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UK Climate Projections science report: Marine and coastal projections

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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	–	–

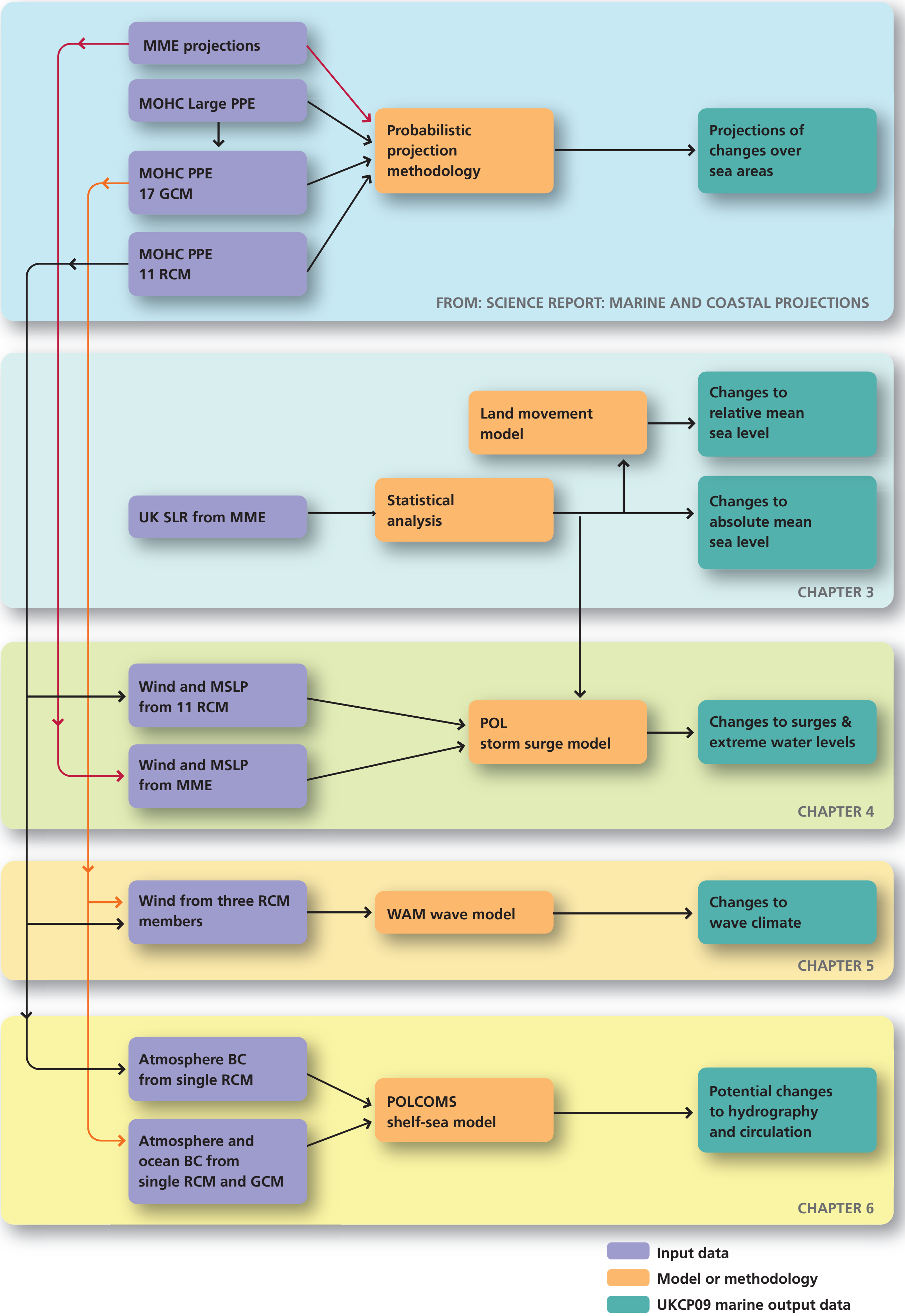
The inclusion of an extreme coastal flooding scenario

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
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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

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2 The climate models

A set of global and regional climate models have been set up by the Met Office Hadley Centre. An experimental design has been chosen that allows an estimate to be made of uncertainty of future climate projections.

Here we have combined the spread from the Met Office Hadley Centre models with that from alternative climate models produced by other international climate research institutes.

The Met Office Hadley Centre model ensemble is referred to as the Perturbed Physics Ensemble (PPE), whilst the international model ensemble is termed the Multi-Model Ensemble (MME). An understanding of the choice and experimental set up of climate modelling is important because these supply driving information for shelf sea and wave models reported in subsequent chapters. A particularly important aspect of the climate model output with regards to marine projections around the UK is changes in storminess and these are discussed here.

Key Findings

- **The available climate models provide suitable driving data with which to force models of extreme sea level (Chapters 3 and 4), waves (Chapter 5) and shelf hydrography (Chapter 6). However, since the driving models for the marine scenarios may not sample the full range of known uncertainties, each uncertainty range quoted should be regarded as a minimum range.**

- **The ensemble of Met Office Hadley Centre models (PPE) typically shows a slight weakening and southward movement of the storm track over the UK.**

- **The ensemble containing models from other climate research centres (MME), typically shows a greater increase in storm intensity, but less latitudinal movement in track position. In contrast to the PPE, a MME latitudinal shift can be either northward or southward.**

Introduction

The marine scenarios describe projected climate changes in the shelf seas around the UK. However, since the enhanced greenhouse effect (Figure 2.1), which drives these changes, involves the accumulation of radiatively absorbing gases in the atmosphere and takes place at a global scale the maritime models must be connected to climate models.

This chapter gives a brief overview of these climate models and presents results on one key aspect of their behaviour, the projected changes in the intensity and track of atmospheric storms over Europe. This feature is highlighted because in the present day climate it is known to have a major impact on UK shelf waters. The downscaling approaches used in the marine report are well-validated — as discussed in detail in the following chapters. However, the validity of the marine projections is predicated on the validity of the driving global climate models. The MME members provide a good estimate of possible climate outcomes to 2100. They provide both mean and variance of surface climate variables (temperature, precipitation, sea level pressure) at low spatial resolution (typically a few hundred kilometres) but high temporal resolution over the globe. Some models take the Earth's climate system into regimes which cannot be validated directly because the long-term changes are greater than those which have occurred during the period of recorded observations. However some validation against proxy data from different climatic regimes in Earth's history has been performed (e.g. Hewitt *et al*, 2006). Validation of the driving global climate models is discussed in more depth in *UK Climate Projections science report: Climate change projections.*

2.1 Overview of the Met Office Climate Modelling System

Climate models are currently the most credible tools for making projections of future climate over the next 100 yr. A range of different climate models exist, from the simplest energy balance models to the most sophisticated global circulation models (GCMs; see, for example, McGuffie and Henderson-Sellers, 2004). The most complex models divide the world into a series of grid boxes (Figure 2.2) and simulate the behaviour of the atmosphere and oceans on this grid by solving the equations which describe their motion and thermodynamics.

The Met Office Hadley Centre global climate model, HadCM3 (Gordon *et al.* 2000; Pope *et al.* 2000) is a general circulation model, coupling atmosphere and ocean modules. HADCM3 has been shown to have considerable skill at simulating the global climate (e.g. Stott *et al*. 2000). The model divides the atmosphere into a horizontal grid (2.5° x 3.75°) with 19 distinct layers, and the ocean into a grid (1.25° x 1.25°) with 20 vertical layers. Processes at scales smaller than the grid size are usually represented by simple relationships between the large scales and these smaller scales. Because the parameters in these relationships are often not precisely known, the model can be run with a range of parameter values and still credibly reproduce an observed climate. To estimate uncertainty in projections of the future, we can run each of these plausible model versions beyond the present day and examine the spread of the results. This approach of taking a single model structure and varying the model parameters within that structure is referred to as the PPE (Perturbed Physics Ensemble).

An alternative approach to using the PPE to estimate uncertainty is to take several models from other climate modelling centres that have quite different model structures. This is referred to as the MME (Multi Model Ensemble). In *UK Climate Projections science report: Climate change projections*, results from the PPE and MME are combined to produce probability distributions of future change. For the marine sector, there is currently insufficient information to estimate the probability of future changes in the manner applied in the atmosphere and land surface. However, useful insights about the future maritime climate still can be obtained from the PPE and to a lesser extent MME.

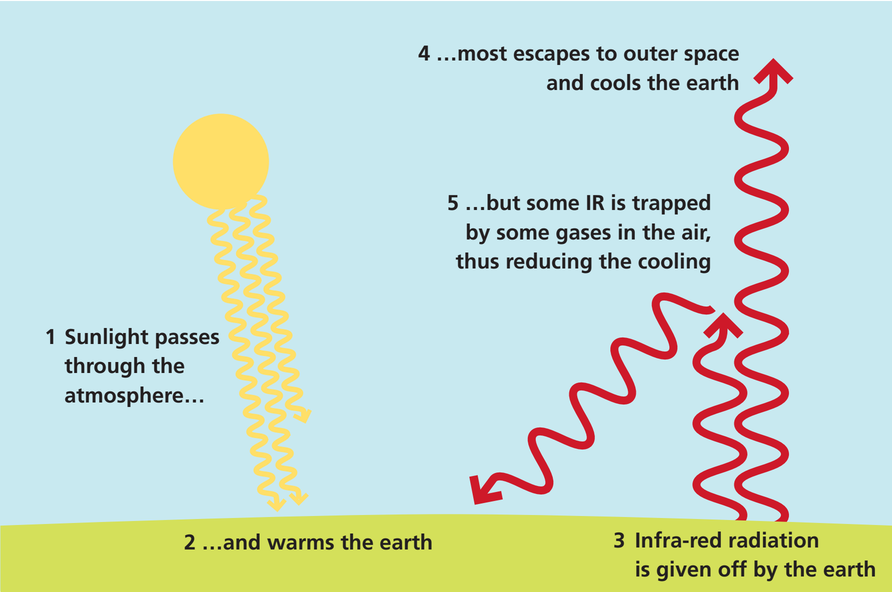


Figure 2.1: Schematic of the greenhouse effect.

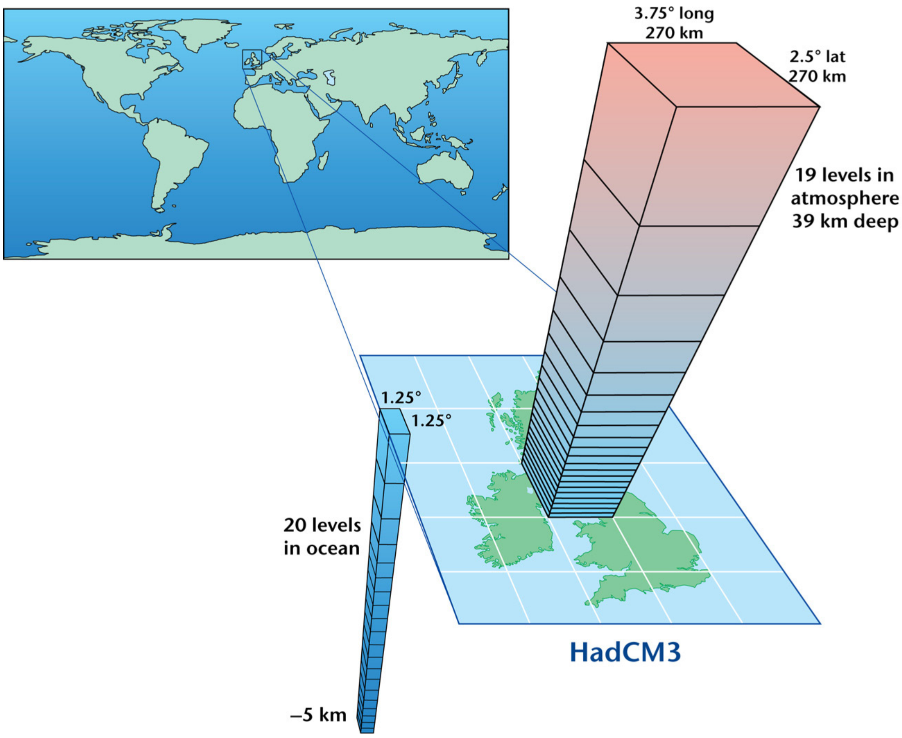


Figure 2.2: Schematic of the HadCM3 coupled climate model.

To make surge, waves and shelf hydrography simulations, detailed projections of driving winds, surface pressure and heat fluxes are required. Neither the global PPE nor MME can provide these on a fine enough spatial scale. Thus, the coupled version of the Met Office global climate model PPE is used to provide atmospheric boundary conditions for a 25 km resolution regional atmospheric climate model (RCM), HadRM3, which is set up to simulate climate over Europe in more detail (Murphy *et al.* 2007). The coupled PPE consists of 17 global model variants, of which one is the standard, or unperturbed model. Each of the 17 variants drive a corresponding version of the regional model, which has equivalent parameter perturbations. These changes are equivalent rather than always identical to the global model parameter changes because some parameter schemes are scale-dependent and this must be accounted for. The RCM can then be considered a downscaled version of the PPE global projection, which is suitable for driving the maritime models discussed in Chapters 4, 5 and 6.

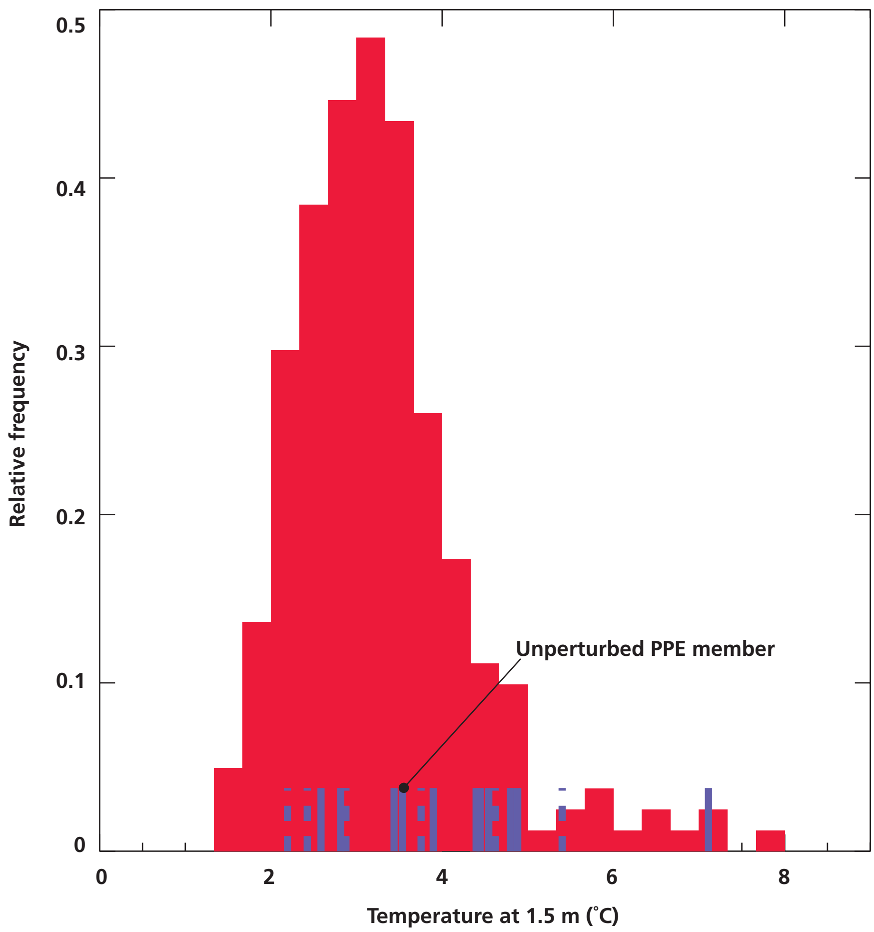


Figure 2.3: Frequency plot of climate sensitivity (eventual temperature rise after a doubling of CO_2) from the fast-to-run global climate models with a simplified ocean (red). Blue lines show the climate sensitivity of the 17 GCMs that comprise the global PPE. Broken blue lines show the six additional members excluded from further analysis.

Some important potential impacts such as harbour seiches take place on spatial scales below those currently represented explicitly by either the RCM or the surge model. Progress in understanding and projecting changes in these impacts is likely to require further local downscaling.

Although 17 versions of the fully coupled global model were used in total, it was later found that the downscaled regional climate of six model versions did not validate as well as the remaining members. These six were excluded from further analysis* leaving eleven members from which to make an estimate of uncertainties. Figure 2.3 presents a distribution of climate sensitivity (the eventual warming expected for a doubling of the atmospheric carbon dioxide concentration) of a large ensemble of global climate models with a simplified ocean (red shading). These are compared to the coupled models used in the marine scenarios (blue lines) to illustrate that the variability of these ensemble members are representative of the variability the larger ensemble.

For the surge simulations the RCMs supply wind speed components at 10 m above the surface and atmospheric pressure at mean sea level to a storm surge model. The shelf sea hydrography model requires the same quantities, plus heat and water fluxes, and river outflow (from a separate, RCM driven model). For the shelf sea wave simulations the GCMs and RCMs provide only the wind components.

The projected changes in shelf hydrography and circulation were driven from a single ensemble member of the PPE — the *unperturbed* model (i.e. the model

* The six excluded members have in common a perturbation which is not shared by any of the other eleven members and so their exclusion is neither arbitrary nor based solely upon validation. For full details see Section 3.2.10 (downscaling for UKCP09) in the *UK Climate Projections science report: Climate projections*.

run with the default parameters). The changes in offshore waves used three model variants of the PPE, including the unperturbed version. The storm surge projections were driven by atmospheric climate changes from 11 PPE model variants, including the three used to look at changes in waves. Thus, consistent projections, using the unperturbed climate model version, exist for all three types of maritime change.

The PPE climate modelling system can, in principle, provide estimates of the thermal-expansion component of time-mean sea level rise. However, because the Met Office Hadley Centre PPE is based around one model structure in which only atmospheric parameters are perturbed, the time-mean sea level rise is instead estimated from the *CMIP3** ensemble of models in the IPCC Fourth Assessment study (the MME in the terminology used here), which have a range of different atmosphere/ocean components. Although we do not have high resolution regional atmospheric data for these models, this approach can be used for absolute time-mean sea level rise, which typically occurs on large spatial scales and so does not require a downscaling step. The MME was also used to make an additional projection of changes in storm surges using a scaling technique.

2.2 Choice of emissions scenario

All of the projections in the marine report use the medium emission (SRES A1B) scenario (Nakićenović and Swart 2000). In this scenario the global mean surface temperature is expected to rise by around 1.7–4.4 °C during the 21st century as atmospheric carbon dioxide concentrations rise to around 700 ppm. The equivalent carbon dioxide concentration (with greenhouse gas forcing from other gases also included) is estimated to rise to in excess of 850 ppm by 2100. The medium emission scenario describes a world that has rapid economic growth, quick spreading of new and efficient technologies, and a global population that reaches 9 billion mid-century and then gradually declines. It also relies on a balance between different energy sources.

Time-mean sea level rise results are also presented for the high (SRES A1F1) and low (SRES B1) emission scenarios. The high emission scenario has similar economic and population trends as the medium emission scenario but more emphasis on power generation from fossil fuels. The low emission scenario represents a more integrated ecologically friendly world, characterised by clean and resource efficient technologies, and lower global greenhouse gas emissions. The global mean sea level for high and low emission scenarios were available directly from the IPCC Fourth Assessment. The UK deviations from the global mean sea level for the high and low scenarios were estimated from the medium emission scenario using a scaling technique.

Surges, waves and shelf sea hydrography were not scaled to high and low emission scenarios because there was no clear indication what should be the choice of emission scenario scaling variable. Furthermore, there were insufficient results available to us in this study to test any speculative scaling.

2.3 Simulated changes in European winter storms

The path and intensity of storms passing over Western Europe have an important impact on the marine environment. For example, the wind and atmospheric pressure associated with these storms leads to storm surges. As mid-latitude

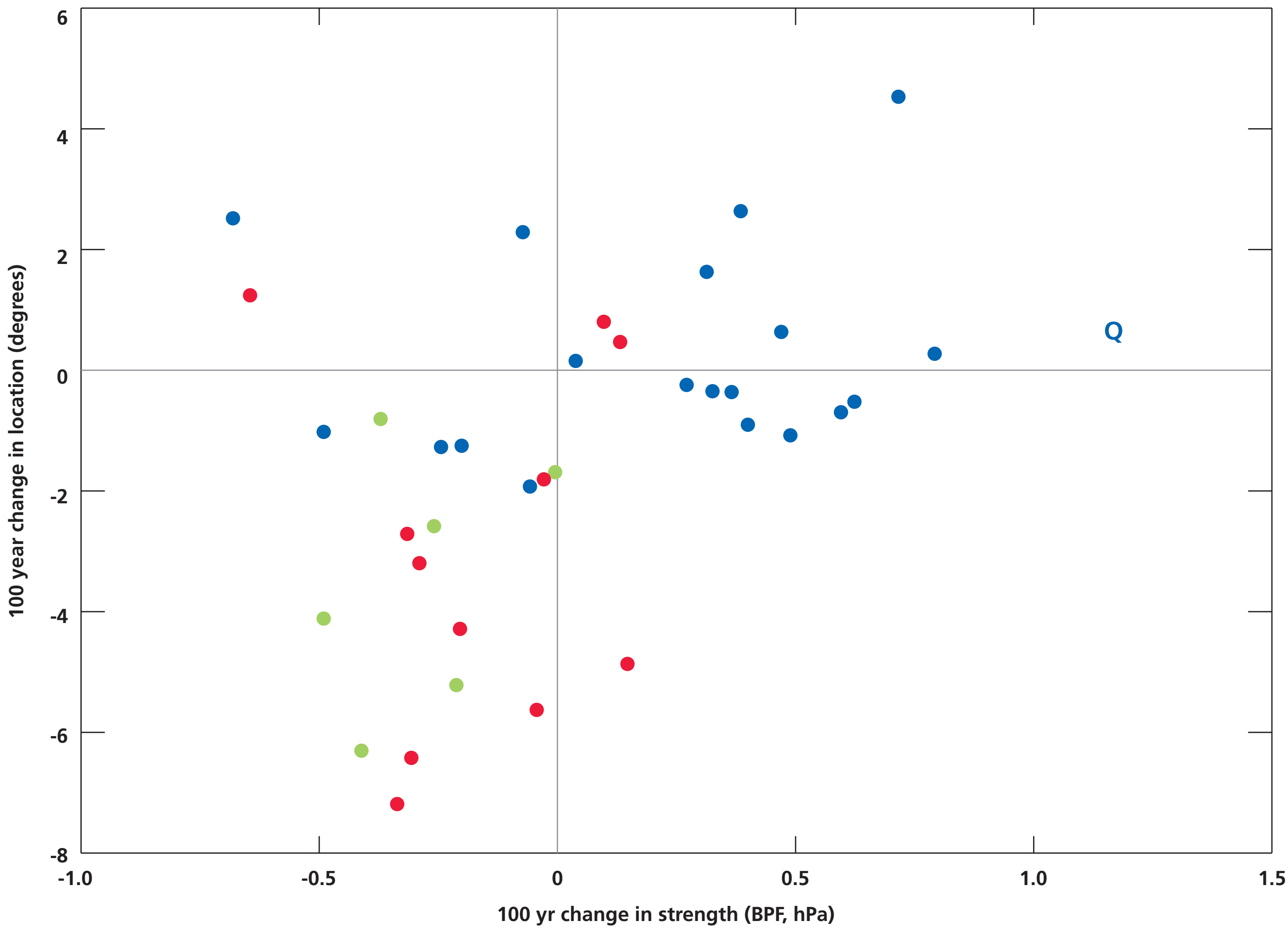
* Coupled Model Intercomparison Project (CMIP3) is a set of climate model experiments from 17 groups from 12 countries with 24 models. The dataset is the largest and most comprehensive international global coupled climate model experiment ever attempted (Meehl *et al*. 2007). For further details refer to: http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php

storms are large-scale phenomena we can study them using information directly from global climate models without the need for downscaling the data to RCM. This also allows us to compare the behaviour of the PPE ensemble members with that of the MME ensemble. The apparent difference in behaviour between the MME and PPE (illustrated below) means that it is desirable where possible to include information from both in assessments, as we do in the surge work.

To quantify storm intensity, mean sea level atmospheric pressure (MSLP) is filtered* to show its underlying signal — the greater the variability of this signal, the greater the storminess. To get an indication of the latitude and strength of the track of the storms arriving at the British Isles we consider a profile along approx 4° west. The location and magnitude of the peak storminess along this profile is compared between the present day and future projections, giving a predicted change in storminess.

Plotting the change in north/south location of the peak storms against the change in strength of the storms allows individual members of the PPE and MME to be compared (Figure 2.4) — these show up as two distinct populations. The PPE ensemble typically shows a slight weakening of the winter storm track accompanied by a southward movement. The MME ensemble has a mix of strengthening and weakening storm tracks, with some members showing northward movement and some a southward movement. Of the members of

Figure 2.4 (below): Projected 21st century change from global climate models in the latitudinal track of winter storms at 4° west against the change in intensity of storms for the MME ensemble (which are coloured blue) and the PPE ensemble. PPE members whose RCM climates validate well against observations are members shown in red. PPE members whose RCM climates do not validate well against observations are shown in green.



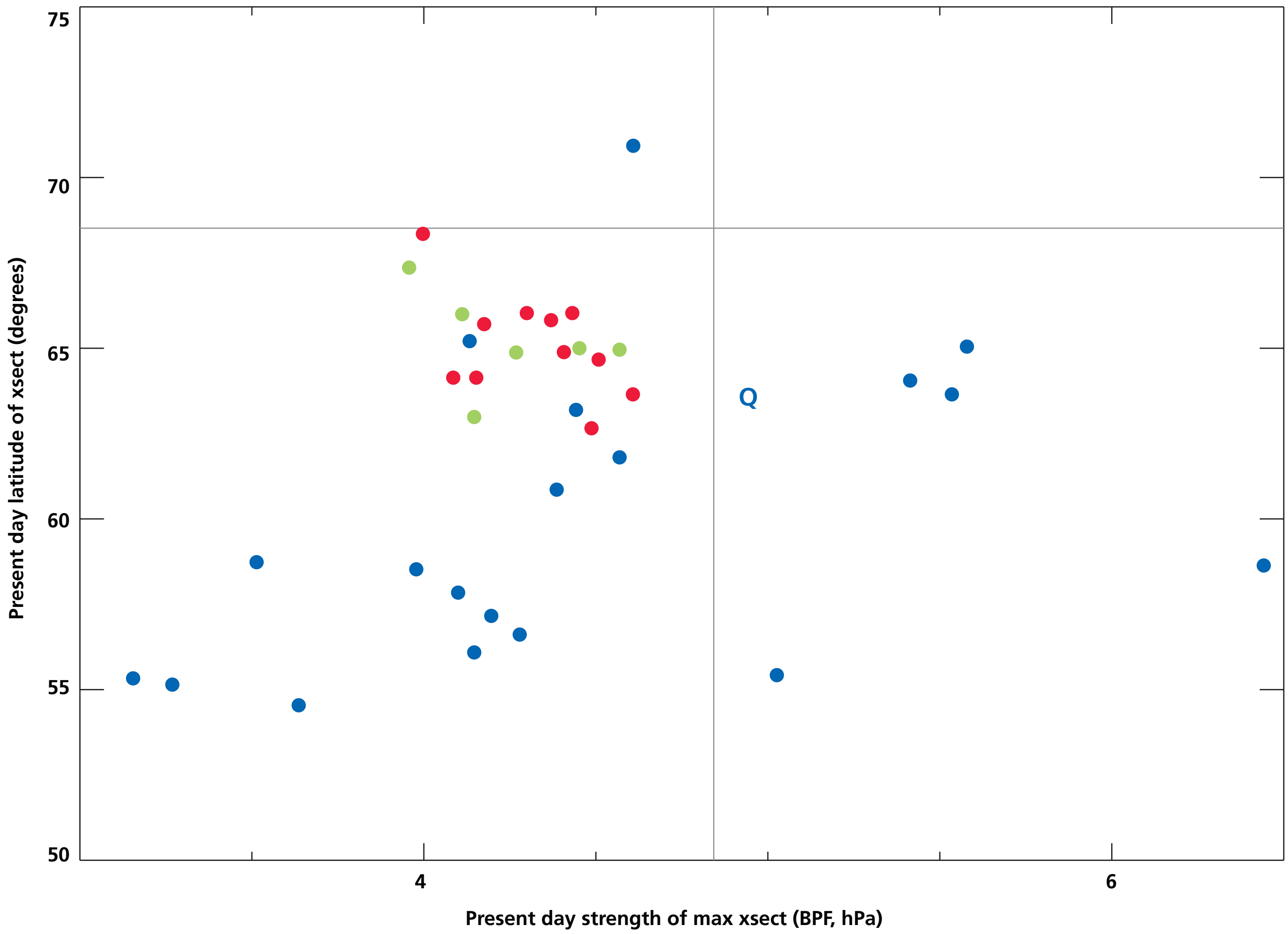
* The MSLP is filtered with a Blackmon (1976) bandpass-filter to de-emphasise all but the 2- to 6-day component, in which most of the intense storm signal resides.

MME that moved south, the amount of southward displacement is less than that seen in the majority of the PPE ensemble. The model with the largest projected increase in storm intensity is labelled model Q.

A comparison of each model's present day simulation with ERA40 reanalysis* data is shown in Figure 2.5. The present day magnitude and location of the peak storminess is included as a cross, thus proximity of data to this cross is a measure of the quality of a model's simulation of the present day winter storm climate. The figure suggests that many (although not all) of the MME ensemble members show a greater error when predicting present day conditions than the PPE ensemble, lending confidence in the PPE. It can be seen that Model Q is in the bottom right-hand quadrant, just to the right of the reanalysis line, i.e. it validates well against reanalysis, at least in terms of the storm track strength at this longitude.

Model Q is a low resolution spectral coupled model which includes a sea-ice model and a free-surface ocean. It does not include a model of sulphate aerosol behaviour. It has an equilibrium climate sensitivity of 3.2 °C, similar to the peak in Figure 2.3 or the unperturbed HadCM3 model. It is of particular interest for this study as, in addition to giving good present day prediction, it projects the largest increase in storm track strength of all model runs. For these reasons, model Q provides the data on which our H++ storm surge scenario is based.

Figure 2.5 (below): Present day bias in the latitude of winter storm tracks at 4° west against the present day bias in intensity for the PPE ensemble and the MME ensemble (key as in Figure 2.4). Straight lines show the location and strength diagnosed from reanalysis.



* ERA40 reanalysis takes archived forecast data and reanalyses it all in a consistent way.

2.4 References

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3 Changes to mean sea level

This chapter gives projections of sea level rise (SLR) around the UK for the 21st century. Previous national projections were included in the UKCIP02 report. We have updated the projections in a number of ways, primarily through using results from the most recent IPCC Fourth Assessment Report and newer estimates of UK vertical land movement.

One component of future SLR is from the melting of large ice sheets. However, there is a lack of current scientific understanding of some aspects of ice sheet behaviour and as such there are known limitations to including this component in sea level projections. In response, we have provided a *High-plus-plus* (H++) scenario for sea level rise around the UK in addition to our main scenarios. The IPCC Fourth Assessment Report provide some illustrative possibilities of how this lack of understanding of ice sheet dynamics might affect sea level projections, and the bottom of the H++ scenario range here is taken from the maximum global mean sea level rise value given by the IPCC Fourth Assessment Report. The top of the H++ scenario range is derived from indirect observations of sea level rise in the last interglacial period, at which time the climate bore some similarities to the present day, and from estimates of maximum glacial flow rate. The upper part of the range of sea level increase is thought to be highly unlikely, but we provide the scenario as some users may find it useful to aid contingency planning (see box in Chapter 1, page 10).

Current Defra flood guidance is based on the maximum of the global sea level range given for the high (SRES A1F1) climate scenario in the IPCC Third Assessment Report along with vertical land movement estimates based on geological data. In the Defra guidance, rates of sea level rise relative to the land are given for three large-scale UK sub-regions and for four time intervals which span the 21st century. Under this guidance for example, the projected increases for London and Edinburgh from 1990 to 2095 would be 90.5 and 72.8 cm respectively. These can be compared to the UKCP09 95th percentile high emission scenario values given here of 83.3 and 69.5 cm. The methodologies used to generate sea level ranges for the UK in this UKCP09 report differ from the current Defra guidance. Here we base the spread of projections from the more recent IPCC Fourth Assessment Report and take local oceanographic and land movement variation into account.

We also used improved methods to estimate vertical land movement using models constrained by a range of observations.

Key Findings

- **Our analysis gives projections of UK coastal absolute sea level rise (not including land movement) for 2095 that range* from approximately 12–76 cm.**

- **Taking vertical land movement into account gives slightly larger sea level rise projections relative to the land in the more southern parts of the UK where land is subsiding, and somewhat lower increases in relative sea level for the north. We have, for example, derived projected 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).**

- **A low probability High++ sea level range has been defined for vulnerability testing. For the UK this absolute SLR estimate is 93 cm to 1.9 m by 2100.**

3.1 What determines sea level?

Global mean sea level can change due to the physical addition/removal of water from the ocean, or from thermal expansion/contraction of the sea water already present. The ocean holds most of the water in the Earth system, but there is also storage of water on land and in the atmosphere. On land, water is stored in the Greenland and Antarctic ice sheets, with lesser amounts in smaller ice caps and glaciers, in land soil moisture, lakes and in constructed reservoirs for human use. Anthropogenic increases in greenhouse gases are expected to increase global mean sea level both by heating the ocean water, thus causing expansion, and through melting of some part of the ice sheets, ice caps and glaciers.

Sea level for a particular region generally differs from the global mean. Local sea level is affected by ocean circulation and by geographical variations in the temperature and/or salinity of the water column. These regional influences are also likely to change under global warming. Local changes in sea level are thus a combination of global mean changes and changes in the patterns of sea level relative to the global mean. Changes in atmospheric surface pressure can also influence regional sea level but this is a relatively small effect on our scales of interest in this chapter (Lowe and Gregory, 2006) and not explicitly treated here. The changes in local sea level relative to the land depend on vertical land movement as well as ocean changes.

There are some uncertainties involved in making projections of sea level into the future which are currently not very well constrained. For this reason, a High-plus-plus (H++) scenario is also developed for vulnerability testing. The top end of this scenario range is currently believed to be very unlikely** to occur during the 21st century, but cannot be completely ruled out.

3.2 Our approach to providing UK sea level projections for the 21st century

In the UKCIP02 report (Hulme *et al*. 2002), the global sea level projections were a combination of model simulations by a Met Office Hadley Centre climate model

* 5th percentile low emissions scenario to 95th percentile high emissions scenario.

** See footnote for Section 3.6 on use of term 'unlikely' in connection with likelihoods.

(HadCM3; Gordon *et al*. 2000; Pope *et al*. 2000) and a range derived from 30-yr averages from the IPCC Third assessment report (IPCC 2001). Estimates of relative UK land movement derived from a single source of geological data (Shennan, 1989) were also included.

More recently, estimates of global mean sea level rise over the 21st century have been produced by various different methods. One method (Rahmstorf, 2007) uses the relationships between observed variations in global sea level and in global surface temperature over the 20th century. This relationship is then applied to 21st century projections of global surface temperature changes (IPCC 2007, Chapter 10), which are thought to be more robust than sea level projections, in order to estimate changes in sea level. This method projects sea level increases of up to 1.4 m by the end of the century, a value which is significantly greater than the estimates in the IPCC Third and Fourth Assessment Reports. There are, however, a number of issues with this method of sea level projection which have led us to believe it is not suitable for use here. These issues include the fact that the projected surface temperature increase over the 21st century is projected to be greater than the 20th century increases used by Rahmstorf (2007) to construct his empirical relationship, possibly by a factor of about 6 for the medium emissions scenario projections and potentially more for some other scenarios (IPCC 2007, Chapter 10). The processes that influence sea level at these much greater temperatures may thus be considerably altered.

For global mean sea level projections, we have therefore used results from the most recent IPCC Fourth Assessment Report (IPCC, 2007). Uncertainties in the sea level projections were treated differently to those in the IPCC Third Assessment Report, so the stated ranges should not be directly compared. The IPCC Fourth Assessment Report gives an estimated range (5th to 95th percentiles*) for sea level increase of 18 –59 cm between present day (assuming a 1980–1999 baseline) and 2090–2099 (Table 3.1). The IPCC Fourth Assessment Report estimates that approximately 70% of the global sea level rise over the 21st century will be due to thermal expansion, with the remainder due to the melting of glaciers, ice caps and combined contribution from the Greenland and Antarctic ice sheets.

There is a lack of current scientific understanding of some aspects of ice sheet behaviour, in particular of recently observed acceleration of glacial outflow at the ice sheet edges. For this reason, the IPCC Fourth Assessment Report discussed potential contributions from this acceleration to 21st century sea level using illustrative possibilities, including: (a) the observed acceleration is temporary variability and will not continue into the future; (b) the acceleration will remain as recently observed; or (c) this part of the contribution will scale linearly with global surface temperature. However, there is no clear evidence that such a scaling is likely to be realistic; this scaling is only used as a measure of the magnitude of

	5th Percentile	Central estimate	95th Percentile
High emissions	26.0	42.5	59.0
Medium emissions	21.0	34.5	48.0
Low emissions	18.0	28.0	38.0

Table 3.1: Global mean sea level rise estimates (cm) from present day (1980–1999) to 2090–2099 for the low, medium and high emissions scenarios (range taken from IPCC 2007).

* In the Marine Report, we are reporting model frequency distributions, not probability; furthermore, we report the 5th and 95th percentiles which should not be confused with the 10th and 90th percentiles of probability of the accompanying report *UK Climate Projections science report: Climate change projections.*

climate change. Furthermore the Fourth Assessment Report acknowledges the increase may be above the highest of their illustrative estimates. The values in Table 3.1 include the assumption (*b*), that the contribution from the acceleration will remain as recently observed, but we revisit the issue of these uncertainties later in Section 3.6 for the H++ scenario.

For regional sea level projections, the global mean sea level changes need to be combined with changes in the geographical pattern of sea level relative to the global mean. As noted above in the IPCC projections, changes in the global mean are projected to be dominated by the thermal expansion, while changes in the pattern primarily reflect ocean circulation and regional density changes.

The IPCC Fourth Assessment Report analysed regional patterns of projected sea level change for simulations by 16 comprehensive atmosphere-ocean models (called the multi-model ensemble or MME here) forced by the medium emission scenario. For comparison we also have regional patterns of sea level change available from the Met Office perturbed physics ensemble (PPE) of coupled global climate models for the same scenario. The MME and coupled PPE ensembles differ in the nature of the models used. The MME models were developed by different international groups and, while not being entirely independent, tend to be notably different from each other in their atmosphere and ocean component models. The coupled PPE models share the same base model, although different

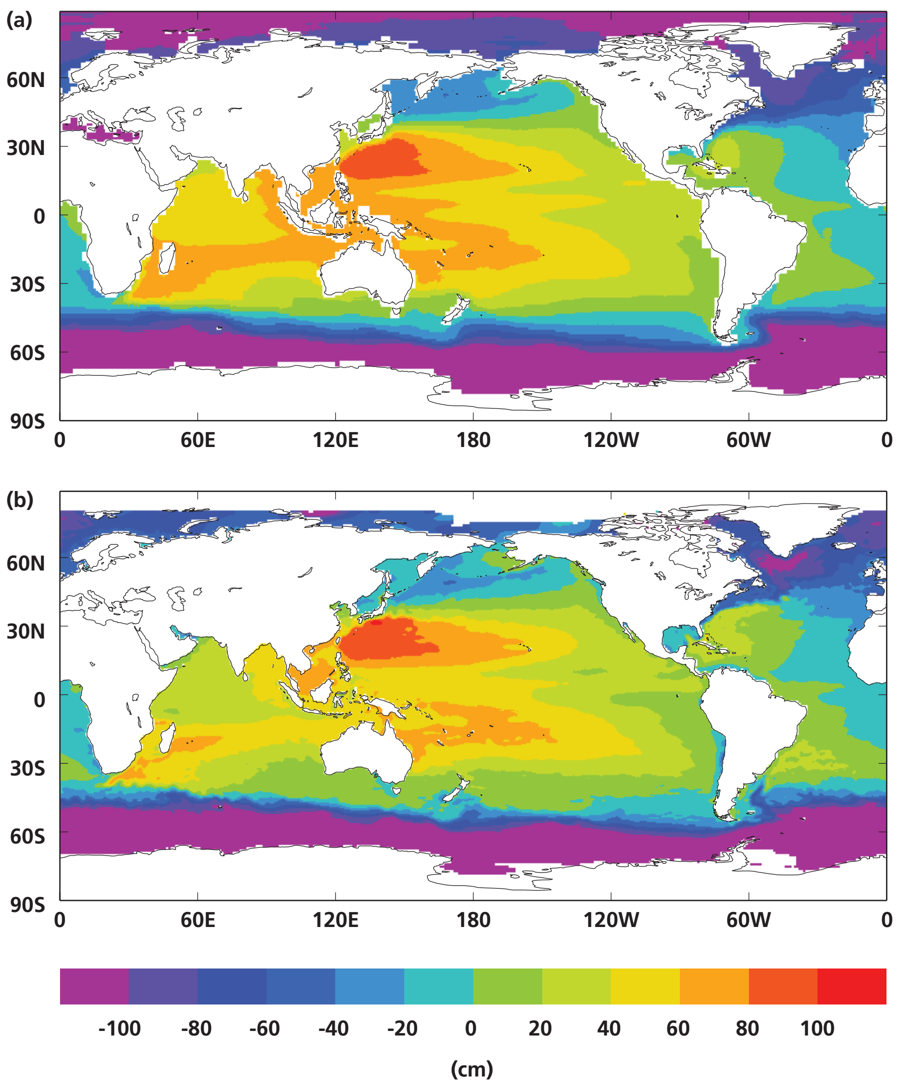


Figure 3.1: Good agreement between the pattern of modelled and observed sea surface height (cm, relative to the global mean) is illustrated by presenting (a) Ensemble mean of the 11 MME model control simulation periods that were run parallel to the 1980–2099 scenario simulations and (b) The sea surface height pattern, derived from observations, as given by the Rio05 dataset (Rio and Hernandez (2004)). The Rio05 dataset was produced by CLS Space Oceanography Division.

parameters used in the atmosphere model component are designed to span a wide range of uncertainty in surface temperature response. For our assessment here, we wish to consider the uncertainty in regional sea level changes that state-of-the-art climate models encompass, so we assessed the range of regional projections relative to the global mean in both model ensembles. We found that this range was much larger in the MME ensemble than in the coupled PPE ensemble for our region of interest. For this reason, we chose to base our estimate of the uncertainty in mean sea level around the UK on the MME ensemble. Here we use 11 of the MME models for which we currently have both the sea surface height projections for the end of the 21st century under the medium emissions scenario and the accompanying sections of simulations with fixed greenhouse gas concentrations, which are used to remove the effect of model drift.

While we have not applied observational constraints to sea level rise estimates (see discussion in Chapter 1), we have attempted to undertake a broad check on the ability of the MME models to represent the geographical pattern of present-day sea level. The ensemble-mean of the MME sea surface height patterns, when simulated without increasing greenhouse gas concentrations, shows broadly good agreement with the observed pattern of sea surface height (Figure 3.1). Although the degree of agreement varies somewhat between the models, this does give us reasonable confidence in the models' representation of physical processes that currently determine regional sea surface height distribution. We have not attempted a detailed regional assessment, as even observed sea level datasets currently show notable differences (e.g. Bingham and Haines, 2006).

3.2.1 Note on the baseline

Much of the UKCP09 analysis uses a baseline for present-day of 1961–1990, for consistency with earlier UKCIP98 and UKCIP02 scenarios. Because the time-mean sea level rise estimates are based on IPCC Fourth Assessment Report results, it is appropriate to use a present day baseline of 1980–1999 for absolute sea level rise for consistency. This difference in baseline will not greatly affect the results. Users wishing to translate the absolute sea level rise results to the 1961–1990 baseline period are recommended to add a further 2.7 cm of sea level rise to the future projection. This is based on there having been an observed global rate of absolute sea level rise of approximately 1.8 mm/yr for the period 1961–2003 (IPCC 2007, Chapter 5). To correct the relative sea level rise a further location-dependent correction needs to be applied to account for the land movement.

3.3 Projected UK sea level changes

The sea level changes over the 21st century around the UK, given by the MME ensemble (actually the subset of 11 discussed in Section 3.2) are shown in Figure 3.2. The component from melt of glaciers, ice caps and ice sheets is not included as models do not directly simulate this term; we consider this term separately later. For the majority of these models the change in sea level around the UK (for region given in Figure 3.3) is similar to their individual global mean change due to thermal expansion (Table 3.2). There are, however, exceptions to this, for example, one model gives an increase around the UK of nearly twice the global mean and one model gives an increase of about half the global mean.

The regional thermal expansion deviations from the global mean thermal expansion are also scaled to high and low emissions scenarios using the methodology of Nicholls *et al*. (2009).

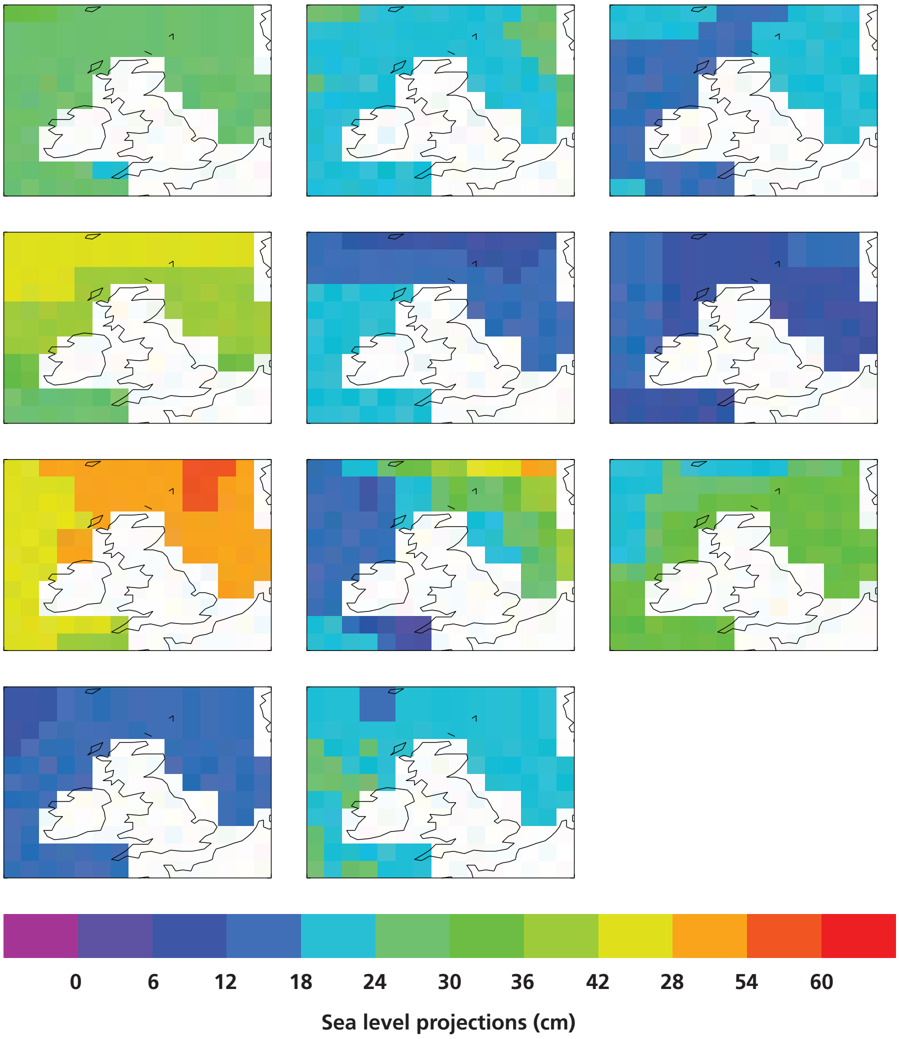
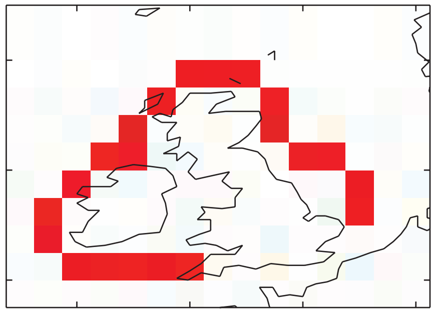


Figure 3.2: Sea level projections (cm) around the UK (not including land ice melt) for the end of the 21st century (2080–2099 relative to 1980–1999) for the medium emissions scenario. The data is from 11 model runs included in the MME (originally collated as part of the IPCC Fourth Assessment, processed and provided by Jonathan Gregory). Here, the data are projected to fit the resolution of the HadCM3 model (1.25° x 1.25°), and a common UK land region imposed.

Figure 3.3 (below): Region used to give projected UK sea level rise (values in Table 3.2) from the MME ensemble projections (after processing them as for Figure 3.2).



UK region change	Global mean change	Ratio of UK to global mean
24.9	27.1	0.92
21.6	20.1	1.08
17.5	21.7	0.81
35.6	33.1	1.07
17.7	16.4	1.08
9.6	18.1	0.53
48.3	24.7	1.96
17.5	19.8	0.88
33.7	22.4	1.50
12.4	12.7	0.97
21.9	19.5	1.13

Table 3.2: The UKCP09 projected 21st century local sea level rise excluding land ice melt terms, averaged around the UK and global sea level rise (cm), together with the ratio of these. These values are from the MME, for the medium emissions scenario. They are calculated for the time period 2080–2099 relative to 1980–1999, with each row relating to a different ensemble member of the MME.

We then combine these estimates with the land ice melt component for the appropriate emissions scenario from the IPCC Fourth Assessment Report, which is assumed to be globally uniform for relatively small ice sheet changes, to give a total (*absolute*) projected sea level change for the UK for three scenarios over the 21st century (Table 3.3), before consideration of land movement. Because these IPCC Fourth Assessment Report global means are given for the 2090–2099 period, combining them with the regional UK values (for 2080–2099) involves a slight inconsistency. However, this has little effect on the final result.

Table 3.3: UK absolute time mean sea level change (cm) over the 21st century (representing average in region shown in Figure 3.3), 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.

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

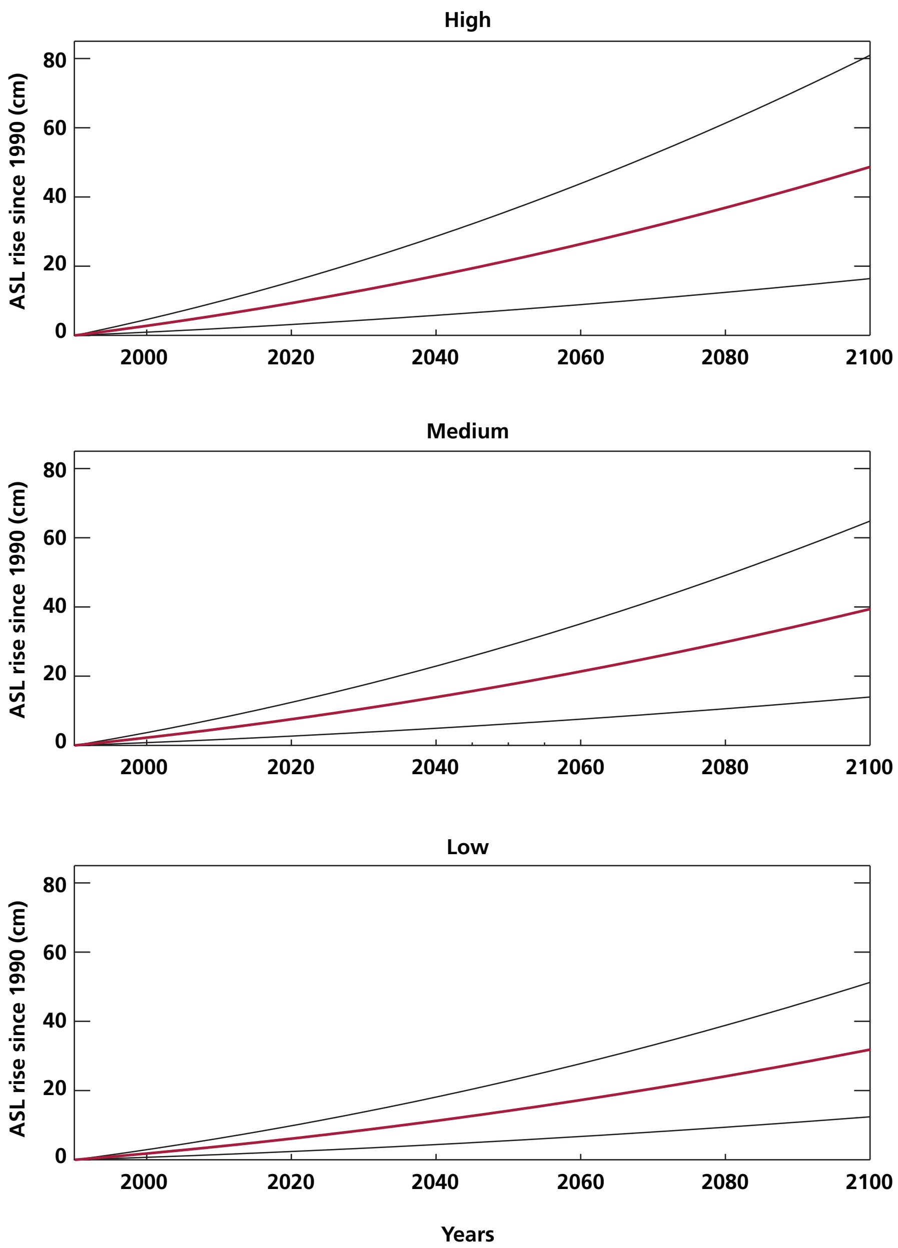


Figure 3.4: Estimated UK absolute sea level (ASL) rise time series for the 21st century (representing the average for masked region shown in Figure 3.3). Central estimates (thick lines) for each of three scenarios (low, medium and high emissions) shown together with range given by 5th and 95th percentiles (thin lines).

Many users will also need estimates of sea level rise around the UK for earlier periods in the 21st century. For these, we used the following methodology. We obtained a global sea level rise time series over the 21st century for the medium emissions scenario which was derived from the MME (Jonathan Gregory, personal communication). We fitted a quadratic function of time (constrained to be approximately zero at 1990) to this time series (and the time series for the 5th and 95th percentile limits). This function was then scaled to give the absolute sea level rise for the UK over the full 21st century (as in Table 3.3) for the alternative emissions scenarios (Figure 3.4).

3.4 Vertical land movement

During the last ice age, the mass of the Eurasian and British-Irish ice sheets (BIIS) caused isostatic deformation that resulted in vertical movement of the Earth's crust throughout Europe and NW Asia. The mantle material below the crust under the ice sheet was displaced leading to a rising of the crust around the ice sheet periphery (glacial forebulge). Melting of the ice sheets removed the load from the depressed crust and allowed the crust to rebound. The resulting vertical land movement is controlled by viscous, elastic and gravitational effects in a process termed Glacial Isostatic Adjustment (GIA). The viscous effect is spatially wide ranging but responds on relatively long time scales (although can start responding within 100 yr), and is the result of the material in the upper mantle

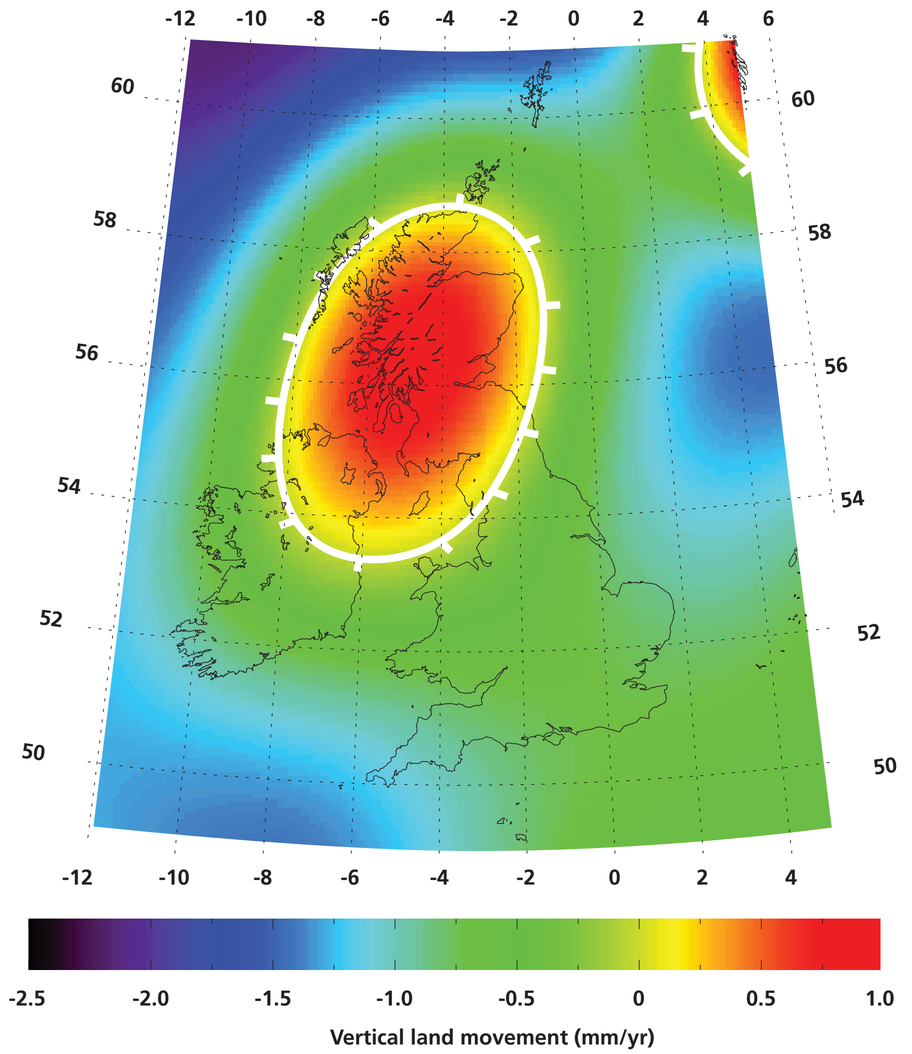


Figure 3.5: GIA map of the vertical land movement (mm/yr) for the UK. The model was constrained by time series (>3 yr since ~2000) of AG corrected CGPS (see the Annex for details). Adapted from Bradley *et al*. (2008).

returning from the forebulge to the area that was depressed by the ice-sheet. It is directly controlled by the viscosity of the mantle. The elastic component of the GIA responds immediately to changes in surface loading and is related to the crust springing back after the ice loading is removed. The final process is related to how the presence of the ice-sheet distorts the geoid.*

The collapse of the Fennoscandia** forebulge is an important component of the GIA currently experienced in the UK, and leads to a general subsidence. Superimposed on this is the effect of the BIIS, which leads to an uplift in Scotland due to the viscous and elastic response, and the subsidence in the BIIS forebulge in England, Wales, and Shetlands. In terms of present vertical land movement in the UK, the GIA processes generally dominate over the negligible vertical component of plate tectonics.

These different processes lead to a complex pattern of uplift and subsidence throughout the UK that has implications on the sea level rise relative to the land (*relative sea level rise*).

3.4.1 Recent studies of UK-wide land movement

UKCIP02 presented a map of vertical land movement in the UK, as suggested by geological estimates of past rates of change (Shennan, 1989). Recently, direct observations of current vertical land movement have become available, using techniques presented in the Annex. Teferle *et al*. (2009) used these observations to produce a comprehensive study of spatial patterns of vertical velocity measurements, with point measurements interpolated to produce a map for the UK.

Another approach is to use a GIA model to infer the velocities over the whole of the UK. GIA is typically modelled with a global geophysical model that includes details of the Earth's vertical structure (e.g. upper and lower mantle viscosity and thickness) to allow response to the loading associated with ice-sheet formation and loss. These models generally include three components; an Earth isostatic adjustment sub-model, a Late Pleistocene*** ice history sub-model, and a sea level sub-model to include the redistribution of water released from the ice. The model of Milne *et al*. (2006) is a typical example of an Earth GIA model. The geophysical sub-model has tuneable parameters that relate to geophysical properties, such as viscosity and thickness of the lithosphere,**** upper and lower mantles, while the ice sub-model requires a time-series of ice coverage thickness. Results of this model, as used by Bradley *et al*. (2008), are included here.

Bradley *et al*. (2008) used the GIA model of Milne *et al*. (2006) and the ice loading of Shennan *et al*. (2006) to produce a map of vertical land movement. Upon constraining model parameters with observations, this modelled map showed a strong correlation with the map derived from measurements given by Teferle *et al*. (2009), thus supporting its use in the present study. The vertical land velocities we use in UKCP09 are taken from Bradley *et al.* (2008) and are treated as constant for the 21st century projections considered in this UKCP09 report. The map of vertical velocities will evolve as further measurements become available.

* The geoid is the surface of equal gravitational potential that the mean sea surface would follow, in the absence of currents and geographical variations in air pressure, temperature and salinity.

** Fennoscandia is a region that includes the Scandinavian Peninsula, the Kola Peninsula, Karelia and Finland.

*** The Pleistocene is a geological epoch from 1.8 million to 10,000 years BP (Before Present) covering the world's recent period of repeated glaciations. The Late Pleistocene extends from 126,000 to 10,000 yr BP.

**** The lithosphere includes the Earth's crust and the uppermost mantle.

	London			Cardiff			Edinburgh			Belfast		
	High	Med	Low	High	Med	Low	High	Med	Low	High	Med	Low
2000	3.5	3.0	2.5	3.5	2.9	2.5	2.2	1.6	1.2	2.3	1.7	1.3
2010	7.3	6.2	5.3	7.3	6.2	5.3	4.7	3.5	2.6	4.9	3.8	2.8
2020	11.5	9.7	8.2	11.5	9.7	8.2	7.5	5.7	4.3	7.8	6.0	4.6
2030	16.0	13.5	11.4	15.9	13.4	11.4	10.7	8.2	6.1	11.1	8.6	6.6
2040	20.8	17.5	14.8	20.8	17.5	14.8	14.2	10.9	8.2	14.7	11.4	8.7
2050	25.9	21.8	18.4	25.9	21.8	18.4	18.0	13.9	10.5	18.6	14.5	11.1
2060	31.4	26.3	22.2	31.4	26.3	22.2	22.1	17.1	13.0	22.9	17.8	13.7
2070	37.2	31.2	26.3	37.1	31.1	26.3	26.6	20.6	15.7	27.4	21.4	16.5
2080	43.3	36.3	30.5	43.3	36.2	30.5	31.4	24.4	18.6	32.3	25.3	19.6
2090	49.7	41.6	35.0	49.7	41.6	35.0	36.5	28.4	21.8	37.6	29.4	22.8
2095	53.1	44.4	37.3	53.1	44.4	37.3	39.2	30.5	23.4	40.3	31.6	24.5

Table 3.4 (above): Central estimates of relative sea level changes with respect to 1990 (cm). Only the central estimates of sea level rise are presented here. These data correspond to Figure 3.6, which also gives the 5th to 95th percentile range.

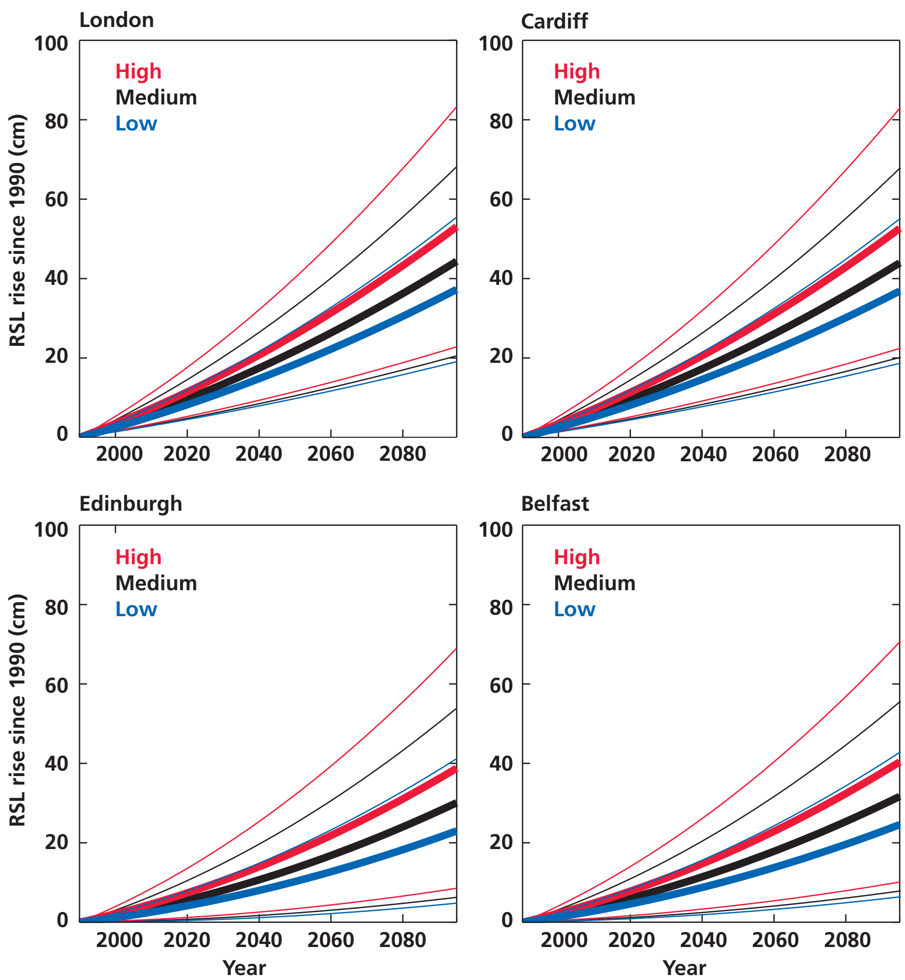


Figure 3.6: Relative sea level (RSL) rise over the 21st century showing central estimate values (thick lines) and 5th and 95th percentile limits of the range of uncertainty (thin lines) for four sample locations around the UK. Values are relative to 1990. Central estimates for each decade are given in Table 3.4.

3.5 Relative sea level rise

In this section we combine absolute sea level changes and vertical land movements into estimates of relative sea level rise. This uses the absolute sea level rise estimates for the UK from Table 3.3 and the land movement estimates from Bradley *et al*. (2008) (Figure 3.5).

Assuming that the vertical land movement rates shown in Figure 3.5 will remain relatively constant over the 21st century, a yearly time series of the influence of vertical land movement on relative sea level was calculated for four sample locations (London, Cardiff, Edinburgh and Belfast). Subtracting these vertical land movement time series from the absolute sea level rise (averaged around the UK, as was done for Figure 3.4) gives time series of relative sea level rise for the low, medium and high emissions scenarios. These projections are given in Table 3.4 (for the central estimate) and shown in Figure 3.6 along with the 5th to 95th percentile range. This range does not include any land movement uncertainty, although Section 3.4 and the Annex suggests this is likely to be small compared to that in the absolute sea level rise estimates. In the User Interface of UKCP09 the user can select projected relative sea level changes for a range of coastal locations. An example map of relative sea level change (using the medium emissions central sea level rise estimate) is shown in Figure 3.7.

3.6 High-plus-plus (H++) mean sea level scenario

In Chapter 1 we introduced the concept of an H++ scenario range for vulnerability testing above our estimated uncertainty range. Here we describe the development of the time-mean sea level component of this scenario. Sea level increases are given from present day (1980–1999) to 2095 for H++, but no time series is presented.

Data which relates to climate changes over the past hundreds of thousands of years can be found in proxy records, for example, in deep ocean sediments, corals or ice cores from the ice sheets. Some such records can be used to infer estimates of past sea level changes. These are indirect estimates, but they provide a possibility of looking at past climates which may bear some relation to projections for the future. Records relating to the last interglacial period climate (about 125,000 yr ago), at which time the major continental ice sheets were similarly located to today and the global mean surface temperatures were comparable to those projected for coming decades (Otto-Bliesner *et al*. 2006), may offer some insight into possible future sea level changes.

Some of the proxy data suggests the possibility that future sea level rise might be greater than the maximum given in Section 3.5 (based on regionalisation of the IPCC Fourth Assessment Projections). Such inferences made from proxy data, together with known limitations in the physics of ice sheet models used in the projections, have led us to provide here a low probability, high impact range for sea level rise around the UK, which we call the High-plus-plus (H++) scenario. This might be used for contingency planning and to help users thinking about the limits to adaptation. We think it very unlikely* that the upper limit of this scenario will occur during the 21st century but cannot yet rule it out completely given past climate proxy observations and current model limitations.

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. From this we

* The use of the terms *likely* or *unlikely* and other such terms used here are not considered in the strictly defined ways used by the IPCC Fourth Assessment.

derive an upper limit of 2.5 m sea level rise for our maximum global mean sea level rise over the 21st century in the H++ scenario (from 1990–2095). We reiterate that while we cannot rule out this amount of global sea level rise, recent observations and model projections do not provide any evidence to suggest it will occur. This amount of sea level rise would require a massive increase in the current observed contribution of ice sheets to sea level rise.

For the maximum sea level rise around the UK in the H++ scenario, we need to adapt the global 2.5 m sea level rise to consider regional deviations from the global mean. For scenarios dominated by thermal expansion components, such as those which give the relative sea level rise estimates in Section 3.5, regional deviations from the global mean are mainly caused by ocean circulation and regional variations in expansion of the ocean. For the maximum sea level rise in the H++ scenario, however, where the global mean sea level rise is dominated by ice sheet melt, changes in the ice load on Greenland can affect regional sea level though GIA mechanisms. Spatial patterns for this have been estimated for particular changes in the Greenland and Antarctic ice sheets (for instance, Tamisiea *et al*, 2001). Allowing for these regional adjustments gives an estimate for the average sea level rise around the UK, under the H++ scenario, of 1.9 m.

One piece of evidence which may relate to the potential for long term acceleration of loss of ice from the ice sheets is from recent observational studies (Rignot and Kanagaratnam, 2006). This suggests that the loss of freshwater from

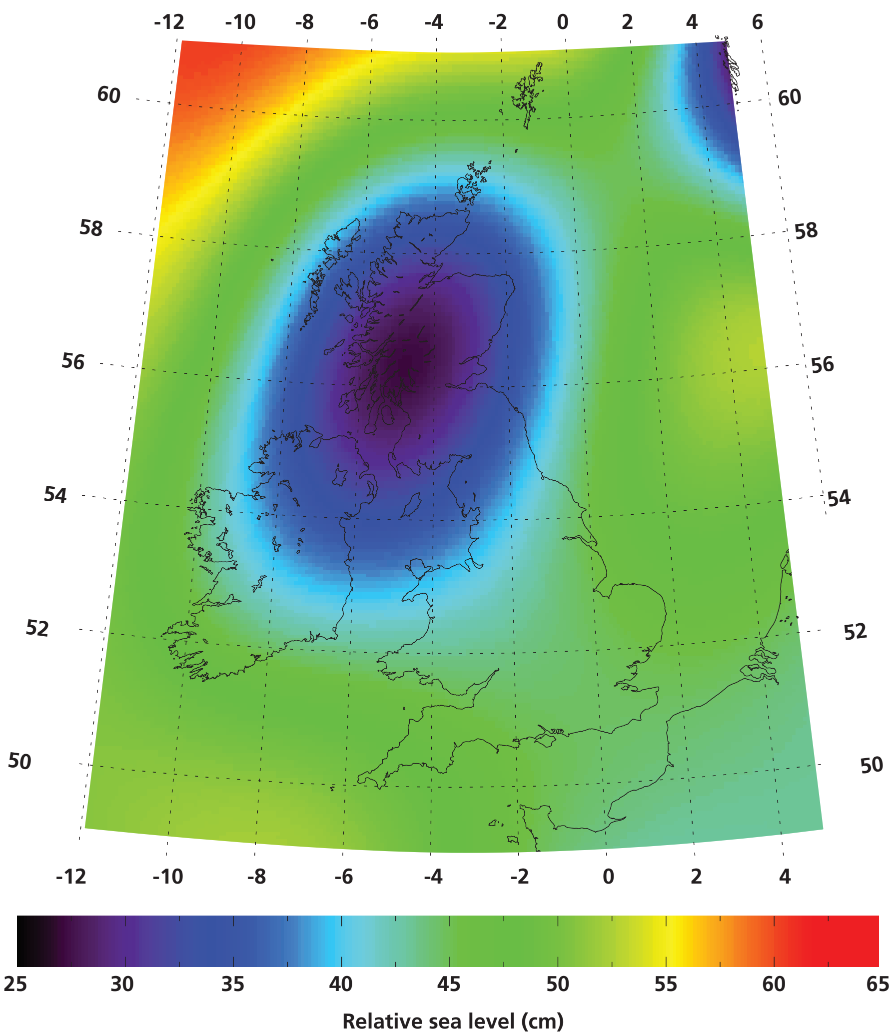


Figure 3.7: Relative sea level change (cm) around the UK over the 21st century. This combines the absolute sea level change estimates averaged around the UK for the central estimate for the medium emissions scenario (Table 3.3) and the vertical land movement as in Figure 3.5. Values are appropriate to 2095.

the Greenland ice sheet to the sea has doubled in the last 10 yr. It is not yet clear, however, if this observed change is part of a long term trend or decadal variability. This increased contribution to sea level rise is from accelerated loss into the sea of ice at the margins, as well as from increased liquid water runoff relative to the accumulation of snow. Parts of the West Antarctic ice sheet rest on bedrock below sea level and so the melting of its fringing glaciers is sensitive to increases in the surrounding ocean temperature. Many of these glaciers have also seen increased speeds as their floating ice tongues (ice shelves) have thinned and, in some cases, broken up entirely (Rignot, 2006). However, even if the tide water glaciers, the fastest flowing glaciers around Greenland, were to increase their discharge of ice to the ocean by an order of magnitude, they would still only raise sea level of order 10–20 cm by 2100 (estimated using values given in Rignot and Kanagaratnam, 2006). The fastest flowing glaciers around Antarctica are currently a factor of about 4 slower than those in Greenland (Rignot and Kanagaratnam, 2006; Rignot *et al*. 2008). Using a simple scaling of the estimated recent contribution to sea level changes from accelerated ice flow with global mean surface temperature, the IPCC Fourth Assessment estimated that this might give up to 17 cm (for the high emissions scenario) additional global mean sea level rise during the 21st century. However, whilst they did not rule out larger increases, they noted that rapid ice sheet changes, such as the collapse of the West Antarctic Ice Sheet are not considered likely to occur in the 21st century, and we support this view here. Adding the 17 cm scaled discharge contribution to our maximum previous estimate for the UK (Table 3.3; 95th percentile) gives us 92.8 cm of sea level increase, which we take to be the bottom of the H++ range.

Recently Pfeffer *et al*. (2008) provided an alternative estimate of constraints on 21st century SLR. They consider the degree of acceleration of outlet glaciers and ice streams on Greenland and Antarctica that would lead to large increases in SLR. After considering maximum observed glacial movement rates they concluded SLR in excess of 2 m was physically untenable. When our slightly larger thermal expansion estimate is combined with Pfeffer *et al*.'s (2008) ice melt and GIA is allowed for, a worst case risk rise is again estimated at approximately 2 m for the UK region. This alternative evidence for 2 m as a sensible maximum value in sensitivity testing adds extra confidence in our earlier estimates for the top of the H++ range.

In summary, our H++ scenario range for time-mean sea level rise around the UK is 93 cm to approximately 1.9 m. Beyond our qualitative statement that the top of this range is very unlikely to occur in the 21st century we make no attempt here to assign a precise probability to this event. Improvements in models and continued monitoring may, in the future, help us to estimate the likelihood of this type of event or rule it out completely.

3.7 Results presented in the UKCP09 User Interface

The User Interface will allow the results presented in this chapter and many additional results to be displayed via an interactive web-based interface. It will contain the following time-mean sea level information:

- Absolute sea level rise time series for the UK for high, medium and low emissions scenarios (central estimate, and 5th and 95th percentile).

- Relative sea level rise around the UK, combining absolute sea level rise and vertical land movement, at user specified coastal locations.

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4 Changes in surges and extreme water levels

In this chapter we describe model projections of changes to storm surges and extreme water levels around the UK. We use a new eleven member perturbed-physics ensemble (PPE) climate model developed at the Met Office Hadley Centre (Met Office) to drive a Proudman Oceanographic Laboratories (POL) storm surge model. In particular we examine changes in return levels for return periods of 2, 10, 20 and 50 yr. A return level can be loosely described as the level expected to be exceeded on average once during the return period, and is useful in planning for extreme conditions.

First we show, by comparison with observations of 50-yr return levels, that the new models are generally better at simulating present day surge than those used in UKCIP02. Then we look for future trends in the model projections of storm surges using a sophisticated statistical technique. The trends that we find are physically small everywhere around the UK, and in many places can be accounted for by natural variability. We find that the surge level we expect to be exceeded on average once in 2, 10, 20 or 50 yr is not projected to increase by more than 9 cm by 2100 anywhere around the UK coast (not including the mean sea level change).

The range of uncertainty in surge trends found from the Met Office/POL models only includes that driven by the differences between the eleven members of the PPE climate model ensemble. However, other international climate models give a wider range of change in the strength of storms over the UK and we consider storm surge increases inferred from these too. We don't have enough information from these models to quantify the probability of these increases but instead we use the models to develop an improbable but plausible high-end range of surge changes, called H++. This range is beyond the Met Office projections, and is unlikely to occur by 2100 but cannot be completely ruled out. This approach uses the non-Met Office model that reproduces the current storm regime over the UK well but has the greatest UK increase in storm intensity in the future. When the H++ surge and mean sea level scenarios are combined, the inferred increases in the 50-yr return period extreme water level are large in places around the UK (Figure 4.10), increasing by as much as 3 m by 2100 at some locations.

Key Findings

- **Confidence in the Met Office/POL models to simulate the present day regime of extreme surges has improved.**

- **Around the UK the size of surge expected to occur on average about once in 50 yr is projected to increase by less than 0.9 mm yr (not including relative mean sea level change) over the 21st century. In most locations this trend cannot be clearly distinguished from natural variability. Thus our assessment suggests that this component of extreme sea level will be much less important than was implied by UKCIP02, where corresponding values exceeded 5 mm yr in places.**

- **The largest trends are found in the Bristol Channel and Severn Estuary, where the trend is for an increase in the 50-yr skew surge return level of around 0.8 mm yr, not including relative mean sea level change.**

- **Since the PPE does not sample the full range of known uncertainties, the uncertainty range quoted for surge from the Met Office models should be regarded as a minimum range.**

- **The international climate model that projects the strongest changes in storms over the UK may project larger increases in storm surge height around the UK than found from the Met Office projections. This is treated as a high end surge H++ scenario.**

- **Mean sea level rise and changes in storm surges have been combined to produce changes in extreme water levels.**

4.1 Why study storm surges?

Storm surges are short-lived increases in local water level above that of the tide. They are driven by atmospheric pressure gradients and winds, typically in shallow seas. When they occur at or near a high tide large surges are liable to cause flooding. Previous extreme surge events, such as that during winter 1953, have led to a considerable loss of life and damage to property around the coastline of the southern North Sea. In England alone more than 300 people died and 24,000 properties were seriously damaged in the 1953 coastal flooding event.

In a global study, Woodworth and Blackman (2004) found that trends in extreme high water levels were dominated by changes to mean sea level. For the UK a similar conclusion is reached, that is, although extreme sea levels have changed there is no observational evidence for regional trends in either storm surge frequency or magnitude over recent decades. There have been many previous attempts to use coupled climate models to estimate a future storm surge climate in the North Sea (e.g. Langenberg *et al*. 1999; Lowe, Gregory and Flather, 2001 (henceforth LGF); Hulme *et al*. 2002; Woth *et al*. 2005). Typically these studies use coarser regional climate models than the models used in UKCP09. Although some results (e.g. Hulme *et al*. 2002) suggest upward temporal trends in extreme surges along the east coast of Britain, the uncertainty in the results was poorly quantified (Lowe and Gregory, 2005) and some lacked credible verification. This work attempts to provide a more robust quantification of that uncertainty.

In UKCIP02 both the relative time mean increase in sea level and the change in storminess were found to be important. Their relative importance varied from location to location but much emphasis was placed on the southern North Sea where changes in storminess had their biggest effect and the increase in the height of extreme sea levels was greater than either the absolute sea level rise, the vertical land movement or their combined effect (the relative sea level rise). In this chapter we present improved estimates of the uncertainty in future extreme surges. A case study focusing on using the results for the Thames region is presented in Chapter 7.

4.2 Projection methodology

4.2.1 The surge modelling system

Chapter 2 describes the experimental set-up of the atmospheric climate models used to drive the models of marine change around the United Kingdom. The winds and surface pressure from the regional climate model members of the Met Office perturbed physics ensemble (henceforth PPE) forced by the medium emissions scenario are used here to drive the Proudman Oceanographic Laboratory's 12 km resolution barotropic storm surge model. The same surge model (POLCS3) is used operationally to provide coastal flood warning in the UK as part of the Storm Tide Forecasting Service (STFS). The model produces a numerical simulation of the North Sea tides and surges, and is described in detail by Flather (2000). Validation of the operational model is performed monthly by comparison with observed sea level data from the UK national tide gauge network (see http://www.pol.ac.uk/ntslf/surgemonthlyplots), and an annual summary of STFS performance is published (e.g. Wortley *et al*. 2007). The operational model has been shown to perform particularly well during extreme storm surges in the southern North Sea (Horsburgh *et al*. 2008), forecasting surge in the Thames estuary to within 10 cm when driven by re-analysed* meteorology. The tide-surge model covers the

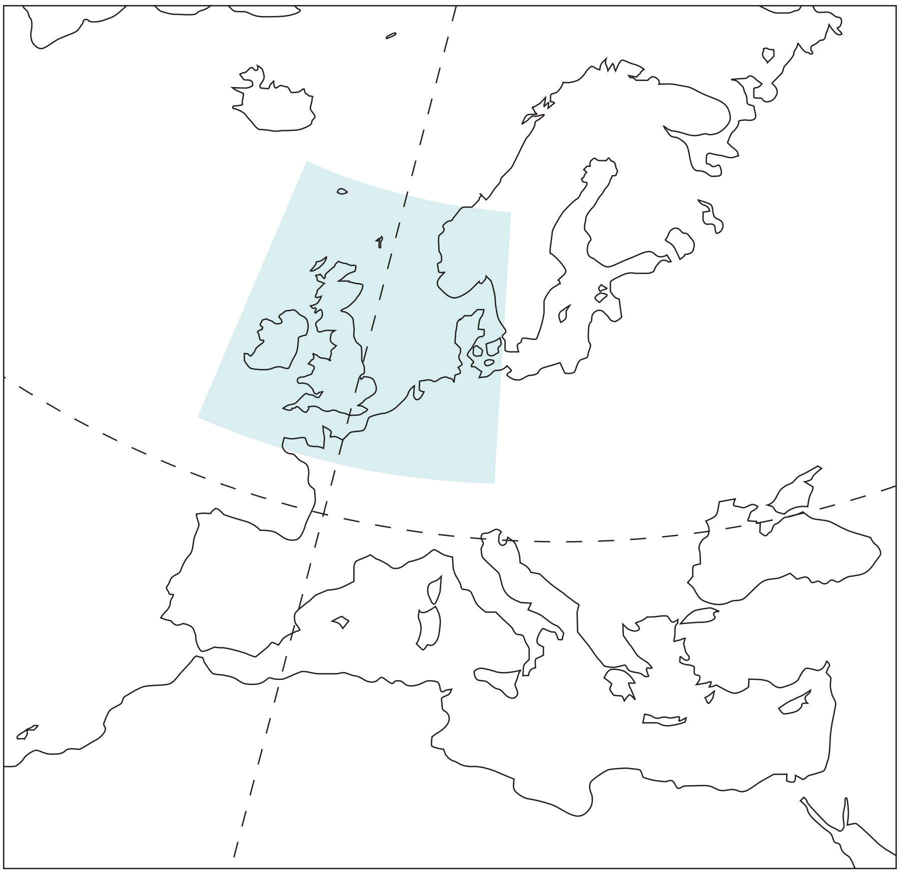


Figure 4.1: Approximate domain of the surge model (shaded). The outer square shows the regional atmospheric climate model (RCM) domain.

entire northwest European continental shelf as shown in Figure 4.1. Tidal input at the model open offshore boundaries consists of the largest tidal constituents. (The tide at any location can be thought of as being a combination of several different waves each having different characteristic oscillation periods. These are referred to as constituents.) Modelled surge residuals are derived by subtracting a tidal model simulation from one forced by both tide and atmospheric forcing from the regional climate model.

In this work the surge model is driven by atmospheric forcing from each of eleven members of the PPE regional climate model ensemble, producing the combined response to winds, surface pressure gradients and tides. This captures the tide–surge interaction where the principal effect of the surge on the tide is to alter the times of high and low water and the effect of the tide on the surge is the modulation of surge production. Since winds are most effective at generating surge in shallow water, peaks in surge residual (defined above) are consistently obtained 3–5 h prior to the predicted high water (Horsburgh and Wilson, 2007). A more significant and practical measure than the surge residual is the skew surge (see Figure 4.2), which is the difference between the elevation of the predicted astronomical high tide and the nearest (in time) experienced high water (e.g. de Vries *et al*. 1995). Experienced high water here refers to either observed or modelled high water. Unlike the climate model, the surge model parameters (e.g. frictional coefficients) are not perturbed because previous operational use has shown that the uncertainty in future surge height is very likely to be dominated by uncertainty in driving winds and pressure rather than surge model parameters.

It is important to emphasize here that the surge models do not include time-mean sea level change directly. Time-mean sea level change is considered in Chapter 3. However, LGF found that to a first-order approximation, modest amounts of time-mean sea level rise and changes in surge can be added linearly around the United Kingdom. Our own recent sensitivity study for larger time-mean sea level increases drew a similar conclusion, even for mean sea level rise in excess of 2 metres.

4.2.2 Surge model trend statistical analysis methods

Both observed and modelled surge extremes vary from year to year. To decide whether the century-scale trends that we see in our modelled extremes are

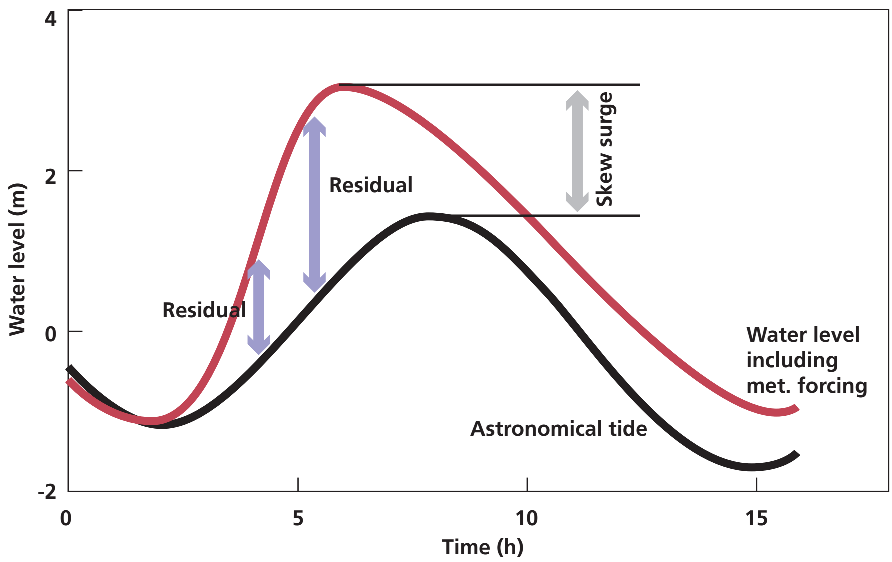


Figure 4.2: Schematic diagram showing how skew surge and surge residual are evaluated. The surge residual changes through the tidal cycle, usually peaking before either the astronomical or the met-forced tide. The skew surge is evaluated just once and is a more useful measure.

* Re-analysis can be thought of here as reprocessing archived observations to put them into a form suitable for driving the surge model.

likely to be simply a part of this variability or a result of climate change, we fit a statistical model called the generalised extreme value (GEV) distribution to our modelled extreme skew surges. We use five modelled extremes from each modelled year. Two of the three GEV parameters (location and scale) are allowed to vary as linear functions of time.

Because of the internal variability, the fit is not exact. Comparing the imprecision of the fit with the size of the century-scale trends enables us to assess the probability that the trend in the extremes is simply a part of the internal variability. To make this comparison we use the full 149 yr simulation (1951–2099) from the 11-member PPE. This is an improvement over the UKCIP02 work which compared two 30-yr time slices from each end of the run. This improvement is possible due to increases in computer processing speed.

In Section 4.6 we report the size of the trends, a measure of the uncertainty in the trends, and the probability that a trend of this size would be expected simply as a result of variability, rather than climate change. For example, if the probability of the trend occurring due to variability is small (e.g. 1%) it is more likely the results are showing a climate-change signal.

4.2.3 Comparing the climate/surge simulator with observations

Validation of the climate/surge modelling system was performed by comparing surge results simulated for the near-present day with observations (Table 4.1). With the exception of only one location, the new system represents an improvement over earlier work, i.e. the difference between the observed and modelled quantity is smaller for the model used in UKCP09 than for the model used by LGF at all but one location.

Table 4.1 (below): 50-yr return levels (RL) of residuals for 15 UK ports. Observed 50-yr return levels are compared with two different modelling studies: the present study and the earlier study of Lowe, Gregory and Flather (2001) (LGF), which was comparable in its present-day validation to UKCIP02. For the two models, both absolute value and the ratio of modelled to observed value is presented. The final column indicates locations at which the new results show an improvement on LGF. The UKCP09 data are taken from the first 30 yr of the unperturbed model run. The observed results alone were originally presented by Flather *et al.* (1998).

Port	Observed 50 yr RL (m)	UKCP09 50 yr RL		LGF 50 yr RL		UKCP09 improves on LGF?
		(m)	Ratio to observed	(m)	Ratio to observed	
Wick	1.11	1.02	0.92	0.91	0.82	yes
Aberdeen	1.25	1.05	0.84	0.82	0.65	yes
North Shields	1.66	1.12	0.67	0.96	0.58	yes
Whitby	1.98	1.19	0.60	1.09	0.55	yes
Immingham	2.14	1.60	0.75	1.52	0.71	yes
Lowestoft	2.36	1.89	0.80	1.85	0.78	yes
Felixstowe	2.50	2.01	0.80	2.05	0.82	no
Southend	2.91	2.82	0.97	2.36	0.82	yes
Dover	1.77	1.60	0.91	1.44	0.81	yes
Newlyn	1.02	0.70	0.69	0.65	0.64	yes
Ilfracombe	1.49	1.20	0.80	0.88	0.59	yes
Milford Haven	1.44	1.05	0.73	0.85	0.59	yes
Holyhead	1.51	1.18	0.78	1.03	0.68	yes
Heysham	3.16	2.32	0.73	1.60	0.50	yes
Millport	1.72	1.70	0.99	1.34	0.78	yes

As expected, some differences do occur between model and observations with the model typically underestimating surge extremes compared to observations. This is largely due to the resolution, both spatial and temporal, of the atmospheric forcing and the local bathymetric resolution of the surge model. Modelled elevations represent an average value over a grid box of area approximately 12 x 12 km, and this will generally differ from a corresponding tide gauge value at a specific location due to local effects (e.g. local winds and wave set-up). Despite these limitations considerable skill in simulating extreme surges is demonstrated.

Further validation specific to the Thames estuary was performed using skew surge data based on observed water level records for Sheerness and Southend. Again good agreement between the model and observations was seen, and it was demonstrated that the climate/surge modelling system is capable of simulating a surge event with water elevations at Southend similar to those seen during the 1953 coastal flooding event.

4.3 Projected climate-driven changes in surges

Using the method described above (in the section titled *Surge model trend statistical analysis methods*), we find that the physical significance of the trends in the storminess-driven component of extreme sea level is small. (It must be noted that at this stage we have not combined these with mean sea level change.) For example the maximum fitted trend in the PPE ensemble mean for any of the four return periods considered (2,10, 20 and 50 yr), at any location around the UK coastline, represents an increase of less than 0.9 mm yr. This can be compared with observed global mean sea level rise during the period 1961–2003 of around 1.8 mm yr (IPCC, 2007) or the top-end absolute sea level rise projected for the UK for the 21st century of around 75 cm in 100 yr (see Chapter 3).

Figures 4.3–4.6 show the PPE ensemble mean trend in return level for four different return periods (2, 10, 20-and 50 yr) for locations around the UK mainland coast.*

The figures also show a measure of the uncertainty in the PPE ensemble mean trends and a measure of the probabilities of such trends occurring due to variability (rather than climate change). As may be expected, the statistical significance generally decreases as we move to longer return periods and the uncertainties increase. The probabilities of the increases being due to variability (shown in the right-hand panels) are based on the assumption of a normal distribution of the ratio of trend to uncertainty. Whilst the extremes themselves follow a different (extreme value) distribution, this assumption is not unreasonable for the trends. The probabilities are assessed on a point-by-point basis, without regard to any spatial coherence.

* Negative trends are included in the grey shading of each plot, since their magnitude is of little interest. However, for completeness, we remark that in each case the absolute value of the most negative trend is comparable to the largest positive trend.

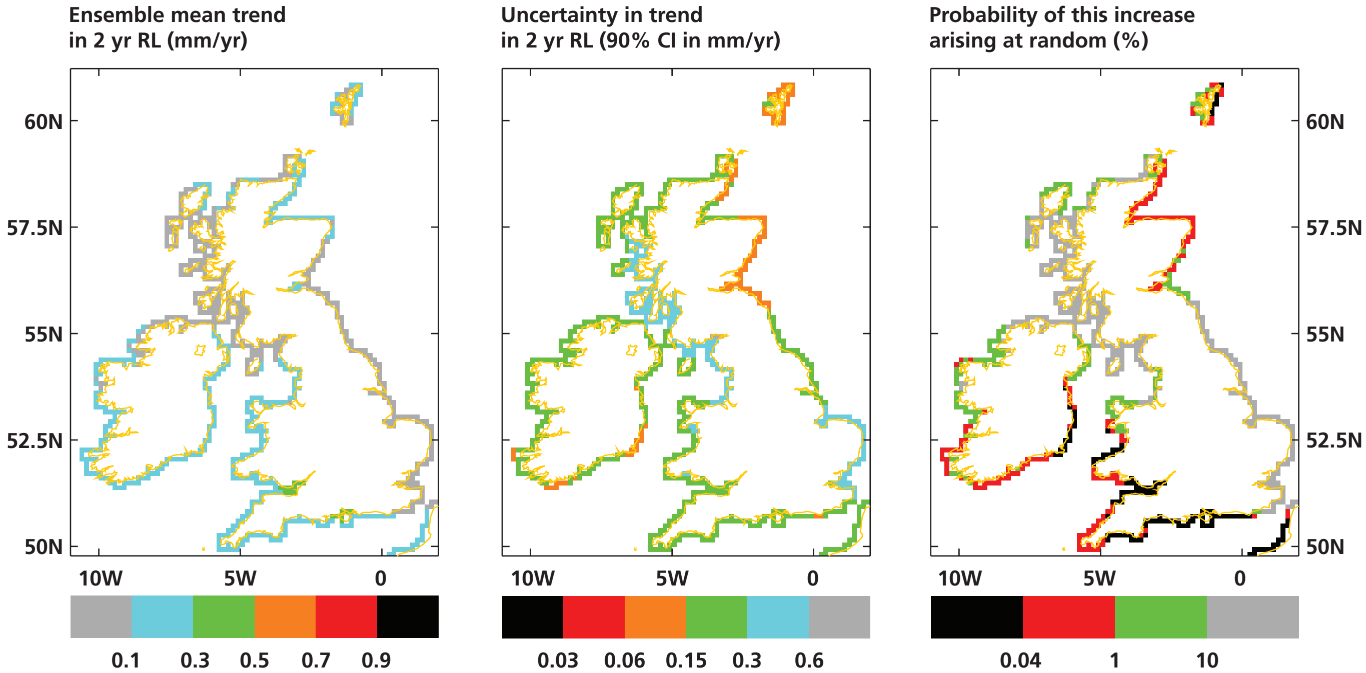


Figure 4.3: PPE ensemble mean trends in 2 yr skew surge return level from the storminess component only. Negative trends are included in the grey shading.

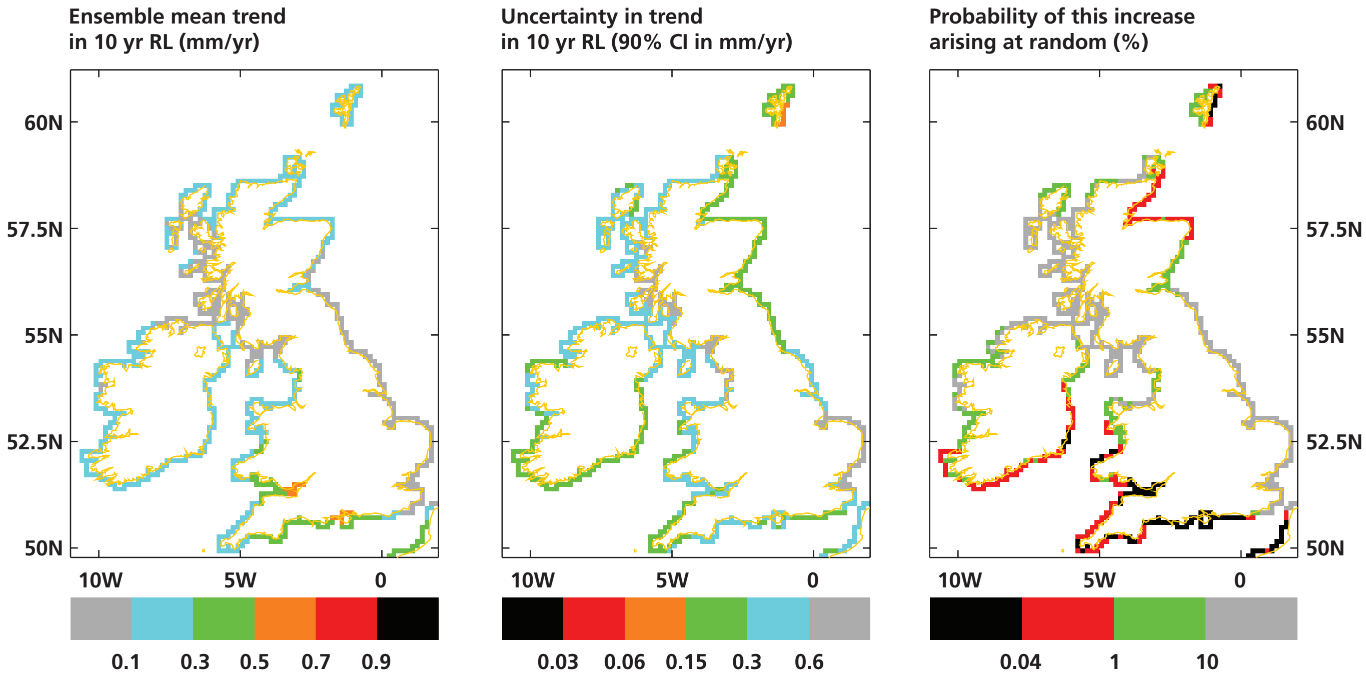


Figure 4.4: PPE ensemble mean trends in skew surge 10 yr return level from the storminess component only. Negative trends are included in the grey shading.

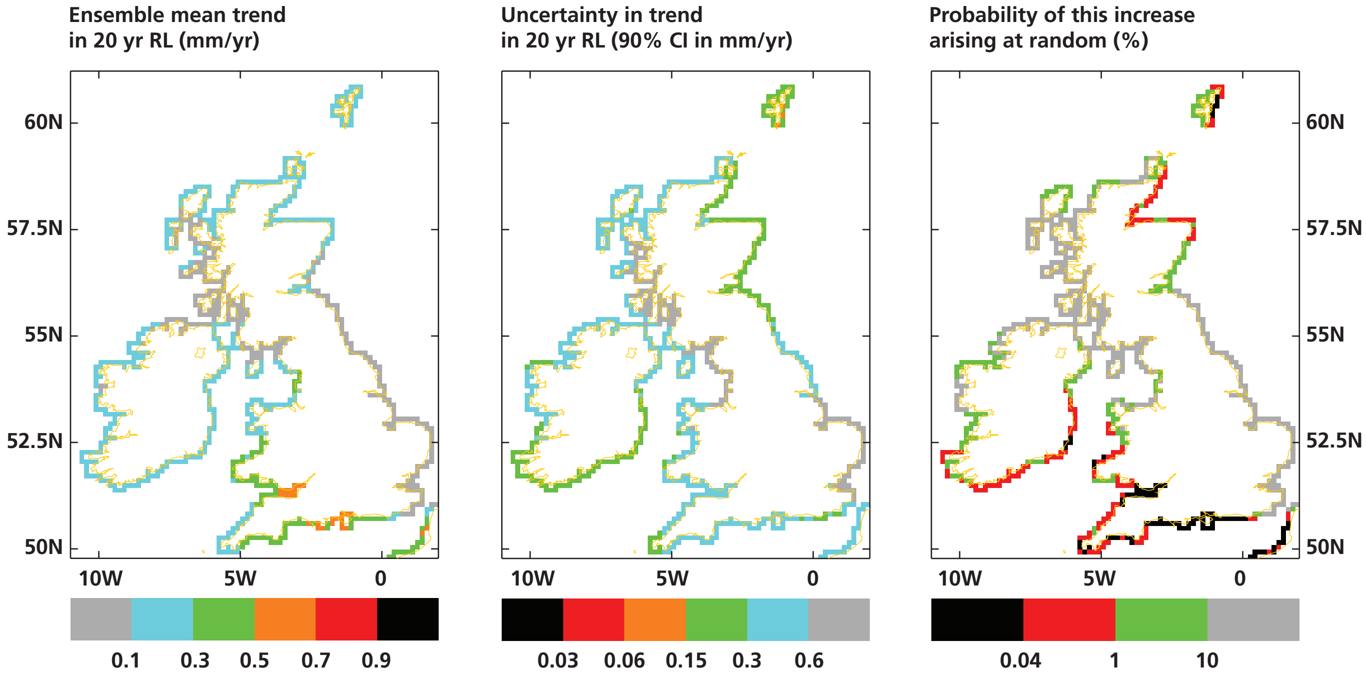


Figure 4.5: PPE ensemble mean trends in 20 yr skew surge return level from the storminess component only. Negative trends are included in the grey shading.

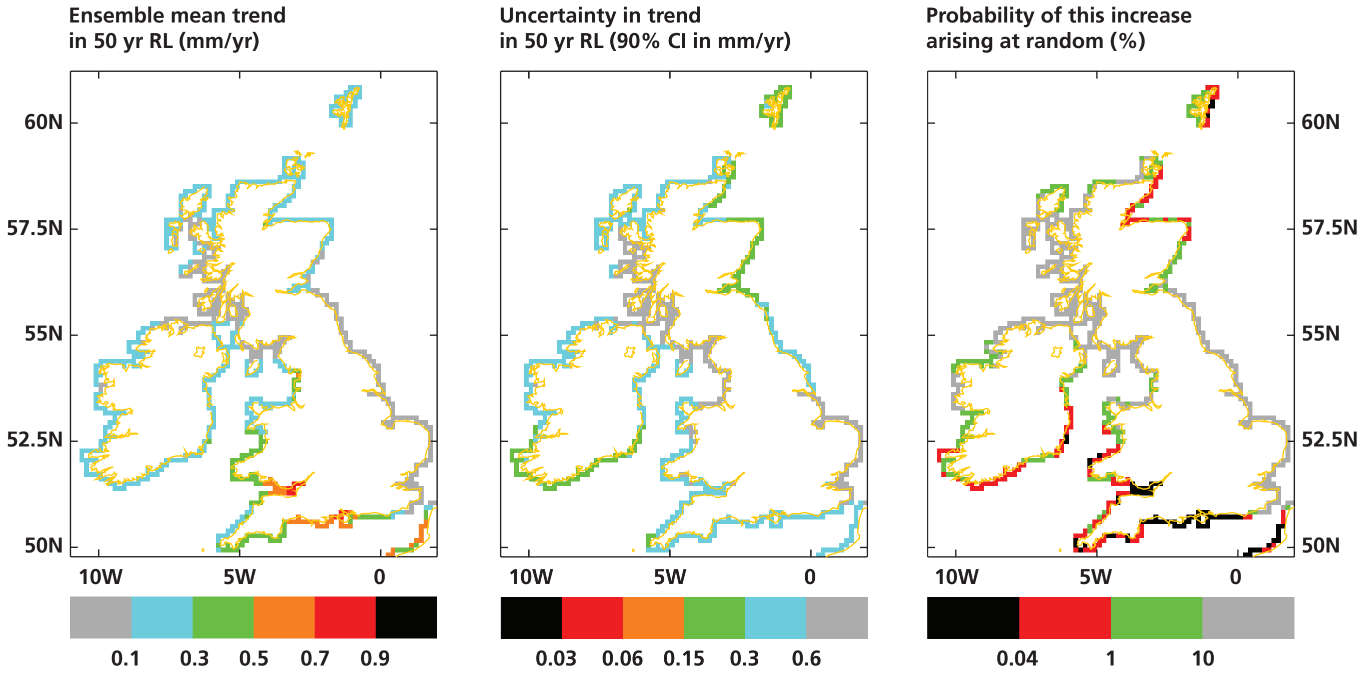


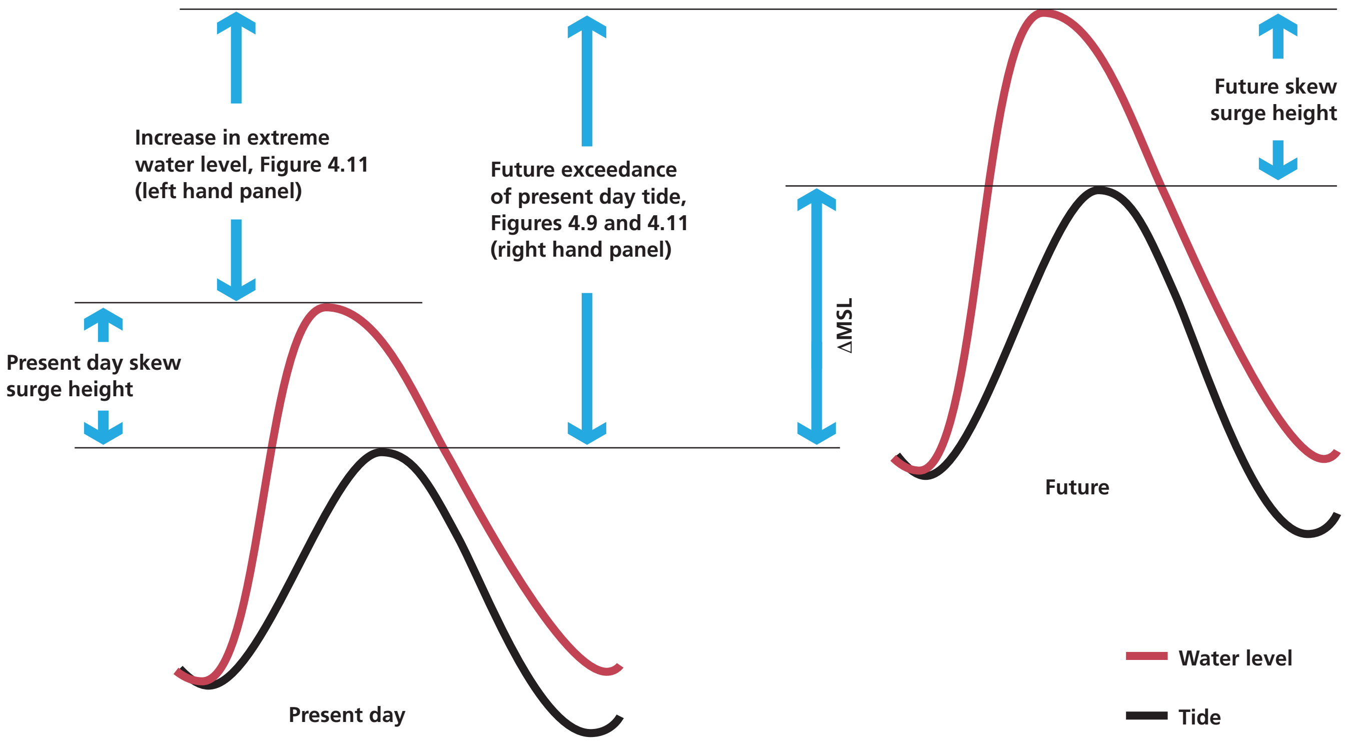
Figure 4.6: PPE ensemble mean trends in 50 yr skew surge return level from the storminess component only. Negative trends are included in the grey shading.

4.4 Combining changes in storm surges and sea level rise

The trends given above (calculated from a 149-yr run of each of the 11 PPE ensemble members) are combined linearly with a near-present day surge baseline and relative mean sea level change data presented in Chapter 3, to give the exceedance of present-day astronomical high tides by projected future extreme water levels. LGF showed that it is reasonable to add mean sea level changes of up to 0.5 m linearly to the storminess-driven change component around the UK coast and our own case study (specific to the outer Thames Estuary) suggests that this is valid even for mean sea level changes up to 3 m. Our results imply that the principal effect of such a mean sea level increase is on the timing of the signal at the Thames, due to the effect of increased water depth on the speed of propagation. The non-linear effect of a 3 m increase in mean depth on the magnitude of the water level at the outer Thames Estuary for our case study is less than 5 cm.

There are several ways in which a near-present-day baseline might be established, for example on one hand interpolation between available tide gauge data and on the other a simulation, or some combination of the two might be employed. As an illustration we use a baseline derived from a reanalysis-driven simulation. At the Thames location it has been demonstrated that this configuration is able to simulate the observational uncertainty up to at least 50-yr return events. However, users should consider whether an alternative baseline will be more appropriate to their application. The relationship between the baseline, changes in skew surge and changes in mean sea level are shown in Figure 4.7. The baseline and a measure of its uncertainty are shown in Figure 4.8.

Figure 4.7: Schematic showing how changes in mean sea level and skew surge combine. The figures where these quantities are reported are also indicated. The future exceedance of present day tide is equal to the sum of the present day skew surge plus the increase in extreme water level. The increase in extreme water level* is equal to the mean sea level rise plus the change in skew surge height.



* Extreme future water level is the difference in water level between: (1) a present day 1 in 50 yr return period surge which is added to the present day mean water level; and (2), a future year surge height (e.g. from a 1 in 5 yr to a 1 in 50 yr return period surge), which is added to a future year water level.

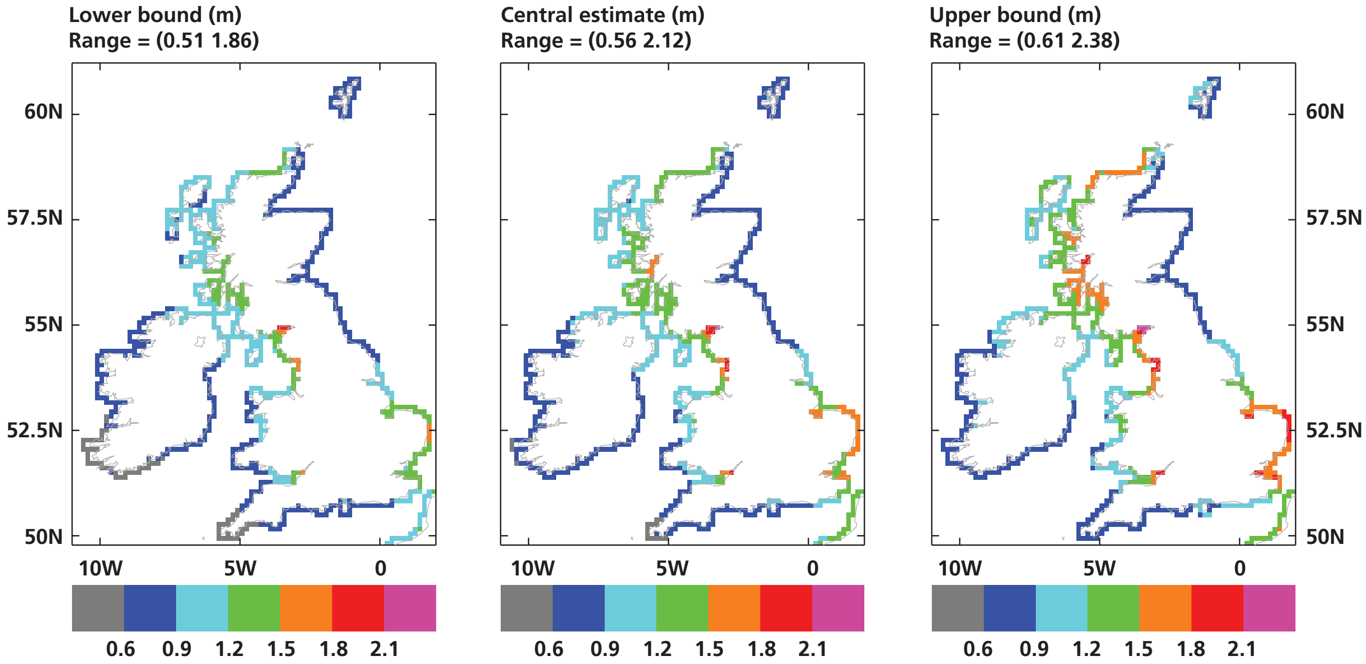


Figure 4.8: Illustrative present-day baseline of skew surge (present-day extreme sea level above astronomical tide) 50-yr return levels (m). The central panel shows the estimated central value. Left and right panels show the lower and upper bounds of the 90% confidence interval.

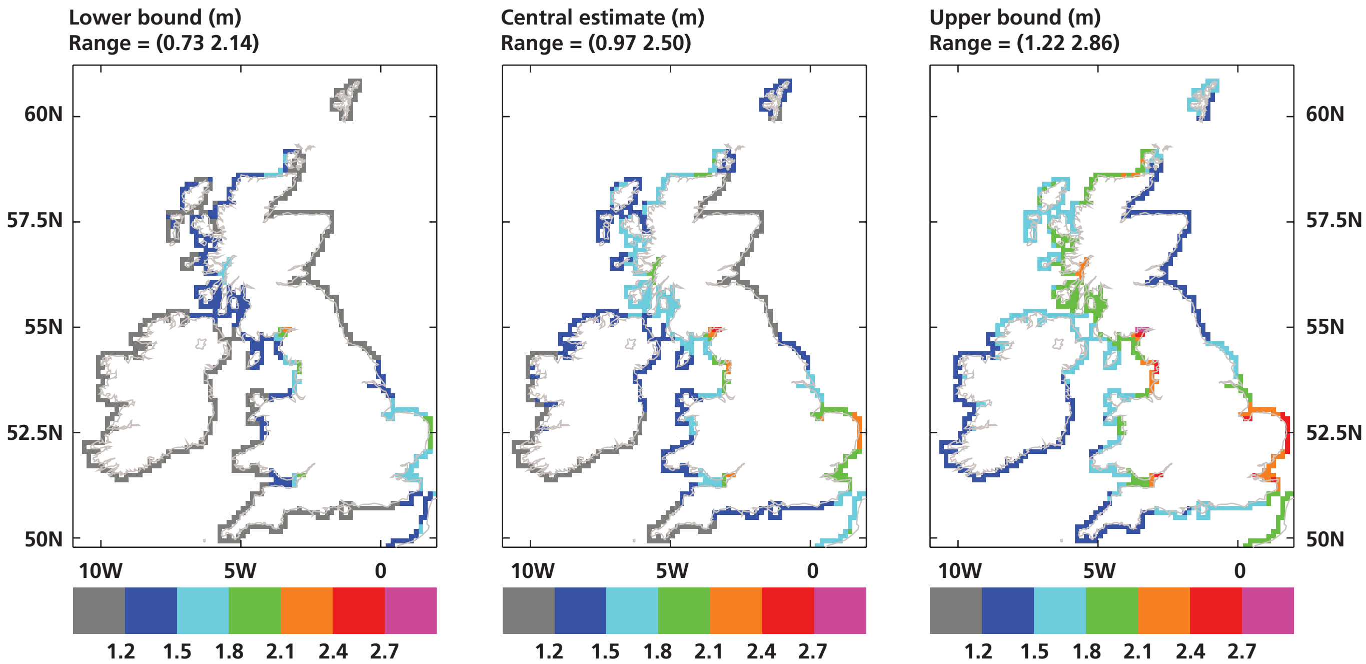


Figure 4.9: Exceedance of present-day astronomical high tides by projected future extreme water 50-yr return levels for 2095 (m). The central panel shows the estimated central value. Left and right panels show the lower and upper bounds of the 90% confidence interval. Grey shows any value < 1.2 m.

Uncertainty in the return levels of exceedance of present-day astronomical high tides by projected future extreme water levels is estimated by combining uncertainties in the modelled surge trend, uncertainties in the modelled 2095 mean sea level, and uncertainties in the present-day surge baseline under an assumption of independence and normality of uncertainties. As described in Chapter 3, we do not include any land movement uncertainty because this is likely to be small compared to the other uncertainties.

The combined results are shown in Figure 4.9. In this figure the grey shading indicates any value less than 1.2 m. The full range of values in the region shown is reported at the top of each panel.

4.5 H++ surge component

The concept of an H++ scenario* was discussed in Chapter 1. Changes in atmospheric storminess were discussed in Chapter 2. The surge component of the H++ model scenario comes from comparing 21st century changes in simulated large-scale indicators of storminess and then selecting the IPCC multi-model ensemble (henceforth MME) member with the largest increase in some measure of storminess over the UK region. This member is labelled Q in Figure 2.4. Two simple downscaling approaches, described in the box, are then used to estimate the resulting increase in surge height.

Model Q has a particularly small present day bias in storminess when compared with reanalysis (observed) data. Thus, while there is some evidence to reject or down-weight some of the MME ensemble this cannot be applied to model Q. This suggests it is necessary to investigate the effect that this model's projected

The two scaling approaches to simulation of model Q storm surge

The MME models are global climate models and so we do not have available the necessary high temporal and spatial resolution wind and pressure fields needed to drive the surge model. As far as we are aware model Q has not been downscaled using a consistent regional climate model to a scale suitable for driving the storm surge model. An alternative strategy is to scale our PPE results in a way which makes them become consistent with model Q. Our first scaling is based on changes in storminess as measured by the Blackmon band-pass filtered pressure deviation.

However, other scaling approaches are equally plausible. Our second approach is to scale by the UK Gale Index, which is another well-recognised measure of storminess. Whereas the Blackmon band-pass filtered pressure deviation gives a spatially-varying measure of temporal variations in pressure at a location, the UK Gale Index (Hulme and Jones, 1991) gives a temporally-varying measure of spatial variations in pressure at a particular time.

* The H++ model scenario describes a range for vulnerability analysis. Whilst the top end of this scenario cannot be ruled out based on current understanding, it is regarded as very unlikely to occur during the 21st century. However, it is not possible to quantify this low probability; very unlikely in this context does not refer to the IPCC definition.

** The Thames Estuary (TE2100) project reported in Chapter 7 uses the same H++ surge simulations but reports the 5-yr return period event.

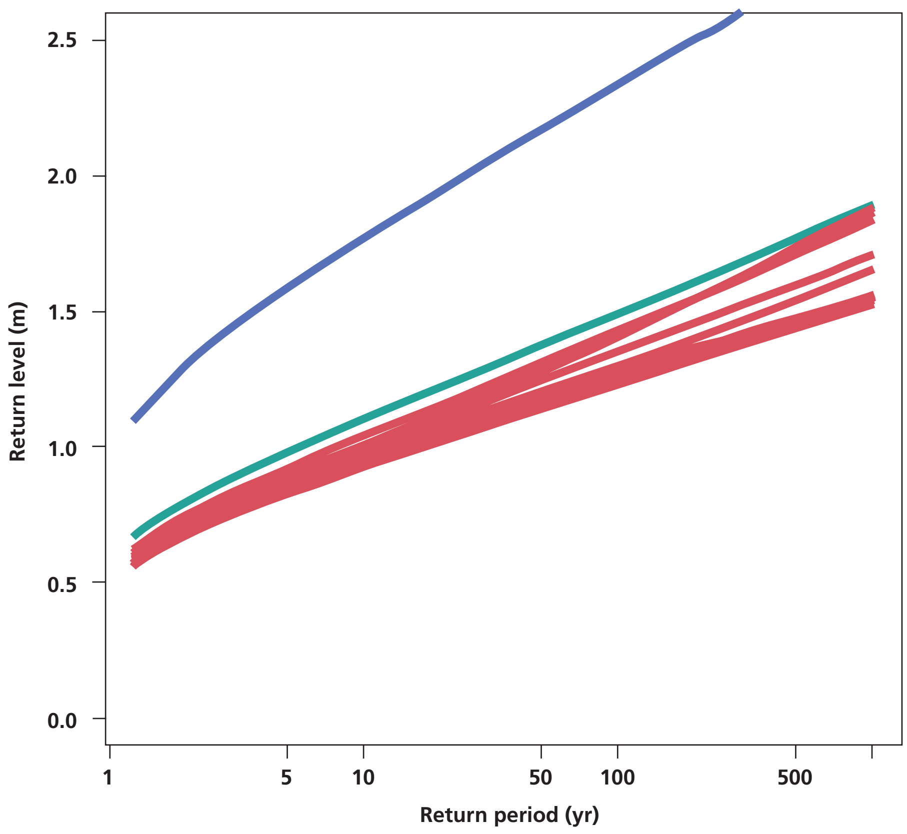


Figure 4.10: Skew surge return level curves (not including mean sea level change) at the Thames Estuary for raw PPE ensemble (red lines) and simulated results for MME model Q for the end of the 21st century (approx 2080–2099) using two different scaling approaches (blue and green lines). The green curve contains little evidence of a climate signal. The dark blue curve has a significant climate change signal.

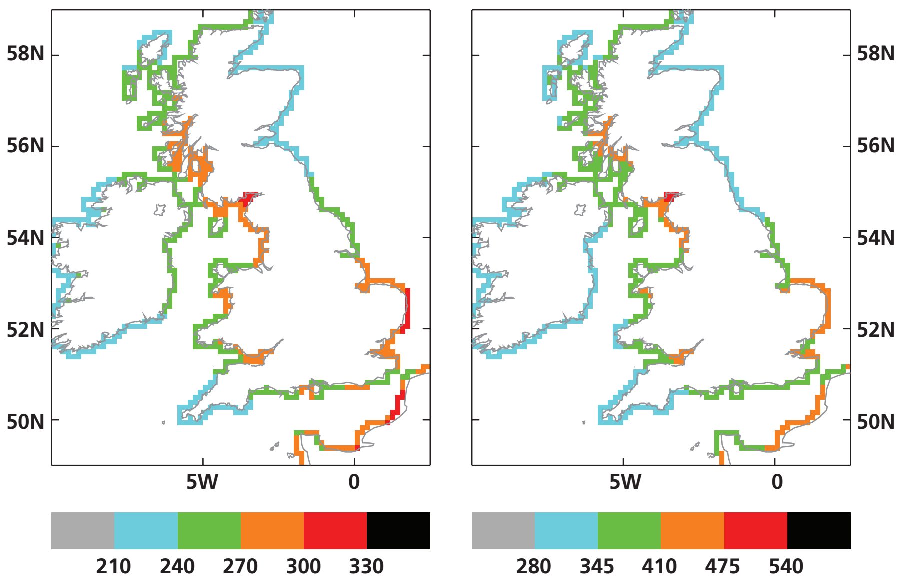


Figure 4.11: Left-hand panel: H++ 21st century change in extreme sea level for the 50-yr return period (cm) including upper value of H++ mean sea level change under the high end of the extreme but very unlikely H++ model scenario*. Right-hand panel: 50-yr return level of exceedance of present-day astronomical high tides by projected future extreme water for the end of the 21st century under the high end of the H++ model scenario, including upper value of H++ mean sea level change.

* The result near the Thames Estuary is consistent with that derived for the TE2100 project, and is reported in Chapter 7.

changes in 21st century storminess could have on extreme sea levels. The impact of the first scaling approach at one location (in the Thames Estuary) is shown by the blue line in Figure 4.10, and the impact of the second scaling approach is shown by the green line. This gives a H++ range of 21st century skew surge 50-yr return level increase (not including mean sea level change) of approximately 0.2 m to 0.95 m at the Thames Estuary.

4.6 Combining the mean sea level and surge component of H++

For the Thames Estuary, our H++ surge 21st century increase range is approximately 0.2–0.95 m and our H++ mean sea level 21st century increase range is 0.93–1.9 m. Here we combine the upper ends of the H++ surge and MSL ranges to give the 21st century combined H++ changes around the whole of the UK coastline shown in the left-hand panel of Figure 4.11. The right-hand panel of Figure 4.11 shows exceedance of present-day astronomical high tides by projected future extreme water levels at the top end of the extreme but very unlikely H++ range (see Figure 4.7 for a schematic explanation of these terms). As stated in Section 4.4, this is the estimated difference between a future extreme sea level and a present day high tide. All of the atmospherically-driven part of this change is derived from model data, i.e. the exceedance of present-day astronomical high tides by projected future extreme water levels is not based on an observed baseline of present-day skew surge, but rather on the model simulation of present day. While we do not attempt to derive a probability for this scenario it should be viewed as being very unlikely to occur during the 21st century. It is presented to provide justification for not ruling out options for adaptation until the science is more certain.

4.7 Results presented in the UKCP09 User Interface

The UKCP09 User Interface will allow the results presented in this Chapter and many additional results to be displayed via an interactive web-based interface. It will contain the following extreme sea level information:

- Projected long-term trends in skew surge for the return periods 2, 10, 20 and 50 yr at user-specified coastal locations.
- Uncertainty in projected long-term trends in skew surge for the return periods 2, 10, 20 and 50 yr at user-specified coastal locations.
- Statistical significance of the projected long-term trends in skew surge.

4.8 References

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5 Climate driven changes in waves

In this chapter we examine the projections of future wave climate around the UK driven by winds from a subset of the Met Office climate model ensemble members. The wave model which is used is based on the well-tested third-generation spectral model WAM implemented on two grids: a coarse 1° grid for the whole and a 12 km model of the NW European continental shelf. The models were run using three sets of atmospheric model wind forcing from low, mid and high climate senstivity variants of the Met Office perturbed physics ensemble (PPE). All results are for the medium emissions scenario.

Key Findings

- **The wave model has been well-validated previously and here it is shown to be in reasonable agreement with the ERA-40 reanalysis (which is a comprehensive global hind-cast of the last 40 yr of waves and wind, combining model fields with a wide range of observations) for the present-day wave climate for the NE Atlantic.**

- **Seasonal mean and extreme waves are generally expected to increase slightly to the SW of the UK, reduce to the north of the UK and experience little change in the North Sea. There are large uncertainties especially with the projected extreme values.**

- **Changes in the winter mean wave height 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. Projections of longer return period wave heights will reflect the same pattern but with larger error bars.**

- **Here we present a first look at the range of uncertainty. Only three ensembles were used (out of 11) so the spread is clearly a minimum estimate. The simulation corresponding to low climate sensitivity shows larger increases of wave height but the latitudinal pattern remains similar in each case.**

- **One wave model simulation was carried out for the whole 140 yr to examine natural variability. The large inter-annual variability in wave parameters, especially extreme values, shows that looking at differences between two 30-yr time slices is of limited value in determining trends. Statistically significant trends in annual maximum wave height of –0.3 cm/yr are identified to the north of Scotland.**

5.1 Introduction

Changes in coastal wave climate, as a result of climate change, 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 important to estimate how the wave climate might alter in the future as a result of anthropogenic climate change, and produce scenarios for the 21st century that are consistent with climate change estimations of other variables. 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 and the wave direction will have an impact on the alongshore transport of sediment.

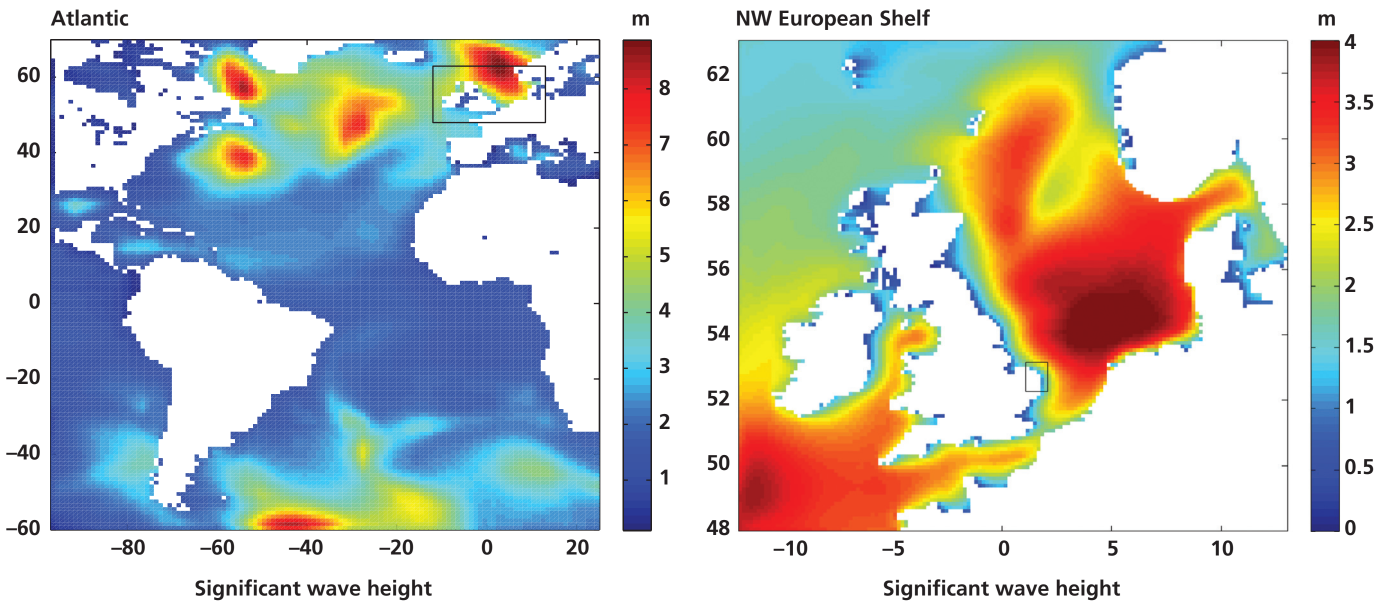
5.2 Methodology

In order to downscale the effect of climate change to the local wave climate, a set of nested ocean surface wave models are driven by a set of nested climate and coupled ocean-climate models. The climate models are described in Chapter 2. Three members of the Met Office PPE are used to drive the wave models, representing low, mid and high climate sensitivity to give a crude minimum estimate of the minimum model uncertainty. The mid sensitivity model is the unperturbed ensemble member. All results are for the medium emissions scenario.

5.2.1 Wave model set-up

To estimate the wave climate in UK waters and to provide boundary conditions for coastal modelling, such as the modelling of the morphological evolution of the coastline and offshore sandbanks, Met Office climate model winds are used to provide driving data for Atlantic and regional surface wave models. The

Figure 5.1: Snapshot of model SWH (in metres) in the Atlantic and North West European shelf domains. The box in the left panel shows the boundary location in the Atlantic wave model where wave information is passed to the North West European shelf wave model. The box in the right panel shows a typical nesting procedure where information could be passed to a smaller scale model (in this case for the Norfolk coast) in which the waves are transformed inshore for use in modelling morphological evolution of the coastline.

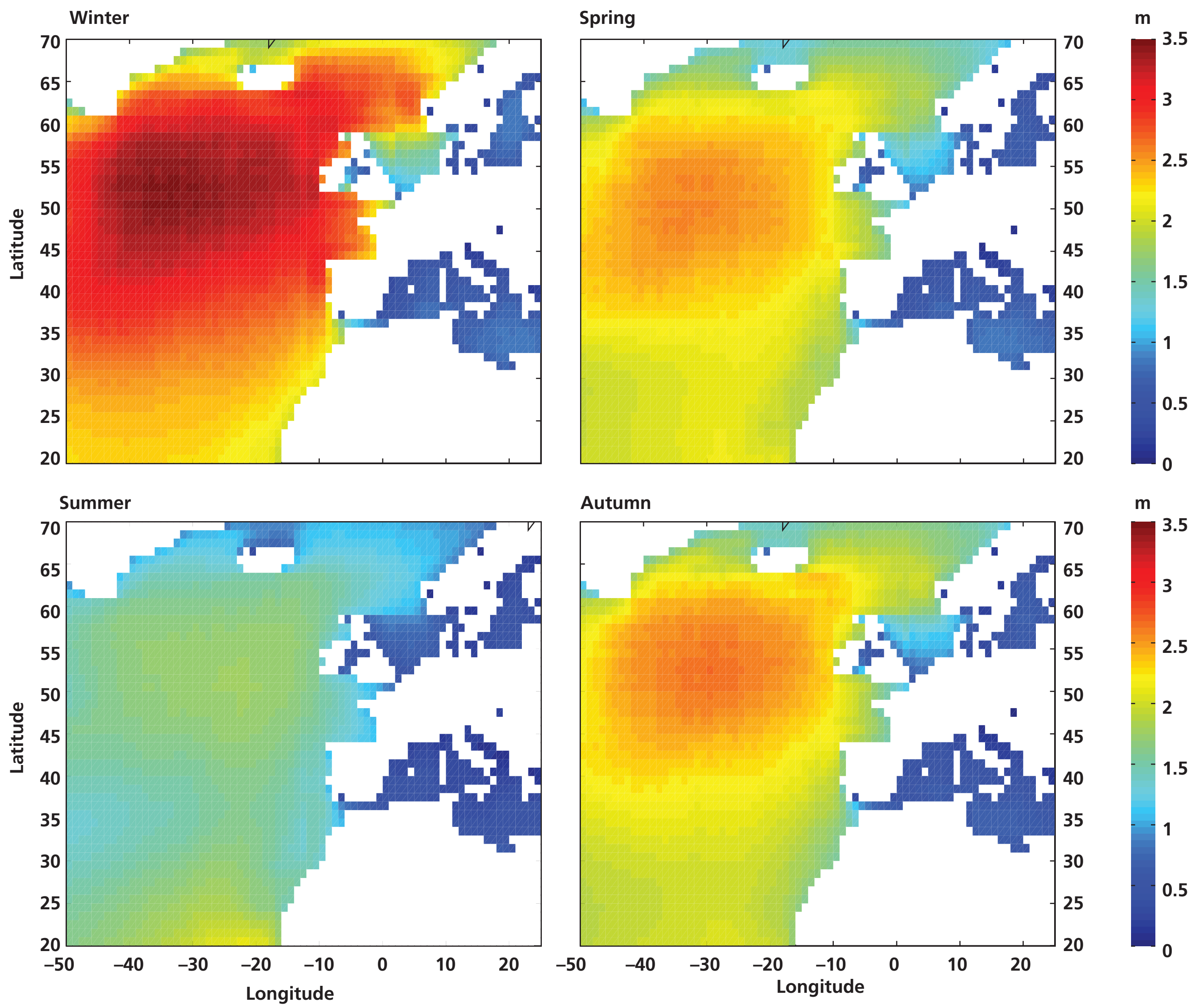


global climate model (GCM) provides winds for the Atlantic wave model and the regional climate model (RCM) provides winds for the regional wave model.

The wave model used here is the PROWAM model (Monbaliu *et al*. 2000), which is a modified version of the WAM cycle-4 third generation wave model (Komen *et al*. 1994). This wave model is a spectral (phase-averaged) wave model which includes wave generation by wind, non-linear wave-wave interactions and dissipation processes including white-capping and bottom friction. (The term 'spectral' model means it produces estimates for wave energy for a range of wave frequencies and directions, rather than resolving individual waves.) PROWAM is a version of WAM developed to run on higher spatial resolution than the standard WAM model and also includes some extra shallow-water processes. The wave model is run on two domains. The first is a 1° × 1° degree deep water model of the whole Atlantic. This is used to provide wave boundary conditions for a higher resolution, regional, shallow water wave model on the North West European continental shelf, run on a 1/6° longitude by 1/9° latitude (~12 km) grid. The two model domains are shown in Figure 5.1.

The inclusion of the South Atlantic in the coarse resolution model allows occasional swell events generated in the Southern Ocean winter (northern hemisphere summer) to propagate into the regional wave model domain. (Swell is generally

Figure 5.2: Seasonal means of model SWH (in metres) of swell waves for the period 1980–1989. Top left panel is winter (DJF), top right panel is spring (MAM), bottom left is summer (JJA), and bottom right is autumn (SON).



low-amplitude, low-frequency wave energy that can propagate for very long distances across the ocean with little dissipation once it has left the storm region where it was generated.) Although swell events from the Atlantic may not have much effect on the wave climate in the North Sea, they can be important for coastal impacts in the SW of England. Figure 5.2 shows the simulated seasonal mean swell significant wave height, for the decade 1980–1989, in the NE Atlantic, taken from the coarse resolution wave model. Figure 5.3 also shows the annual maxima and 99th percentiles of swell energy for the same region.

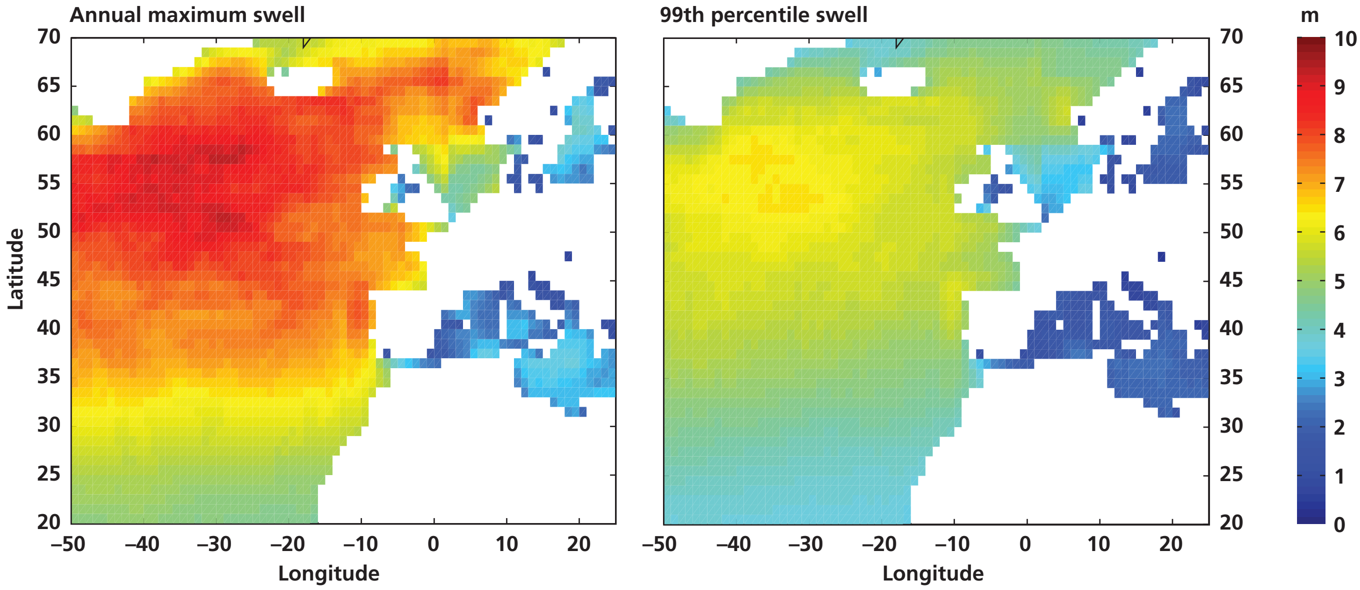
By comparing an experiment where no South Atlantic was included in the nesting procedure, to one where the South Atlantic was included, the importance of swell energy from the South Atlantic was estimated. Although the difference in wave energy entering the smaller domain is small (around 5%), individual events may be important and the inclusion of the South Atlantic in the Atlantic wave model is justified, particularly as the computational overhead is quite low (making the entire wave simulation system 1.2 times slower).

The North West European shelf model simulates waves at some distance from shore and if these predicted waves are to be used to study coastal impacts including morphological modelling of the coastline (modelling changes in the coastal shape and position due to erosion, deposition and transport of sediment), they must be transformed in-shore by a high-resolution model which takes account of near-shore processes including tides and surges, and used in conjunction with sediment transport models. The regional wave model supplies full wave spectral information for particular areas of interest, such as the Norfolk coast in the southern North Sea (which is susceptible to coastal flooding and erosion), as well as providing separate integrated parameters (e.g. SWH, peak period and mean direction) for wind-sea (locally-generated waves) and swell for the entire NW European continental shelf. The wave model is run for the same periods (1960–1990 and 2070–2100) for the three RCM ensemble members but for the mid climate sensitivity experiment it was also run through the intervening period to provide a full 140 yr projection.

5.2.2 Model performance

The high quality of the wave fields produced by WAM has been demonstrated in various validation studies, using both *in-situ* measurements and data from

Figure 5.3: Annual maxima and 99th percentile of SWH (in metres) of swell waves for the period 1980–1989.

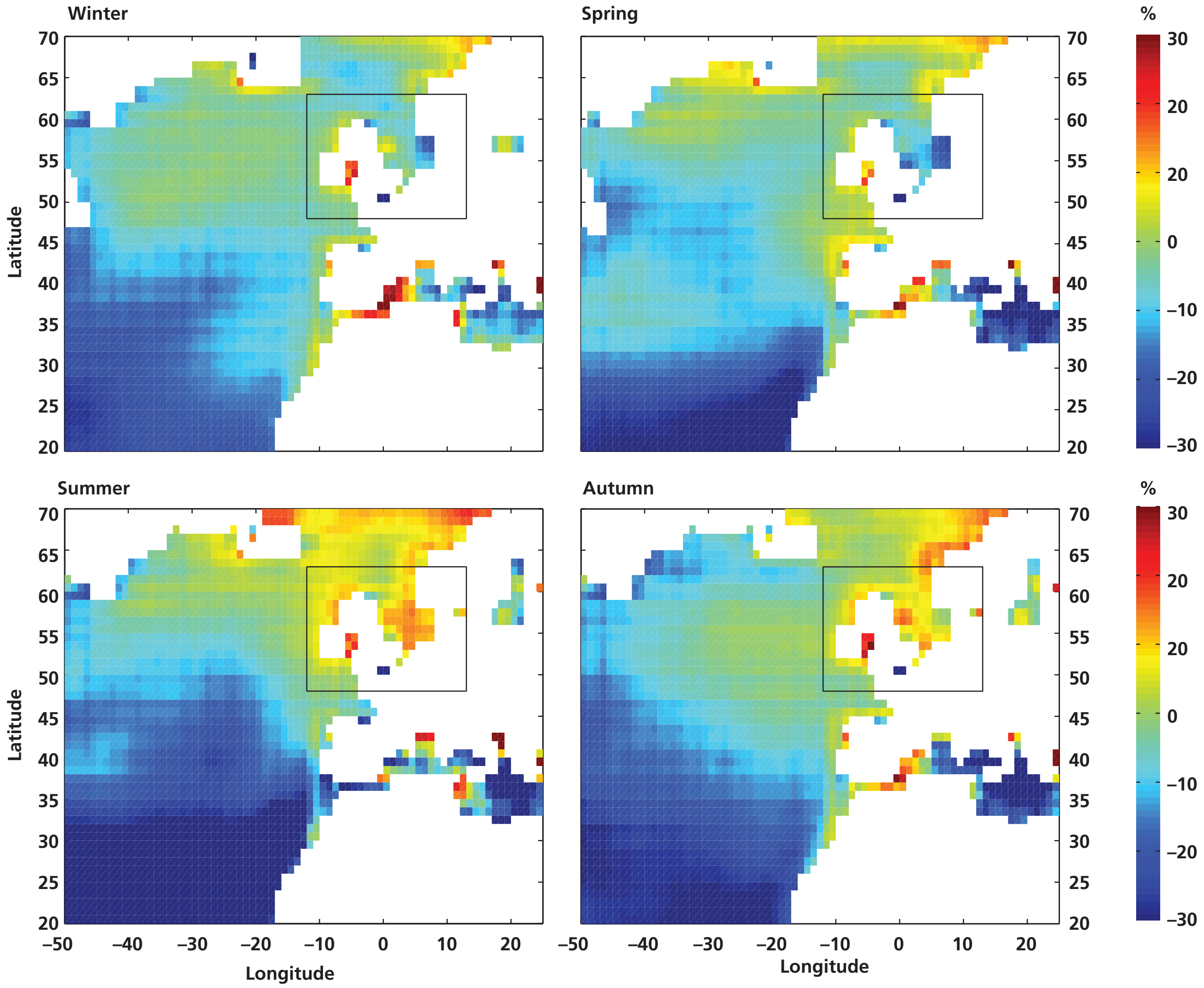


satellites. Furthermore these studies include both short term and long term (up to one year) validation periods (Romeiser 1993). Here we also validate the modelled present-day wave climate statistics against results from the ERA-40 reanalysis.

The ERA-40 project was run by the European Centre for Medium-Range Weather Forecasts (ECMWF). It consists of climate and wave model hind-casts for the period of over 40 yr, from 1957 to 2002. The data were then reanalysed using a compilation of observations of parameters such as wind speed and wave height, including satellite altimeter and buoy data, to give a composite of model and observations. This dataset provides excellent coverage for the wave climate and is useful for comparisons of this type. The details of the wave climate produced by the ERA-40 project can be found in Sterl and Caires (2005).

Although event-by event comparison cannot be performed for the wave model output in this study, since the model uses climate model forcing rather than hind-cast winds, seasonal and annual statistics of the near present-day portion of the climate model-driven wave simulations can be compared to statistics of observed wave fields. To this end, the statistics of the wave output in the coarse resolution

Figure 5.4: Percentage difference in seasonal mean SWH between ERA-40 and coarse wave model results driven by mid sensitivity GCM winds, for the period 1980–1989. Top left panel is winter (DJF), top right panel is spring (MAM), bottom left is summer (JJA), and bottom right is autumn (SON).



Atlantic model are compared to the statistics of the reanalysed wave fields from the ERA-40 hindcast. Although the product of a model, the ERA-40 waves are driven by assimilated winds and are reanalysed using *in-situ* and remote observations (Sterl and Caires, 2005). The ERA-40 dataset is therefore a useful dataset to compare model output to over large domains such as the Atlantic.

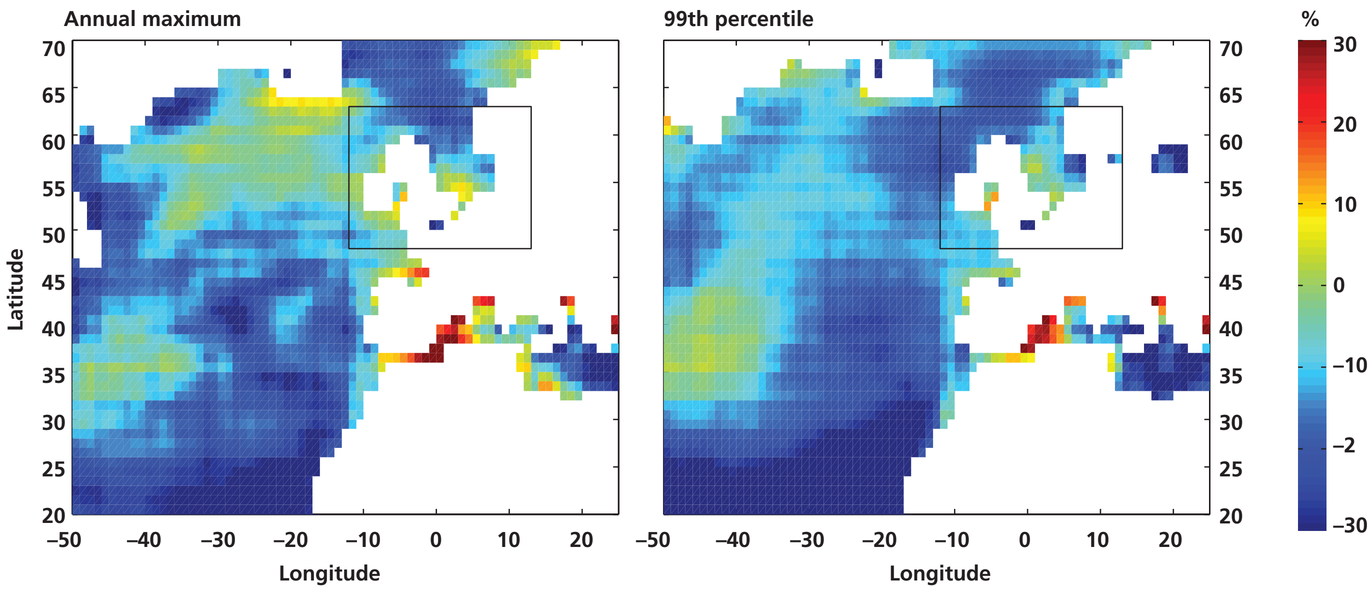
Figure 5.4 shows the percentage difference in the seasonal mean SWHs for the period 1980–1989 between the ERA-40 dataset and the coarse resolution wave model driven by the mid sensitivity climate model ensemble member winds, focusing on the North Atlantic region. The coarse model does not include details of Antarctica and the Southern Ocean, and hence overestimates the wave heights in the South Atlantic and, as a result of swell propagation, over-estimates low latitude wave heights. However, good agreement is seen between ERA-40 and the model in the NE Atlantic, which is the area from which we extract boundary forcing for the regional model (shown by the box).

Figure 5.5 shows the percentage difference in the annual maxima and 99th percentile of SWH for the period 1980–1989 from the ERA-40 dataset and the coarse resolution wave model driven by the mid sensitivity ensemble member winds. Again, the model shows larger values than the ERA-40 dataset in the South Atlantic. In general the annual maxima are larger in the coarse resolution Atlantic wave model, including the NE Atlantic.

5.3 Projected future changes in wave climate for the Atlantic

Figure 5.6 shows estimated changes in the seasonal means of SWH in the NE Atlantic for the mid sensitivity ensemble member, for both the total wave spectrum and the swell part of the spectrum. These changes were calculated by taking two 10-yr time-slices and calculating seasonal means for these periods, then taking the difference between the two. In this case the decades 2080–2089 and 1990–1999 were used. The patterns of change in the seasonal mean wave heights are similar for total sea and for swell, i.e. the swell dominates the seasonal mean wave height, especially in spring and summer, whereas in autumn

Figure 5.5: Percentage difference in annual maxima (left panel) and 99th percentile (right panel) of SWH between ERA-40 and coarse wave model results driven by mid sensitivity GCM winds, for the period 1980–1989.



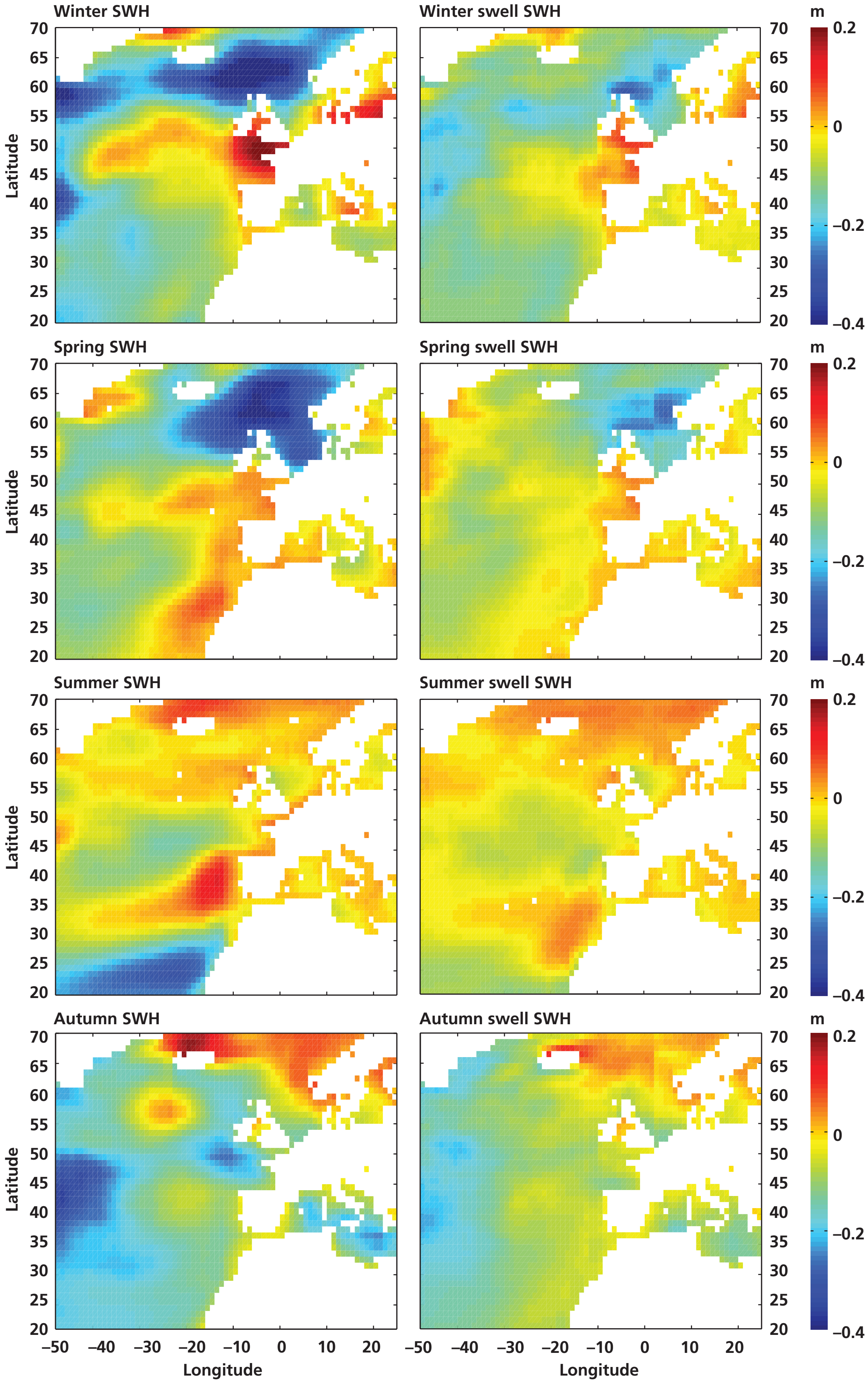


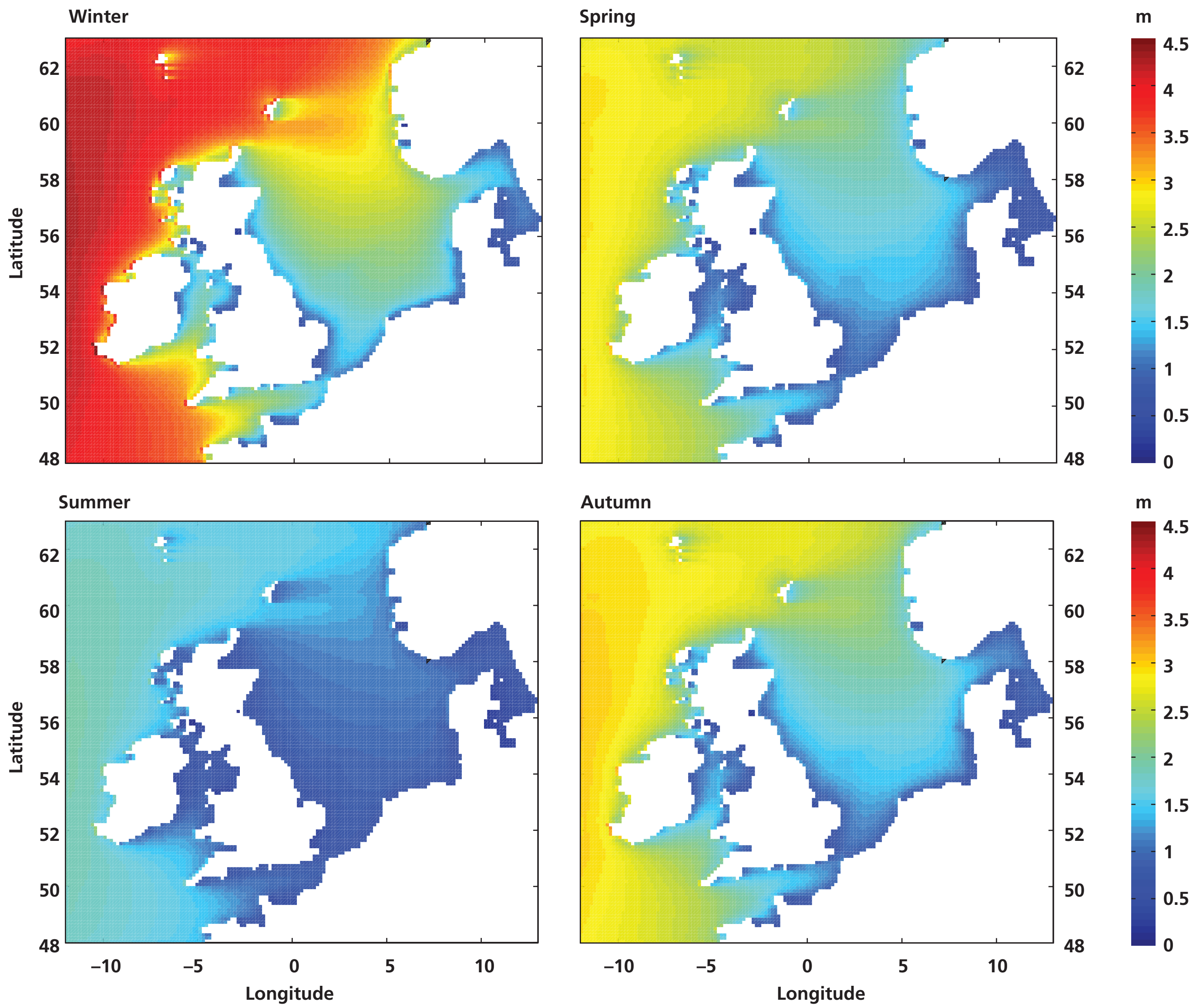
Figure 5.6: Changes in seasonal means of SWH (in metres) in the NE Atlantic from the periods 1990–1999 and 2080–2089. Left Panels show results for the total spectrum, while right panels show results for the swell part of the spectrum. Wave climate is for the unperturbed ensemble member run.

and winter the changes in total wave height due to changing storms in the North Atlantic can be seen. Note that the colour scale goes from –0.4 to +0.2 m so there are larger decreases in wave height in some regions compared to the places where it increases.

Winter mean SWHs show an increase in the NE Atlantic and SW Approaches to the UK, and a reduction in the seas north of the UK. These changes may be due to shifts in the latitude of storm tracks across the UK (Wolf and Woolf, 2006). Wolf and Woolf (2006) show that a reduction in monthly mean and maximum wave height to the north of the UK could be produced by a more southerly storm track.

Spring mean SWHs show a similar spatial pattern of change to the winter means. Summer means show an altogether different pattern of changes, with mainly positive changes across the entire NE Atlantic and UK waters. The North Atlantic experiences the least number of storms in the summer, and any changes in summer means may be due to changes in the propagation of swell from other regions such as the South Atlantic.

Figure 5.7: Present-day (1960–1990) seasonal means of SWH (in metres) for the CS3 domain. Top left is winter (DJF), top right is spring (MAM), bottom left is summer (JJA), and bottom right is autumn (SON).



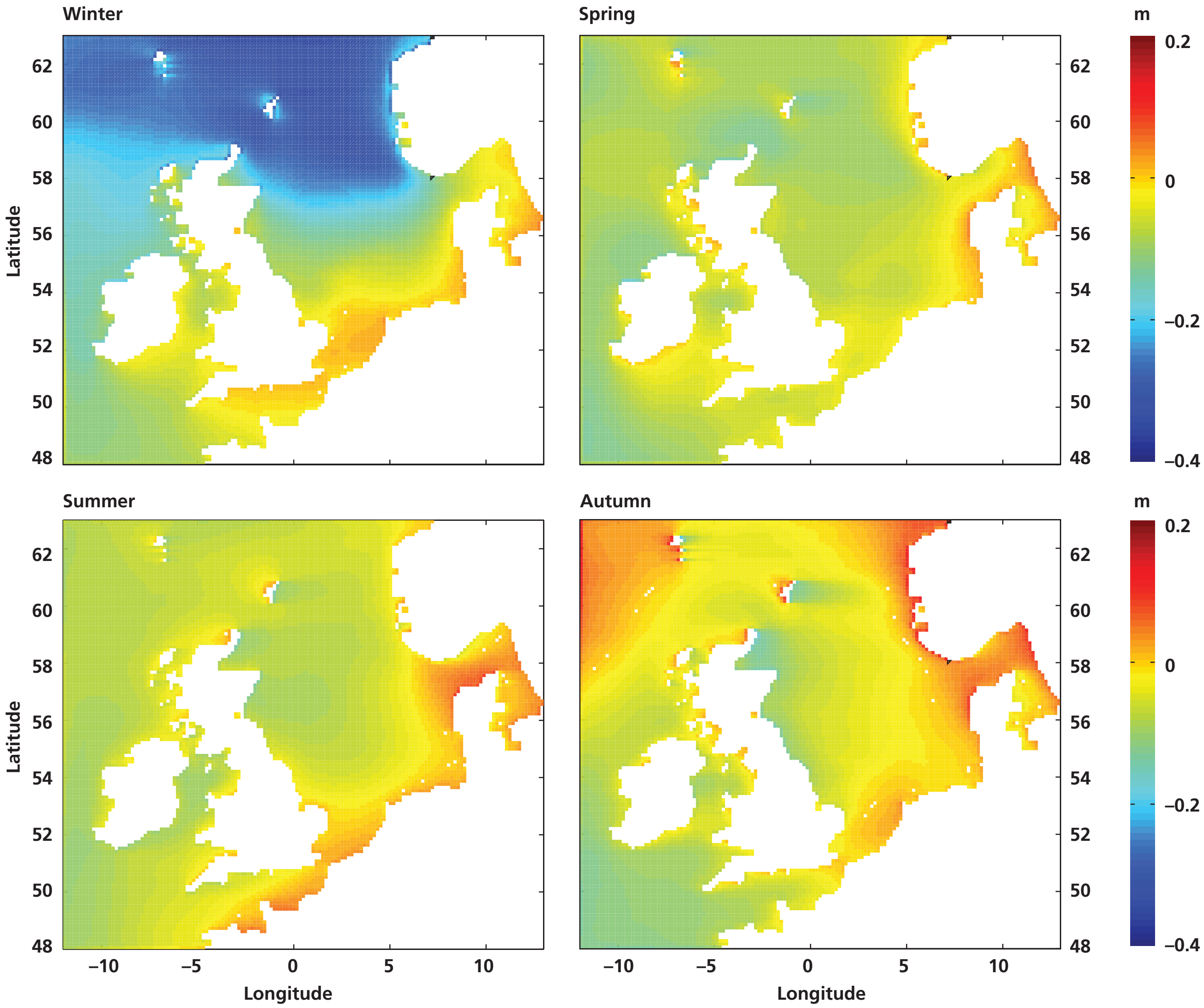
5.4 Projected future changes in wave climate for the UK

Details of the projected changes in wave height for the UK are presented below. The seasonal mean statistics and also extreme values, especially the winter maximum and annual maximum wave height, were considered.

Figure 5.7 shows the seasonal mean SWH for the period 1960–1990 for the European shelf wave model. The higher wave heights in winter, autumn and spring can clearly be seen compared to summer. Highest wave heights are experienced to the west of the UK in the Atlantic Ocean, especially to the NW of Scotland.

Figure 5.8 shows changes in these seasonal means, based on a time-slice comparison of the statistics using the two periods 1960–1990 and 2070–2100 (note the colour scale is as in Figure 5.6). The change in winter mean shows a distinctive pattern dominated by a latitudinal dependence. To the south of the UK there is generally a small increase in winter mean wave height; this includes the English Channel and the southern North Sea. To the north of the UK there is a larger reduction in SWH. This spatial pattern may suggest an intensification of

Figure 5.8: Changes in seasonal means of SWH (in metres) from 1960–1990 to 2070–2100. Top left is winter (DJF), top right is spring (MAM), bottom left is summer (JJA), and bottom right is autumn (SON).



westerly winds and a reduction in northerly winds, which may also be related to a change in storm tracks (Wolf and Woolf, 2006). The pattern changes through the seasons, with the summer mean SWH showing only positive changes around the southern and eastern North Sea. The autumn pattern is quite different with an increase in wave height to the NW of Scotland.

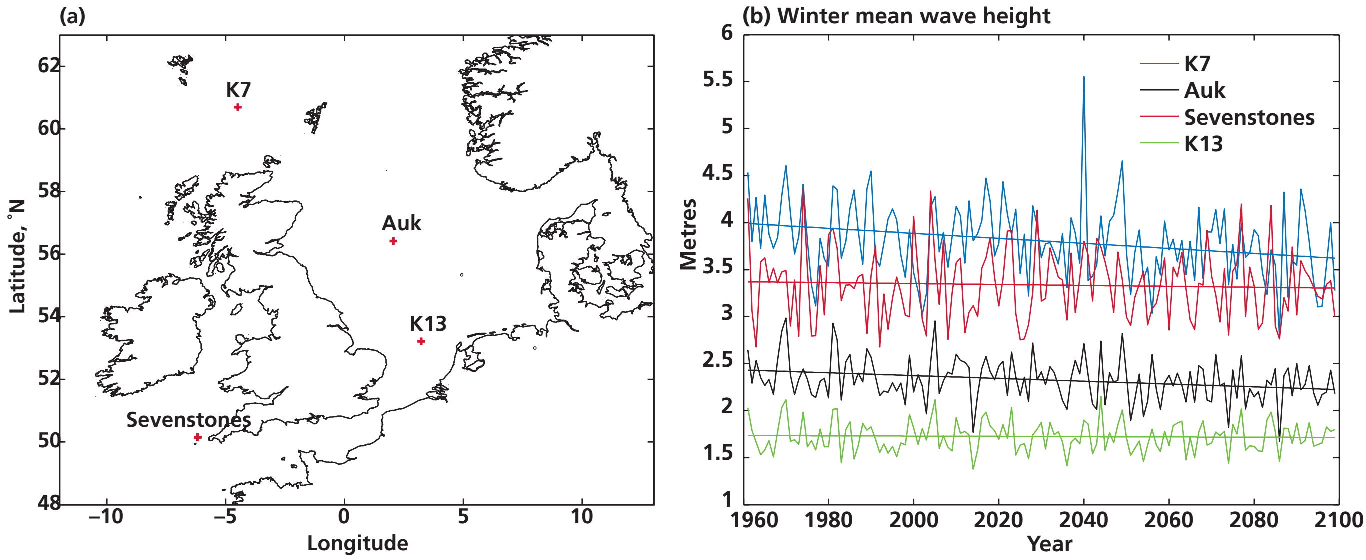
5.4.1 Confidence limits and uncertainty

It is important to know how robust the projections are and if possible place confidence limits on the results. Various sources of uncertainty exist: wave model error, natural variability in the climate system, climate model sensitivity to the choice of various parameters and uncertainty in future projection of greenhouse gas forcing. We have already discussed the wave model error and in this study we are only using the medium-high emissions scenario. We now further examine the uncertainty due to natural variability and the climate model sensitivity.

In order to take into the account the natural variability in wave height, the entire time-series 1960–2100 was examined (for the mid sensitivity ensemble member only). Examples are shown from selected points in different sea areas around the UK, shown in Figure 5.9(a). These are chosen to coincide with locations of wave observations at Met Office buoys K7 to the north of Scotland and Seven Stones Light Vessel to the SW of England, K13 (KNMI) in the southern North Sea, and the Auk (Shell UK) oil platform in the central North Sea. Time series of the winter mean wave height at these locations is shown in Figure 5.9(b). There is a clear downward trend at K7 and a small downward trend at Auk but little change in the southern North Sea or Seven Stones. It may be seen that there is quite a large amount of inter-annual variability in these time series, although the winter mean SWH is quite a stable variable as it is based on a relatively large number of values.

The issue of statisitical significance is highlighted when we look at the annual maxima which have a much larger error bar. Figure 5.10 shows changes in the annual and winter maxima between the two 30-yr time slices. Areas that are masked out (dark red) are points where the differences are statistically insignificant at the 95th percentile level (based on Student's t-test).

Figure 5.9: (a) Map of CS3 model area showing locations of selected output points: K7, Seven Stones, Auk and K13. (b) 140-yr time series of winter mean SWH for the four locations, showing trend lines.

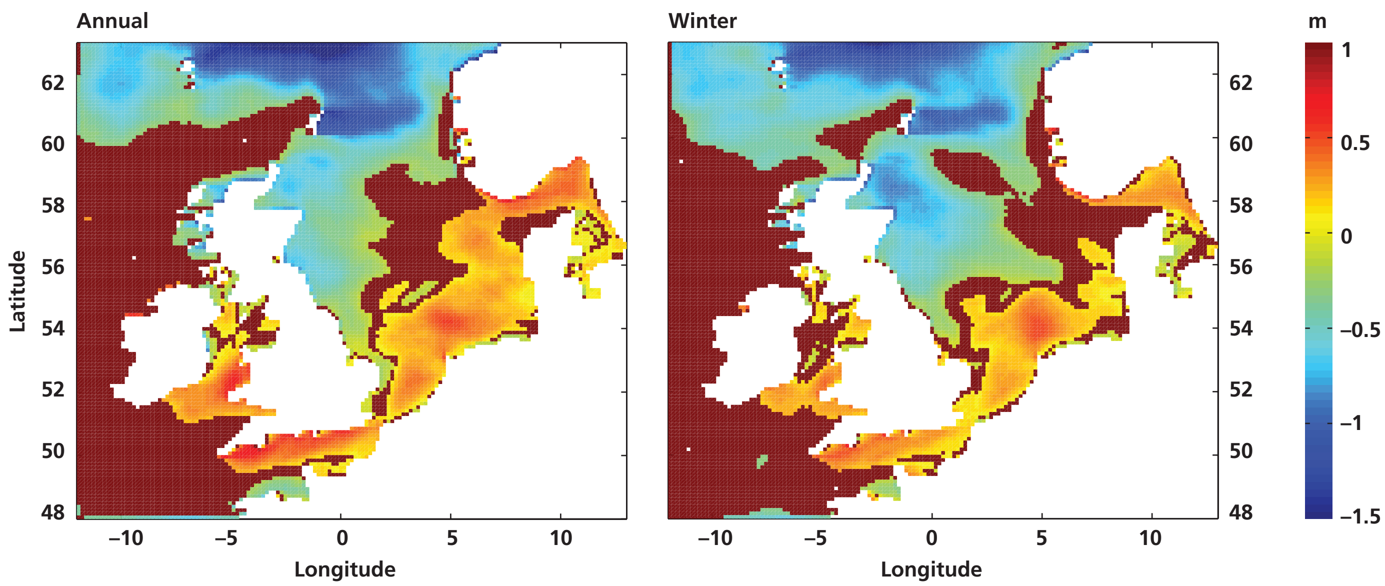


The changes in the annual maximum SWH reflect changes in the winter maximum, as expected, and show a similar spatial pattern to changes in the winter mean. The English Channel and the southern North Sea experience positive changes in wave-height, with a transition to negative changes in the NW Approaches and the northern North Sea. Projections of longer return period wave heights will reflect the same pattern but with larger error bars.

In another approach a generalized extreme value (GEV) distribution is fitted to the r-largest SWH events per year. For each point in the model domain, the top 10 independent events in each year are taken. This probability distribution has three parameters, termed scale, shape and location. By fitting different types of GEV models, the statistical significance of any trends in the extreme values can be evaluated. Based on the approach of Coles (2001), two different GEV models are fitted to the data. The first is the model where the location parameter is constant with time, and the second is one where the location parameter is a linear function of time. By comparing the maximum log-likelihood of the fit of these models to the data, statistical significance of any trends can be detected. The statistical extreme value analysis and significance tests are similar to those discussed in Chapter 4. There is no significant trend at any station except K7 where the trend from the GEV is found to be –0.3 cm/yr. The areas of no significant trend are similar to those identified in Figure 5.10.

The uncertainty in the future projections is explored further by examining the changes in wave height in two of the PPE members, which represent low and high climate model sensitivity. The equivalent plots are shown in Figures 5.11 and 5.12. In Figure 5.11, for the low sensitivity ensemble member, we see the winter and spring pattern of changes to be similar to the mid sensitivity case, with a larger increase in wave height to the south of the UK and an increase in wave height in the SW Approaches. In summer the latitudinal pattern is reversed with a slight reduction in wave height to the SW and an increase to the north and in the North Sea. In autumn there is an increase in wave height almost

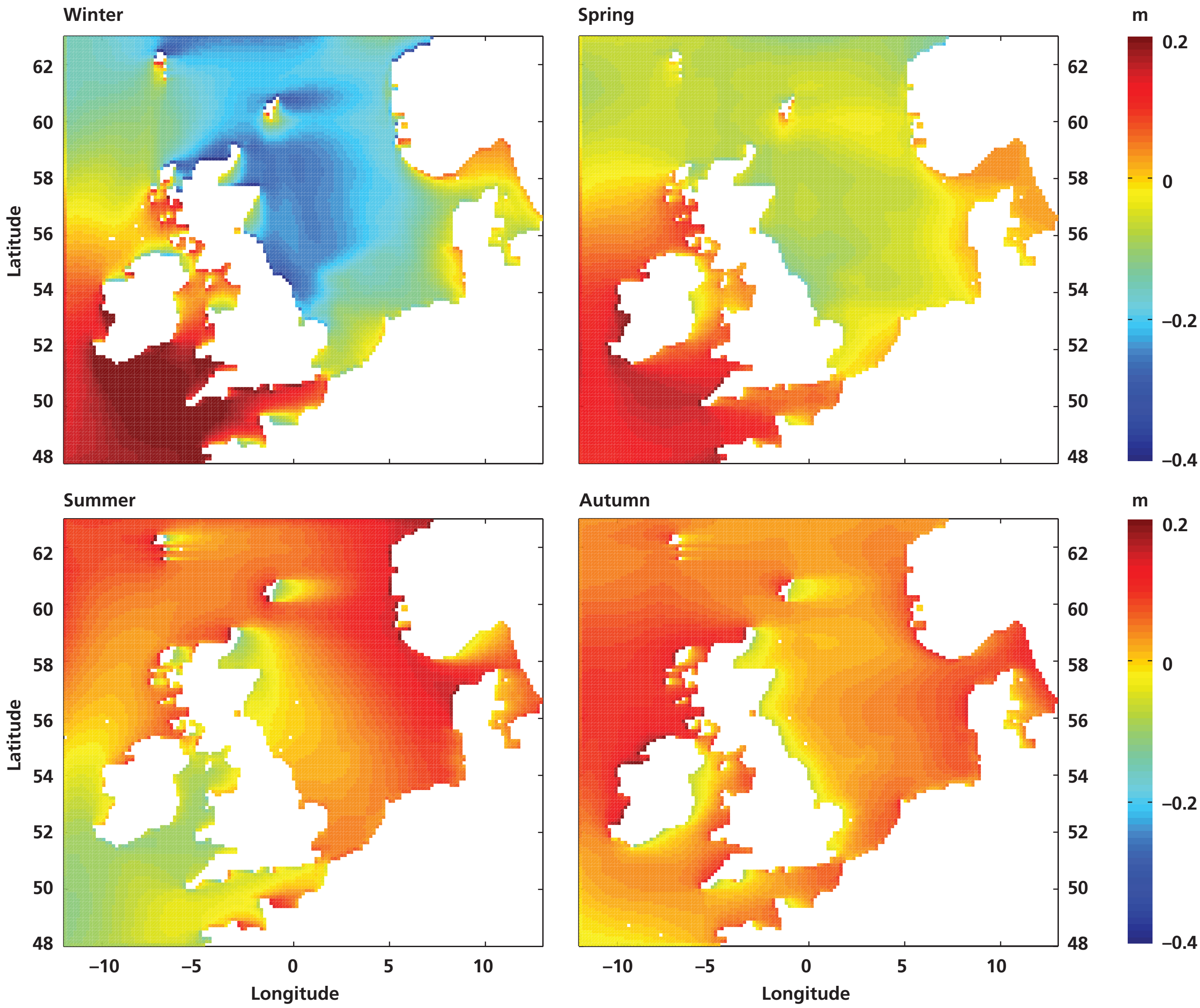
Figure 5.10: Changes in mean annual and winter maxima of SWH from 1960–1990 to 2070–2100. Left panel is mean annual maxima and right panel is mean winter (DJF) maxima. Areas that are masked out (dark red) are points where the differences are statistically insignificant at the 95th percentile level.



everywhere except on east-facing coasts, suggesting these increases are due to an intensification of westerly winds. The results for the high sensitivity ensemble member in Figure 5.12 show quite different results although there is a latitudinal variation similar to Figure 5.8. We still see the reduction in winter wave height to the north of the UK. Increases of winter mean wave height are quite localised on the south coast of the UK and Ireland. The autumn increase of wave height to the NW has disappeared.

Figure 5.13 shows the differences in mean winter and mean annual maxima for the three ensemble members. The pattern is similar in all cases and consistent with the changes in mean winter SWH with a reduction to the north of Scotland and an increase to the south and SW of England. However there is substantial variation between the ensemble members with the largest changes in maximum SWH occurring in the ow sensitivity case.

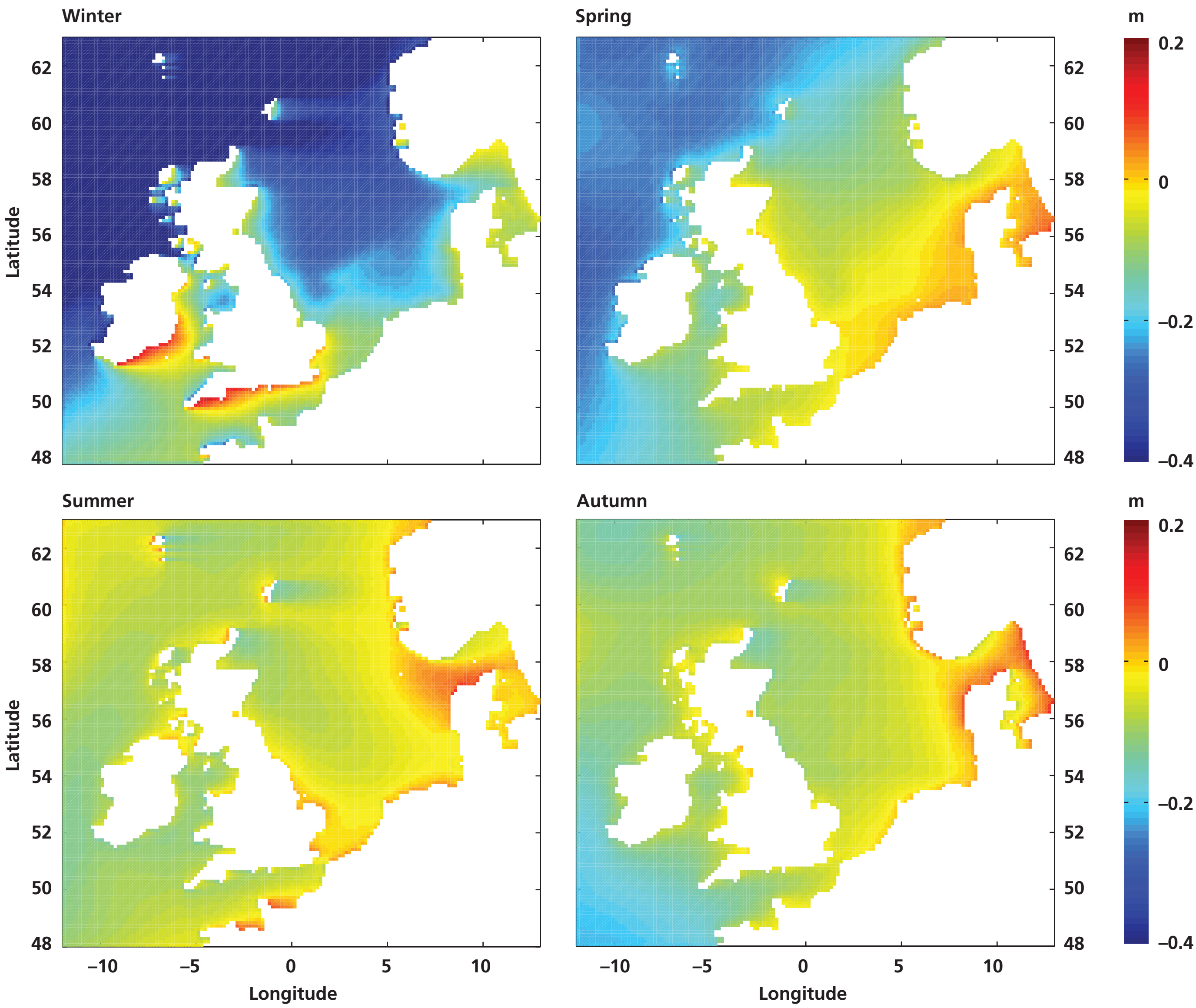
Figure 5.11: Changes in seasonal means of SWH (in metres) from 1960–1990 to 2070–2100. As for Figure 5.8, for low sensitivity ensemble member.



It is difficult to interpret details of these patterns without further knowledge of the changes in the wind patterns which are occurring in the climate model. There may be a change in the prevalence of high and low pressure systems, storm tracks may shift in latitude and become more or less intense. The effect on waves is an integration of the effects of wind speed, fetch and duration. Further work is needed to understand these results fully and they only represent a limited sample of the climate model sensitivity as only the unperturbed plus two perturbed ensemble members are used. These samples serve to illustrate qualitatively the amount of uncertainty in future projections.

Other wave parameters can be examined, e.g. mean wave period, Tm02, although the interpretation of any changes is more difficult. Only the results for the mid sensitivity PPE forcing are examined. In Figure 5.14 the winter mean and maximum wave period for the present day are plotted in the left column,

Figure 5.12: Changes in seasonal means of SWH (in metres) from 1960–1990 to 2070–2100. As for Figure 5.8, for high sensitivity ensemble member.



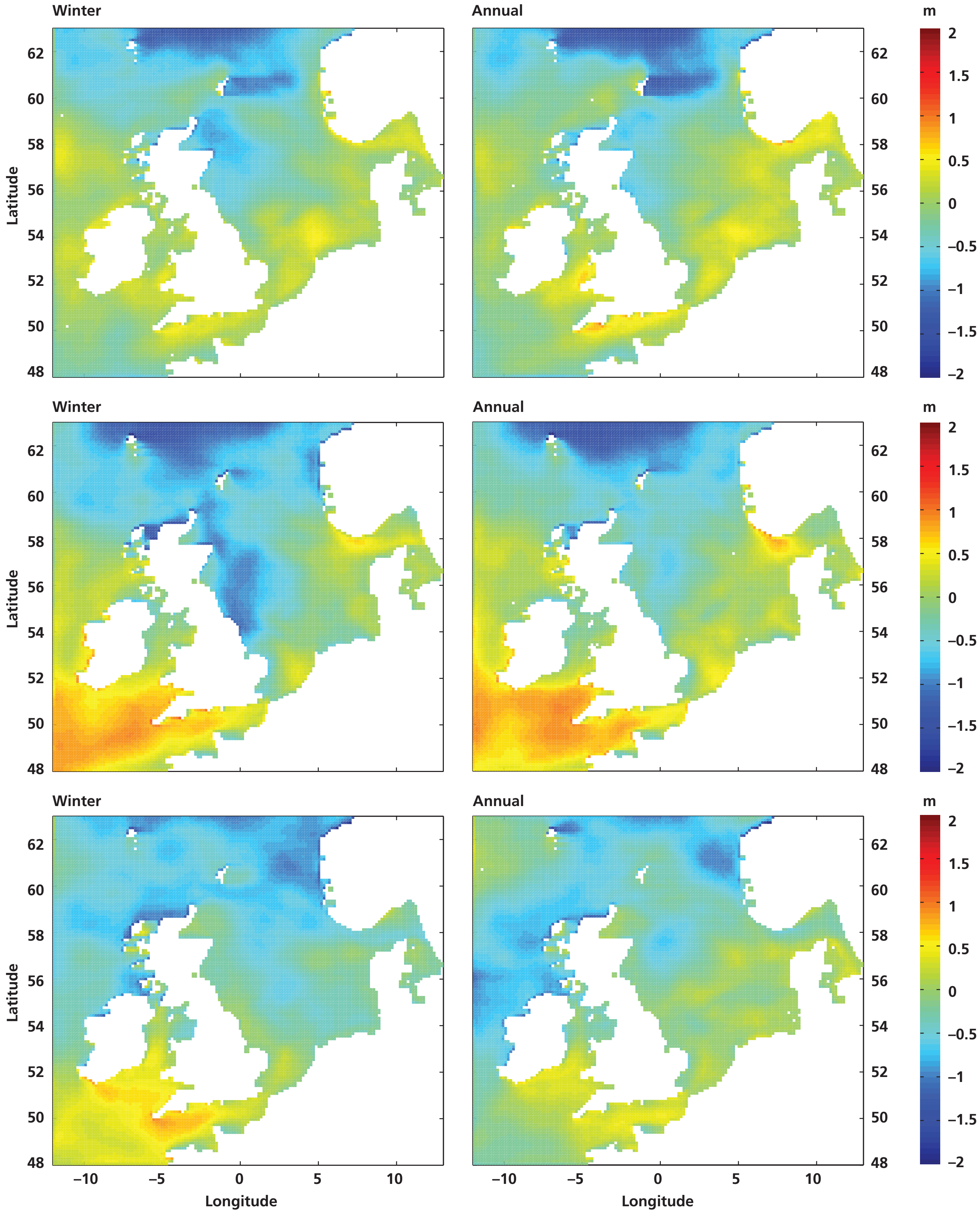
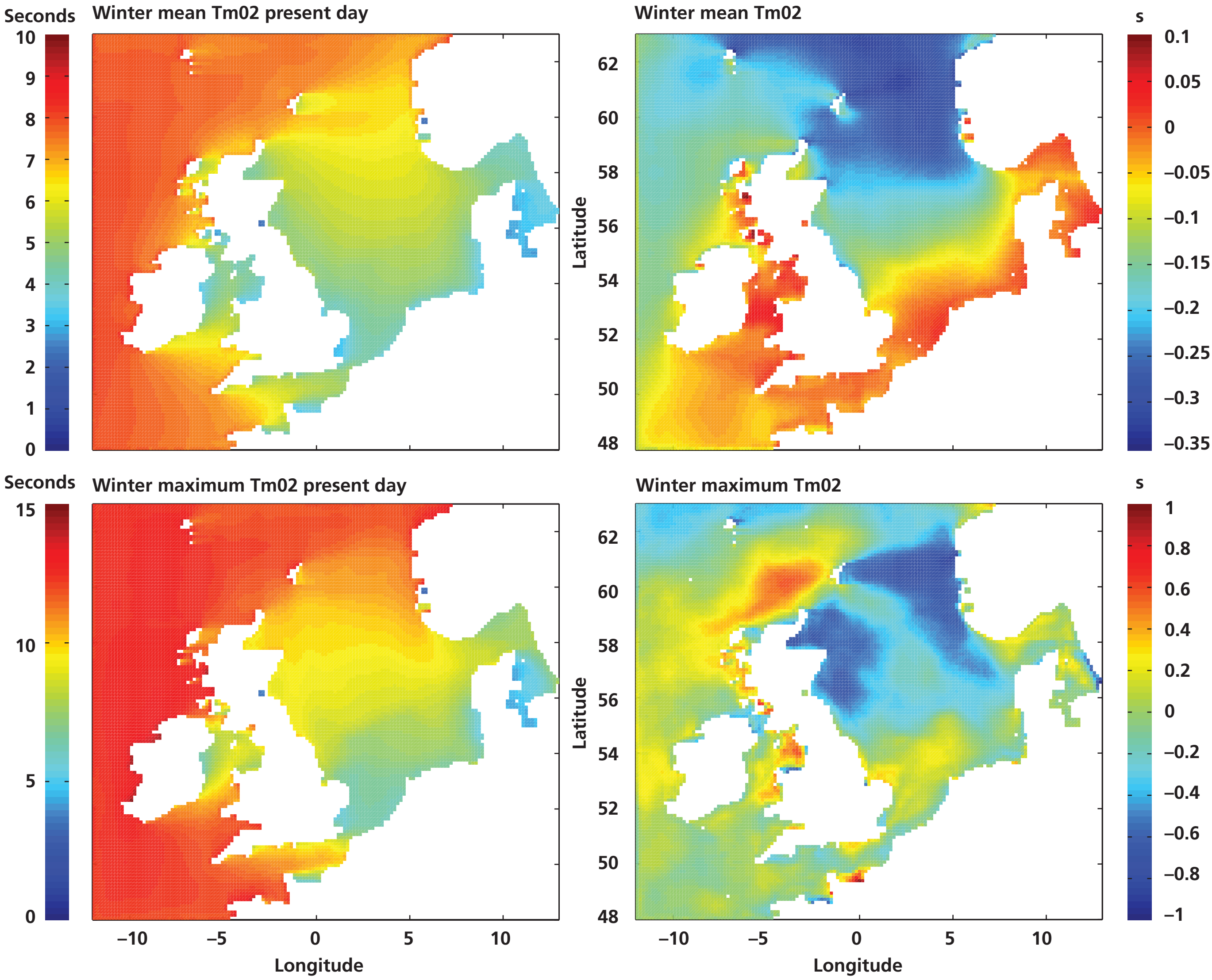


Figure 5.13: Changes in mean winter maximum SWH (left column) and mean annual maximum SWH (right column) (in metres) from 1960–1990 to 2070–2100. Top row is mid sensitivity ensemble member, middle row is low sensitivity and bottom row high sensitivity member.

with differences in the right column. Longer wave periods are seen to the west and north of the UK due to the longer fetch in these areas. The projected future changes show an increase in the mean to the south and a decrease to the north, while the maximum wave period increases to the west and north of the UK and is reduced to the east especially in the northern North Sea, but these changes are quite small (maximum ± 1 s).

Figure 5.15 shows the frequency distribution of wave directions plotted as a wave rose for four locations around the UK (as in map in Figure 5.9(a) for the present-day and future wave climate. At K7 and to a lesser extent at Seven Stones there are more waves from the SW in the future scenario, whereas in the North Sea there are more waves from the north although the main characteristics of the distribution remain similar to the present.

Figure 5.14: Changes in mean winter Tm02 (top right panel) and mean winter maximum Tm02 (bottom right panel) (in metres) from 1960–1990 to 2070–2100. Left panels show present day.



5.5 Conclusions

The wave model results presented in this chapter clearly show the existence of some skill in the climate model-wave model system. Furthermore, the projections of the future suggest some significant changes in wave climate around the UK by 2100. The main, statistically significant, result, based on a mid climate sensitivity version of the Met Office wind forcing for a medium emissions scenario, is that there is a projected increase in winter wave heights to the S and SW of the UK for both mean and extreme wave heights and a reduction in wave height to the north of the UK. Changes in the winter mean wave height are projected to be between –35 and +5 cm. Changes in the annual maxima are projected to be between –1.5 and +1 m. Changes in wave period and direction are rather small and more difficult to interpret. Further work is needed to fully interpret the wave projections in the light of changes in weather patterns from the climate model results.

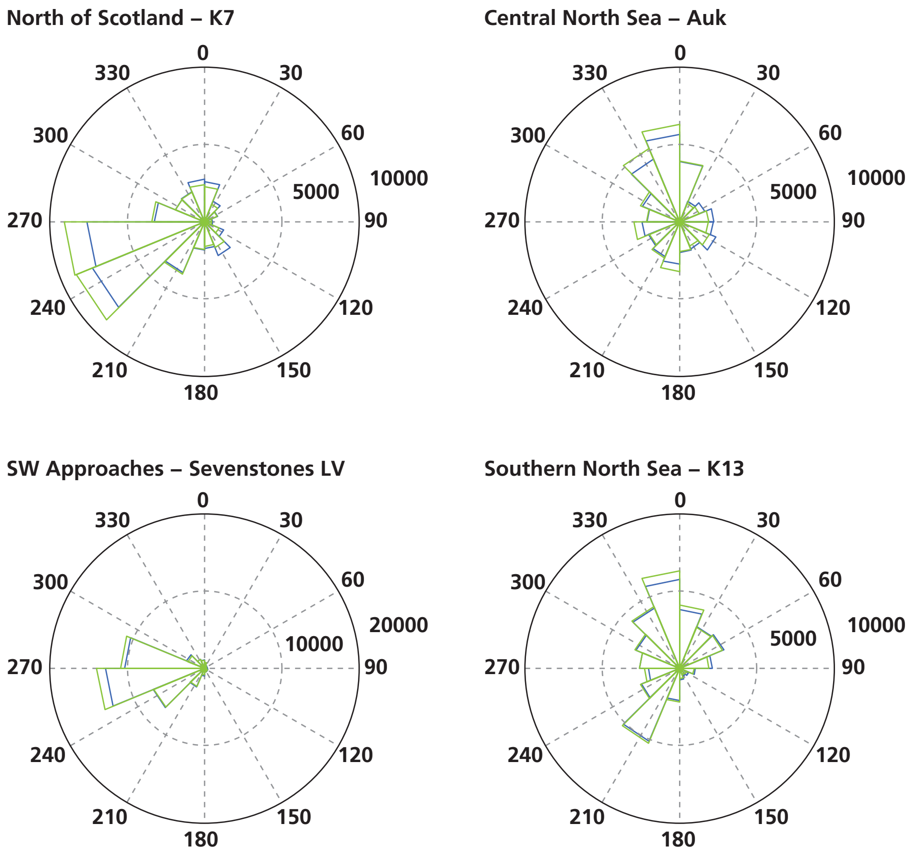


Figure 5.15: Changes in mean wave ('from') direction at four locations around the UK. Top left is to the north of Scotland, top right is the central North Sea, bottom left SW Approaches and bottom right the southern North Sea. Blue shows the present day and green the future climate projection (mid sensitivity ensemble member).

5.6 References

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6 Potential changes in the hydrography and circulation of the northwest European continental shelf

This chapter describes model projections of changes to water temperature, salinity, the stability of the water column and currents around the UK. The results are obtained by using one member of the Met Office Hadley Centre regional model ensemble (known as the PPE) to provide the meteorological forcing for the Proudman Oceanographic Laboratory Coastal Ocean Modelling System. Results are presented for the time periods 1961–1990 and 2070–2098. Future projections are for the medium emissions scenario.

As the techniques employed here are new, no attempt has yet been made to incorporate uncertainty into the future projections. Instead the single scenario provides a physically plausible illustration of one future that might be realised under the medium emissions scenario. Additional work is needed before we can estimate the range of uncertainty in future changes.

Key Findings

- **The seas around the UK are projected to be 1.5–4 °C warmer, depending on location, and ~0.2 p.s.u. fresher by the end of the 21st century. The change in salinity is particularly dependent on the projected change in the storm tracks owing to the latter's effect on precipitation.**

- **Seasonal stratification strength is projected to increase but not by as much as in the open ocean.**

- **This stratification is projected to start ~5 days earlier and breakdown ~5–10 days later each year, hence extending the stratified period.**

- **Changes in the open ocean (especially the circulation) are particularly uncertain due to the proximity of the model boundary.**

6.1 Introduction

There is already substantial evidence for the warming of the shallow seas of the northwest European shelf over the past decades based on analysis of satellite radiometer data (e.g. Gomez-Gesteira *et al*. 2008) and long term monitoring of point time-series and repeat sections (Hughes and Holliday, 2006; van Leussen *et al*. 1996). Trends in the salinity are less clear, but the evidence suggests a freshening to a minimum in the 1980s–1990s followed by an increase in salinity after that (Evans *et al*. 2003; Holliday *et al*. 2008a). However, year-to-year variations tend to dominate the salinity variability.

Here we use a numerical model to investigate how climate forcing late in the 21st century might influence the hydrography and circulation of the northwest European continental shelf seas. Particular emphasis is placed on the surface and near sea bed temperature and salinity, the stability of the water column, and the volume transports across a number of key sections shown on Figure 6.1. The future period of interest is 2070–2098 and is compared with conditions typical of 1961–1990, the UKCP09 baseline.

Investigations of climate change impacts on the hydrography and circulation of shelf seas are at an early stage of development. Hence, the conclusions reached here are tentative, exploring possibilities rather than trying to make precise predictions. As a first look, we have limited our investigation to the two time periods mentioned above. The scenario forcing is derived from the Met Office Hadley Centre Regional Climate model (RCM), which in turn is forced by a mid climate sensitivity member of the coupled global climate model PPE ensemble (specifically the unperturbed member) using the UKCP09 Medium Emissions Scenario (SRES A1B). However, we anticipate that further simulations will be carried out using a range of ensemble members to better quantify uncertainty, in a similar way to that used for investigating coastal flooding by storm surges. The experimental set-up of the driving RCM is described more fully in Chapter 2.

6.1.1 Mechanisms for climatic influence on shelf seas

Atmospheric, oceanic and riverine forcing all have a role in controlling the temperature, salinity and circulation of shelf seas. Atmospheric forcing is in the form of surface fluxes of heat, momentum and freshwater, and horizontal gradients in the atmospheric pressure. Since about 90% of the extra heat trapped in the climate system (by anthropogenic greenhouse gas emissions) is contained in the ocean (IPCC, 2007, Chapter 5), it is natural to expect significant temperature changes in seas over the next 100 yr.

The spatial distribution of temperature on the northwest European continental shelf is to a large extent determined by the effects of vertical mixing processes on the water column, with horizontal heat transport playing a more minor role (this is quantified below). Features of particular importance in tidally active seas are the seasonal thermal stratification and the formation of tidal mixing fronts. Thermal stratification arises where tidal and wind generated turbulence is insufficiently energetic to vertically mix an otherwise stable column. Tidal mixing fronts occur at the boundaries of areas where this vertical mixing can occur. Where the water column remains stratified, the deeper part of the water column remains close to the winter temperature while the upper part of the column warms rapidly under summer heating conditions (Figure 6.2 shows an example of this). The stratification of the column breaks down in the late autumn with increased wind and convective mixing. Given that the whole water column is in rapid communication with the atmosphere for a large fraction of the year, simply increasing the air temperature will not necessarily lead to an increase in the summer time stratification (as might be expected for the open ocean where temperatures at large depth change on centennial rather than seasonal time scales). In the case of shallow seas the variation of stratification is dependent on changes in the relative surface heat flux between winter and summer. In addition, the non-linear dependence of the water density on temperature plays a role.

The salinity distribution of shelf seas is primarily determined by the balance between inputs of fresh river water and saline oceanic water. The surface forcing (precipitation and evaporation) plays a role in setting the overall salinity budget and large scale gradients. Changes in precipitation not only affect the salinity budget but also the salinity component of the vertical density structure. This can play a significant role in pre-conditioning the vertical density structure and influence the onset of thermal stratification. In contrast, river discharges can have a dramatic effect on near-coastal regions (up to ~20 km from the coast), introducing large variations of salinity over short time scales (hours to weeks). Hence, changes in runoff (from precipitation over land) would be expected to have a large effect on near coastal salinity, stratification and currents. On a larger scale the combined effect of river discharges is to generate coastal currents (e.g. the Norwegian Coastal Current), which can form a substantial part of the circulation of shelf seas.

The basin-scale oceans influence the coastal seas through the impingement of larger scale currents onto the shelf and a number of smaller scale processes that mediate the ocean-shelf exchange (Huthnance, 1995). Because of the tendency for large scale ocean currents to flow around steep topography, rather than crossing onto the continental shelf, the northwest European shelf can be seen as a quasi-isolated system on time scales of ~1 yr (Wakelin *et al*. 2009). This is particularly applicable to properties that are strongly constrained by surface forcing, most notably the temperature field. In this case, where the transit time across the shelf is slow compared with the seasonal cycle, temperature fluctuations arising from variability in the open ocean temperature are generally lost. In contrast, there is no direct feedback between the surface salinity and the atmosphere, so the salinity field is highly dependent on the exchange of water with the open ocean (Huthnance, 1997).

In many shelf seas, tides provide the most energetic process for transport and mixing. These are determined by well established astronomical forces and by the bathymetry and coast line (changes in these are not considered here). In open shelf seas, tidal conditions might be expected to change only very slowly and hence tidal mixing has the potential to limit some of the effects of varying atmospheric forcing. For example, the locations of tidal mixing fronts are largely insensitive to the details of the atmospheric forcing (Young and Holt, 2007) and are not expected to change greatly under future climate conditions.

6.2 Methodology

Here we describe the set-up of the shelf sea model and validation of its simulation when driven by a climate model for near present day conditions. The climate model is the downscaled version of the unperturbed mid climate sensitivity member of the PPE and is more fully described in Chapter 2.

6.2.1 The shelf sea model

The Atlantic Margin (AMM) application of the Proudman Oceanographic Laboratory Coastal Ocean Modelling System (POLCOMS; Holt and James, 2001) has been run operationally by the UK Met Office since 2002,* using a 1/9° latitude by 1/6° longitude grid (~12 km) with 34 levels in the vertical (Wakelin *et al*. 2009). In the present study this model is modified to accommodate

* http://www.metoffice.gov.uk/research/ncof/shelf/browser.html

forcing by the RCM; specifically the domain is reduced to that shown in Figure 6.1. The model simulations are then forced in a similar fashion to those in the operational implementation. Three-hourly surface winds and pressure are used to drive the dynamics and 6-hourly turbulent and radiative heat fluxes together with precipitation and evaporation provide surface temperature and salinity boundary conditions (these turbulent heat fluxes are adjusted to take account of the difference between the RCM sea surface temperature and the model SST). Lateral open boundary conditions of temperature, salinity and residual depth mean currents and sea surface height are derived from a mean annual cycle of a 40-yr (1960–1999) simulation of the AMM model. Fifteen tidal constituents from a North Atlantic tidal model are also used in boundary conditions. Freshwater discharges from the rivers flowing into this region are taken from a hydrological model (run at the Centre for Ecology and Hydrology; Bell *et al*. 2007) forced by the same RCM simulation as used for these shelf sea simulations. In these experiments the exchange with the Baltic is treated as a simple freshwater inflow based on a mean annual cycle. No account is made for changes in this exchange under future climate conditions. Given the pattern of circulation in the North Sea this is unlikely to significantly affect the results across most of the on-shelf area. However, it may have a more significant impact around the coast of Norway, which is downstream of the Baltic.

Three model experiments using the same shelf sea model are considered here forced by both Met Office regional climate model data and European centre for medium-range weather forecasting (ECMWF) re-analysis data:

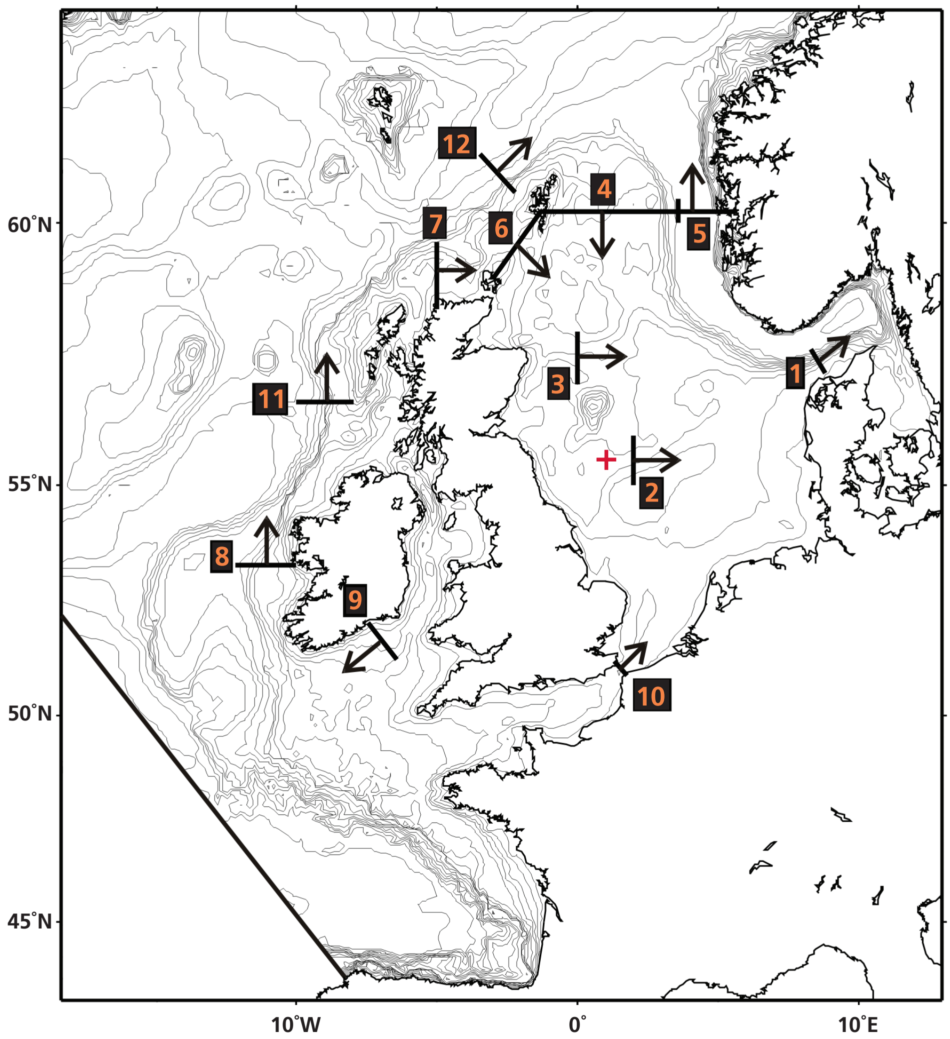


Figure 6.1: Model domain, bathymetry; sections used for flux calculations and location of time series in Figure 6.2 (marked by +).

1. RCM-P Recent past 1961–1990 Met Office RCM forcing
2. RCM-F Future scenario 2070–2098 Met Office RCM forcing
3. ERA-P Recent past 1961–1990 EWMWF ERA-40 forcing

In the recent past experiments (RCM-P and ERA-P) the shelf sea model is initialised from rest with a present day temperature and salinity climatological initial condition. For the future scenario experiment (RCM-F) a mean depth profile of the change in ocean temperature and salinity between the future period and the simulated past is added to the shelf sea initial conditions and the boundary

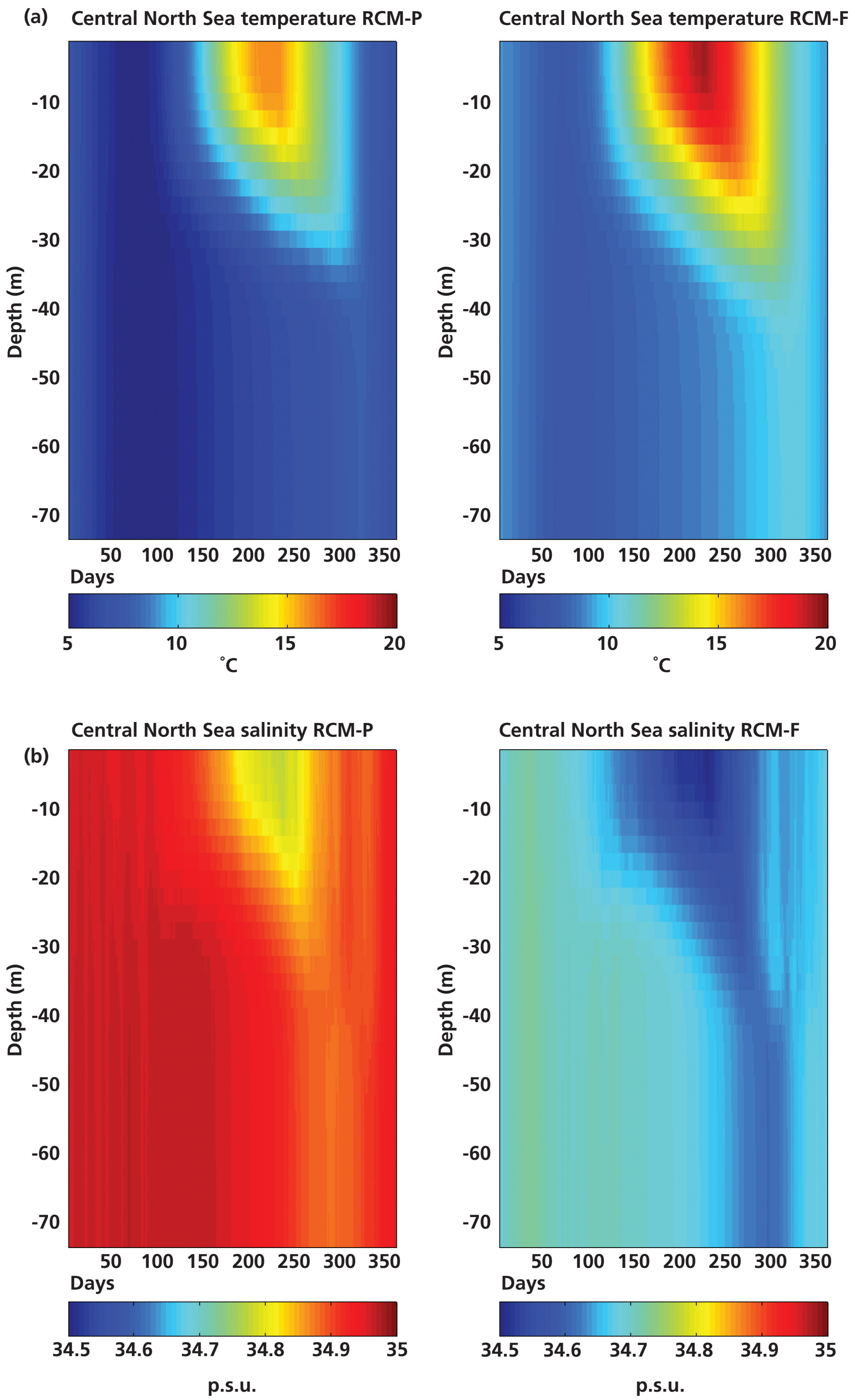


Figure 6.2: Mean annual cycle times series of temperature (a) and salinity (b) profiles in the central North Sea from RCM-P (left) and RCM-F (right). The *x* axis of these plots shows the day of the year starting on 1 January. Each profile shows the seasonal cycle stratification, with an onset in spring due to increased heating and a breakdown in autumn with increased mixing from storms and surface cooling.

conditions described above. This profile is taken from the ocean component of the global scale coupled PPE member used here. In both cases a single year spin-up is carried out (and discarded). The reanalysis forced experiment serves as a guide to the validation process and as to how well the RCM forced shelf sea model reproduces recent past conditions.

6.2.2 Model validation

The hydrography of the RCM-P near present day simulation is validated using temperature and salinity observations from the ICES data base.* Approximately 200,000 profiles are available in the region considered here for the period 1960–2005. Previous validation of POLCOMS hindcast simulations has focused on comparisons of model and observations co-located in space and time (e.g. Holt *et al*. 2005). A direct comparison such as this is not possible for the climate model forced simulations because of natural variability. Hence, the approach adopted here is to average observed data from each month onto the model grid and compare this with the corresponding average values for that month from the model. This provides a gridded (but not interpolated) monthly comparison between the model and observed temperature and salinity; an identical approach is used for RCM-P and ERA-P. Values for surface and near bed temperature and salinity are considered here. Example fields (surface temperature and salinity for June) are shown in Figure 6.3. This demonstrates the coverage of data available for validation, being particularly concentrated in the North Sea with only sparse coverage in the Celtic Sea and open ocean regions of the model.

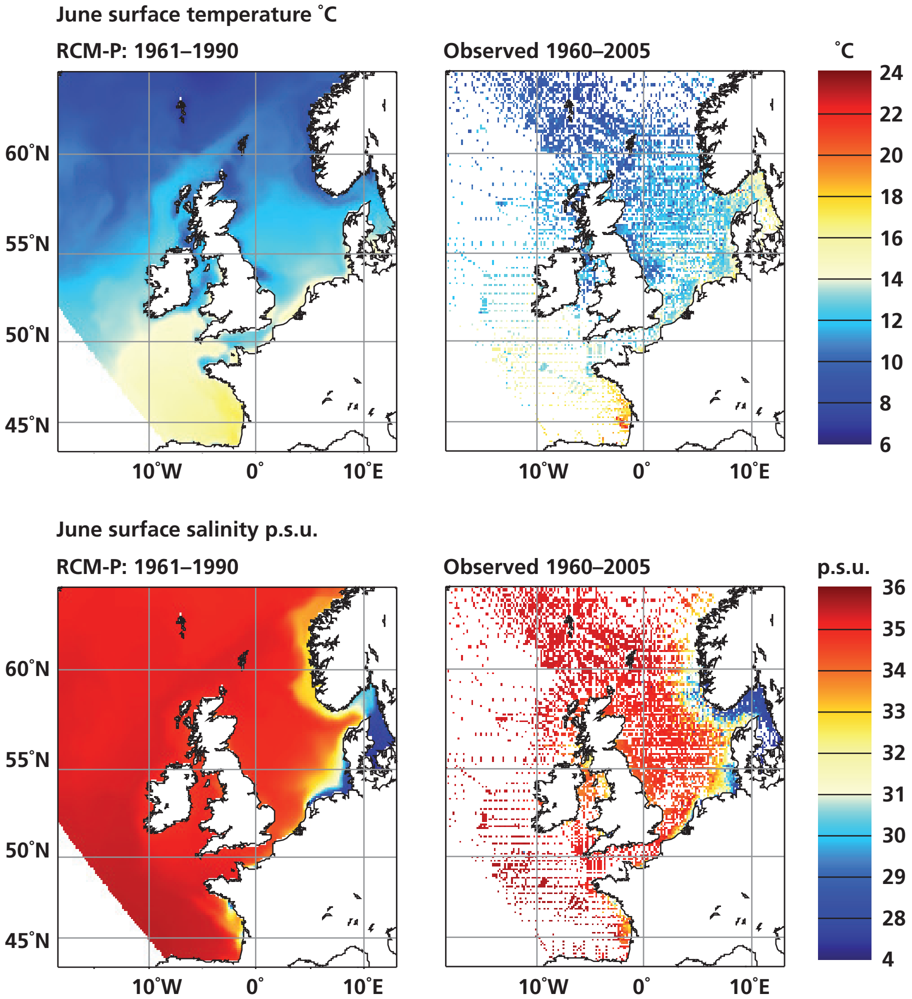


Figure 6.3: Contrast between model (RCM-P; left) and observed (right) June surface temperature and salinity. For the analysis, the available data for this month has been averaged onto the individual 12 x 12 km model grid cells. White cells indicated no available data.

* http://www.ices.dk/ocean/aspx/HydChem/HydChem.aspx

The similarity of the patterns seen in Figure 6.3 is promising; spatial correlations are typically R^2~0.7 for temperature and R^2~0.8 for salinity. However, a more detailed examination over three water column depth ranges (depth classes D1: 600 > *H* > 200 m, D2: 200 > *H* > 40 m, D3: *H* < 40 m) reveals some key differences.

Both the RCM-P and the ERA-P simulations show a negative surface temperature bias (model too cold). The root-mean-square (RMS) errors in temperature show little seasonality or variation between water depth classes (being 1.3 °C for ERA-P and 1.5 °C for RCM-P); although the open shelf regions (water column depth class D2) is generally the most accurately modelled (1.0 °C for ERA-P and 1.3 °C for RCM-P). The salinity errors also show little seasonality, but here there is a marked variation with depth class. The model generally shows a positive bias (model too saline) in surface salinity (of 0.5 p.s.u.* for ERA-P and 0.4 p.s.u. for RCM-P) and a negative bias in near sea bed salinity (of -0.3 p.s.u. for ERA-P and -0.7 p.s.u. for RCM-P). In deeper water this arises from excessive mixing. Again the open shelf water column regions have the smallest RMS errors, ~0.7 p.s.u. for both experiments. The shallowest water column regions (class D3) show substantially increased RMS error (2.6 p.s.u. for both experiments), but are no more biased than the deeper water regions (clases D1 and D2). This reflects the much higher degree of salinity variation in the shallow coastal regions, and when these errors are normalized by the (spatial) standard deviation of the observations, the salinity in near coastal regions is seen to be better modelled (relative to the variability here) than in other depth classes. Generally surface salinities and surface temperatures are well modelled, near bed temperatures less so and near bed salinities need to be treated with some caution.

In most cases the experiment RCM-P gives marginally poorer results than ERA-P, in terms of RMS error and also some significant increases in bias. The model errors relative to observations seen in this comparison are similar to those seen in several other assessments of operational model or re-analysis forced simulations (discussed in Holt *et al*. 2005). This indicates that the nature of the forcing considered here (climate model instead of weather forecast model) does not unduly compromise the simulation (some biases accepted), but rather that RCM-P is subject to similar uncertainties in the forcing fields as previous simulations, e.g. in the heat flux and vertical turbulence parameterisations (see Holt and Umlauf, 2008).

From this evaluation we can conclude that whilst there are some differences between RCM-P and observations, the modelling system does demonstrate some skill at simulating the shelf sea variables of interest.

6.3 Projected changes in temperature and salinity

Since the 1980s the sea surface temperature of the seas around the UK have risen at a rate of about 0.2–0.6 °C, and seven of the warmest years in UK coastal waters since records began in 1870 have occurred in the last decade (MCCIP, 2008). The model simulations considered here allow us to explore how the currently observed warming trend in the shelf seas (Holliday *et al*. 2008b) might evolve during the 21st century. The seasonal** mean sea surface temperatures (Figure 6.4) show a substantial warming between RCM-P (1961–1990) and RCM-F

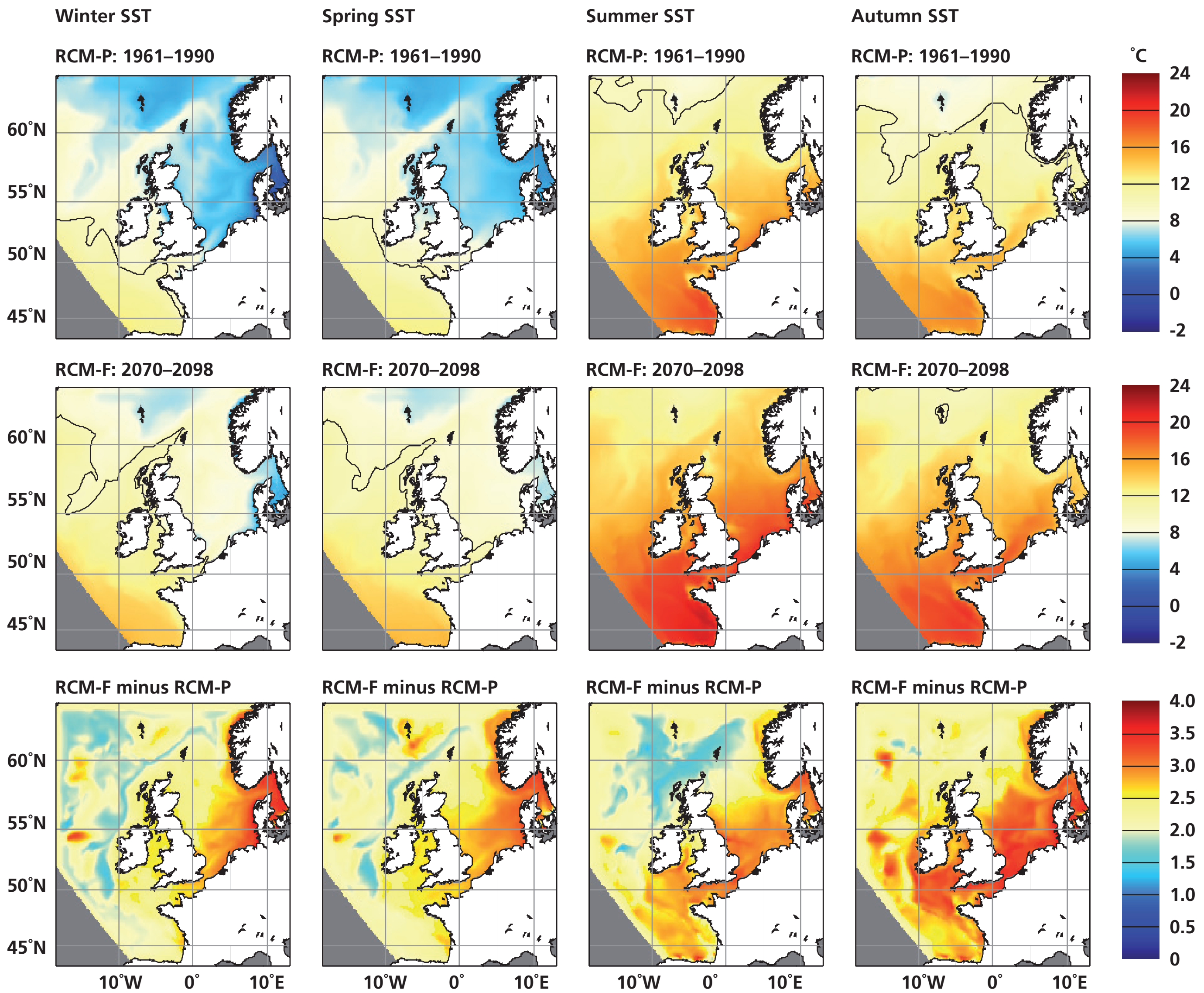
* By convention salinity is correctly shown with no units, but for clarity we note salinity with practical salinity units (p.s.u.).

** Seasons are defined: winter is December to February; spring is March to May; summer is June to August; and autumn is September to November.

(2070–2098) throughout the year with considerable regional variability. In the open ocean, shelf edge regions and northern North Sea, temperature increases throughout the year of ~1.5 –2.5°C are projected to occur. Larger increases of ~2.5–4 °C are projected for the Celtic, Irish and southern North Sea. The latter amounts to a trend of ~0.3 °C/decade, with increases generally being largest in the autumn. The changes in near bed temperature (Figure 6.5) graphically demonstrate how the whole of the water column on the shelf is affected by changes in atmospheric forcing, even in summer, in contrast to the deep ocean where only a small degree of warming is seen. The tidal mixing fronts are clearly seen by the distinction between cooler bottom water in stratified regions and warmer water in well mixed regions. The bottom water in seasonally stratified regions is warming less rapidly than the surface, with a consequent increase in this stratification, which is discussed in the next section.

A simple heat budget has be inferred by calculating the seasonal mean surface heat flux and the depth integrated change in heat by horizontal transport (the advective transport heat flux). The latter is not so meaningful in deep water so is masked at water depth greater than 500 m. Comparing the seasonal surface heat-flux and the transport heat-flux (Figure 6.6) demonstrates that, as is often

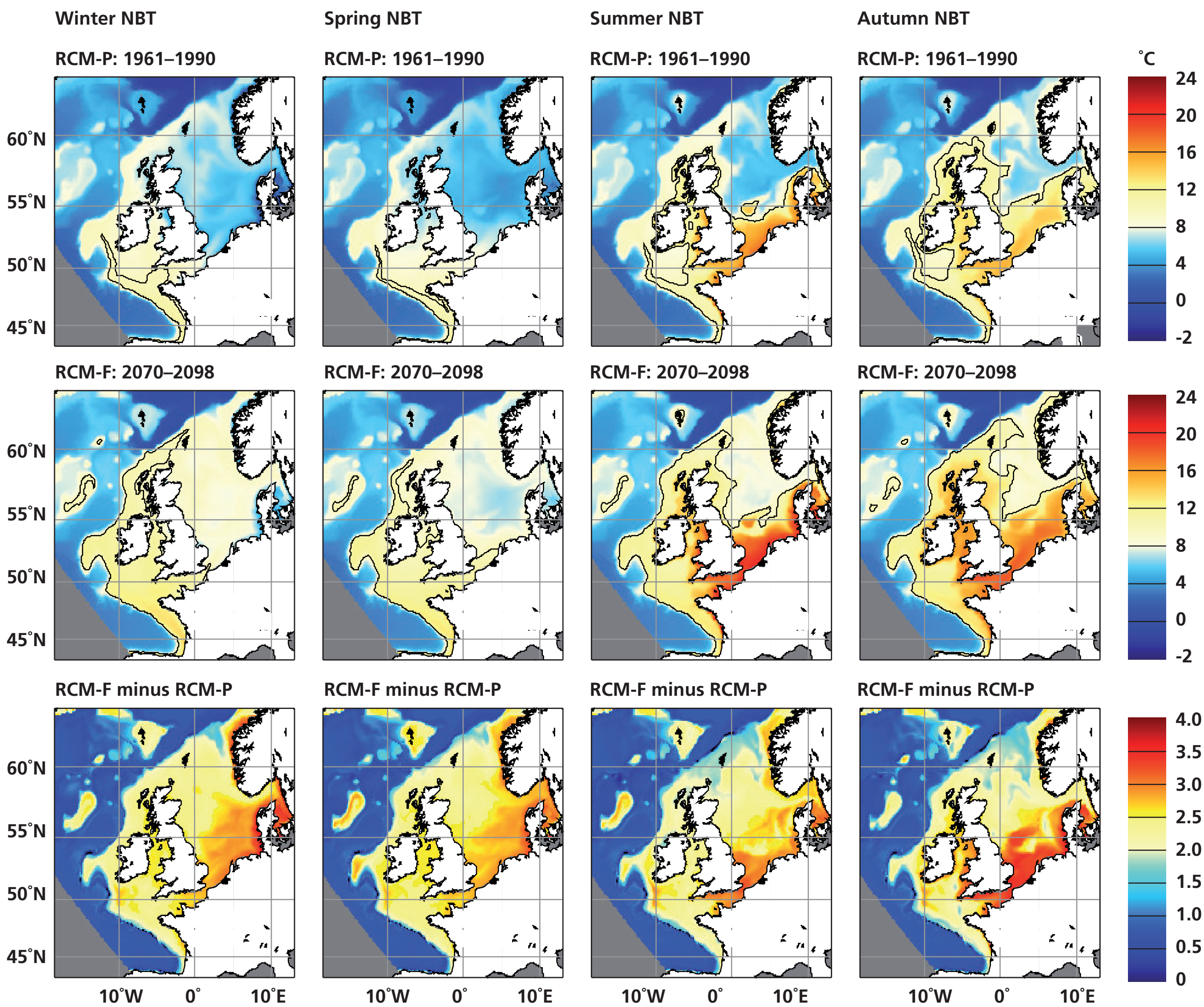
Figure 6.4: Seasonal mean sea surface (SST) temperature for RCM-P (1961–1990) and RCM-F (2070–2098) and the difference between them.



assumed, the former dominates. The transport term is relatively small but consistently warms the whole region. This quantifies, and to some extent belies, the common supposition that UK waters are warmed by the North Atlantic. For example, the Celtic Sea and most of the North Sea shows only small warming by horizontal heat transport throughout the year. The main region warmed by the transport heat-flux follows the shelf-edge current from Ireland, around west and north Scotland into the northern North Sea. Warmer water also enters the Norwegian trench (at depth) from the northeast Atlantic during the summer and autumn.

When the differences between the future (2070–2098) and past (1961–1990) model experiments are examined (Figure 6.7) they show the surface heat flux increases substantially more in the winter than the summer, particularly in the north of the region. The main change in the horizontal heat transport component is the reduction in the warming north of Scotland (except in Autumn), reflecting changes in the circulation. There are strong changes in the transport heat flux in the Norwegian Trench between RCM-P and RCM-F: an increase in winter and a reduction in summer and autumn. These experiments also show an increase in horizontal heat transport warming in the central North Sea.

Figure 6.5: Seasonal mean near bed temperature (NBT) for RCM-P (1961–1990) and RCM-F (2070–2098) and the difference between them. Note the strong gradients on the shelf in the summer arise from the difference between water that is well mixed (warmer) and stratified (cooler).



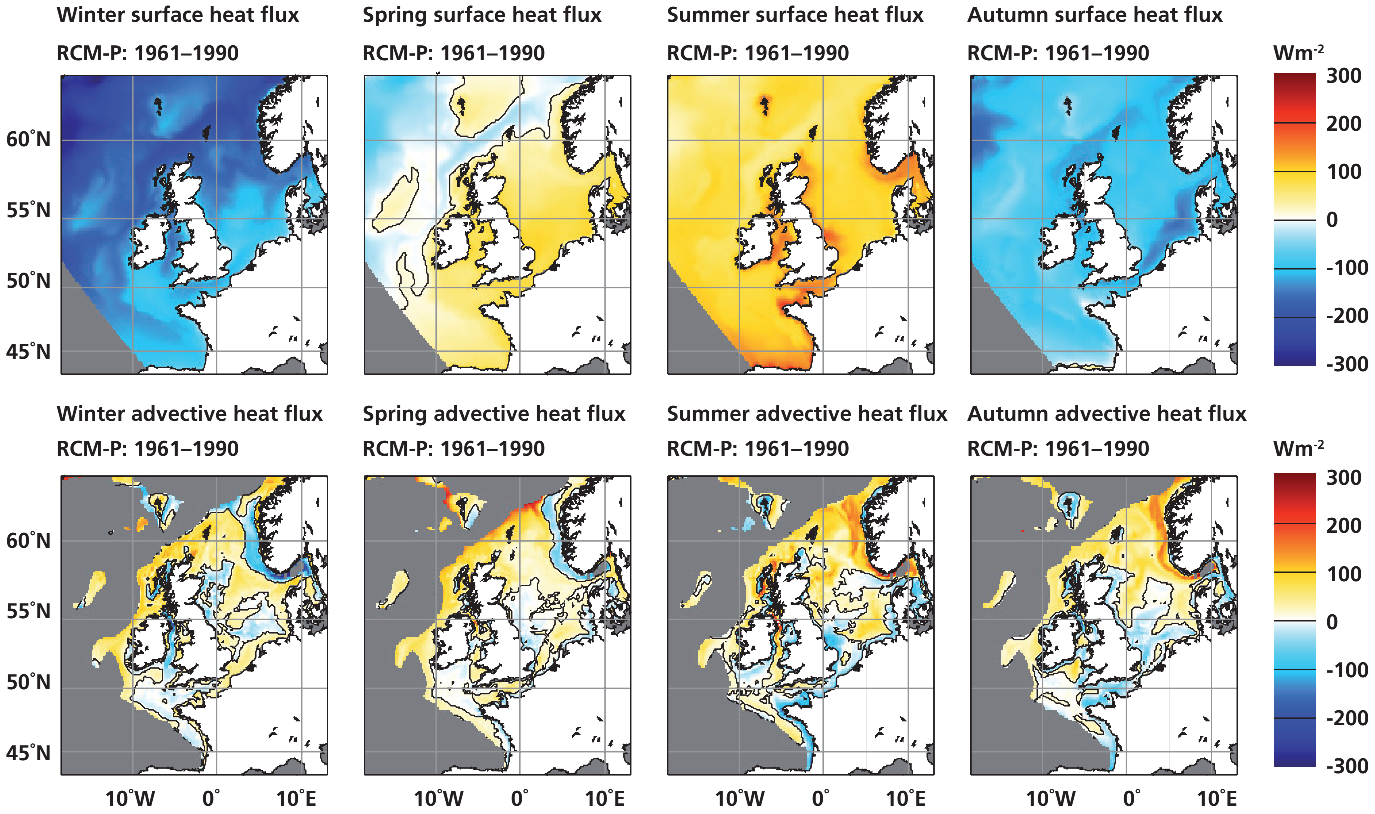


Figure 6.6: Seasonal heat-flux for the RCM-P (1961–1990) experiments: surface (top) and depth integrated horizontal transport heat flux (bottom). When the surface heat flux is positive the ocean is, on average, being heated by the atmosphere, when negative heat from the ocean provides a source of heat for the atmosphere.

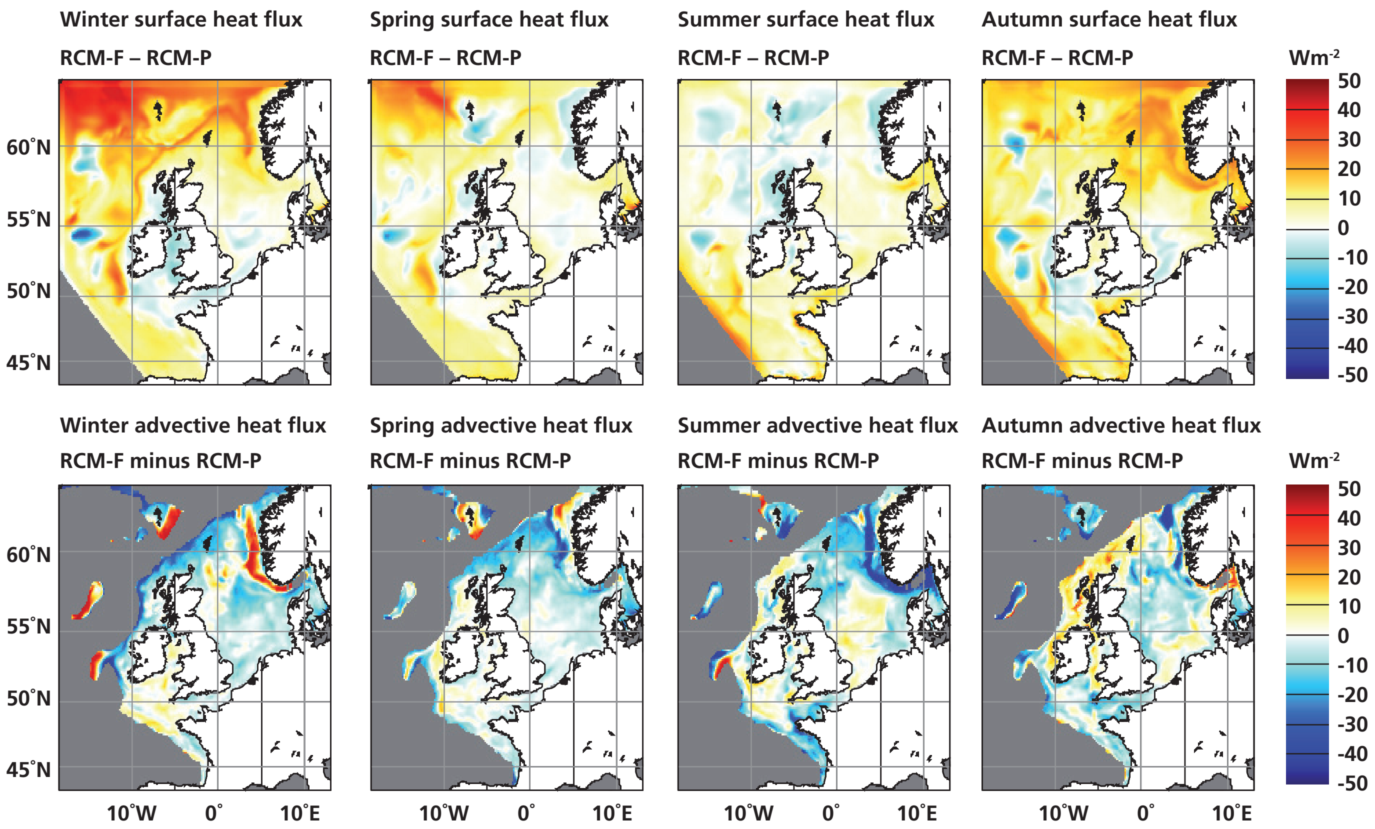
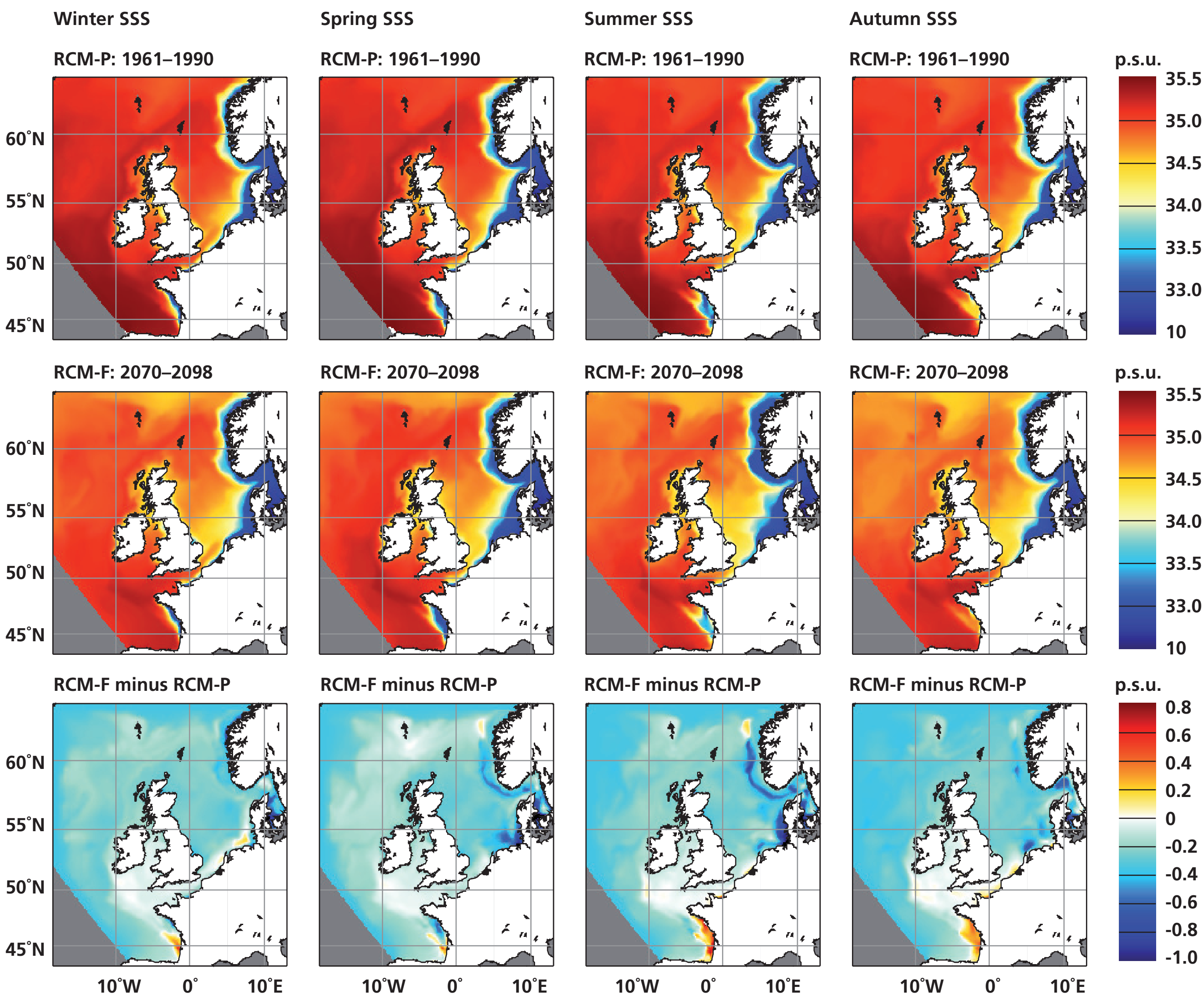


Figure 6.7: Change in seasonal heat-flux between RCM-F (2070–2098) and RCM-P (1961–1990): surface (top) and depth integrated horizontal transport heat flux (bottom).

The seasonal mean salinity (Figure 6.8) shows some substantial differences between RCM-P and RCM-F, particularly the freshening of the surface waters of the northeast Atlantic and the North Sea by ~0.2 p.s.u. In contrast, the Celtic and Irish Seas show a weaker change of ~0.1 p.s.u. The relative importance of the surface, riverine and oceanic forcing on the shelf sea salinity can be inferred from the steady-state salinity balance. The mean (on-shelf) salinity changes from 34.7 to 34.5 p.s.u. from RCM-P to RCM-F. This arises primarily from an increase in the precipitation minus evaporation term from 0.0074 Sv (1 Sv $=10^6\ m^3\ s^{-1}$) in the RCM-P to 0.009 Sv in the RCM-F compared to a smaller increase in river outflow from 0.0122 to 0.0126 Sv. There is also a reduction in the salinity of the oceanic water transported onto the shelf (also by ~0.2 p.s.u.), and a steady-state balance implies an associated volume flux of water from the open ocean onto the shelf of 1.3 Sv in RCM-P and 1.4 Sv in RCM-F. While the precise values depend on the details of the transport processes, this analysis demonstrates that changes in atmospheric and ocean salinity forcing dominate over changes in riverine forcing on the shelf scale. The same is unlikely to be true in the regions directly affected by the river outflow (e.g. ~20 km from the coast of continental Europe).

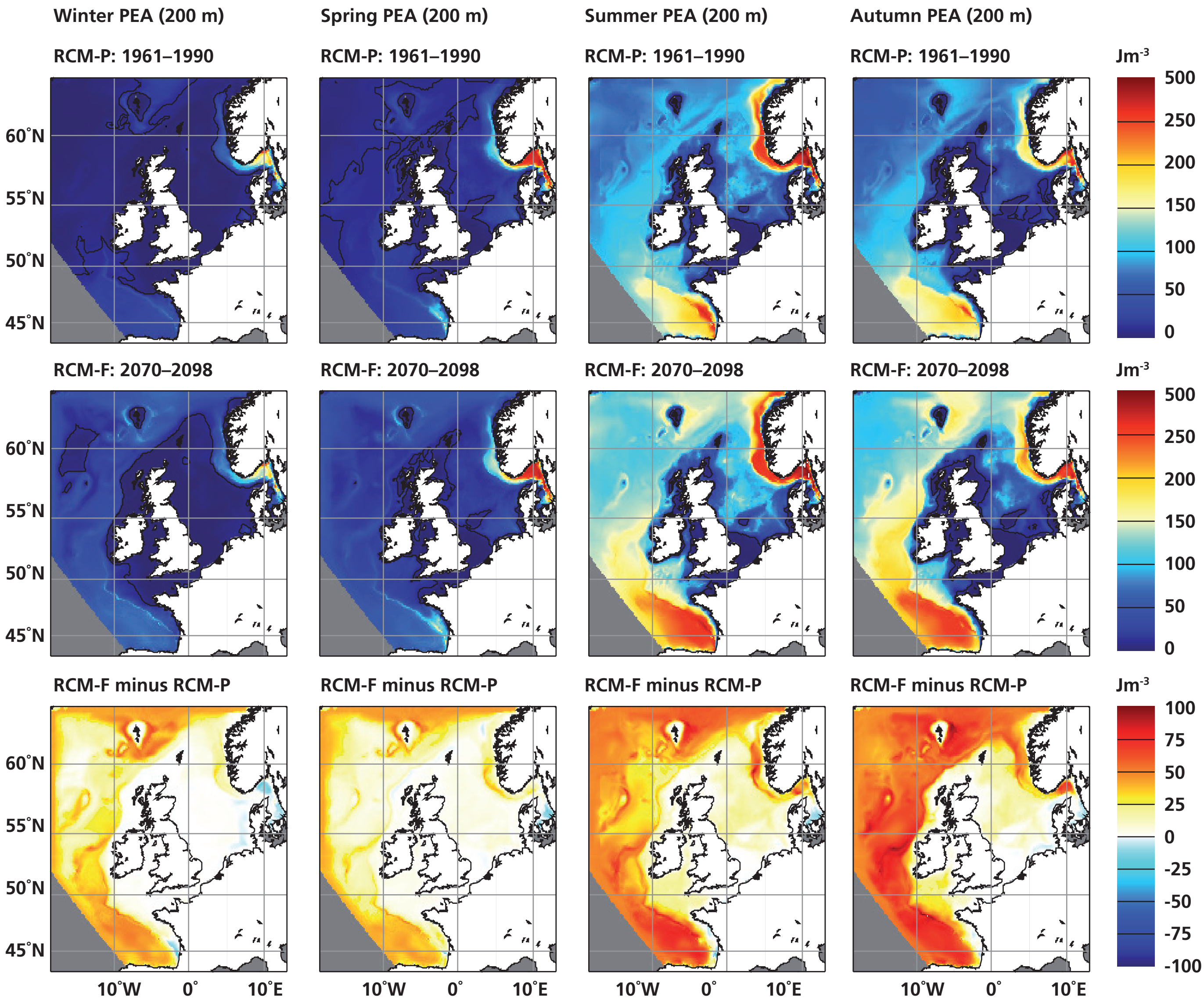
Figure 6.8: Seasonal mean sea surface salinity (SSS) for RCM-P (1961–1990) and RCM-F (2070–2098) and the difference between them.



6.4 Projected changes in water column stratification

The density stratification of shelf seas is well characterised by a quantity called the potential energy anomaly. This is here defined as the energy (per unit depth) required to completely mix the top 200 m of the water column. For convenience the potential energy anomaly is defined to be positive for stable stratification (essentially where denser cooler or saltier water lie beneath lighter fresher or warmer water). Hence, this represents the potential energy that must be added (usually from a loss of kinetic energy) to completely mix the water column. Comparing the seasonal mean potential energy anomaly (Figure 6.9) between the future time slice (RCM-F) and the recent past (RCM-P) shows the future forcing produces a substantial increase in stratification across the whole region, except in those areas that are permanently well mixed; and that this increase is largest in the autumn. The extent of the stratification (indicated on the shelf by the 10 Jm^{-3} contour) does not greatly change, but where stratification does occur, its strength increases under the future forcing. The increase in stratification is substantially larger (both in absolute terms and proportionately) in the deep ocean than the shelf regions. The general conclusion is, therefore, that tidally active shelf seas are unlikely to experience the strong increase in stratification expected in the deep ocean (e.g. the mean profiles from the global scale coupled

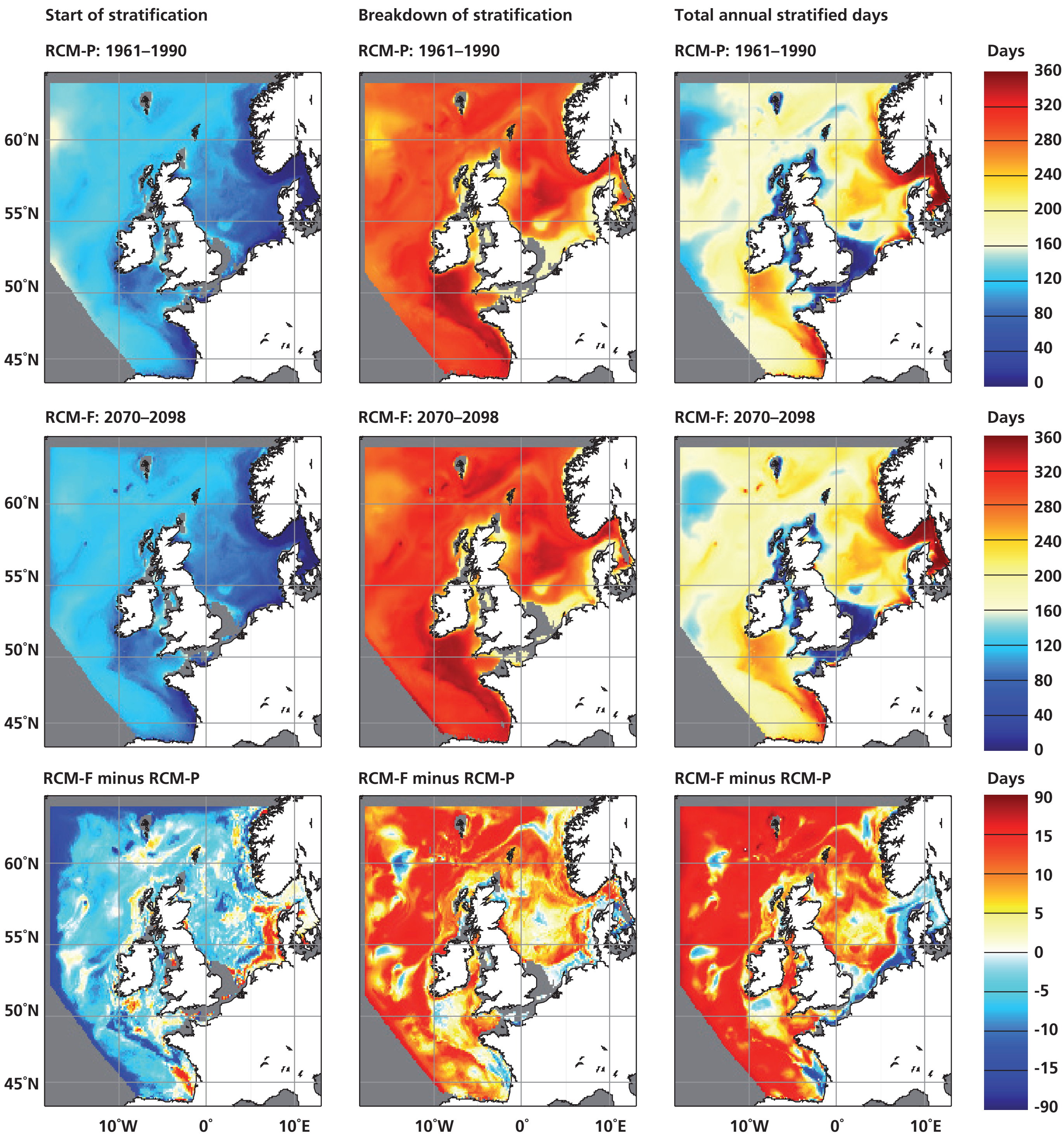
Figure 6.9: Seasonal mean potential energy anomaly (a measure of water column stratification) in RCM-P (1961–1990), RCM-F (2070–2098) and the difference between them.



PPE model used to adjusted the boundary conditions show a ~50% increase in potential energy anomaly from the past to the future time slice). Instead a weaker increase is likely, resulting from the increased expansivity as the water warms, increased precipitation, and changes in the horizontal heat transport. Figure 6.7 demonstrates that changes in the seasonal heat flux are unlikely to contribute greatly to this.

While by this measure the increase in the strength of stratification is projected to be weaker in shelf seas than the open ocean, these smaller changes may still have important implications; particularly when/where the stratification is weak. For example spring phytoplankton blooms can be triggered by very small

Figure 6.10: Mean timing of seasonal stratification from RCM-P (1961–1990), RCM-F (2070–2098) and the difference between them. The figure shows day of the year (1 January is day 1) when persistent seasonal stratification starts and ends, and the total number of stratified days.

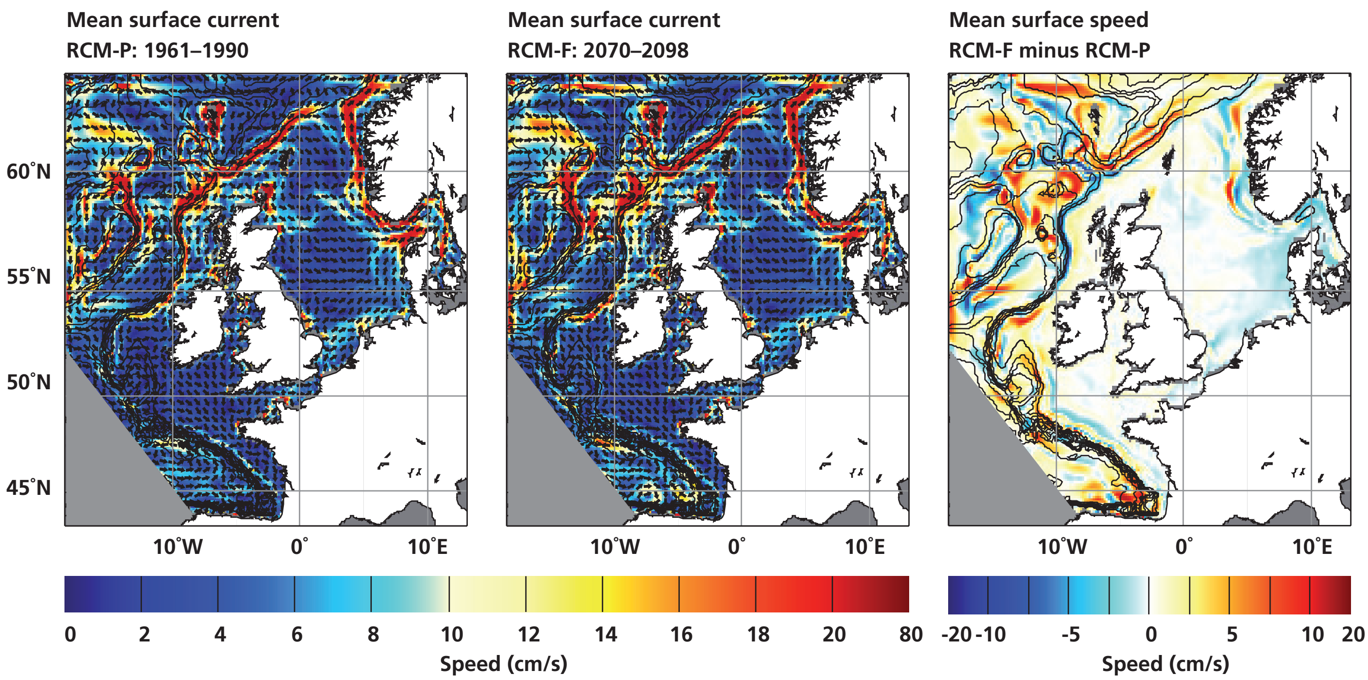


increases in water column stability. To explore this further, we examine the changes in the timing of the onset of seasonal stratification* in the spring and of the breakdown in the autumn. Figure 6.10 shows the timing (in days from 1 January) of the onset of persistent seasonal stratification and its breakdown for RCM-P and RCM-F, and the total number of stratified days. It demonstrates that seasonal stratification occurs ~5 days earlier in the future scenario (typically the 5 April) than the recent past (typically 10 April) across the whole shelf, with larger changes in the shelf break region west of the Celtic Sea. This is analogous to spring coming earlier in terrestrial systems. An exception is the salinity stratified regions off the coast of continental Europe. Here, the onset of stratification is delayed by ~10 days. The breakdown of stratification in the autumn occurs about 10 days later (in the future time slice compared with the recent past) across much of the region (accounting for the stronger SST warming trend in autumn noted above). However, the pattern is patchier than the onset and there are a number of regions that show little variation. These include the central North Sea, the Celtic Sea and the sea east of Scotland. Hence, the overall increase in the duration of the stratified period is typically 15 days except in these regions where it is closer to 5 days.

6.5 Projected changes in circulation

The mean surface circulation (Figure 6.11) shows substantial variations in the open ocean regions of the model domain between the recent past (RCM-P) and future scenario (RCM-F) model experiments. The circulation on the shelf is, in comparison, much less changed between these two model experiments. The largest effect is in the slope-shelf region where the slope-current to the west of Scotland (Souza *et al*. 2001) reduces substantially, whereas the portion of this current north of Scotland accelerates. There is also a marked reduction (by ~20%) in flow of water from East Anglia, along the continental coast to the German Bight. Across the majority of the shelf, however, there is little qualitative change in the circulation pattern. This is primarily dictated by the shape of the basin/topography, the locations of tidal mixing fronts and coastal currents.

Figure 6.11: Mean surface currents from RCM-P (1961–1990), RCM-F (2070–2098) and the difference between them. For clarity only every fourth current vector is shown.



* Here defined as a sustained surface to bottom density difference equivalent to -0.5 ˚C and a mixed layer of shallower than 50 m.

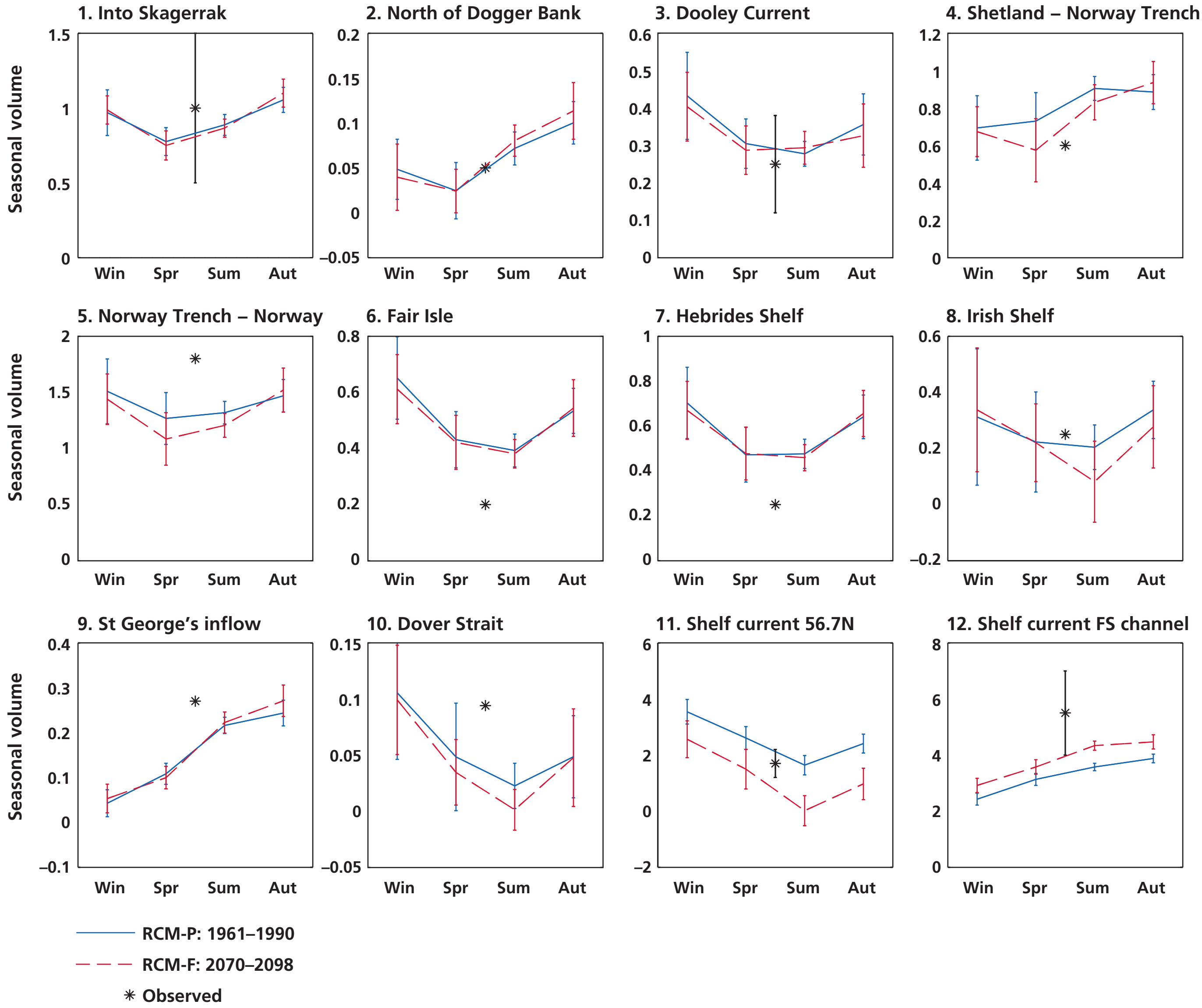


Figure 6.12: Seasonal volume fluxes across the sections shown in Figure 6.1. For RCM-P (1961–1990) and RCM-F (2070–2098) observed summer values from the literature are shown, along with estimates of variability where available (Brown *et al.* 2003; Brown *et al.* 1999; Danielssen *et al.* 1997; Fernand *et al.* 2006; Holt *et al.* 2001; Prandle *et al.* 1996; Svendsen *et al.* 1991; Turrell *et al.* 1992)

To quantify the seasonal changes in the circulation we examine the transports across the sections shown in Figure 6.1. Figure 6.12 shows the substantial reduction in the slope-current west of Scotland (noted above) and the shelf-edge current west of Ireland. This is accompanied by an increase in the slope current in the Faeroe-Shetland Channel. Comparing the fluxes produced by RCM-F and RCM-P on the shelf, the Fair Isle Channel current closely matches the Hebrides shelf-edge current and both show little variation, whereas the flows into the North Sea east of Shetland do show a reduction in spring and summer. These currents flow into the Dooley current and on into the Skaggerrak, but there is little variation in either of these currents. This suggests that there is little large scale change in the transport of water into the North Sea, despite the strong variations in the slope current, and that the effects of changes in across-shelf-edge transport are limited to the shelf-edge regions. This supports the supposition that the northwest European shelf is isolated from the details of the circulation occurring in the northeast Atlantic. The changes in the horizontal transport component of the heat flux (Figure 6.7) seen in the central North Sea would therefore relate to local changes in circulation.

There is some evidence that the increased summer stratification causes increased density driven circulation at tidal mixing fronts. This circulation is in the form of sub-surface jets located above the bottom front. The effect here is seen as a weak increase in the transport during the summer north of Dogger Bank and into the St. George's Channel.

6.6 Conclusions

Temperature and salinity change: The most noticeable and robust impact of climate change on shelf seas around the UK in the next century is a temperature increase. This amounts to about 1.5 °C–4 °C, depending on location, by the end of the 21st century in the medium emission scenario with the increase being larger in shelf seas than the open ocean. The difference between shelf and open ocean occurs because shelf seas are shallower than the winter mixed layer depths of the open ocean. However, the effects of surface temperature on the heat flux and the effects of the horizontal heat transport means this increase is not proportionate with decreasing depth, as would be expected if the surface heat flux were to simply increase. A reduction in salinity of ~0.2 p.s.u. is also suggested, but higher uncertainties in the forcing (precipitation, evaporation and river flows) and the ocean-shelf transport mean this conclusion is less robust than the projected temperature increase.

Stratification strength: These simulations suggest an increase in stratification in shelf seas over the 21st century, but that this is significantly weaker than in the open ocean. However, the characteristics of seasonal stratification in shelf seas differ from those in the open ocean, owing to the presence of mixing from the sea bed. Hence, a direct comparison of the strength of the stratification may not demonstrate the true relative significance of the changes in each system.

Timing of stratification: Seasonal stratification generally occurs earlier in the year by ~5 days and breaks down later by typically 5–10 days, and hence the duration of the stratified period is increased across the whole shelf.

Stratification location: On average, the location of fronts and the extent of the stratified regions are not seen to greatly change in the future simulation, but the importance of salinity stratification is seen to be enhanced (e.g. Figure 6.2).

Circulation changes: These model results show a reduction in the slope current by the end of the 21st century. Such a conclusion needs to be treated with caution since the results are almost certainly affected by the proximity of the model boundaries and the limited information available there.

In summary these simulations have demonstrated that the shelf seas are likely to experience the effects of climate change over the next century in a different way to the deep ocean. The simulations have demonstrated the ability of shelf sea models to examine future climate change but large uncertainties remain and cannot yet be quantified. To better quantify these general trends requires simulations that account for the oceanic influence of the North Atlantic and exchange with the Baltic more accurately, and to better understand the uncertainty in these trends requires simulations based on an ensemble of scenarios.

6.7 Results presented in the UKCP09 User Interface

The User Interface will eventually allow the results presented in this chapter and many additional results to be displayed via an interactive web-based interface (http://ukclimateprojections.defra.gov.uk). Additional results will be made available by the LINK database (http://badc.nerc.ac.uk/data/link).

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7 Thames Estuary 2100 case study

The Environment Agency set up the Thames Estuary 2100 (TE2100) project to provide a plan to manage flood risk in the Thames Estuary for the next 100 yr. Central to this is adapting to the uncertain effects of climate change. This will drive changes to sea level, storm surge height and frequency, and river flows. The project commissioned work with the Met Office Hadley Centre, the Proudman Oceanographic Laboratory and the Centre for Ecology and Hydrology to try to better understand the uncertainties surrounding these changes. This has provided a major contribution to the UKCP09 Marine report.

The work confirms that it will be essential to monitor the rate and progress of key climate change effects such as ice sheet melt and develop better predictive science to support this. The TE2100 project's success will depend on monitoring and adjusting as the century progresses.

Key Findings

- **New projections of the likely range of future mean sea level around the Thames Estuary approximately agree with current Defra planning advice. An additional enhanced ice sheet contribution could cause mean sea levels to rise by up to 2 m by 2100. However, a 2 m increase by 2100 is considered very unlikely.**

- **21st century increases in storm surge height and frequency in the southern North Sea are less likely than previously thought.**

- **The TE2100 project has taken an adaptive approach that can cope with large ranges of change if needed. These new results confirm that this is a sensible way forward.**

7.1 Introduction

In January 1953 a large storm surge caused extensive flooding on the East Coast including the Thames Estuary. Three hundred people lost their lives and London narrowly escaped a major flood. Following the 1953 floods the Thames Barrier and associated defence improvements were planned and built over a 30-yr period to protect London to a high standard from tidal flooding. Given the challenge of future climate change and the long timescales required to plan for any changes, the Environment Agency has set up the Thames Estuary 2100 (TE2100) project. This project is developing a Flood Risk Management Plan for London and the Thames Estuary for the next 100 yr.

Figure 7.1: The current Thames barrier in the open position.

7.2 The issue

London and the Thames Estuary has always been subject to flood risk. It is currently protected to a high standard (generally the 1000 yr return level estimated for the year 2030) — this high standard is justified by the high value of property protected. The design of the Thames Barrier allowed for some sea level rise but did not make any specific allowance for changes due to climate change in fluvial flows coming down the Thames or changes in the size of storm surges arising in the North Sea. Rising sea level, rapidly increasing development within the tidal flood plain and an ageing flood defence infrastructure mean that flood risk is increasing and by the year 2030 improved arrangements will be required if flood risk management standards are to be maintained at present levels throughout the 21st century.

TE2100 has to devise a plan that will cope with the uncertainties that climate change and differing socio-economic futures present. The plan looks to manage flood risk by a balance of relevant measures such as the timing and design of future flood defences, resilience of new and existing development and flood warning systems and emergency responses.

7.3 The solution

TE2100 has devised an approach to the development of the strategy centered on trying to deal with the uncertainties in projections of future climate and development along the Thames. It has developed a method of testing different flood management options or packages of measures relevant to each reach of the Estuary, which are then progressively iterated and tested against a decision testing framework. This framework has tested the suitability of the options against differing futures driven by a range of socio-economic and climate change scenarios. Options can be refined and the most resilient, effective and cost beneficial solution arrived at. Using this method it has been possible to detect thresholds, which will be critical to differing options. For example modifying the existing barrier and defences will only cope with a certain level of sea level rise and increase in storm surge.

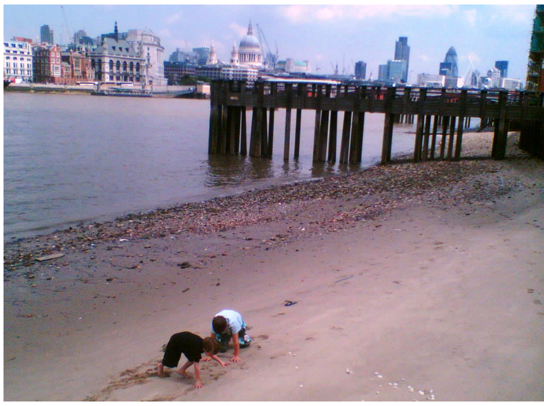


Figure 7.2: The Thames provides a vital resource for London.

The approach is based largely on the Risk, Uncertainty and Decision Making Technical Report produced by the Environment Agency for UKCIP (Willows and Connell, 2003) and other tools and assessment criteria based on existing and developing guidance. TE2100 has also worked with partners in Holland, Germany and Belgium in the ESPACE Project (European Spatial Planning Adapting to Climate Events) to develop and refine trans-national methods. The involvement of stakeholders in London and the Estuary is critical to success. TE2100 has and will continue to work with a wide variety of groups to ensure that the final

Flood Risk Management Plan will, as far as possible, be compatible with the varying interests that the Estuary supports. To support the development of the plan an extensive study programme has been carried out alongside a continuous dialogue with stakeholders. This has enabled full understanding of the processes and issues critical to testing and developing a range of flood risk management options.

7.4 Working with uncertainty in climate change projections

The effect of climate change on world ocean, sea and river levels is a key driver of the TE2100 plan. In London and the Thames Estuary climate change is likely to have an effect on:

- average sea and tide levels
- the frequency and severity of North Sea storm surges
- fluvial flows coming down the Thames and its tributaries.

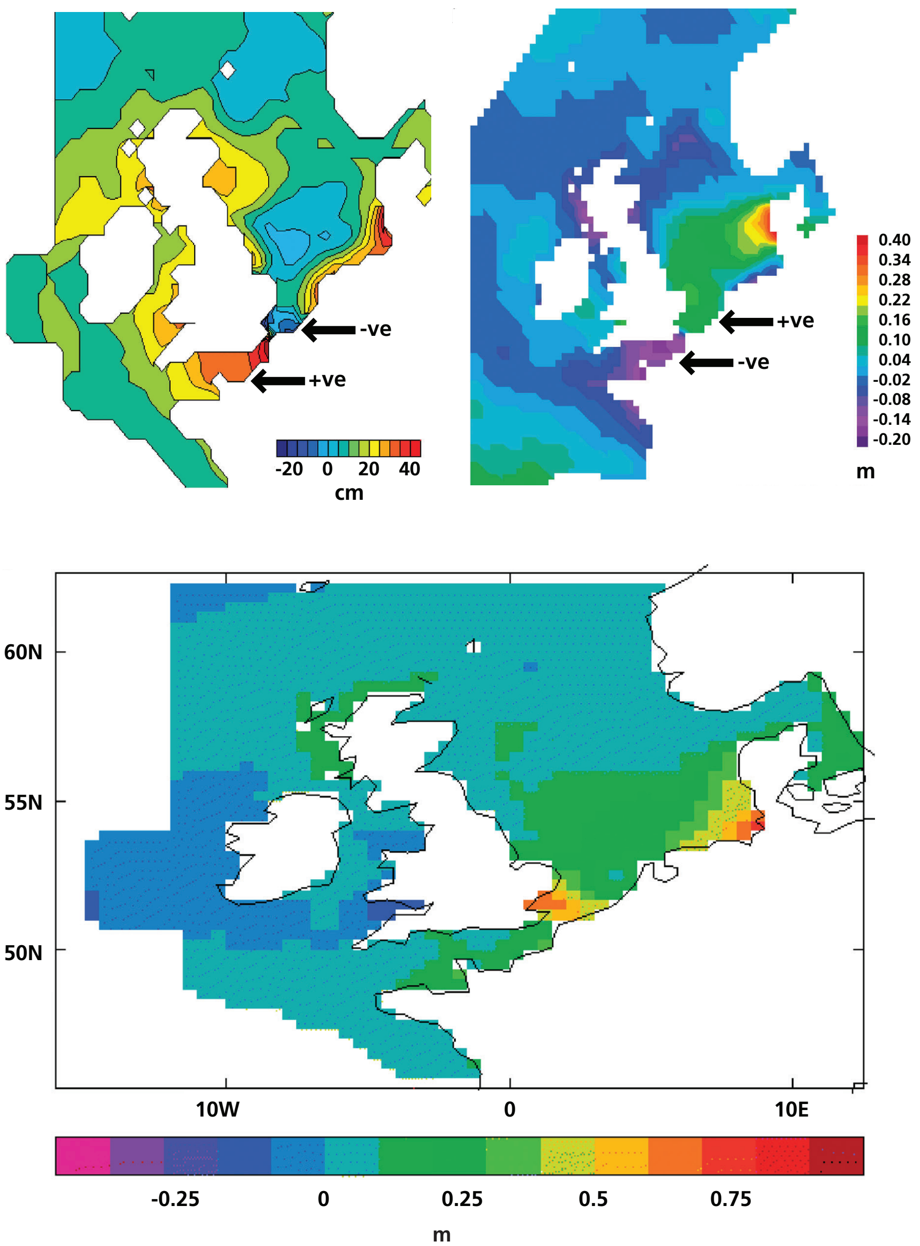
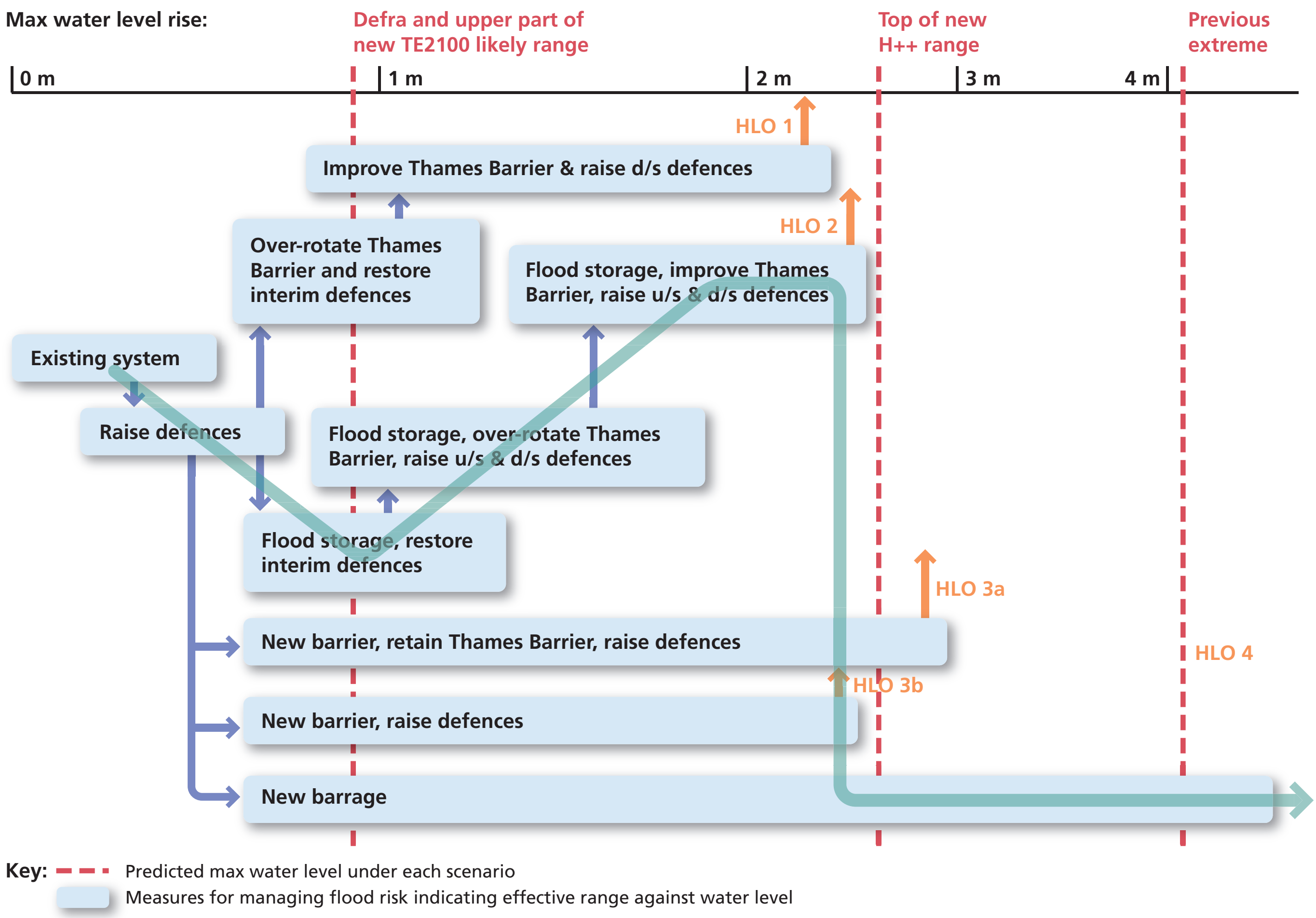


Figure 7.3: Projected 21st century changes in 50 yr storm surge height due to changes in storminess alone forecast by three different climate models (clockwise from top left: HadCM2/HadRM2, ECHAM4 and HadAM3H/HadRM3H), illustrating the large uncertainty which surrounded extreme sea level change in the Thames Estuary prior to the TE2100 project. (After Lowe and Gregory, 2005.)

In addition to the approach set out above, it is essential to try to better understand the uncertainty and probability of future climate change effects. Therefore the project has been working directly with the Met Office Hadley Centre, the Proudman Oceanographic Laboratory and the Centre for Ecology and Hydrology to drive research on this issue. At the start of the project the UKCIP02 scenarios projected an increase at the mouth of the Thames of up to 1.3 m in storm surge by the 2080s whilst other modelling studies projected a decrease (see Figure 7.3). This range of uncertainty could lead to a very large variation in the level of future flood risk management planning and a large associated difference in costs. The new research was commissioned specifically to look at the uncertainties surrounding storm surge, relative sea level rise and river flows in a consistent manner. This work was commissioned in conjunction with the research going ahead for the UKCP09 scenarios. It has the added benefit of giving an output on mean sea level and extreme sea level relevant to the whole of the UK. The research has been a major contributor to the UKCP09 marine projections.

Pending the outcome of this research the project devised four scenarios to use to develop the options. The first three — Defra, Medium High, and High Plus were based on Defra PAG3 guidance and the UKCIP02 scenarios. However, following scientific research on ice cap melt presented at the Avoiding Dangerous Climate Change Conference (http://www.stabilisation2005.com/index.html) in 2005, a H++ scenario was devised to identify a worst-case estimate. This included worst case estimates for each element of extreme water level change. The H++ scenario initially developed has now been replaced with a range as outlined in Chapters 3 and 4 of this report.

Figure 7.4: High Level Options. The dark blue path shows a possible future adaptation route (or pathway) in the event of extreme change (>4 m rise). The vertical dashed lines show TE2100 scenarios including the new revised H++ range described in Chapters 3 and 4 of this report.



In 2007, TE2100 produced its High Level Options, which have been the subject of extensive online stakeholder engagement. These are a set of adaptation response options (HLO1, 2, 3a, 3b, and 4). Each option consists of a pathway or route through the century that can be adapted to the rate of change that we experience. They are described in Figure 7.4 which essentially shows how the four differing options perform against a range of TE2100 climate change scenarios including the latest findings.

It can be seen from Figure 7.4 that not only are the options flexible, but it is possible to move from one adaptation option to another depending on the actual rate of change that occurs in reality.

The project has now developed its plan which has recently been made available for public consultation. The results of the climate change work undertaken are critical to this. The most important results were:

- The results give greater confidence that the project has been planning for the right potential range of water levels this century.
- The previous worst-case scenario can be revised down from increases in maximum water levels of 4.2–2.7 m. The 2.7 m result relates to the 5-yr return period event.
- With a reduction in worst case scenario for this century, it is even less likely that a tide-excluding estuary barrage will be needed to manage flood risk.
- Options for managing flood risk in west London need to be tested against a potentially greater increase in flows than we previously planned for.

7.5 Decision-making with an uncertain future

The range of flood management options presented in the final plan will protect London and the Thames Estuary against all plausible sea level rise scenarios over the next century, up to and including the top of the new H++ range for increases in extreme sea levels at the Thames Estuary. The plan contains detailed guidance on how its recommendations should be applied in the event of the more extreme change projections being realised. This guidance will consider whether increased flood risk is driven by the climate or other issues such as socio-economic development and will show how lead times for major interventions need to take account of any such changes. An illustration is given in Figure 7.5.

7.6 Monitoring and forecasting

The effectiveness of the final plan will depend on a continuing process of periodic review — every 5 yr or so. Critical to this will be the need for ongoing review of the progress of climate change and revised future projections. The Environment Agency will be working with the Met Office Hadley Centre and others to ensure that this monitoring is in place.

7.7 Next steps

The results of this recent research have been used alongside continued engagement with London and Estuary stakeholders to refine the TE2100 flood management options. The TE2100 plan has recently been launched for full public consultation, and will be submitted to Defra in early 2010.

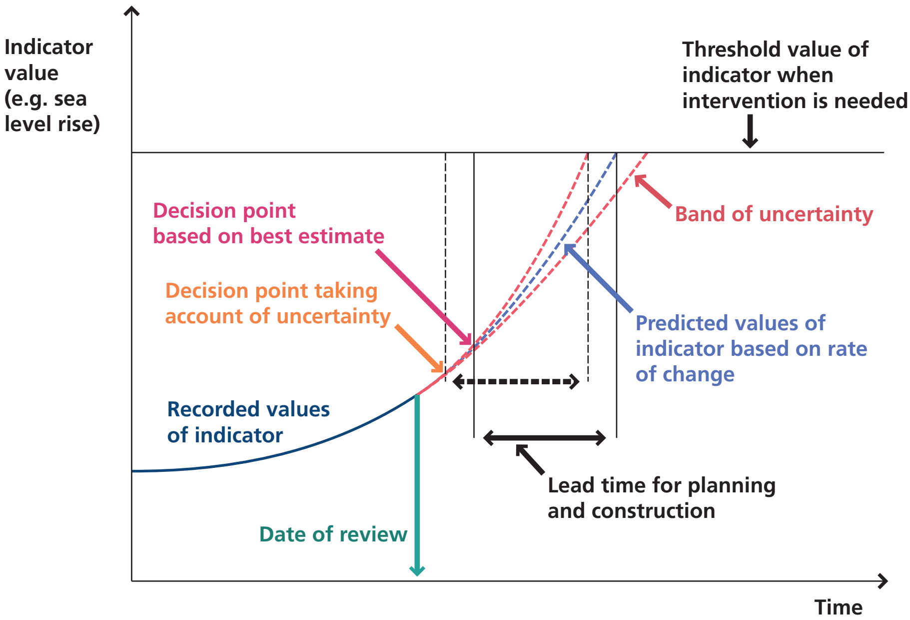


Figure 7.5: Decision making with an uncertain future.

7.8 References

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Annex

Because the land movement scenarios in UKCIP02 resulted in considerable debate, we include here a discussion and inter-comparison of estimates from a range of different sources that are now available.

Arisaig beach, Scotland

A1 Observational and modelled vertical land movement

Field observations of land level change include measurements with Continuous Global Positioning System (CGPS), inferred movement from absolute gravity (AG) and geological measurements. GIA models also provide estimates of UK vertical land movement. The most recent model results are constrained by observations.

A1.1 Continuous Global Positioning System (CGPS)

Long term GPS measurements can give a very accurate measurement of current vertical and horizontal land movements, at sub-millimetric precision (Johansson *et al*. 2002). Within the UK there is a comprehensive network of CGPS stations. These include 10 stations located at tide gauges (CGPS@TG) run by the Proudman Oceanographic Laboratory (POL), and 33 non-tide gauge CGPS, run by various organisations. This network is supplemented by the Ordinance Survey GPS stations which are designed for general survey purposes and as such many of them do not satisfy the requirement for this analysis (i.e. length of data record, stable monumentation with respect to bedrock, lack of anomalous trends (Bradley *et al*. 2008)).

There are several sources of inaccuracies in measurements of CGPS that need to be corrected for, including atmospheric, satellite-related and station-related systematic error. These are generally corrected for by modelling the effect of the components and removing them from the signal. Despite the removal of these errors, there is a generally accepted systematic error between measurements from CGPS stations and other estimates, for example:

- Prawirodirjo and Bock (2004) compared GIA model outputs with CGPS measurements from North America and Northern Europe, and noted that CGPS gave a consistent (positive) offset compared to modelled values, of +1.1 and +1.7 mm/yr respectively.

- When comparing measurements of vertical land movement from co-located CGPS and Very Long Baseline Interferometry (VLBI), MacMillan (2004) noted that CGPS measurements were 1.5 mm/yr more positive compared to the VLBI measurements.

- CGPS vertical land movement measurements were compared with AG at Newlyn, as part of the European Sea Level Service – Research Infrastructure project. Again CGPS measurements (+1.7±2.5 mm/yr) were found to be more positive than the AG measurements (+0.6 mm/yr).

With this in mind, the CGPS measurements provide a reasonably good spatial coverage; however, they include a vertical systematic offset that needs to be accounted for.

A1.2 Absolute gravity

As gravity changes with elevation, very accurate point measurements over time can be used to quantify changes in land elevation. The method is labour intensive and requires particular site conditions (in buildings built on solid rock, away from the gravitational influence of ocean tides, etc.), and so only three sites in the UK are routinely monitored for AG; Lerwick, Aberdeen and Newlyn. These sites were chosen to cover the range of modelled GIA vertical land movements in the UK, (subsidence at Newlyn, no change at Aberdeen, and subsidence at Lerwick).

Generally the AG measurements are considered to be highly accurate, however, they are time consuming (while CGPS measurements are automatic, AG measurements are typically made over a period of several days, near annually), and so limited in their spatial coverage. Therefore, AG measurements are predominantly used to correct the CGPS measurements, leading to an accurate combined dataset (termed AG-corrected CGPS), that has a good spatial coverage.

A1.3 Geological data

Geological data has long been a source of vertical land level velocities in the UK, and was the primary source of information in UKCIP02. Rising land levels (relative to the sea level) can strand beaches and other coastal features. Provided the integrity of these features remain, dating and measuring the elevation can give accurate palaeo sea levels. The UK has some of the longest time-series of Holocene/Late Pleistocene sea level elevation points, with the longest stretching back to ~15,000 years before present. Such datasets allow independent assessment of the land level movement estimated by CGPS and AG. Early studies by Shennan (1989) and more recently Shennan and Horton (2002), used these measurements so to produce vertical velocity maps for UK.

Shennan *et al*. (2006) gave a comprehensive review of UK geological evidence to support GIA models, although with few data points from Devon and Cornwall. The geological data is also used to derive a map of the ice coverage during the last ice age, used in subsequent GIA studies.

Careful consideration of the measurements in Devon and Cornwall by Gehrels (2006), in particular accounting for the relatively sparse nature of data from this part of the country, suggested that the rates presented by Shennan and Horton (2002) could be double the actual values in this area. This regional study highlights the requirement for more geological and CGPS data from the South West of England.

For a detailed description of CGPS, AG and geological record theory, measurement and practicality, refer to the Defra technical report *Absolute Fixing of Tide Gauge Benchmarks and Land Levels* (Bingley *et al*. 2007).

A1.4 Vertical land movement in the UK

Teferle *et al*. (2009) produced a comprehensive study of the spatial patterns of vertical velocity in the UK, using CGPS and AG, supported by geological/ geophysical evidence. These data were used to produce an observation based map of vertical land movements in the UK. CGPS data was analysed from the 44 CGPS@TG and non TG CGPS stations in the UK (and Brest, France) with 15 ordinance survey CGPS stations. The spatial resolution of the AG-corrected CGPS data allowed the development of a map of the vertical land movements in the UK (they produced maps using a number of processing techniques). Estimates of vertical land movement based on these measurements are presented in Table A1.1. A similar map of UK vertical land movements was obtained by Bradley *et al*. (2008) when using a model to investigate the mechanisms behind vertical land movement in the UK (Figure 3.5, used in this study). A strong correlation was found between the CGPS measurements of Teferle *et al*. (2009) and the GIA model forced by the ice field loading of Shennan *et al*. (2006). The model, described by Milne *et al*. (2006), uses lithospheric and mantle parameters optimised to the AG corrected CGPS in addition to the geological forcing data. The GIA modelled vertical rates were within the CGPS error bounds for 12 of the 16 sites considered, while the remaining four sites were outside the error bounds by less that 0.1 mm/ yr, suggesting that the modelled rates give a generally good representation of the actual rates. As further data becomes available (with increased CGPS time-series, and additional geological data, especially in Southwest England), these results will evolve.

Table A1.1 (below): Summary of observed (geological and AG-aligned CGPS) and modelled vertical land velocities (mm/ yr) for the UK. The CGPS is taken from Teferle *et al.* (2009) (the version denoted by them as *filtered BSW5.0 globally transformed PPP (PPPGTF)*) and the GIA modelled values are interpolated from Bradley *et al.* (2008). Italicised, geological data represents relative sea level change according to Shennan and Horton (2002), included here to allow comparison to UKCIP02. Geological values for Northern Ireland (**) represent absolute vertical land level (Orford *et al.* 2007). Locations in brackets refer to site name of Shennan and Horton (2002), and to the capitalised location code of Teferle *et al.* (2009). Errors are given as ±1 standard deviation. * denotes visual linear interpolation from published figures (no uncertainty estimate is possible for these values).

Location	AG-CGPS	Modelled GIA	Geological
London (Thames, BARK)	−1.2±0.55	−0.71	*−0.74*
Plymouth*	*−1.5	−0.49	*N/A*
Exeter (SW England Devon, DUNK)	−1.4±1.08	−0.86	*−1.23*
Lowestoft (East Anglia, LOWE)	−1.17±0.4	−0.86	*−0.61*
Bristol* (Bristol Channel)	*−1.0	−0.72	*−0.76*
Portsmouth (Hampshire, PMTG)	−1.15±0.46	−0.80	*−1.23*
Liverpool (Mersey, LIVE)	0.51±0.43	−0.30	*−0.21*
Leeds (LEED)	−0.82±0.31	−0.44	*N/A*
Newcastle (NE England Central, NEWC)	0.37±0.61	−0.76	*0.11*
Cardiff* (Sth Wales Glamorgan)	*−1.0	−0.67	*N/A*
Aberystwyth (Mid Wales, ABYW)	−1.23±0.5	−0.47	*−0.38*
Bangor* (Nth Wales	*0.5	−0.16	*−0.29*
Glasgow (Clyde, GLAS)	0.45±0.39	0.84	*1.53*
Edinburgh (SE Scotland, EDIN)	1.07±0.35	0.65	*1.15*
Aberdeen (Aberdeen, ABER)	−0.84±0.49	0.36	*0.69*
Thurso (Wick, THUR)	−0.13±0.56	0.06	*0.42*
Mallaig (Arisaig, MALG)	0.39±0.44	0.66	*1.01*
Kirkwall*	*−0.5	−0.21	*<0.0*
Lerwick (LERW)	−0.65±0.54	−1.07	*<0.0*
Belfast (SE Ulster)	N/A	0.50	**0.65±0.88
Londonderry (NW Ulster)	N/A	0.40	**0.68±0.88
Isles of Man (IOMN)	0.63±0.87	0.32	*0.45*
Channel Isles	N/A	−0.88	*N/A*

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- Monitor climate variability and change at global and national scales, and use models to attribute recent changes to specific factors such as human activity.
- Quantify and reduce uncertainty in projections of climate change, particularly at a local scale and of extremes, and use this information to inform adaptation strategies.
- Define and assess the risk of dangerous climate change, whether gradual, abrupt or irreversible.
- Assess scientific aspects of options for mitigating climate change and its impacts.
- To advise government, business, the media and other stakeholders.

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UKCIP was established in 1997, and based at the School of Geography and the Environment, Oxford. Defra funds UKCIP for the UK Government, Scottish Government, the Welsh Assembly Government and Department of the Environment Northern Ireland.

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