean sea level

The rate of global mean sea level rise over the last 55 years is estimated to have been 1.8 (\pm 0.2) mm per year, based upon 177 coastal tide gauges with near global coverage and correcting for vertical land movements due to glacial isostatic adjustment (GIA). A sparse dataset of tide gauges suggests a similar rate applied over the past century (Church *et al.*, 2008; IPCC, 2007; Holgate and Woodworth, 2004).

Since 1992, near-global satellite radar altimetry has suggested a rate of nearer to 3 mm per year (Holgate and Woodworth, 2004; Nerem *et al.*, 2006). Although this hints at a recent acceleration of the global sea level trend, similar rates have been observed in portions of the longer record so it is not yet clear if the higher rate of sea level rise will be sustained into the future.

Although there is a great deal of local variability in the measured values, mean sea levels around the UK mostly exhibit rises that are consistent with the global mean value of 1.8 mm per year (Woodworth *et al.*, 2009).

Extreme sea levels

The surge and wave climate of the North Atlantic and its adjacent shelf seas have been the subject of considerable study. 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 either 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.

It is prudent to also examine evidence of changes in the drivers of surge and extreme waves around the UK, namely mid-latitude storm systems. The WASA project (WASA, 1998) examined the hypothesis of a worsening storm climate in this region over the 20th century and identified an increase in storminess at the end of the last century, however this increase was consistent with well-known and significant decadal variability. Recent work by Allen *et al.* (2008) further suggests that changes in storm frequency over the last several decades of the 20th century is likely to be natural variability.

2. What could happen in the future?

Global and regional mean sea level in the 21st century

Our understanding of future mean sea level rise contains a large degree of uncertainty. The latest IPCC report (IPCC, 2007) projects a range of 0.18-0.59m of sea-level rise between 1980-1999 and 2090-2099, incorporating uncertainty in both future greenhouse gas emissions and in the simulation of physical processes. The report stresses that the contribution from ice melt is highly uncertain and describes three plausible ice melt scenarios, with the highest adding 0.17m to the total but it acknowledges even greater increases are possible.

Since the IPCC report, new estimates of 21st century sea level rise have been published. Several of these recent studies were based on simple parametric relationships between global sea level and global surface temperature. Regressive techniques are then used to calibrate the relationship, using long tide gauge records or geological data, and future sea levels are projected by supplying IPCC projected temperature rise as input to the functional relationship. Some of these studies have suggested that 21st century rises larger than 1m cannot be ruled out (e.g. Rahmstorf, 2007; Jevrejeva *et al.*, 2008). These simple models do not attempt to describe the complete dynamics or thermodynamics of the oceans, and there is no consensus over their applicability (e.g. Holgate *et al.*, 2007 for a description of some limitations of using this type of modelling approach).

The spatial patterns of future sea level rise in the IPCC report (IPCC, 2007) show considerable deviations from the global mean value. Furthermore, the projections from different models are notably different from each other, although some common features include: typically smaller sea level changes in the southern ocean, large magnitude of change in the Arctic, and notable variations near western boundary

currents. These spatial variations result from changes in the ocean density structure, due to both temperature and salinity changes, and circulation changes. In the Atlantic, changes in the spatial patterns of sea level rise may be associated with changes in the Meridional Overturning Circulation (MOC).

A recent model study by Yin *et al.* (2009) showed that the most pronounced effects of any change to the MOC would be felt along the US and Canadian east coast. A complete cessation of the MOC could produce up to 40cm changes very quickly (over a few months). On longer (multi-decadal) time scales such a scenario could also produce sea level changes in the east Atlantic, but this is far less certain. Other studies (e.g. Kuhlbrodt *et al.*, 2009) have shown higher levels of change under MOC cessation conditions with patterns of maxima that extend farther east than in Yin *et al.* (2009) suggesting a dependency, to an extent, on the climate model used and its spatial resolution. The current consensus amongst scientists is that a complete collapse of the MOC is very unlikely but not impossible.

A second important cause of spatial sea level variation results from the gravitational influence of ice mass on the oceans. A simple illustration is given by Mitrovica *et al.* (2001) who use an elastic Earth model to show how the rapid melting of major ice sources gives rise to unique spatial changes in Earth's gravity field (as well as to the volume of water in the oceans). The resultant gravitational attraction on the mass of the ocean produces a net sea level change which has a distinctive spatial pattern (so-called "fingerprinting"). As an example, within approximately 1000 km of Greenland melting ice would produce a sea level fall (compensated for by a greater than average rise further away).

The most recent 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 the spread of projections from the most recent IPCC model assessment (IPCC, 2007). Changes in the global mean are projected to be dominated by the thermal expansion, but changes in the ocean circulation and regional density changes cause local deviations from the global mean (IPCC, 2007). Table 1 shows the sea level change, excluding vertical land movements, for the UK for three emission scenarios over the 21st century. Including both scenario uncertainty and climate model uncertainty gives a projected range of sea level rise over the 21st century of approximately 12 to 76cm.

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

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 are given for the period 1980–1999 to 2090–2099. These reference periods are based on earlier IPCC baseline choices.

During the last ice age thick ice sheets covered a much larger land area than they do today. Melting of the ice sheets over geological timescales removed the load and allowed the crust to rebound. The deformation of the solid Earth and the perturbation to the gravity fields resulting from the mass redistribution is referred to as glacial isostatic adjustment (GIA). A consequence of the adjustment is a change of sea level relative to the land. 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).

Combining vertical land movements with the IPCC projected sea level changes gives an estimate of the time series of relative sea level rise for the low, medium and high emissions scenarios. A complete description of the GIA process also contains terms which affect sea level through changes to the shape of ocean basins and gravitational effects (e.g. Shennan *et al.*, 2009). 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. These terms were not included in UKCP09. Their contribution (a maximum of 3cm per century) is relatively small compared to the explicit uncertainty in the IPCC projections, and the much larger sea level rises that are described below in section 1.2.2.

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 relative sea level for the north. For example, UKCP09 projects relative sea level increases for 1990–2095 of approximately 21–68 cm for London and 7–54 cm for Edinburgh (5th to 95th percentile for the medium emissions scenario. The 95th percentile is raised by around 15cm if the higher emissions scenario is considered). The full spread of results can be found in Lowe *et al.* (2009) or downloaded directly from the UKCP interactive user interface (<http://ukclimateprojections-ui.defra.gov.uk/ui/admin/login.php>).

A low probability high impact sea level scenario

In this section we provide a single scenario of sea level rise to aid contingency planning. Such a large amount of sea level rise is thought to be highly unlikely during the 21st century but cannot be ruled out completely at present.

The least certain component of future sea level rise is due to a lack of current scientific understanding of aspects of ice sheet behaviour. Therefore there are known limitations to including this component in sea level projections. Following UKCP09 (Lowe *et al.*, 2009) a low probability high impact scenario for sea level rise around the UK has been developed. It is derived from indirect observations of sea level rise in the last interglacial period, combined with estimates of maximum glacial flow rate.

Proxy records in deep ocean sediments, corals or ice cores from the ice sheets can be used to infer estimates of past sea level changes. During the last interglacial period (about 125,000 years ago) the major continental ice sheets were in a similar position to today and the global mean surface temperatures were comparable to those projected for coming decades (Otto-Bliesner *et al.*, 2006). Data from this era may offer some insight into possible future sea level changes. Using Red Sea sediment data, Rohling *et al.* (2008) estimate average rates of sea level rise during the last interglacial period of 1.6 ± 0.8 m per century. This implies an upper limit of approximately 2.5m sea level rise for maximum global mean sea level rise over the 21st century. Such a large sea level rise requires a degree of ice melt that would in turn affect regional sea levels through GIA mechanisms. If the spatial patterns of adjustment suggested by Tamisea *et al.* (2001) are adopted then the low probability high impact scenario for contingency planning is estimated as 1.9m. This is consistent with the findings of Pfeffer *et al.* (2008) who concluded that 21st century sea level rise in excess of 2m appears to be physically impossible on the basis of observed glacial movement.

Several strands of evidence point to there being only a very low probability of such large sea level increases occurring during the 21st century. The value we used is based on the maximum rate of rise observed by Rohling *et al.* (2008) during a period much longer than a century, and Pfeffer concluded in his study that sea level rise of less than 1m during the 21st century is much more likely than a rise of 2m.

Furthermore, the observational record of outlet glaciers and ice streams is short and so recent accelerations might represent decadal variability rather than the start of a long-term trend. Detailed modelling work by Nick *et al.* (2009) for a single large Greenland glacier showed that periods of glacier flow speed up are likely to be followed by a slow down, and so cautioned about drawing conclusions of permanent acceleration from short observational records.

Thus, two types of future projections are presented here, a range based on current process based models, and a larger event that is very unlikely to occur during the 21st century but which cannot yet be ruled out completely.

Extreme sea levels in the 21st century

One possible consequence of climate change is a change in the future frequency of extreme surge events. This hypothesis is typically tested by cascading atmospheric information from a global scale general circulation model (GCM) of climate, through a regional climate model (RCM) that can simulate mesoscale meteorological processes, to regional hydrodynamic surge (or wave) models. This methodology has been applied previously to storm surges in the North Sea by Lowe *et al.* (2001), Hulme *et al.* (2002), Woth *et al.* (2005), and Debernard and Roed (2008). All these studies identify certain areas where there is an increase in surge magnitude in future climate scenarios, but there is no agreement over its magnitude or which regions will be affected. Furthermore, the changes to extreme water levels have recently been found to be of the same order as the natural climatological variability.

Previous coupled climate-surge modelling studies have contained three main methodological drawbacks. The key quantity examined in all previous research on storm surge climate (e.g. Lowe *et al.*, 2001; Hulme *et al.*, 2002) has been the non-tidal residual (i.e. the time series obtained by subtracting a tidal run from the fully forced surge model run). Many properties of the residual time series are thus an artefact of small changes to the timing of predicted high water. Secondly, all the previous studies attempted to identify long-term trends by fitting stationary extreme value distributions to 30-year time-slices at either end of the (typically 150 year) simulations. Establishing the statistical significance of changes is thus difficult because this approach does not sample the decadal and multi-decadal natural variability known to affect European storminess (e.g. Jenkins *et al.*, 2007). Finally, the grid resolution of both RCM and hydrodynamic surge model has not previously been sufficient to properly resolve all of the relevant physical processes. Consequently modelled extreme water levels have previously been underestimated.

Recent work reported in UKCP09 Chapter 4 (Lowe *et al.*, 2009) addresses these deficiencies and further quantifies model uncertainty by linking the winds and surface pressure fields from the regional climate model ensemble to a 12 km resolution storm surge model. The atmospheric models were all forced by the medium emissions scenario. Extreme storm surges (both observed and modelled) exhibit large inter-annual variability. To examine changes to the frequency and magnitude of large storm surges a statistical method was applied based on the generalised extreme value (GEV) distribution. Parameters within the GEV model were allowed to vary with time, facilitating an analysis of the full 149 yr simulation (1951–2099) from the 11-member Met Office climate model. This represents an improvement over all earlier work that compared time slices.

The storm surge which statistically is expected to occur once every 50 years is defined as the so-called 50 year return level. The analysis considered the maximum fitted trend in the ensemble mean for four return periods: 2, 10, 20 and 50 years. 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, which implies a change to large storm surges of less than 10cm over the 21st century. This is clearly less significant than either observed or projected rises in global mean sea level rise (see section 1.2.1 above). We conclude that the physical significance of any trends in the storminess-driven component of extreme sea level is small. The same lack of any trend in future storminess, and therefore storm-related marine impact, has been reported independently by Bengtsson *et al.* (2009).

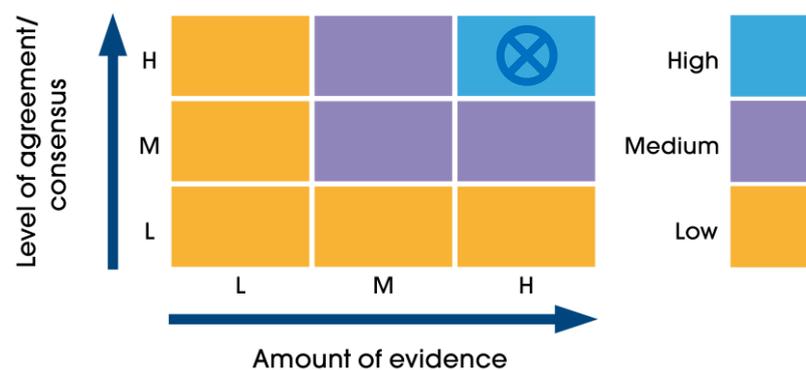
Just as with the mean sea level component, an extreme ‘H++’ scenario was developed for storm surges. As with sea level, this scenario is considered low probability but not impossible. The approach was to construct an empirical index of UK storm intensity and apply it to the range of global climate models used in the IPCC fourth assessment report. One of those IPCC models had a greater increase in this “intensity index” than any of the Met Office ensemble members. When storm surge forcing winds were scaled up accordingly, Lowe *et al.* (2009) estimated that this could hypothetically add up to 0.7m to the 5-year return period skew surge in 2100. Such large storm increases were only implied by a single climate model and alternative scaling methods led to lower increases, but the figure provides a plausible upper limit for contingency planning.

Increases in sea level beyond 2100

It is very likely that increases in mean sea level rise will continue beyond the 21st century. This is because it is likely to take at least several hundred years for the climate system to reach equilibrium even if greenhouse gas concentrations are stabilised in the next few decades. Prior to the equilibrium being reached heat will continue to be added to the ocean causing thermal expansion to continue. Furthermore, several climate models predict that if the Greenland ice sheet and Western Antarctic Ice Sheet pass critical thresholds their loss may continue even if greenhouse gas concentrations are subsequently reduced. These thresholds are often expressed in terms of temperature (IPCC, 2007) but their precise values are still uncertain.

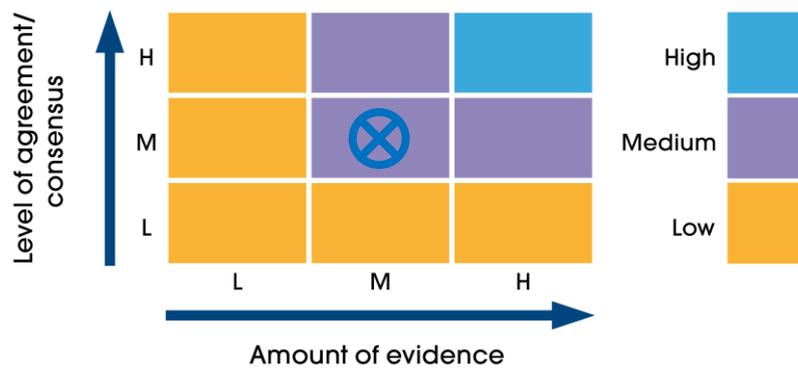
3. Confidence in the science

What is already happening: **High**



The observational evidence (for “what is already happening”) is of the highest quality and has, through the IPCC process and the references herein been subjected to considerable scientific analysis.

What could happen: **Medium**



The largest challenges for future projections of sea level, or sea level extremes, is the inherent uncertainty in climate model predictions that is due to the treatment of small scale processes, insufficient knowledge of the initial state, and aspects of the physical world whose physics are not completely understood. Ensemble simulations, where several versions of the climate model are run can help quantify this uncertainty. Perturbed parameter models were used in the storm surge projections of UKCP09. Multi-model ensembles use models from several international institutes; this ensures a further level of robustness and was used in the mean sea level projections of UKCP09.

The H++ scenario is synthetic and contains very large uncertainty. Such a large amount of sea level rise is thought to be highly unlikely during the 21st century but cannot be ruled out completely.

The single largest uncertainty for mean sea level projections is the ice melt contribution in response to increased global mean temperatures. This ranges from global sea level rises of 10-20cm, as considered within IPCC (2007), to values of 1-2m (e.g. Rohling *et al.*, 2008).

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. Better quantification of the contribution of land ice to sea level rise is essential. In particular whether the amount of sea-level rise resulting from ice lost from the Greenland ice sheet and Western Antarctic Ice Sheet is likely to continue increasing.
2. The regional variability of sea level changes is poorly addressed at the current resolution of global general circulation models used for climate projections. Obviously, regional sea level response is what is required for planning and adaptation.
3. There is scope for the use of further advanced statistics in the design and interpretation of probabilistic forecasting. The forthcoming programme at the Isaac Newton Institute, "Mathematical and statistical approaches to climate modelling and prediction", will begin to address this.

See: <http://www.newton.ac.uk/programmes/CLP/index.html>

4. A more realistic representation of storm track and cyclogenesis (formation of mid-latitude depressions) in climate models. This will, in part, be addressed as the

spatial resolution of climate models approaches that of short-range weather models as computer power increases.

There is wide agreement on these key challenges.

5. 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.

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 focussed. 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.

For further details regarding the socio-economic impacts of sea level rise readers are directed to the MCCIP Annual Report Card (ARC) 2010-11 Science Reviews on coastal flooding (Horsburgh et al., 2010) and coastal erosion (Masselink & Russell, 2010).

6. References

- Allan, R., Tett, S. and Alexander, L. (2008) Fluctuations in autumn-winter storms over the British Isles: 1920 to present, *International Journal of Climatology*, **29**, 357-371.
- Bengtsson, L., Hodges, K.I. and Keenlyside, N. (2009), Will Extratropical Storms Intensify in a Warmer Climate? *Journal of Climate*, **22**, 2276-2301.
- Bradley, S., Milne, G.A., Teferle, F. N., Bingley, R. M., & Orliac, E. J. (2008). Glacial isostatic adjustment of the British Isles: New constraints from GPS measurements of crustal motion. *Geophysical Journal International*, doi:10.1111/j.1365-246x.2008.04033.x..
- Church, J.A., White, N.J., Aarup, T., Wilson, S., Woodworth, P.L., Domingues, C.M., Hunter, J.R. and Lambeck., K. (2008) Understanding global sea levels: past, present and future, *Sustainability Science*, **3**, 9-22.
- Debernard, J.B. and Roed, L.P. (2008), Future wind, wave and storm surge climate in the Northern Seas: a revisit, *Tellus*, **60**(A), 427-438.
- Holgate, S.J. and Woodworth, P.L. (2004) Evidence for enhanced coastal sea level rise during the 1990s, *Geophysical Research Letters*, **31**, L07305, doi:10.1029/2004GL019626
- Holgate, S.J., Jevrejeva, S., Woodworth, P.L. and Brewer, S. (2007) Comment on "A semi-empirical approach to projecting future sea level rise", *Science*, **317**, 1866b. DOI:10.1126/science.1140942
- 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
- Hulme, M., Jenkins, G.J., Lu, X., Turnpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J., Murphy, J.M., Hassell, D., Boorman, P., McDonald, R. and Hill, S. (2002) Climate change

- scenarios for the United Kingdom: The UKCIP02 scientific report, Tyndall Centre for Climate Change Research, School of Environmental Science, University of East Anglia, Norwich, 120pp.
- IPCC (2007). *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. & Miller, H. L. (Eds.)). Cambridge University Press, Cambridge, UK and New York, NY, USA, 996 pp.
- Jenkins, G.J., Perry, M.C., and Prior, M.J.O. (2007), The climate of the United Kingdom and recent trends, Met Office Hadley Centre, Exeter, UK.
- Jevrejeva, S., Moore, J.C., Grinsted, A. and Woodworth, P.L. (2008) Recent global sea level acceleration started over 200 years ago? *Geophysical Research Letters*, **3**, L08715, doi:10.1029/2008GL033611. 5.
- Kuhlbrodt, T., Rahmstorf, S., Zickfeld K., Vikebo, F.B., Sundby, S., Hoffman, M., Link, P.M., Bondeau, A., Cramer, W., Jaeger, C. (2009) An integrated assessment of changes in the thermohaline circulation, *Climatic Change*, **96**, 489-537.
- Lowe, J.A., Gregory, J.M. and Flather, R.A. (2001), Changes in the occurrence of storm surges around the United Kingdom under a future climate scenario using a dynamic storm surge model driven by the Hadley Centre climate models, *Climate Dynamics*, **18**, 179-188.
- Lowe, J.A., Howard, T., Pardaens, A., Tinker, J., Holt, J., Wakelin, S., Milne, G., Leake, J., Wolf, J., Horsburgh, K., Reeder, T., Jenkins, G., Ridley, J., Dye, S. and Bradley, S. (2009). UK Climate Projections science report: Marine and coastal projections. Met Office Hadley Centre, Exeter, UK. ISBN 978-1-906360-03-0
- Masselink, G. and P. Russell (2010) Coastal Erosion *in* MCCIP Annual Report Card 2010-11, MCCIP Science Review, 18pp. www.mccip.org.uk/arc
- 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**, 1026-1029.
- Nerem, R.S., Leuliette, E. and Cazenave, A. (2006) Present-day sea-level change: A review, *Comptes Rendus Geoscience*, **338**, 1077-1083.
- Nicholls R. J., Hanson S, Herweijer C, Patmore N, Hallegatte S, Corfee-Morlot J, Chateau J, Muir-Wood R, (2008). Ranking port cities with high exposure and vulnerability to climate extremes - Exposure estimates. Report available online from OECD Working papers
- Nick, F.M., A. Vieli, I.M. Howat & I. Joughin (2009), Large-scale changes in Greenland outlet glacier dynamics triggered at the terminus. *Nature Geoscience*, **2**, 110 – 114.
- Otto-Bliesner, B. L., Marshall, S. J., Overpeck, J. T., Miller, G. H., Hu, A. and CAPE Last Interglacial Project members (2006), Simulating Arctic climate warmth and icefield retreat in the last interglaciation, *Science*, **311**, 1751–1753.
- Pfeffer, W. T., Harper, J. T. and O'Neel, S. (2008). Kinematic constraints on glacial contribution to 21st-century sea level rise. *Science*, **321**, 1340–1343.
- Rahmstorf, S. (2007) A semi-empirical approach to projecting future sea level rise, *Science*, **315**, 368-370.
- Rohling, E. J., Grant, K., Hemleben, C., Siddall, M., Hoogakker, B. A. A., Bolshaw, M. & Kucera, M. (2008). High rates of sea level rise during the last interglacial period. *Nature Geoscience*, **1**, 38–42. (doi:10.1038/ngeo.2007.28).
- Shennan, I., Milne, G.A., and Bradley, S. (2009) Late Holocene relative land- and sea-level changes: providing information for stakeholders. *GSA Today*, 19 (9), doi: 10.1130/GSATG50GW.1
- Tamisea, M. E., Mitrovica, J. X., Milne, G. A. and Davis, J. L. (2001). Global geoid and sea level changes due to present-day ice mass fluctuations, *Journal of Geophysical Research*, **106**, 30849–30863.
- WASA (1998) Changing waves and storms in the northeast Atlantic? *Bulletin of the American Meteorological Society*, **79**, 741-760.

- 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**, 19-30.
- Woodworth, P. L. and Blackman, D.L. (2004) Evidence for systematic changes in extreme high waters since the mid-1970s. *Journal of Climate*, **17**, 1190-1197.
- Woth, K., Weisse, R. and von Storch, H. (2005), Climate change and North Sea storm surge extremes: an ensemble study of storm surge extremes expected in a changed climate projected by four different regional climate models. *Ocean Dynamics*, **56**(1), 3-15.
- Yin, J.J., Schlesinger, M.E. and Stouffer, R.J. (2009) model projections of rapid sea-level rise on the northeast coast of the United States. *Nature Geoscience*, **2**, 262-266.