UK Climate Projections science report: Marine and coastal projections

Jason A. Lowe, Tom Howard, Anne Pardaens, Jonathan Tinker, Geoff Jenkins, Jeff Ridley, *Met Office,*
James Leake, Jason Holt, Sarah Wakelin, Judith Wolf, Kevin Horsburgh, *Proudman Oceanic Laboratory,*
Tim Reeder, *Environment Agency,* Glenn Milne, Sarah Bradley, *University of Durham*, Stephen Dye, *Marine Climate Change Partnership (MCCIP)*

June 2009

Acknowledgements

We would like to thank the Environment Agency, and in particular its Thames Estuary 2100 project, who funded the Met Office Hadley Centre research into storm surge uncertainty and part funded the assessment of sea level rise uncertainty which has contributed to this report. It demonstrates a strong commitment to using the latest climate change science to drive future planning for flood risk management.

The wave simulations were funded by the Tyndall Centre for Climate Change Research through the coastal programme (http://www.tyndall.ac.uk/research/programme5/).

Some of the data used in validation of the storm surge modelling system were supplied by the British Oceanographic Data Centre as part of the function of the National Tidal & Sea Level Facility, hosted by the Proudman Oceanographic Laboratory and funded by the Environment Agency and the Natural Environment Research Council.

We wish to acknowledge the contributions made to this work by

Dr Emma Eastoe, Dept of Maths and Stats, Lancaster University
Prof. Roland Gehrels, University of Plymouth
Dr Peter Good, Met Office Hadley Centre
Dr Ben Gouldby, HR Wallingford
Prof. Jonathan Gregory, National Centre for Atmospheric Science and Met Office Hadley Centre
Dr Glen R. Harris, Met Office Hadley Centre
Prof. Robert Nicholls, University of Southampton
Prof. Julian Orford, Queens University, Belfast
Marie-Helene Rio and the CLS Space Oceanography Division, France
Graham Siggers, MSc DIC CSci MCIWEM, HR Wallingford
Prof. Jonathan Tawn, Dept of Maths and Stats, Lancaster University
Prof. Rob Wilby, Loughborough University

Reviewers

Prof. Corinna Schrum, Geophysical Institute, University of Bergen, Norway
Prof. Jaak Monbaliu, Katholieke Universiteit Leuven, Belgium
Dr Neil Wells, School of Ocean and Earth Science, University of Southampton
Kathryn Humphrey, Adapting to Climate Change Programme, Defra
Karl Hardy, Flood Management, Defra
Paul Buckley, Cefas
Dr Stephen Dye, Cefas
Roger Street, UKCIP
Anna Steynor, UKCIP
Dr Paul Bowyer, UKCIP
Richard Lamb, UKCIP
Dr Emma Verling, JNCC
Guy Winter, Scottish Government
Vanessa Bashford, Defence Estates
Dr Craig Wallace, National Oceanographic Centre, Southampton
Dan Laffoley, Natural England
Dr John Baxter, Scottish Natural Heritage
Brendan Forde, Department of the Environment of Northern Ireland

Reviewers' comments have been extremely valuable in improving the final draft of this report. However, not all changes requested by all reviewers have been accepted by the authors, and the final report remains the responsibility of the authors.

Contents

1 Introduction and overview

The UK has a long maritime heritage and the marine and coastal environment continues to play an important role in the national culture and economy. United Kingdom waters cover an area approximately three times greater than its land and the UKs coastline is the longest in the EU. Over half a million people are directly employed in maritime activities (e.g. shipping, tourism, fisheries) and 95% of international trade into and out of the UK passes through its sea ports (EU Maritime Policy Facts and Figures United Kingdom http://ec.europa.eu/maritimeaffairs/). In 2004 sea-fish with an initial value of £513 million were landed by the UK fishing fleet. It has been estimated that the total turnover of the marine sector in 1999–2000 was just under £70 billion, of which almost £40 billion was due to Oil & Gas and Leisure. Beyond the direct maritime economy the UKs marine environment provides a number of important goods and services to the UK. Along the coast, more than £150 billion of assets are estimated to be at risk from flooding by the sea, with an excess of £75 billion at risk in London alone (estimated from Halcrow, 2001).

An evidence base is growing that shows that climate change is already having an impact on the marine environment across all the components that contribute to UK governments vision for “clean, safe, healthy, productive and biologically diverse oceans and seas” (Defra, 2008; MCCIP, 2008). Good estimates of what could happen in the future marine environment and how this might impact issues as diverse as flooding, habitat conservation and food safety are becoming of increasing importance for adaptation and risk planning. We provide here a set of scenarios that may be used to assess how vulnerable particular sites or sectors are to future climate change. Our interest extends outwards from the coastal zone and into the waters of the shelf seas around the UK. The chapters of this report include:

- An introduction to the climate models and ensembles (Chapter 2)
- Projections of sea level rise (Chapter 3)
- Changes in surges (Chapter 4)
- Changes in offshore waves (Chapter 5)
- A first look at a scenario of change in the surface and sub-surface temperature, salinity and circulation of the seas around the UK (Chapter 6)
- An example case study for use of the data from these models (Chapter 7)
- A more detailed description of the vertical land movement methodology (Annex).

This report can be read as a stand-alone overview of marine change around the UK, showing key findings and detailing the science used. For more detail and direct application to answer specific questions it can be used in conjunction with the UK Climate Projections User Interface. This allows access to the derived datasets from the simulations presented here (wave data are not available through the interface as the chapter has been drawn from work outside of UKCP09). The UK Climate Projections User Guidance gives advice on how the information in this report and via the User Interface can be used.

The structure and approach of the UK Climate Projections marine scenarios is very different to that of the UK climate projections over land described in *UK Climate Projections science report: Climate change projections*. The projections over land are based around a particular climate projection methodology that enables a probability of changes to be estimated. An alternative, simpler methodology is used in this report.

The three Science Reports, and the methodologies used to generate the UKCP09 projections, have been reviewed, firstly by the project Steering Group and User Panel, and secondly by a smaller international panel of experts. Reviewers' comments have been taken into account in improving the reports.

The science is not yet at a point where the same type of approach can be reliably applied to models of the marine environment so the majority of this report presents the latest model projections as individual scenarios, providing best estimates of uncertainty ranges only where it is credible to do so. What the marine scenarios have in common with each other is that, with the exception of the changes of mean sea level, the models used to provide them are driven by atmospheric forcing from the same Met Office Hadley Centre climate model or set of models. Therefore, there is a consistency between the scenarios of changes in storm surges, shelf sea hydrography and circulation, and waves, which has previously not been possible to achieve. This means that it is now more credible to compare marine climate changes across a range of sectors. Future changes are projected for the UKCP09 medium emissions scenario (SRES A1B, Nakićenović and Swart, 2000) except for mean sea level rise and atmospheric variables above sea areas where all three UKCP09 projections are considered (Low corresponding to SRES B1 and High corresponding to SRES A1FI emissions scenarios). For full details of the scenarios used in UKCP09 and uncertainty in future emissions please see *UK Climate Projections science report: Climate change projections,* Section 2.3.

It is recognised that the mixture of presentations included in this report could be confusing to the reader, but in each case they represent what we believe to be the best scenarios given current limitations in climate modelling.

1.1 Organisation of this report

Chapter 2 of this report describes the global and regional climate models that have been used to provide the mean sea level rise projections and also give the driving input (e.g. surface conditions over the 21st century) to the range of marine models used in UKCP09. Figure 1.1 shows these common inputs schematically. It also briefly reports on projections of large-scale future changes in atmospheric storms from Met Office climate models (more information is also given in Annex 6 of *UK Climate Projections science report: Climate change projections*) and the climate models used in the IPCC Fourth Assessment. As many of the shelf sea and coastal impacts will depend on changes in atmospheric storminess this helps to establish the context for subsequent chapters.

Chapter 3 deals with projections of sea level rise, both absolute and relative to land. The absolute sea level rise is that averaged around the British Isles, and originates from projections made by an ensemble of international climate models from different modelling centres (known as a multi-model ensemble or MME) which gives us a measure of uncertainty. The chapter also discusses the possible implications of recently reported accelerated melting of the Greenland and Antarctic ice sheets. Estimates of absolute sea level rise, together with new estimates of vertical land movement derived from observationally constrained land models, are used to calculate relative sea level change (i.e. relative to land) around the UK.

Chapter 4 of this report looks at projections of change in extreme water levels. These are estimated using the Proudman Oceanographic Laboratory storm surge model (POLCS3), which is driven by winds and pressures from the Met Office regional climate model (RCM). Uncertainty in the changes in extreme water levels come from two sources: uncertainty in sea level rise and uncertainty in changes in meteorology. The estimate of uncertainty in sea level rise is incorporated by using the analysis described in Chapter 3. The uncertainty due to changes in meteorology is included by driving the surge model with an ensemble of simulations of the Met Office RCM (known as the regional PPE, see Chapter 2, Section 1). Recognising that this ensemble might not fully reflect the uncertainty in meteorological changes, we also include an estimate of changes in extreme water levels from the same storm surge model driven by projections from the climate model, selected from the MME, which shows the largest changes in storminess. Results are presented at a resolution of 12 km over the European Shelf. This chapter builds on the work by Lowe and Gregory (2005).

Chapter 5 shows projected changes in the offshore wave climate around the UK. These projections were made by the Proudman Oceanographic Laboratory running a variant of the Wave Analysis Model (WAM) as part of the Tyndall Centre Coastal Simulator project. They use a subset of members from the same driving Met Office RCM ensemble used for the surge and shelf hydrography simulations in Chapters 4 and 6, and are thus considered consistent.

Chapter 6 reports on projected changes in temperature, salinity, and currents of the water-column in the seas around the British Isles. The projections are taken from two model experiments of the Proudman Oceanographic Laboratory Coastal Ocean Modelling System (POLCOMS) for the time periods of 1961–1990 and 2070–2099. Projections are again available at a resolution of 12 km but no information on uncertainty is given with these projections as these experiments have so far been undertaken with driving meteorology from a single member of the Met Office RCM ensemble.

For users of UKCP09 the level of uncertainty may make planning and adaptation difficult. To address this, **Chapter 7** gives an example of the use of UKCP09 data in a real planning and adaptation project. The chapter contains a case study of the impacts of adapting to the sea level rise and storm surge projections given in Chapters 2–4. The subject of this study is the protection of London from flooding by the Thames Barrier and the results are taken from the TE2100 project, which was funded by the Environment Agency. The chapter shows how UKCP09 results can be used in practice.

Finally, the **Annex** provides further detail into measurement techniques of vertical land movement, as this was a contentious issue in UKCIP02.

1.2 Uncertainty in the marine scenarios

In the UKCP09 report *UK Climate Projections science report: Climate projections,* emphasis is placed on probabilistic projections of future climate. This might take the form of "there is an X% probability of the temperature in Southern England rising by Y°C by 2100". The probability is an expression of our uncertainty in future climate. This uncertainty arises from three main sources: uncertainty in our understanding of climate and the related ability of models to simulate the climate, uncertainty in future emissions, and the degree to which we can simulate the effects of natural variability for a particular time in the future.

In the future the uncertainty arising from understanding and from climate models might be reduced but this is a long term aim. Over the next few years the best we hope to achieve is to quantify rather than reduce the uncertainty using our current range of models. In *UK Climate Projections science report: Climate projections* the uncertainty in model simulations is estimated by combining the projections of numerous climate model simulations for the same emission scenarios (a climate model frequency distribution) with each model's ability to match observed constraints, such as past warming. In the marine scenarios we do not attempt to quantify a probability of future changes. We make cruder estimates of the minimum uncertainty range (together with some discussion of a *low probability, high impact* scenario range) where possible.

We choose to do this for several reasons. First, knowledge gaps in our understanding of marine processes (e.g. deep ocean mixing processes, which affect ocean circulation and mean sea level) mean that current models may not simulate the full range of possible futures. Second, even where we might estimate the range of possible futures there is an insufficient number of model simulations (e.g. of climate driven changes in waves) to credibly fill in the range between the projected highest and lowest values. Finally, insufficient work has been carried out in the maritime community on suitable observational constraints for projections of global and local marine and coastal climate change. By the next UKCIP assessment it is hoped that progress has been made in these areas.

Given these limitations, uncertainty is illustrated in a number of different ways.

- For mean sea level rise, although the models contain known physical relationships and have been tested against observations during their development, their results are not formally constrained by observations. It is, therefore, not correct to refer to these frequency distributions in terms of probability. Rather, we present frequency distributions based on these current models that can be interpreted with statements such as "50% of the models available project sea level rise to be greater than Z cm".

- When we present the 5th to 95th percentile range this should be interpreted as 90% of the modelled results lying between these bounds.

- For storm surges, simulations were produced using wind and surface pressure data from the 11-member version of the Met Office RCM. While this provides our current best estimate of the spread of model results we cannot yet be certain that they span the full range of credible storm surge changes. However, we have tried to account for this using large-scale projected atmospheric changes sampled from the international climate model community and using them to scale results from Met Office RCM ensemble. Again, we cannot make a statement about probability; instead we give a minimum estimate of the uncertainty range.

- For the wave projections only three simulations were made. Assuming all three are credible (and many aspects of the present-day climate of the driving climate models do look credible) this will give a minimum estimate of the uncertainty range.

- For the shelf sea hydrography and circulation only a single future simulation was made so no statement can be made about a range of uncertainty.

Another source of uncertainty, that of unknown future emissions of greenhouse gases, has been included for sea level rise to some extent, by presenting simulations for the three UKCP09 scenarios, High, Medium and Low. Clearly, there is a difference in projections between these potential future emission scenarios, which implies that there is still scope for modifying the climate in the 21st century by altering global emissions.

The following table shows which sources of uncertainty (row) have been addressed in each UKCP09 Marine Scenarios product (column). The key is as follows. 'P': uncertainty addressed using the perturbed physics ensemble. 'M': uncertainty addressed using the multi-model ensemble. 'E': emissions uncertainty addressed as described above. 'O': uncertainty addressed using observations and other evidence. '3': indicates that a crude assessment of uncertainty based on only three ensemble members has been made. '1': Only one climate model simulation has been used in this projection, providing a first look at the plausible outcome but does not attempt to quantify uncertainty. '–': indicates no H++ scenario was developed for this product. None of the symbols imply that the full range of uncertainty from the source has necessarily been evaluated.

Source of uncertainty	**UKCP09 Marine Scenarios Product**			
	Sea level	**Surge**	**Hydrography**	**Waves**
Atmospheric physics: Large scale cloud	M	P	1	3
Carbon and methane cycle uncertainty	1	1	1	1
Emissions uncertainty	E	1	1	1
Ocean physics uncertainty	M	1	1	1
H++	O	M	–	–

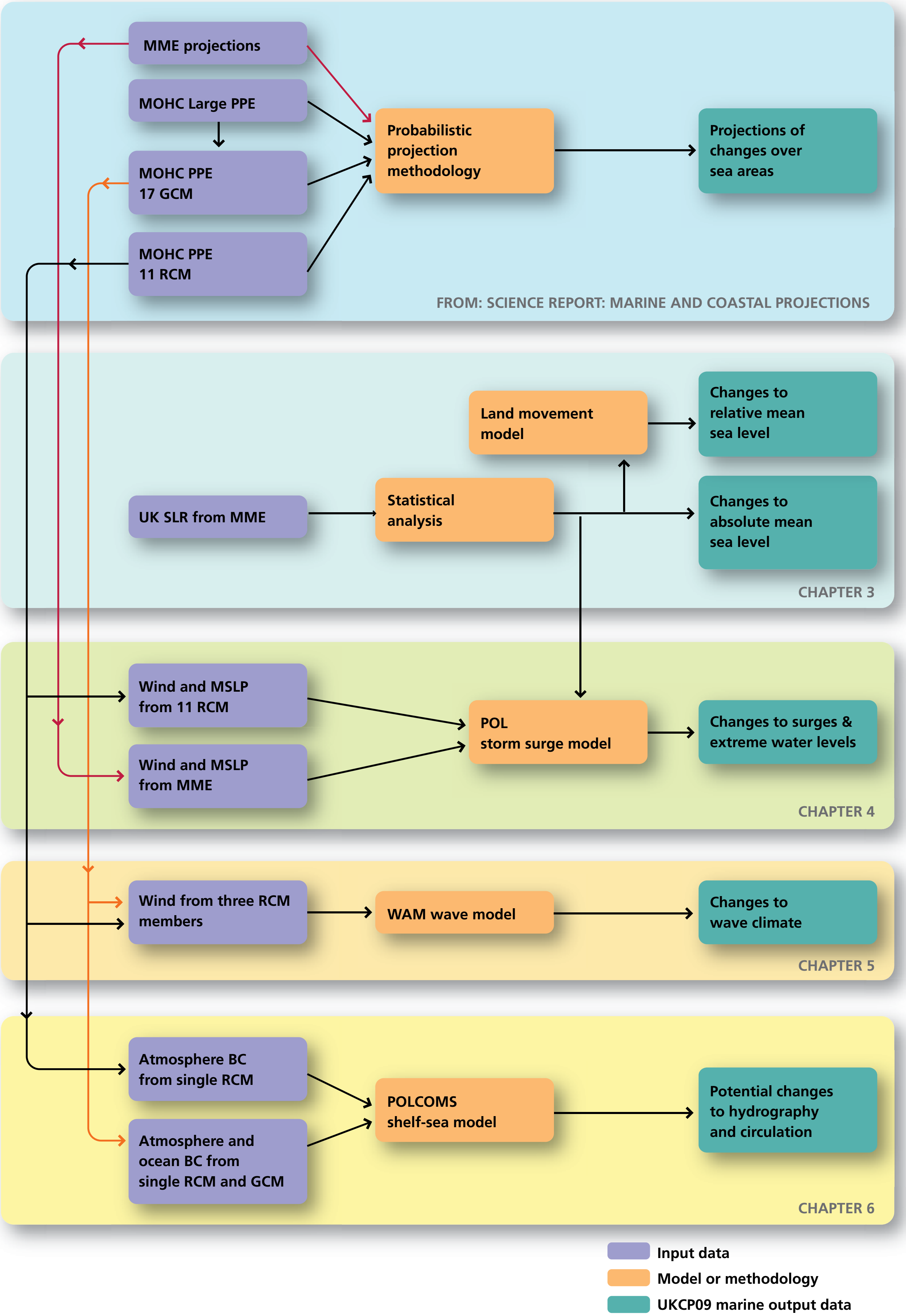
The inclusion of an extreme coastal flooding scenario

Some potential users of UKCP09 have requested a high-end coastal flooding scenario that lies above our best estimates of uncertainty for 21st century sea level rise and storm surges. In response we have developed a High-plus-plus (H++) scenario that represents a wider range of relative mean sea level rise and storm surge changes. The H++ range is not intended to replace our likely range of SLR and future surges, but rather it provides users with estimates of SLR and surge increase beyond the likely range but within physical plausibility. It is useful for contingency planning when a higher level of protection might be needed. H++ might also be used to justify a monitoring strategy. Unlike the other results presented in UKCP09 this range should not be interpreted as a likely range; the upper end of H++ is in fact very unlikely to occur by 2100.

Scientifically, H++ is an attempt to quantify emerging understanding of dynamic ice sheet processes described but not fully quantified in the IPCC Fourth Assessment Report and storminess changes projected in the Fourth Assessment Report but beyond the range simulated in the Met Office models. The MSL component of the H++ scenario depends on expert interpretation of limited high-end model results and indirect observations from past climate change events. The surge component is an attempt to place an upper bound on the increase in extreme sea levels based on current plausible models of storminess change. This high risk, low probability scenario was developed in collaboration between the Met Office and the Environment Agency.

Note, *likely* and *unlikely* do not have the same precise statistical description as in the IPCC AR4 Report.

Figure 1.1 (opposite): Components of the UKCP09 marine scenarios. Note: RCM is a Met Office Hadley Centre regional climate model, which covers the European region. GCM is a Met Office global climate model. PPE is the Perturbed Physics Ensemble from the Met Office group of climate models with 17 GCM members and 11 corresponding RCM members that validate well. MME (Multi-Model Ensemble) is an ensemble of projections from international climate models used in the IPCC Fourth Assessment. The various ensembles are described in detail in Chapter 2. SLR is sea level rise. MSLP is the atmospheric pressure at mean sea level. BC are the driving boundary conditions passed from the climate models to the various marine models. POLCOMS is the Proudman Oceanographic Laboratory Coastal Ocean Modelling System. WAM is the Wave Analysis Model. POL is the Proudman Oceanographic Laboratory.


MME projections
MOHC Large PPE
MOHC PPE 17 GCM
MOHC PPE 11 RCM
Probabilistic projection methodology
Projections of changes over sea areas
FROM: SCIENCE REPORT: MARINE AND COASTAL PROJECTIONS
Land movement model
Changes to relative mean sea level
UK SLR from MME
Statistical analysis
Changes to absolute mean sea level
CHAPTER 3
Wind and MSLP from 11 RCM
Wind and MSLP from MME
POL storm surge model
Changes to surges & extreme water levels
CHAPTER 4
Wind from three RCM members
WAM wave model
Changes to wave climate
CHAPTER 5
Atmosphere BC from single RCM
Atmosphere and ocean BC from single RCM and GCM
POLCOMS shelf-sea model
Potential changes to hydrography and circulation
CHAPTER 6
Input data
Model or methodology
UKCP09 marine output data

1.3 References

Defra (2008). Marine Program Plan 2008/2009.

Halcrow (2001). National Appraisal of Assets at Risk from Flooding and Coastal Erosion, including the potential impact of climate change. Final Report to Defra. http://www.Defra.gov.uk/environ/fcd/policy/NAAR1101.pdf

Lowe, J.A. & Gregory, J. M. (2005). The effects of climate change on storm surges around the United Kingdom. *Philosophical Transactions of the Royal Society London*, **363**, 1,313-1,328. doi:10.1098/rsta.2005.1570.

MCCIP (2008). Marine Climate Change Impacts Annual Report Card 2007–08 (Eds. Baxter, J., Buckley, P. & Wallace, C.), Summary Report, Marine Climate Change Impacts Partnership, Lowestoft.

Nakićenović, N. & Swart, R. (Eds.) (2000). Special Report on Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, 599 pp.