UK Climate Impacts Programme

DEFRA
Department for
Environment, Food & Rural Affairs

Tyndall°Centre
for Climate Change Research

Met Office
Hadley Centre

Climate Change Scenarios for the United Kingdom

The UKCIP02 Scientific Report

April 2002

Climate Change Scenarios for the United Kingdom:
The UKCIP02 Scientific Report

© M. Robinson

© M. Robinson

This report was prepared by:

Mike Hulme, Xianfu Lu, John Turnpenny
Tim Mitchell (Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich)

and

Geoff Jenkins, Richard Jones, Jason Lowe, James Murphy, David Hassell, Penny Boorman, Ruth McDonald, Steven Hill (Hadley Centre for Climate Prediction and Research, Met. Office)

This report should be referenced as:

Hulme,M., Jenkins,G.J., Lu,X., Turnpenny,J.R., Mitchell,T.D., Jones,R.G., Lowe,J., Murphy,J.M., Hassell,D., Boorman,P., McDonald,R. and Hill,S. (2002) *Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report,* Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK. 120pp

The work was commissioned and funded by the Department for Environment, Food and Rural Affairs as part of the UK Climate Impacts Programme.

April 2002

ISBN 0 902170 60 0

CONTENTS

Page

Acknowledgements iii

Executive Summary iv

CHAPTER 1 - AN INTRODUCTION TO THE UKCIP02 CLIMATE CHANGE SCENARIOS 1

1.1 Our changing climate 1
1.2 What are scenarios? 2
1.3 The UKCIP02 climate change scenarios 2
1.4 Uncertainties 5
1.5 The structure of the report 6

CHAPTER 2 - RECENT TRENDS IN GLOBAL AND UK CLIMATE 8

2.1 Global warming and its causes 8
2.2 Long-term trends in regional temperature 10
2.3 Long-term trends in precipitation and snow cover 11
2.4 Long-term trends in circulation patterns and gales 13
2.5 Long-term trends in marine climate and sea level 13
2.6 Average 1961-1990 climate in the UK 14
2.7 Conclusion 15

CHAPTER 3 - CREATING GLOBAL AND UK CLIMATE CHANGE SCENARIOS 16

3.1 Greenhouse gas emissions and concentrations 16
3.2 Climate response 17
3.3 Regional climate change over the UK 19
3.4 Comparison with the UKCIP98 scenarios 21
3.5 Exploring the implications of scientific uncertainties for future UK climate 21

CHAPTER 4 - FUTURE CHANGES IN UK SEASONAL CLIMATE 26

4.1 How accurate is the climate model? 27
4.2 Future changes in average temperature 28
4.3 Future changes in average precipitation 28
4.4 Future changes in average seasonality 36
4.5 Future changes in inter-annual variability 36
4.6 The evolution of temperature and precipitation 39
4.7 Future changes in other surface variables 42
4.8 Future changes in derived surface variables 51
4.9 Qualitative summary and comparison with the UKCIP98 scenarios 52

CHAPTER 5 - FUTURE CHANGES IN UK DAILY CLIMATE 54

5.1 Daily data and analyses 54
5.2 Future changes in daily precipitation extremes 54
5.3 Future changes in daily temperature extremes 61
5.4 Future changes in daily-average wind speed 65
5.5 Future changes in other variables using daily data 67
5.6 Qualitative summary and comparison with the UKCIP98 scenarios 70

CHAPTER 6 - FUTURE CHANGES IN SEA LEVEL AND UK MARINE CLIMATE 72

6.1 Future changes in global sea level this century 72
6.2 Future changes in global sea level in the long-term 73
6.3 Future changes in regional sea level 74
6.4 Future changes in extreme sea levels and coastal flooding 75
6.5 Future changes in surface marine climate 77
6.6 Qualitative summary and comparison with the UKCIP98 scenarios 80

CHAPTER 7 - UNCERTAINTIES AND WIDER ISSUES 81

7.1 Uncertainties in scenarios of climate change 81
7.2 Emissions uncertainties 82
7.3 Feedbacks from the carbon cycle and atmospheric chemistry 82
7.4 Uncertainties due to the method of pattern-scaling 83
7.5 Uncertainties due to model development 84
7.6 Uncertainties due to changes of scale 87
7.7 The effects of natural variability 87
7.8 Possible changes to the Gulf Stream 89

CHAPTER 8 - MITIGATION SCENARIOS 91

8.1 Introduction 91
8.2 The Kyoto Protocol 91
8.3 Stabilisation of greenhouse gas concentrations 91

CHAPTER 9 - FURTHER WORK AND DEVELOPMENTS IN RESEARCH 93

9.1 Additional data analyses from HadRM3 experiments 93
9.2 Probabilistic predictions of future climate 94
9.3 Emissions scenarios 94
9.4 Development of the Hadley Centre global environmental model 95
9.5 An improved UK regional climate model 95
9.6 Marine climate change scenarios 95
9.7 Decadal climate forecasting 95

Bibliography and Literature Sources 97

Appendix 1 An Introductory Guide to Choosing and Using Climate Change Scenarios 99
Appendix 2 The HadCM3, HadAM3H and HadRM3 Models and Experiments 102
Appendix 3 Improvements in the 2002 Scenarios Compared to the 1998 Scenarios 105
Appendix 4 The UKCIP02 Scenario Data Files and Web Site 106
Appendix 5 The SRES Emissions Scenarios 107
Appendix 6 Glossary of Technical Terms 108
Appendix 7 The Observed UK Climate Data Set 110
Appendix 8 The IPCC Data Distribution Centre 112

On-line sources of UKCIP02 scenario data and related climate change information

Acknowledgements

Data Providers
Climate Impacts LINK Project, Climatic Research Unit, School of Environmental Sciences, UEA, UK
Dr Peter Challenor, Southampton Oceanography Centre, University of Southampton, UK
Dr Aryan van Engelen, Climatological Services, KNMI, Netherlands
Chris Folland, Hadley Centre, Met Office, Bracknell, UK
Dr John Harrison, Department of Environmental Science, University of Stirling, Scotland, UK
Professor Phil Jones, Climatic Research Unit, School of Environmental Sciences, UEA, UK
Professor Ian Shennan, Department of Geography, University of Durham, UK
Professor Keith Smith, Department of Environmental Science, University of Stirling, Scotland, UK
Dr Bill Turrell, Marine Laboratory, Aberdeen, Scotland, UK
Dr Phil Woodworth, Proudman Oceanographic Laboratory, Bidston, UK

Analysis and Software Providers
Hadley Centre, Met Office, Bracknell, UK, in particular: Dr Jonathan Gregory, Dr Peter Cox, Dr David Roberts, Dr Colin Johnson, Dr Tim Johns and Dr Richard Wood
Professor Phil Jones, Climatic Research Unit, School of Environmental Sciences, UEA, UK
Professor Robert Nicholls, Flood Hazard Research Centre, Middlesex University, UK
Dr Tim Osborn, Climatic Research Unit, School of Environmental Sciences, UEA, UK
Dr Sarah Raper, Climatic Research Unit, School of Environmental Sciences, UEA, UK

External Reviewers
Professor Nigel Arnell, Department of Geography, University of Southampton, UK
Dr Iain Brown, UK Climate Impacts Programme, Oxford, UK
Professor Tim Carter, Finnish Environment Institute, Helsinki, Finland
Dr Richenda Connell, UK Climate Impacts Programme, Oxford, UK
Dr James Curran, Scottish Environmental Protection Agency, Scotland, UK
Dr Caroline Fish, Global Atmosphere Division, DEFRA, London, UK
Dr Filippo Giorgi, The Abdus Salem International Centre for Theoretical Physics, Trieste, Italy
Professor Phil Jones, Climatic Research Unit, School of Environmental Sciences, UEA, UK
Professor Robert Nicholls, Flood Hazard Research Centre, Middlesex University, UK
Dr Tim Osborn, Climatic Research Unit, School of Environmental Sciences, UEA, UK
Professor Martin Parry, Jackson Environment Institute, School of Environmental Sciences, UEA, UK
Dr Havard Prosser, The National Assembly of Wales, Cardiff, Wales, UK
Nick Reynard, NCRAOA, Environment Agency, Reading, UK
David Richardson, Flood Management Division, DEFRA, London, UK
Michael Rose, Land Management Improvement Division, DEFRA, London, UK
Dr David Warrilow, Global Atmosphere Division, DEFRA, London, UK
Dr Peter Whetton, Climate Impacts Group, CSIRO, Victoria, Australia
Dr Rob Wilby, Department of Geography, Kings College London, UK
Dr Diana Wilkins, Global Atmosphere Division, DEFRA, London, UK
Guy Winter, Scottish Executive, Edinburgh, Scotland, UK
Dr David Woolf, Southampton Oceanography Centre, University of Southampton, UK
Dr Phil Woodworth, Proudman Oceanographic Laboratory, Bidston, UK

Photographs
Mike Robinson, Norwich, UK

Design
Shorthose-Russell, Norwich, UK
Catherine Cook, UK Climate Impacts Programme, Oxford, UK

We acknowledge our debt to the UKCIP98 climate change scenario report upon which this one builds. We particularly note the contribution made by the Climatic Research Unit in the School of Environmental Sciences at the University of East Anglia to this earlier report and in developing a number of scenario analysis methods over recent years.

EXECUTIVE SUMMARY

What is this report for and what does it contain?

1. This report presents a set of four scenarios of future climate change for the UK based on our current understanding of the science of climate change. They have been commissioned and funded by the Department for Environment, Food and Rural Affairs for the UK Climate Impacts Programme (UKCIP). The climate change scenarios (known as UKCIP02) provide a common starting point for assessing climate change vulnerability, impacts and adaptation in the UK. The scenarios are designed to be used in conjunction with other UKCIP reports and products.

2. The UKCIP02 report contains the following information:

- it *summarises* the changes that are already occurring in global and UK climate;
- it *presents* four alternative climate change scenarios for the UK, including information about changes in average climate, in some selected daily weather extremes, and in average and extreme sea levels around the coast;
- it *discusses* the main uncertainties that influence our confidence in these descriptions, and illustrates the importance of some of them;
- it *directs* users to further sources of information, both quantitative and qualitative, that will assist them in using the UKCIP02, and other, climate change scenarios when conducting scoping, impacts or adaptation studies in the UK.

3. The UKCIP02 scenarios represent an advance in our description of future UK climates compared to the scenarios published for UKCIP in 1998. This is because they are based on new global emissions scenarios published in 2000 by the Intergovernmental Panel on Climate Change (IPCC) in their Special Report on Emissions Scenarios, and because they are based on a series of climate modelling experiments completed by the Hadley Centre using their most recently developed models. The scenarios describe four alternative future climates for the UK labelled, respectively, **Low Emissions**, **Medium-Low Emissions**, **Medium-High Emissions** and **High Emissions**. A new 5 km observed monthly climate data set for the UK for the period 1961 to 2000 has also been prepared.

4. No probabilities can be attached to these four climate futures – in line with the IPCC, we do not suggest that one is more likely than another. While they represent a wide range of possible future climates, the UKCIP02 scenarios do not capture the *entire* range of future possibilities.

How has climate changed?

5. Global temperature has risen by about 0.6ºC over the last 100 years, and 1998 was the single warmest year in the 142-year global instrumental record. A large part of the warming over the latter part of this period is likely to be due to human activities and cannot be explained solely by our understanding of the natural variability of the climate system.

6. The UK climate has also changed over the same period, and many of these changes are consistent with the warming of global climate. Central England temperature rose by almost 1ºC through the twentieth century. The decade of the 1990s was the warmest in central England since records began in the 1660s. The warming over land has been accompanied by a warming of UK coastal waters. Hot summer days with daytime temperature in central England exceeding 25ºC have become more common – almost twice as many on average during the 1990s compared to the first half of the twentieth century - while days with air frosts have been declining in frequency. The UK's thermal growing season for plants is now longer than at any time since the start of the record in 1772.

7. Winters across the UK have been getting wetter, with a larger proportion of the precipitation falling in the heaviest downpours, while summers have been getting slightly drier. The average rate of sea-level rise during the last century around the UK coastline, after adjustment for natural land movements, has been approximately 1 mm per year. Although the last decade has seen an increase in gale frequency in the UK, this increase is not unprecedented in the historic record.

How will future emissions affect future climate?

8. Much of the change in climate over the next 30 to 40 years has already been determined by historic emissions and because of the inertia in the climate system. We are likely, therefore, to have to adapt to some degree of climate change however much future emissions are reduced. The climate of the second half of the twenty-first century, and beyond, will[1] be increasingly influenced, however, by the volume of greenhouse gases emitted by human society over the coming decades.

9. By the 2080s, the UKCIP02 scenarios suggest that atmospheric carbon dioxide concentrations may[2] be between 525 parts per million (**Low Emissions** scenario) and 810 parts per million (**High Emissions**). This represents an increase from the average 1961-1990 concentration of 334 parts per million of between 57 and 143 per cent, and is between almost two and three times the pre-industrial concentration of 280 parts per million. The atmospheric carbon dioxide concentration in 2002 is about 370 parts per million.

10. Even if global emissions of carbon dioxide eventually fall below today's level, as assumed in the UKCIP02 **Low Emissions** scenario, the future rate of global warming over the

(1) The word 'will' is used in the Executive Summary where we have High Confidence about an outcome (see Box B on p7)
(2) The word 'may' is used where we have less than High Confidence about an outcome.

present century may be about four times that experienced during the twentieth century. If the emissions rate increases to approximately four times today's level – the **High Emissions** scenario – the future warming rate may be about eight times that experienced during the twentieth century.

How will UK climate change?

Annual changes

11. Average annual temperatures across the UK may rise by between 2ºC and 3.5ºC by the 2080s, depending on the scenario. In general, there will be greater warming in the south east than in the northwest of the UK, and there may be more warming in summer and autumn than in winter and spring. Under a **High Emissions** scenario, the southeast may be up to 5ºC warmer in summer by the 2080s.

12. The temperature of UK coastal waters will increase, although not as rapidly as over land, with again the greatest warming in the south. Offshore waters in the English Channel may warm in summer by between 2ºC and 4ºC by the 2080s.

13. Annual average precipitation across the UK may decrease slightly, by between 0 and 15 per cent by the 2080s depending on scenario, although there are likely to be large regional and seasonal differences.

14. Snowfall amounts will decrease significantly throughout the UK, perhaps by between 30 and 90 per cent by the 2080s.

Seasonal changes

15. By the 2050s, typical spring temperatures may occur between one and three weeks earlier than at present and the onset of present winter temperatures may be delayed by between one and three weeks. This is likely to lead to a lengthening of the thermal growing season for plants. The amount of heating and cooling required in buildings will also change.

16. The seasonal distribution of precipitation will change, with winters becoming wetter and summers perhaps drier across the UK and with the biggest relative changes in the south and east. Precipitation in the **High Emissions** scenario may decrease in summer by 50 per cent by the 2080s in the southeast and increase in winter by up to 30 per cent.

17. Summer soil moisture by the 2050s may be reduced by about 30 per cent over large parts of England for the **High Emissions** scenario, and by 40 per cent or more by the 2080s.

Changes in weather extremes

18. High summer temperatures will become more frequent and very cold winters will become increasingly rare. A very hot August, such as experienced in 1995 with average temperature 3.4ºC above normal, may occur as often as one year in five by the 2050s, and three years in five by the 2080s, for the **Medium-High Emissions** scenario. Even for the **Low Emissions** scenario, about two summers in three may be as hot as, or hotter than, the summer of 1995 by the 2080s.

19. Extreme winter precipitation will become more frequent. By the 2080s, winter daily precipitation intensities that are experienced once every two years on average, may become up to 20 per cent heavier. Very dry summers - like 1995 – may occur in half the years by the 2080s, while very wet winters like 1994/95 may occur on average almost once a decade for the **Medium-High Emissions** scenario.

20. A combination of high temperatures and dry conditions in summer will also become more common. By the 2080s, virtually every summer over England and Wales – whether for the **Low Emissions** or **High Emissions** scenario – may be warmer and drier than the summer of 2001.

Other effects on climate

21. As climate warms, specific humidity – the absolute amount of moisture in the atmosphere - will increase through the year, although relative humidity may decrease, especially in summer. Cloud cover in summer and autumn may decrease, especially in the south. Summer sunshine and solar radiation may correspondingly increase.

22. There is much greater uncertainty about future changes in wind speed and direction and we have little confidence about the regional changes in average or extreme wind speeds. It is possible that there will be fewer days of fog in winter, although again this conclusion is not robust.

How will sea level change?

23. As global temperature warms, global-average sea level may rise by between 7 and 36 cm by the 2050s, and by between 9 and 69 cm by the 2080s. The majority of this change will occur due to the expansion of warmer ocean water. It appears unlikely that the West Antarctic ice-sheet will contribute much to sea-level rise during the twenty-first century.

24. Relative sea level (including the effect of land movements) will continue to rise around most of the UK shoreline, the rate depending on region and scenario. By the 2080s, and depending on scenario, sea level may be between 2 cm below and 58 cm above the current level in western Scotland, and between 26 and 86 cm above the current level in southeast England.

25. Extreme sea levels, occurring through combinations of high tides, sea-level rise and changes in winds, will be experienced more frequently in many coastal locations. For some east coast locations, for example, a water level that at present has a 2 per cent probability of occurring in any given year, may have an annual occurrence probability of 33 per cent by the 2080s for the **Medium-High Emissions** scenario. Sea-level rise may also lead to deeper water in the near-shore

zone allowing waves with greater energy to reach the shoreline.

26. Even if concentrations of greenhouse gases in the atmosphere are stabilised, there remains an inescapable commitment to further substantial increases in sea level over many centuries due to the extremely slow response of the oceans to changes in air temperature.

What will happen to the Gulf Stream?

27. The Gulf Stream will continue to exert a very important influence on UK climate. Although its strength may weaken in future, perhaps by as much as 25 per cent by 2100, it is unlikely that this would lead to a cooling of UK climate within the next 100 years since the warming from greenhouse gases will more than offset any cooling from a weakening of the Gulf Stream. (All of the changes in climate described in this report reflect this weakening of the Gulf Stream). Nevertheless, we do not understand enough about the factors that control this ocean circulation to be completely confident about this prediction, especially in the longer-term.

What are the new features of the UKCIP02 scenarios?

28. Users of the UKCIP98 scenarios suggested a number of improvements that would make future scenarios more useful for impacts and adaptation studies in the UK. We have taken these suggestions into account in designing the new scenarios. In particular, we have addressed the four most prominent concerns:

- *the need for greater regional detail* - by basing the UKCIP02 scenarios on a higher resolution (50 km grid) model than was used in 1998 (300 km grid);

- *the need for estimates of changes to extremes of weather and sea-level* - by using the regional model and by providing a larger set of analyses examining changes in such extreme events;

- *advice on the possibility of rapid climate change, in particular a significant change in the Gulf Stream* - by drawing upon new work completed at the Hadley Centre and elsewhere;

- *guidance on how to handle uncertainty* - by explaining and illustrating the relative importance of different sources of uncertainty such as future greenhouse gas emissions, inter-model differences and the representation of feedbacks in models. We have also assigned a relative confidence scale, based on the expert judgement of the authors, to summary statements at the end of relevant chapters.

29. There are two main sources of uncertainty that influence descriptions of potential future climates - uncertainties in future emissions of greenhouse gases (which depend on society's choices), and uncertainties in how the climate system will respond to these emissions (scientific uncertainty). The UKCIP02 climate change scenarios illustrate the range of uncertainty arising from future emissions, but do not illustrate the scientific uncertainty. However, results from other global climate models, albeit at a coarser resolution, are used to reveal and estimate the importance of scientific uncertainty for future UK climate change scenarios.

What are the main differences compared to the UKCIP98 scenarios?

30. The two sets of scenarios are largely consistent, although there are a number of differences. The four UKCIP02 scenarios show slightly larger warming rates over the UK than the four 1998 scenarios, especially for the **Low Emissions** scenario. This is partly because we use a model with a higher effective sensitivity and partly because we now consider the effects of changing sulphate aerosol concentrations. The UKCIP02 scenarios show a higher atmospheric concentration of carbon dioxide for the **Medium-High Emissions** and **High Emissions** scenarios than the 1998 scenarios. This is mainly because the new scenarios assume higher global emissions of carbon dioxide during the twenty-first century. The UKCIP02 scenarios show slightly smaller rates of sea-level rise than the 1998 scenarios, especially for the **High Emissions** scenario. This is because improvements in the way the thermal expansion of ocean waters and the dynamics of land glaciers are modelled suggest that sea-level rise is slightly less sensitive to global warming than was understood to be the case four years ago.

31. The UKCIP02 scenarios suggest that summers may become drier across the *whole* of the UK – not just in England and Wales - and by a larger amount than was the case in the 1998 scenarios. In the 1998 scenarios, spring and autumn became wetter, but the UKCIP02 scenarios suggest these seasons may become slightly drier. For Scotland, the UKCIP02 scenarios show significantly different changes in precipitation patterns compared to earlier scenarios. The new 2002 scenarios suggest different patterns of change in average wind speed compared to the 1998 scenarios. These changes in wind speed are still relatively small, however, and it remains the case that we have little confidence in the simulated changes in the UK wind regime. The UKCIP02 scenarios include a more comprehensive analysis of changes in some aspects of extreme weather and extreme sea levels than was the case with the 1998 scenarios. Since these changes derive from a higher resolution model that simulates extreme weather better than the global model used for this purpose in 1998, in general we have more confidence in the results reported here than those in 1998.

How should the scenarios be used?

32. An examination of all four UKCIP02 climate change scenarios is desirable in any impact assessment or adaptation study. This is especially true for detailed studies relating to major investment decisions, which should also ideally include

an examination of the results from other climate models. For studies where the aim is to scope out the size of the problem, a minimum of two contrasting scenarios should be examined. The UKCIP02 scenarios provide greater detail than was reported in UKCIP98, and many – but not all - of the qualitative results are consistent with the earlier scenarios. Adaptation strategies should be flexible enough to cope with differences between climate model results and between successive generations of climate scenarios.

33. Although the UKCIP02 scenarios are derived from a high-resolution model and the results presented at a resolution of 50 km, users should be wary of over-interpreting the significance of geographical differences over these small scales.

How will climate change research help in the future?

34. Research is currently in progress on several fronts to improve understanding of climate change and our ability to make predictions. This includes work on still higher resolution models, improved representation of important small-scale physical processes and large-scale biogeochemical feedbacks, and new techniques for assigning probabilities of occurrence to different global and regional climate scenarios. Nevertheless, uncertainties about what climate we will experience in the decades ahead will remain considerable for some time to come, not least because of the intractable uncertainty about future global emissions of greenhouse gases and other climate-altering pollutants.

Chapter 1 - An Introduction to the UKCIP02 Climate Change Scenarios

This report for the UK Climate Impacts Programme (UKCIP) describes and presents four possible climate futures for the United Kingdom[3]. The differences between these climate change scenarios are a result of different global emissions scenarios, these differences in emissions in turn resulting from alternative paths of world development. The scenarios therefore illustrate the possible effect on UK climate over the coming century of choices being made around the world about technologies, about lifestyles and about values, all of which affect the future growth in emissions of greenhouse gas and other pollutants.

These four scenarios are not the only possibilities for future UK climate. There are many scientific uncertainties that affect our ability to predict future climate. The current state of knowledge means that only a few of them can be formally and explicitly reflected in our climate change scenarios. These scientific uncertainties are nevertheless very important and may lead to our experiencing a climate somewhat different to the ones presented here. We therefore illustrate and describe in the report the possible effects on UK climate of the most important of these scientific uncertainties.

A brief introduction to choosing and using climate change scenarios in a variety of applications is provided in Appendix 1. Users of the UKCIP02 scenarios are encouraged to read these suggestions.

1.1 Our changing climate

Climate is changing. Our industrial economy, through its reliance on carbon-intensive energy and the associated emissions of carbon dioxide and other greenhouse gases, continues to alter the properties of the Earth's atmosphere, as it has now done for many decades. In less than two hundred years we have increased the atmospheric concentration of these greenhouse gases by some fifty per cent relative to pre-industrial levels. The consequences of this change for the planetary atmosphere are beginning to be felt and as reported by the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) there is now convincing evidence for a growing human influence on global climate. Evidence is also emerging that these changes in climate are altering some of the physical and biological systems of the planet. Given the inertia in our energy systems and the long memory exhibited by the climate system, this human-induced climate change will become increasingly important relative to natural climate variability during the century to come (Figure 1). Efforts to reduce greenhouse gas emissions in the future may well slow the rate of future warming, but during the coming century these efforts will not arrest it completely. There is therefore a pressing need to adapt to climate change. Climate also varies for reasons which are natural. These include volcanic eruptions and changes in solar output for year-to-year and decade-to-decade variations, as well as natural oscillations within the climate system, such as the North Atlantic Oscillation and the El Niño-Southern Oscillation (ENSO). On much longer time-scales such as centuries and millennia, natural changes in the circulation of the world's oceans and in the orbital characteristics of the Earth are known to have had profound impacts on global climate.

There is now convincing evidence for a growing human influence on global climate.

Natural variations in climate will always be with us and there is some prospect that we may eventually be able to develop skilful climate forecasts for periods of up to a decade by exploiting emerging knowledge about the natural causes of climate variation. Predicting the evolution of climate over longer time-scales than this, however, will clearly require us to understand and quantify the increasing role that humans are having on world climate. Climate statistics of the recent past do not provide us with an adequate description of the future. A thirty-year (or even longer) sequence of past weather data - the conventional period established by the World Meteorological Organization to define climate – is insufficient to define the probabilities of certain weather extremes occurring in the future. For a wide variety of planning, management and investment applications we are therefore increasingly aware of the need to predict as accurately as we can not only the seasonal climate variations to be experienced next year or over the next few years, but also the climate change to be encountered over the decades to come. For this purpose we need to use scenarios of future climate.

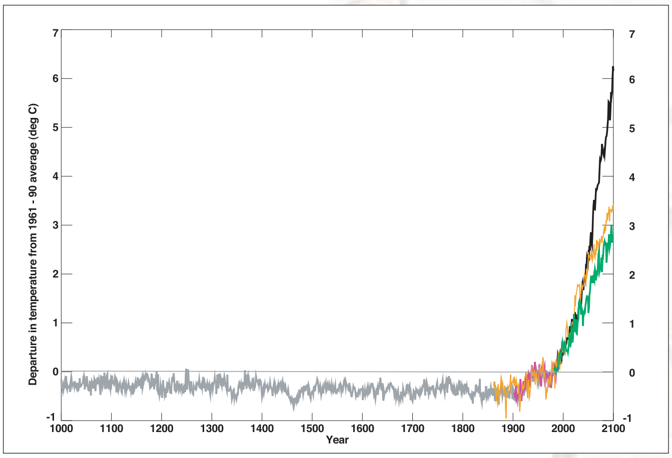

Figure 1: Past and future temperature for the Northern Hemisphere expressed as anomalies from a 1961-1990 average.
= reconstructed from environmental data for 1000 to 1980;
= observed from thermometers for 1901 to 1999;
= a single model simulation for 1860 to 2100 with "observed" natural and anthropogenic forcings to 2000 and then a mid-range emissions scenario from 2000 to 2100;
= a single model simulation for 1981 to 2100 using a low emissions scenario;
= a single model simulation for 1981 to 2100 using a high emissions scenario.
All simulations were carried out using the HadCM3 model. [Source: adapted from IPCC, 2001]

(3) *We also show* model results *for the Republic of Ireland, since the model used covers this territory, but we do not include any analyses involving* observed *data since these were not available to us.*

1.2 What are scenarios?

Scenarios are plausible descriptions of how things may change in the future. For many years, scenarios have been used by businesses, governments and the military as a basis for strategic planning. Scenarios contain plausible estimates of future changes in, for example, economic performance, population patterns and forms of governance. These socio-economic scenarios provide a framework for structured thinking about how the future may unfold. Scenarios should not be construed as being desirable or undesirable in their own right and are usually built as descriptions of possible, although not necessarily preferred, developments. Scenarios can provide a range of possible future greenhouse gas emissions as inputs to global climate model experiments – as used to create the climate change scenarios described in this report. They can also provide the reference information required for the assessment of the impacts of climate change and of the options to adapt - information such as the level of economic activity in different world regions, rates of technological change, or population growth.

As this report shows, the future climate we experience depends to a substantial extent on choices made by societies and individuals about technologies and about lifestyles. Understanding these dimensions of climate change are vital when considering possible mitigation policies and measures, and when designing strategies to allow society to adapt to the changes ahead. Such understanding requires social scientists, economists and engineers, as well as natural scientists, to be involved with policy-makers in the effort of designing, predicting and managing future climate.

A single climate change scenario by itself will not reveal anything about uncertainty.

Any plausible description of future climate will depend upon assumptions about future emissions of greenhouse gases and other pollutants, i.e., will depend on the choice of emissions scenario. All other things being equal, a scenario in which greenhouse gases are low should yield a less rapid climate change than one in which emissions are high. A climate change scenario therefore is a coherent and internally-consistent description of a future change in climate under specific assumptions about the growth of emissions of greenhouse gas and other pollutants and about other factors that may influence climate in the future. A single climate change scenario by itself will not reveal anything about uncertainty, whereas a set of scenarios can be used to illustrate at least some of the uncertainties that effect future climate.

We need also to distinguish between a *climate scenario* and a *climate change scenario*. Climate scenarios are different from climate change scenarios in that they describe possible future *climates* rather than possible future *changes* in climate. Climate scenarios usually – although not always – combine observations about present-day climate with estimates of the change in climate; these changes in climate are most commonly - although not always – constructed using results from global or regional climate model experiments. This report mostly describes future climate change scenarios for the UK. Through the UKCIP web site, however, we also make available four climate scenarios, these having been created by combining the changes in climate described in the report with recent climate observations.

1.3 The UKCIP02 climate change scenarios

The past four years

Since the UKCIP98 climate change scenarios were published in November 1998 there have been many changes in the way climate change has been understood by scientists, perceived by society and responded to by government and business. The scientific understanding of climate change has advanced, these advances being summarised in the Third Assessment Report of the IPCC published in the summer of 2001. For example, climate model experiments can now be conducted without recourse to "flux adjustments" - artificial corrections which stop the climate model drifting away from reality. Advances in computing power have also enabled larger sets of experiments to be conducted using higher resolution global atmospheric models - 150 km resolution rather than about 300 km – and the use of the regional model has allowed information from the 150 km experiments to be resolved at 50 km resolution. The UK can now be represented by 104 grid boxes instead of just four grid boxes as was the case a few years ago. The IPCC have also developed and approved a new range of emissions scenarios, published in the IPCC Special Report on Emissions Scenarios (SRES). These SRES scenarios are based on more complete descriptions of four views of how the world may develop over the coming century and replace earlier emissions scenarios.

The UKCIP98 scenarios have been used widely in climate impacts research throughout the UK and the emphasis on stakeholder-led research within UKCIP has led to them being used in many more different ways and by a larger range of organisations than was the case just four years ago. The summaries in the UKCIP report *"Climate change: assessing the impacts – identifying responses"* published in May 2000 indicate the range of uses of the 1998 scenarios.

Some users continue to require only a semi-quantitative description of future climate representing relatively large regions. Other users increasingly need descriptions of future weather events for smaller areas, or changes in the frequency or severity of future weather events. This places greater demands on the way in which extreme weather events are represented in climate change scenarios. There is also now an increasing interest from some users in using a range of scenarios for options appraisal, in some instances with a desire for explicit probabilities to be attached for use in risk assessment and management exercises. There is also a range of time horizons considered relevant depending on the type of decision to be made by the scenario user. Water companies may be concerned with changing operating conditions over the mid-term (10-50 years), while coastal and building engineers or forestry managers may need to consider

Stakeholder	Decision	Scenario Requirements	UKCIP Study
Countryside and conservation managers	Evaluating and managing a changing natural environment	Guided sensitivity analysis combining historical variations in climate with future changes in climate under a range of scenarios	MONARCH
Regional land use planners	How to assess relative vulnerability and plan for change across different sectors	Regional scenarios with a wide range of climate outputs	Sub-UK and regional assessments
Regional coastal and flood defence managers	Developing a risk assessment for a coastal "cell" or river catchment	Geographically explicit scenarios, showing the likelihood of changes in extreme weather events	RegIS
Water resource managers	Evaluation of the future water supply/demand balance and whether to plan for new resources	Regional scenarios with explicit probability assessment; return period of extreme weather events	CC:DEW

Table 1: Some examples of stakeholder uses for climate change scenarios.

longer-term horizons (50-70 years). Some examples of these different needs are provided in Table 1.

Users of the UKCIP98 scenarios have consistently requested that the next set of climate change scenarios be improved for use in impacts and adaptation assessments by providing:

- greater regional detail;
- estimates of changes to extremes of weather and sea level;
- advice on the possibility of rapid climate change, in particular a "collapse" of the Gulf Stream and possible cooling;
- guidance on the likelihood of possible future climates and how to handle uncertainty.

These developments and new requirements have influenced the design of the UKCIP02 climate change scenarios.

The design of the UKCIP02 climate change scenarios

If we had perfect knowledge of the future and a perfect ability to model the climate system, we would be able to make a single confident prediction of the evolution of future climate. Since we possess neither capability, the next best option would be to present a range of predictions with a precise probability attached to each. This also is beyond our capability at the present time. What we have done is to create four alternative future climates for the UK that reflect a wide range of possible future emissions, that are based on results from a set of experiments using the most advanced climate modelling capabilities in the world, and that are presented at a resolution of 50 km. We are not able to attach probabilities to these four future climates. This design reflects the developments of the last four years – advances in the science of climate modelling; a new set of IPCC emissions scenarios; a larger, diverse and more sophisticated community of users; and specific requests for scenario improvements from these users.

We are not able to attach probabilities to these four future climates.

In order to meet the user requirements, the Hadley Centre for Climate Prediction and Research undertook carefully designed climate change experiments driven by four different emissions scenarios that essentially span the IPCC SRES emissions range. These experiments used a coupled ocean-atmosphere global model (HadCM3; ~300 km grid interval), which indirectly drove a higher resolution atmospheric global model (HadAM3H; ~120 km grid interval), which in turn was used to drive a high resolution atmospheric regional model for Europe (HadRM3; ~50 km grid interval). These models have a 20-year history of development, have been carefully analysed and evaluated over many model generations, and today represent perhaps the most sophisticated set of climate models anywhere in the world. A brief description of the models and the experiments used is provided in Appendix 2.

The main differences and improvements between the design of the 1998 and 2002 scenarios are highlighted in Appendix 3, as well as some of the more important differences in the results. The UKCIP02 climate change scenario design is described in detail in Chapter 3, but eight essential characteristics of the UKCIP02 scenarios are summarised in Box A. Data files containing descriptions of observed monthly climate and information for the four UKCIP02 scenarios are available from a UKCIP web site (see Appendix 4).

The design of the UKCIP02 scenarios and the content of this report is therefore partly a response to the feedback provided by users of the UKCIP98 scenarios and partly a response to developments in climate science and climate modelling.

Although no single set of scenarios can satisfy all needs, nor fully reflect all the uncertainties affecting future climate, the UKCIP02 scenarios described here are nevertheless suitable for many climate change vulnerability, impact and adaptation assessments conducted in the UK. In particular, we have addressed the four priority concerns expressed by users of the 1998 scenarios in the following ways:

- *greater regional detail;* by basing the scenarios on a high resolution model, we present information for the UK at a spatial scale of 50 km compared to about 300 km in the 1998 scenarios. Users should not, however, mistake greater precision for necessarily greater accuracy. We show results over the Republic of Ireland, as well as over the UK, since the model covers this area.

- *estimates of changes to extremes of weather and sea level;* using the regional model allows a better representation of some extreme weather events and we provide a wider set of analyses examining changes in extremes than in 1998.

Box A: The essential characteristics of the UKCIP02 climate change scenarios

- Each climate change scenario assumes a different greenhouse gas emissions scenario. None of these emissions scenarios includes targeted global or national strategies to mitigate climate change through emissions reductions measures and policies; they merely assume different development paths for the world. The range of emissions scenarios chosen closely reflects the range of emissions published by the IPCC in their Third Assessment Report and we have labelled the resulting climate change scenarios as **Low Emissions, Medium-Low Emissions, Medium-High Emissions** and **High Emissions**.

- The effects of natural internal climate variability, greenhouse gas emissions and sulphate aerosols from sulphur dioxide emissions *are* represented in our climate change scenarios. The effects of natural external influences such as unpredictable volcanic eruptions on climate are *not* considered, neither are the possible but unknown effects that future changes in solar activity may have.

- The climate change scenarios are based exclusively on the experiments recently completed using the HadCM3, HadAM3H and HadRM3 climate models. The same hierarchy of climate model experiments is used as the basis for each scenario. No other climate modelling centre has completed the same range, number or sophistication of climate change experiments as the Hadley Centre, whose models are widely recognised as being amongst the most advanced in the world.

- The range of future UK climate represented here derives from different assumed growth rates in global greenhouse gas and other emissions and *not* from uncertainties related to our ability to model climate. The four climate change scenarios do *not* therefore represent the full range of possible future climate change for the UK.

- Some of the reasons why future UK climate may fall outside the range are considered and illustrated in the report. Greenhouse gas emissions may be slightly lower or higher than those we adopt; different climate models simulate different regional climates for the UK to those simulated by the Hadley Centre; our climate models may not be able to simulate all the important complexities and feedbacks that exist within the climate system.

- We assume that global climate model results can be interpreted at the scale of individual grid boxes (typically 300 km), and that regional climate model results can be interpreted at scales of 50 km, although the model is not necessarily accurate at this resolution. We do not *interpret* results at scales smaller than this, although we *combine* the 50 km changes in average climate with a 5 km observed climate data set to produce descriptions of future actual climate at 5 km scale (see Appendix 4).

- The period 1961-1990 continues to be used as the baseline to ensure consistency with previous UKCIP studies. Nevertheless, climate in the UK is already a few tenths of a degree Celsius warmer than this baseline period. Worldwide, 1961-1990 will continue to be used as a reference baseline in climate change impact studies owing to the greater availability of data compared to 1971-2000. The next official 30-year normal period adopted by the World Meteorological Organization will in fact be the period 1991-2020.

- The scenarios contain descriptions of future climate change over the coming century and much of the information is presented for three different time periods – the 2020s, the 2050s and the 2080s. Climate will of course continue to change beyond this century and decisions that we make now that affect the growth of greenhouse gas emissions will strongly influence how this post-2100 climate unfolds. Even though we do not quantify these longer-term changes in climate, we recognise that they may be very important for society.

- *advice on the possibility of rapid climate change, in particular a "collapse" of the Gulf Stream;* new work at the Hadley Centre and elsewhere has enabled us to say more about the behaviour of the Gulf Stream than was possible four years ago, although our knowledge of its complex dynamics remains rudimentary.

- *guidance on how to handle uncertainty;* we discuss the importance of understanding different sources of uncertainty in the following section, the potential size of the uncertainty introduced by using alternative models in Chapter 3, and an illustrated discussion of a wider set of uncertainties in Chapter 7. We also use, in Chapters 4, 5, and 6, a relative confidence scale when making key statements about aspects of future UK climate.

The UKCIP02 climate change scenarios have also been designed to be used in conjunction with the socio-economic scenarios produced for UKCIP in June 2001 (*"Socio-economic scenarios for climate change impact assessment"* - available from UKCIP), which were in turn based on the 1999 Foresight and 2000 SRES scenarios (see Appendix 5).

Future climate change offers us a challenge to innovate in design and in the way we live. © M. Robinson.

UKCIP provides guidance to researchers on how to use the UKCIP climate change scenarios in impacts and adaptation studies. For UKCIP studies, the Programme offers individual advice, tailored to the needs of the study. In addition, two forthcoming UKCIP publications will provide information relating to the use of the climate change scenarios:

- a UKCIP Technical Report, *"Guidance on handling risk and uncertainty in decision-making for climate change"*

- a short report that describes how to undertake a UKCIP study and provides guidance on how to use the range of UKCIP tools. This document will explain how the climate change scenarios, socio-economic scenarios, guidance on risk and uncertainty and costings methodology, can be used together.

Figure 2 shows a generic framework for conducting integrated assessments of climate change for policy applications and indicates where climate scenarios fit into this framework. The diagram also shows, for the case of the United Kingdom, which organisation has primary responsibility for different components of the national framework.

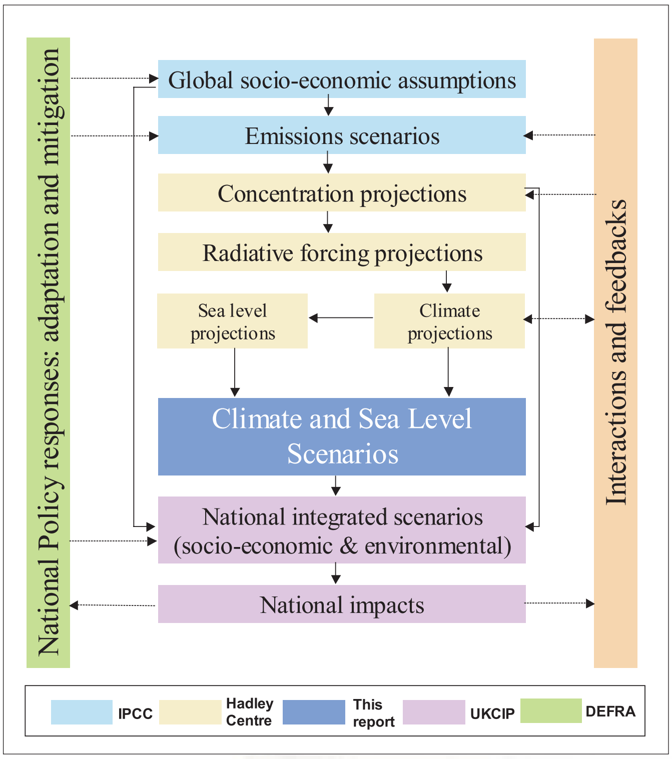

Figure 2: The position of climate scenarios as one component of a framework for conducting integrated assessments of climate change for policy applications. The key suggests the main roles of different organisations in this framework as it applies to the UK. [Source: adapted from IPCC, 2001].

1.4 Uncertainties

The report describes how the climate of the UK may change during the twenty-first century. We say "may change" rather than "will change" because we do not know for certain what will happen to our climate for two main reasons. We do not know what will happen to future global emissions of greenhouse gases and aerosol precursors; nor do we know for sure what effects such future emissions will have on our climate. The first of these uncertainties can be thought of as a consequence of the many possible paths that future society may follow, or *emissions uncertainty;* the second can be thought of as uncertainty about our understanding of how the climate system works, or *scientific uncertainty*.

Emissions uncertainty

The four UK climate change scenarios described in this report clearly illustrate how important emissions uncertainty is for the future climate of the UK. Each climate change scenario is based on a different emissions scenario published by the IPCC SRES. Following the recommendations of the IPCC, we make no attempt to assign probabilities to any one of the four climate change scenarios. Each scenario is based on a different set of assumptions about how the world develops; how likely the scenario is depends on how valid one regards the assumptions to be.

Since these emissions scenarios range from a low growth in global emissions to a high growth, the resulting differences in climate illustrate for the UK just how much the climate we may experience by the end of this century depends on the path and nature of future world development. Differences between emissions scenarios have relatively little effect on the climate we will experience over the next 30 to 40 years – climate warms by roughly the same amount in each case since climate change over this period has already largely been determined by past and current emissions. The different emissions scenarios do make, however, an increasingly large difference to the evolution of climate during the remaining decades of this century, and beyond.

Scientific uncertainty

In contrast to emissions uncertainties, the four UK climate change scenarios described in this report reveal little about how scientific uncertainties affect our description of future climate. This is because each climate change scenario uses results from the *same* hierarchy of climate models developed by the Hadley Centre. Although this hierarchy of models represents the most comprehensive suite of climate models in the world, the model experiments used for our scenarios do not allow a full quantitative description of the sensitivity of future climate to the range of scientific uncertainties. To do this one would need to explore a much larger sample of models, or variants of the same model, both from other modelling centres and from the Hadley Centre. At the time our scenarios were designed, there were no other results from regional models over Europe using SRES emissions scenarios that were known to us.

In the absence of results from other regional climate model experiments, we explored a number of ways in which high resolution regional scenarios could be generated that reflected the results from other *global* climate models. We did not find a scientifically acceptable and quantitative way of doing this. We nevertheless recognise the importance of modelling uncertainties for descriptions of future climate – both at national and sub-national scales - and the report goes to some length to illustrate and describe, both in Chapter 3 and again in Chapter 7, what we can say at present about these uncertainties. Although some advances are being made towards the goal of fully probabilistic descriptions of future regional climate at a 50 km resolution which formally quantify many of these scientific uncertainties, such descriptions remain unattainable at the present time. The UKCIP02 climate change scenarios represent a major advance from the 1998 scenarios; yet they must still be used within their limitations.

The UKCIP02 climate change scenarios represent a major advance from the 1998 scenarios; yet they must still be used within their limitations.

The UKCIP02 climate change scenario report

The report therefore not only presents the four UKCIP02 climate change scenarios, it also identifies the most important scientific uncertainties that constrain our efforts to predict future climate accurately, and assesses their possible significance. The report provides illustrations of alternative future UK climates using results from other climate modelling centres around the world and from earlier versions of the Hadley Centre models. Different models show somewhat different climate responses over the UK to future greenhouse gas emissions, although a number of the simulated changes are common to most models. We strongly recommend that any detailed climate change adaptation strategy explores this wider range of uncertainty and takes into account some of these other results. Appendix 1 and the web sites listed on the inside back cover help users to explore these additional uncertainties for their studies. We also assist users to evaluate the significance of the information presented in the report by adopting a structured system for attaching relative levels of confidence to some of the more important conclusions we reach about future climate change in the UK (see Box B).

1.5 The structure of the report

The report first summarises (Chapter 2) trends in global climate and examines the causes of the recent warming. We also describe recent trends in UK climate, including updates of long time series of temperature, precipitation and gales, and new work on precipitation intensity, the North Atlantic Oscillation and aspects of the marine climate. A new 5 km resolution observed monthly climate data set for the UK covering the period 1961 to 2000 is also introduced. Chapter 3 describes the future emissions scenarios used in the report, and presents the corresponding future carbon dioxide concentrations and changes in global temperature. These are compared and contrasted with the global-scale scenarios adopted in the UKCIP98 report. This Chapter also describes how the four UKCIP02 scenarios were constructed and places these scenarios in the context of results obtained from other climate modelling centres. From this inter-comparison we present some suggestions for users to adopt when exploring the effects of these uncertainties on their particular application.

Chapter 4 presents the range of UKCIP02 climate change scenario outcomes for average seasonal climate for several variables such as precipitation, temperature, humidity, solar radiation, soil moisture and average wind speed. This is a significant improvement on the UKCIP98 report which provided such detail for only one scenario. We also compare the 2002 and 1998 scenarios, indicating where there is consistency between the two sets of scenarios and where there are differences. In Chapter 5 we explore changes in the UK daily climate, providing analysis of return-periods and probability of occurrence for daily extremes of precipitation, temperature and wind speed. This again extends beyond the

Box B: Levels of confidence

In the Executive Summary, and in the summary tables at the end of Chapters 4, 5 and 6, the authors attach levels of relative confidence to a selected set of largely qualitative statements made about future change in UK climate. They are:

- **High Confidence**
- **Medium Confidence**
- **Low Confidence**

These relative levels of confidence are judgements made by the authors of this report, using three different criteria:

- our knowledge of the physical reasons for the changes
- the degree of consistency between different climate models
- an estimate of the statistical significance of the results

Statements in the report conditioned in this way should be interpreted as revealing the relative confidence the *authors* have that a given statement is true. These levels of confidence do not have a formal numerical scale associated with them – they are expert judgements and are therefore relative not absolute. We restrict our use of these levels of confidence to broad qualitative conclusions, and do not attempt to apply them to every statement that we make about future climate, especially quantitative ones. Thus we might attach **Medium Confidence** to the statement, " … there are increases in winter cloud cover", but we would not attach a specific confidence level to a statement such as, " … the 10-year return period daily precipitation intensity in winter over western Scotland increases by 20 per cent".

In adopting categories such as these we follow a similar, but not identical, approach to that adopted for the IPCC Third Assessment Report - the specific scheme used here is our own.

analyses presented in the 1998 report. Changes in aspects of sea level and marine climate around the UK, including sea-surface temperatures and extreme sea levels, are also new to the UKCIP02 report and are described in Chapter 6. In concluding tables in each of Chapters 4, 5 and 6, we attach levels of relative confidence to the key statements made in each chapter.

The wider issues surrounding uncertainties in the design of scenarios and in climate modelling are discussed in Chapter 7. This discussion emphasises again the distinction between uncertainties associated with future greenhouse gas emissions and uncertainties associated with our understanding, and our models, of how the climate system works. We show results from an earlier version of the Hadley Centre regional climate model to emphasise that advances in climate modelling often, if not always, lead to differences in the simulated climates, even if the emissions scenario remains the same. Chapter 8 briefly examines the implications for UK climate of possible strategies to mitigate climate change and Chapter 9 concludes the report with a summary of future work that should lead to improvements in climate change scenario design and construction in the years ahead.

Important scientific references for the data, models and methods used in this report are provided in the bibliography, and a glossary of the more important terms is provided in Appendix 6. Generally, the appendices cover a number of more detailed issues - for example, the descriptions of the emissions scenarios, the construction of the observed climate data set and other sources of climate change scenario data. Many of the results presented in this report are supported with a larger set of maps and data files on an accompanying website operated by UKCIP, details of which are summarised in Appendix 4.

Chapter 2 - Recent Trends in Global and UK Climate

2.1 Global warming and its causes

Many aspects of the world's climate are changing, but global-average surface temperature is the dimension which is changing most clearly. Global temperature has risen by about 0.6ºC since the beginning of the twentieth century (Figure 3), with about 0.4ºC of this warming occurring since the 1970s. 1998 was the single warmest year in the 142-year global instrumental record and 2001 was the third warmest. Some other aspects of the changing global climate are summarised in Box C.

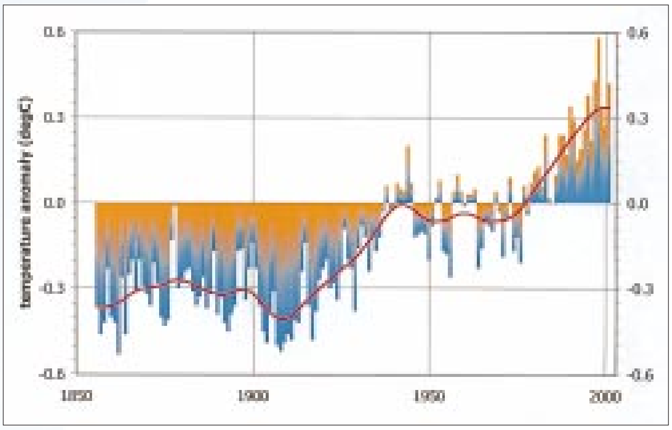

Figure 3: Global-average surface temperature (1860 to 2001), a combination of surface air temperature over land and sea-surface temperature over the oceans. Individual bars show annual values as deviations from the 1961-1990 average; the curve emphasises variations over time-scales of at least 30 years. This data set is maintained by the Hadley Centre and the Climatic Research Unit at UEA and has been used in all IPCC Assessments.

This warming could have been due to a number of causes, some human in origin and some natural. We know that the Earth's climate changes substantially between an ice age and an inter-glacial period (such as the one we are currently enjoying), but these changes occur over time-scales of a thousand years or more and are almost certainly triggered by changes in the Earth's tilt and its orbit around the sun. The Earth's climate also varies naturally as a result of interactions between the ocean and the atmosphere which cause variations in climate from year-to-year, from decade-to-decade and from century-to century. Reconstructions of Northern Hemisphere climate over the past 1,000 years reveal such variability. The warming observed over the past 100 years is clearly larger than these natural variations in climate (see Figure 1 in Chapter 1), suggesting that the recent rise in temperature cannot be solely due to natural variability of the climate system. But what is responsible for the warming?

The recent rise in temperature cannot be solely due to natural variability of the climate system.

Two other natural (and external) factors could be important - changes in the energy output of the sun (which is the driving force for the whole climate system) and explosive volcanoes. These volcanic eruptions emit sulphur gases and various particles into the stratosphere, where they form long-lasting droplets that can cool climate for two-to-three years. The effects of these two factors on historical climate have been examined by using the Hadley Centre model to simulate global climate from 1860 to 2000. Estimated changes in both solar energy and volcanic emissions were used as basic drivers of the experiment. Figure 4 (top panel) shows that, although these natural factors can explain some of the decade-to-decade changes in climate - for example the warming during the early twentieth century – alone they cannot replicate the warming observed over the last 40 to 50 years.

Box C: Some observed changes in global climate

The Third Assessment Report of the IPCC assessed the results of many hundreds of studies undertaken around the world over recent years which examined the evidence for changes in local, regional and global climate. Here, we summarise just a few of the most important conclusions from that assessment about recent observed changes in global-scale climate:

- Over the last half-century, night-time temperatures have increased over many land areas at about twice the rate of day-time temperatures.
- This decrease in the diurnal temperature range is consistent with observed increases in cloud amount, precipitation and total water vapour.
- The length of the freeze-free season in many mid-to-high latitude regions has increased and growing seasons have extended in many Northern Hemisphere mid-latitude regions.
- More intense precipitation events have been observed over many Northern Hemisphere mid-to-high latitude land areas.
- Northern Hemisphere sea-ice amounts are decreasing and there has been a substantial thinning of Arctic sea-ice in late summer to early autumn over recent decades.
- There is a near worldwide decrease in mountain glacier extent and ice mass, consistent with surface temperature increases.
- Sea level increased by about 20 cm between 1900 and 2000.

Over the last one to two hundred years, human activities have also affected climate. Increased concentrations of greenhouse gases such as carbon dioxide (from fossil fuel burning and deforestation), methane (from agriculture and natural gas leakage), and ozone in the lower atmosphere (from the products of vehicle exhausts), trap more energy in the lower atmosphere and thus warm climate. In contrast, different types of aerosols - small particles or droplets – mostly act to cool climate[4] For example, sulphates derived from sulphur dioxide emitted from fossil fuel burning will directly scatter back solar radiation; they can also make clouds brighter which adds to their cooling effect. Large-scale land-cover changes are a third way humans may influence regional climate. Changes in these human factors – except land-cover - were again used to drive the same Hadley Centre model. For these experiments the recent rise in temperature was well replicated, but not the early twentieth century warming (Figure 4, middle panel).

Only when *both* sets of factors - human and natural - were included (Figure 4, bottom panel), could the model produce an adequate simulation of the course of global temperature over the entire 140-year period. This is not conclusive proof that we can attribute recent global warming to human activities – there may be errors in the model or the various forcing factors may have cancelled each other – but it is one piece of evidence we may use when making judgements about the role of humans in causing global climate change.

In addition to examining the changes in *global-average* temperature, the attribution of recent climate change to human activities has also been explored using the *patterns* of observed temperature change. The patterns used have been geographical – changes in temperature across the surface of the Earth - and also vertical – changes in temperature through the depth of the atmosphere as measured by instruments on meteorological balloons and from satellites. This is a much more powerful method than using just global-average temperature alone and has allowed the proportion of temperature rise due to the various factors mentioned above to be estimated – although the error bars are large. Using pattern-correlation techniques the estimate is that, over the period 1947 to 1997, a warming of between 0.35ºC and 0.95ºC has been produced by greenhouse gases originating from human activities. This is partly offset by a cooling of between 0.05ºC and 0.25ºC caused by aerosols of human origin (Figure 5). The combined effect of volcanoes and solar changes is estimated to be quite small, and hence a large part of the 0.25ºC to 0.55ºC warming over this period is likely to be attributable to human activities. Although this analysis has been carried out on a global scale, it is not unreasonable to suppose that at least part of the climate warming observed over the UK (as exemplified by the Central England Temperature and Scottish Islands records shown in Figure 6) can also be attributed to human activities.

A large part of the warming is likely to be attributable to human activities.

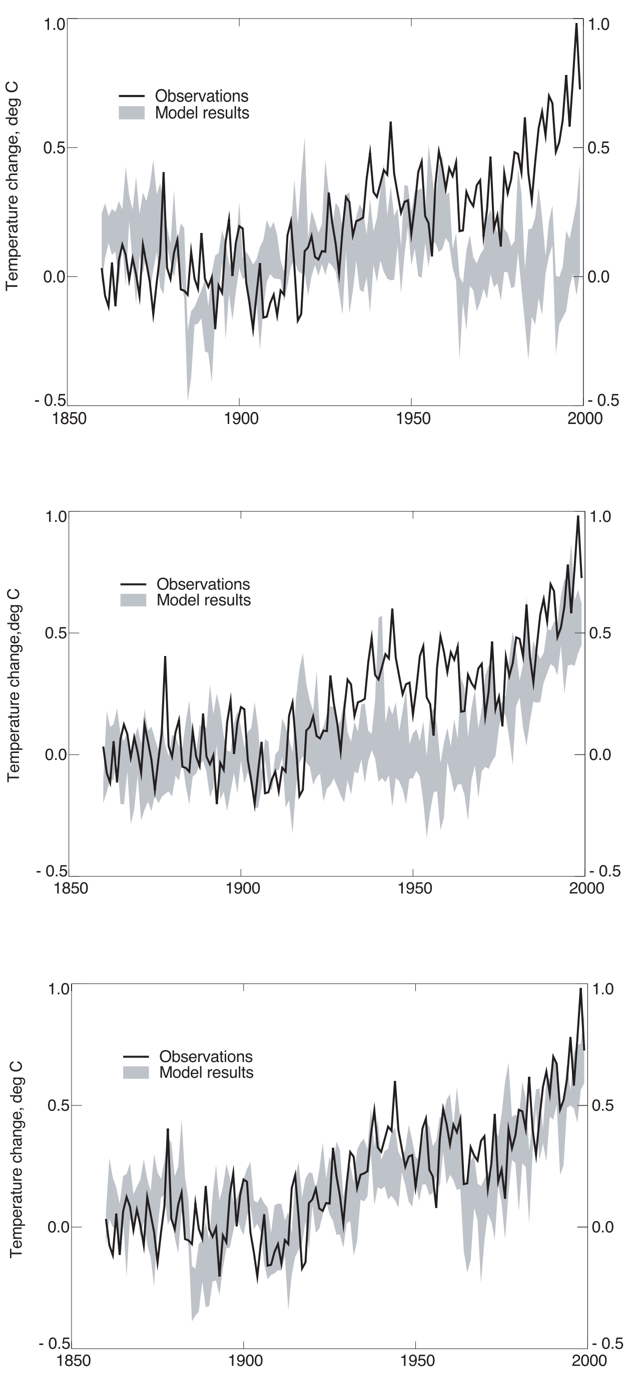

Figure 4: Observed changes in global-average temperature from the 1880-1920 average (black line) compared to that simulated by the model (grey shading) taking into account natural factors (top), human factors (middle), and both sets of factors (bottom). [Source: Peter Stott].

(4) Black soot on the other hand warms climate, but this effect is not considered in the model experiments used for this Report.

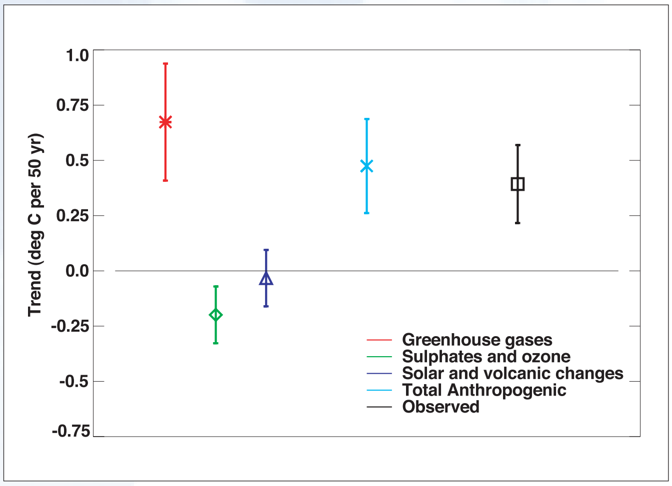

Figure 5: Estimates of contributions to global-average warming, 1947-1997, due to greenhouse gases and aerosols of human origin, and due to natural factors, solar changes and volcanoes. The sum of the human factors is close to the observed temperature increase of 0.4ºC over this period. [Source: Hadley Centre]

2.2 Long-term trends in regional temperature

Variations in temperature, when averaged over a year or decade, are often similar over distances of many hundreds of miles, so temperature has often risen and fallen simultaneously in different parts of north-west Europe. The warming of global climate over the last 140 years has been accompanied by a regional warming in north-west Europe - the Low Countries, Central England (including each individual season), and the Scottish Islands are all warmer now than at any time since each of these independent records began (Figure 6). Of the sixteen warmest years in Central England since 1659, no fewer than eight have occurred since 1989.

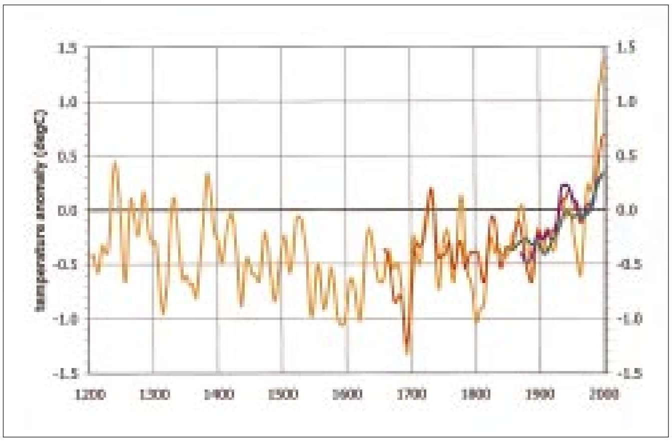

Figure 6: ■ = Annual surface temperature for the world (1861 to 2001), ■ = the Low Countries (1205 to 2000, source: Aryan van Engelen), ■ = Central England (1659 to 2001), ■ = Scottish Islands (1881 to 1999, source: SNIFFER report), all expressed as deviations relative to the 1961-1990 average. All curves are smoothed to emphasise variations over time-scales of at least 30 years. Note: the Low Countries temperature is an average of summer and winter temperature.

The twentieth-century warming over Central England resulted in a lengthening of the thermal growing season[5] by about one month (Figure 7). Most of the increase took place in two distinct phases - between 1920 and 1960 (on average 0.7 days per year) and between 1980 and 2000 (on average 1.7

Frosty spells have decreased in severity, allowing longer thermal growing seasons. © M Robinson.

days per year). The lengthening in the earlier period was due both to an earlier onset of spring and to a later onset of winter, whereas most of the recent lengthening has arisen from an earlier onset of spring (on average 1.5 days per year). The longest thermal growing season in the 230-year daily Central England series occurred in 2000, when it extended for 328 days from 29 January to 21 December. The thermal growing season for this region of the UK is now longer than at any time since the start of the daily temperature series in 1772.

The thermal growing season is now longer than at any time since 1772.

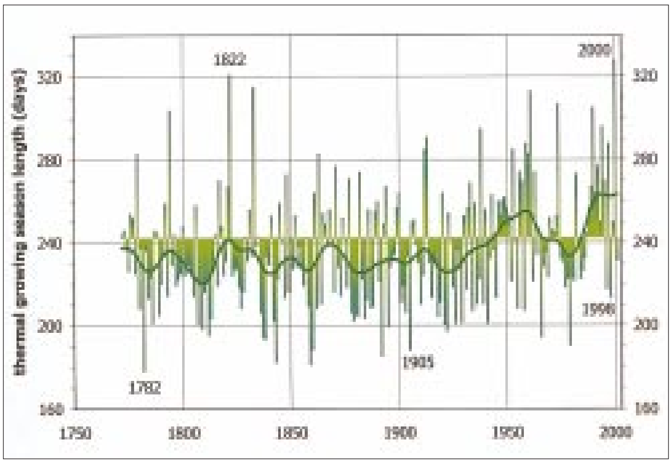

Figure 7: The length of the thermal growing season in Central England (see Box G on p.69 for definition). The bars emphasise deviations in duration from the 1961-1990 average (242 days). The smooth curve emphasises variations on time-scales of at least 30 years.

(5) See Box G on p69 for definition.

The warming of UK climate has also had consequences for daily temperature extremes. An increase in the frequency of "very hot" days in Central England has occurred since the 1960s (Figure 8), with a number of particularly extreme summers being experienced – 1976, 1983, 1990 and 1995. Extremes of temperature – whether intense cold in winter or intense heat in summer - often have their greatest impact, however, when they are sustained over a number of days. "Coldwaves" became less frequent during the twentieth century, particularly during March and November, whereas "heatwaves" became more frequent, particularly during May and July (Figure 9).

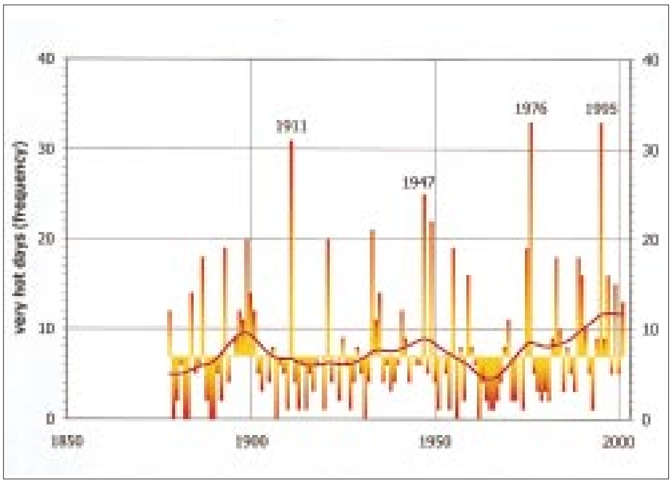

Figure 8: The frequency of "very hot" days, as measured by the number of days when the Central England maximum temperature exceeded 25°C. The bars emphasise deviations from the 1961-1990 average (6.9 days). The curve emphasises variations over time-scales of at least 30 years.

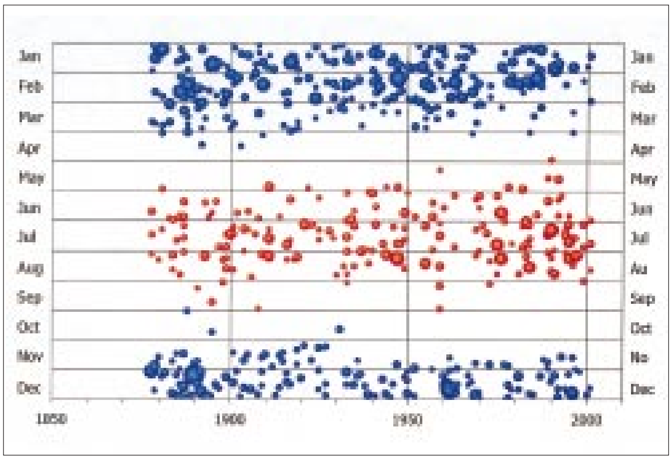

Figure 9: The occurrence of "heatwaves" (red) and "coldwaves" (blue), 1878 to 2001, as measured by a sequence of at least five consecutive days when the Central England maximum temperature exceeded 22°C (heatwave), or when the minimum temperature dropped below 0°C (coldwave). The area of each circle is proportional to the length of the sequence.

In Central England, the 1990s decade (1991 to 2000) was exceptionally warm by historical standards and about 0.5ºC warmer than the 1961-1990 average. Since 1990, new records have been set in the 343-year Central England temperature series for – the two warmest years (1990 and 1999), warmest summer half-year (1995), warmest winter half-year (1994-95), warmest August (1995), warmest October (2001) warmest November (1994), and the warmest 12-month period (November 1994 to October 1995).

The frequency and severity of hot spells has increased, resulting in increasing discomfort in the urban environment. © M Robinson.

2.3 Long-term trends in precipitation and snow cover

Unlike annual temperature, there are no long-term trends apparent in the amount of annual precipitation the UK receives, whether measured over England and Wales (Figure 10) or over Scotland (Figure 11). There is, nevertheless, considerable variability in the annual precipitation amount between individual years and decades. For example, in 2000 – the wettest year in England and Wales in the twentieth century and the third wettest since records began in 1766 – there was 63 per cent more precipitation than in 1996, a recent relatively dry year. The year 2000 also included the wettest autumn in the England and Wales series, when very nearly twice the seasonal average of 257 mm was recorded. Many of the wettest and driest years are common across the UK (for example a dry 1933 and a wet 1872) and wet or dry decades also often occur simultaneously. This indicates that the large-scale changes in circulation – such as the North Atlantic Oscillation – that regulate precipitation variability are generally effective across the whole UK. Exceptions include the 1870s (only England and Wales) and the last 20 years (only Scotland), both periods being unusually wet.

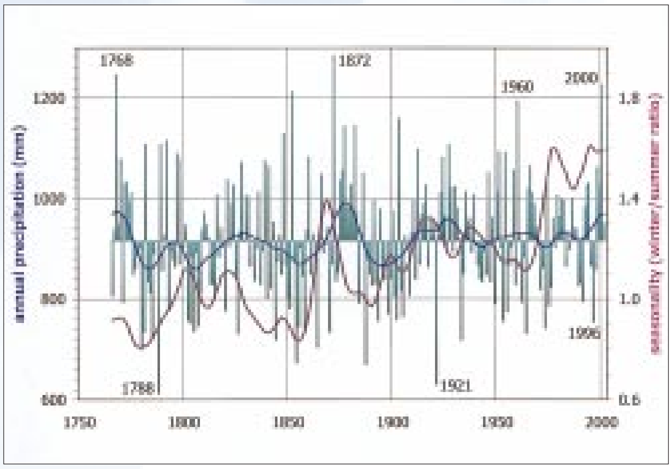

Figure 10: Annual precipitation (mm; 1766 to 2001) over England and Wales - the bars emphasise annual deviations from the 1961-1990 average (916 mm), and the blue curve emphasises variations on time-scales of at least 30 years. The purple curve is the ratio between winter and summer precipitation, smoothed to emphasise variations on time-scales of at least 30 years.

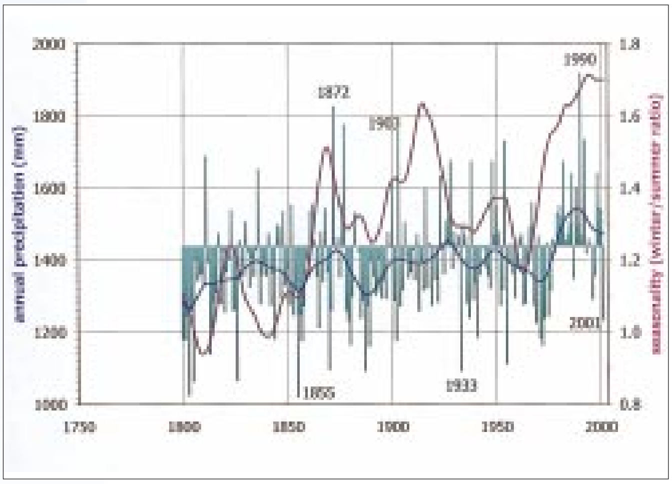

Figure 11: Annual precipitation (mm; 1800 to 2001) over Scotland - the bars emphasise annual deviations from the 1961-1990 average (1430 mm), and the blue curve emphasises variations on time-scales of at least 30 years. The purple curve is the ratio between winter and summer precipitation, smoothed to emphasise variations on time-scales of at least 30 years [Source: Keith Smith; updated].

Although there is no long-term trend in *annual* precipitation, there is a trend in the *seasonality* of UK precipitation. The proportion of precipitation received in winter relative to summer has changed over time, so that winters have never been as wet relative to summers in about 240 years of measurements as they have been over the last 30 years – winters have been getting wetter and summers have been getting drier. For example, between the period 1770 to 1800 and the period 1970 to 2000, annual precipitation in England and Wales increased by only 24 mm, yet winters became 55 mm wetter and summers 45 mm drier. Perhaps more important than changes in the total volume of precipitation received, are trends in the intensity of short-duration precipitation. The contribution of the most intense rainstorms to total winter precipitation has increased across the whole country during the last 40 years (Figure 12). Also increasing has been the proportion of winter precipitation that falls in five day or longer sequences of "heavy" rain. In summer, the opposite has occurred and the contribution of intense rainstorms to the summer total has decreased. There are less consistent and generally smaller trends in precipitation intensity in spring and autumn.

Winters have been getting wetter and summers have been getting drier.

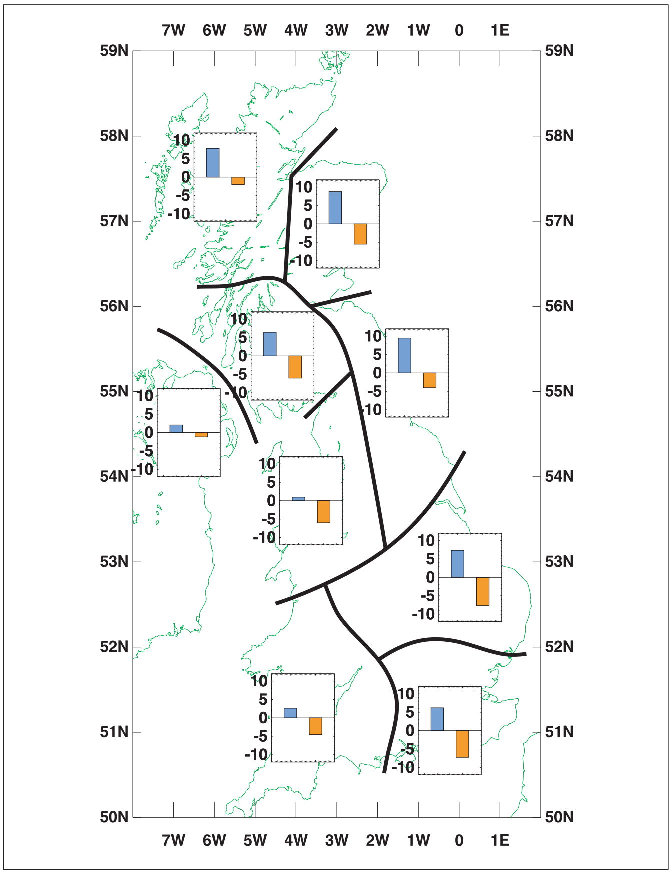

Figure 12: The trend (1961 to 2000) in the fraction of the total seasonal precipitation contributed by the "most intense" precipitation events in winter (left-hand bars) and in summer (right-hand bars) for a number of UK regions. Positive (blue) numbers indicate an increasing trend in the proportion of the total precipitation that comes from the "most intense" events, i.e., "most intense" events are increasing either in frequency or in intensity. The lower bound to the class of "most intense" events is defined (separately for each season and region) by an amount (mm) calculated from the 1961 to 1990 period, namely the daily precipitation exceeded on a minimally sufficient number of days necessary to account for precisely 10 per cent of the seasonal precipitation. [Source Tim Osborn]

Changes in snow climate are particularly important for upland Britain, and can affect winter transport throughout the UK. The relationship between total precipitation, snow cover and temperature is not straightforward. Increased winter precipitation over high land might imply greater snow cover; but this might be compensated by warmer temperatures which alter the ratio of snow to rain. Changing thermal regimes may also affect the snow-lie season. The best data on snow cover in the UK comes from Scotland and Figure 13 shows a regional index of the duration of winter snow-lie based on five representative long-term Scottish stations. Although there is no sustained long-term trend in this index over the full 40-year period, there has been a decrease in the number of snow-lie days since the early 1980s. For example, since the winter of 1987/88 there have been only three winters in Scotland with above average snow cover duration.

A common winter scene in the past, but winter snow is becoming rarer.
© M Robinson.

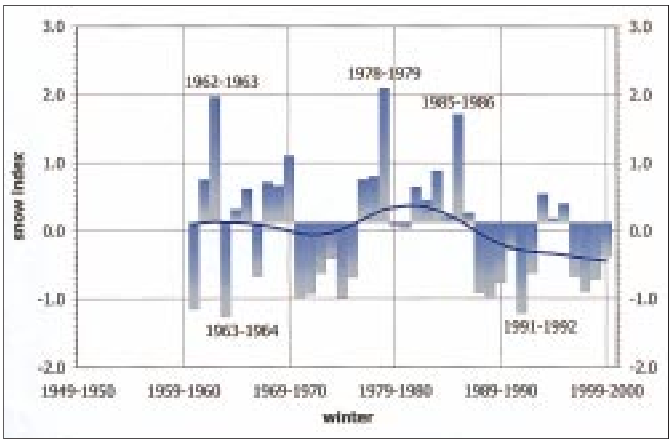

Figure 13: Variation in the Scottish winter snow cover duration index between winters 1960/1961 and 1999/2000. The bars emphasise deviations from the 1961-1990 average (0.12). Units are normalised. The smooth curve emphasises variations on time-scales of at least 30 years [Source: John Harrison].

2.4 Long-term trends in circulation patterns and gales

Many aspects of UK winter climate are strongly influenced by the North Atlantic Oscillation (NAO), an oscillation in the pressure gradient between the Azores and Iceland. When the NAO is positive, the airflow across the UK is more westerly (i.e., from the Atlantic), and hence the winters are windier and wetter, but milder. When the NAO is negative, winds are less westerly (i.e., more often from the continent) and the winters are drier and less windy, but colder. The strength of the NAO varies from one winter to the next, but there are sometimes periods of several years when the NAO stays in a particular phase (Figure 14).

Most severe gales over the UK occur in the winter half of the year and hence there is some correspondence between the NAO index and the frequency of such gales - both increased, for example, between the 1960s and 1980s (Figure 14). There were, however, a number of years at the end of the nineteenth century and early in the twentieth century which also experienced many severe gales and the NAO index was also high during this period. The evidence for the recent increase in gale frequencies over the British Isles being related to human-induced warming remains unconvincing.

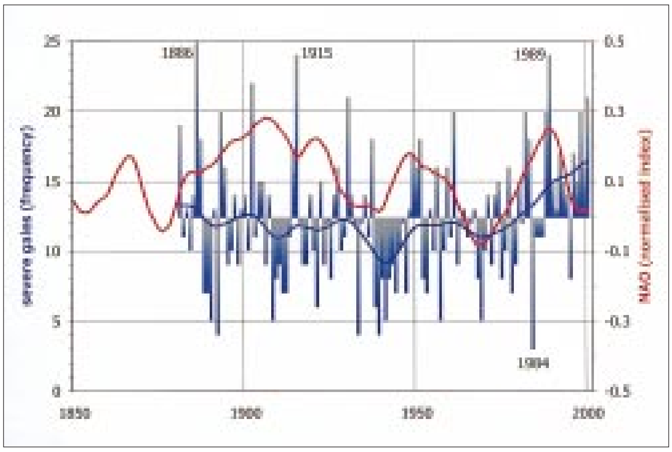

Figure 14: The annual frequency of severe gales over the UK for a July-June year (1881/82 to 2000/01). The bars emphasise deviations from the 1961-1990 average (12.5 gales), and the blue curve emphasises variations over time-scales of at least 30 years. The red curve is the normalised July-June index of the NAO (1850/51 to 2000/01), smoothed to emphasise variations over time-scales of at least 30 years.

2.5 Long-term trends in marine climate and sea level

Sea temperatures in UK coastal waters are affected by interactions between the ocean and the overlying atmosphere and, especially in the shallower regions of the Irish and North Seas, by freshwater run-off. The longest continuing records of sea-surface temperature in UK waters for specific locations (Dover, Eastbourne and Port Erin) show an increase in annually-averaged temperature of about 0.6ºC over the last 70 to 100 years, consistent with the warming observed over land. A broader picture of changes in sea-surface temperature in UK coastal waters can be obtained by extracting information from a global marine temperature database. This is shown in Figure 15 and also reveals that sea-surface temperature has increased by about 0.5ºC during this period, with a substantial increase over the last 20 years. The few long-term records of salinity for UK waters do not indicate any significant long-term trend.

Global-average sea level rose by about 1.5 mm per year during the twentieth century, believed to be due to a number of factors including thermal expansion of warming ocean waters and the melting of land (alpine) glaciers. There was negligible influence from the Greenland and Antarctic ice sheets. Although the rise in relative sea level around the UK during the twentieth century (Figure 16) is partly due to land movements, it is also partly a reflection of this climate-induced rise in global sea level. After adjustment for natural land movements, the average rate of sea-level rise during the last century around the UK coastline was approximately 1 mm per year. On the other hand, evidence from Liverpool and Newlyn - two of the longest records in the UK, although both on the west coast - reveals no long-term (century time-scale) change in UK storm-surge statistics.

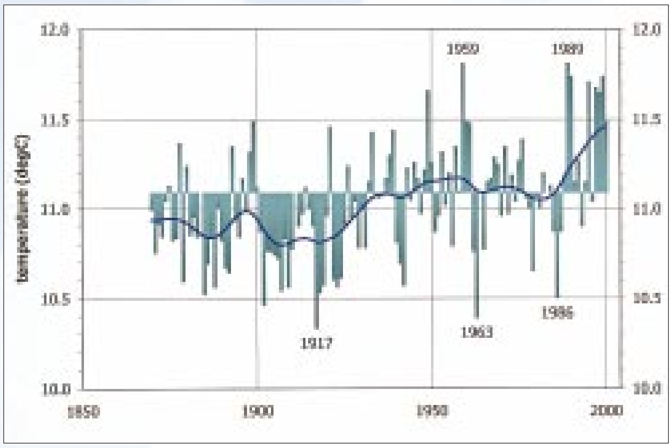

Figure 15: Annual sea-surface temperature averaged around the UK coastline for the period 1871 to 2000. Annual deviations are from the 1961-1990 average (11.1C); the smooth curve emphasises variations over time-scales of at least 30 years. [Source: Hadley Centre, HadISST1.1].

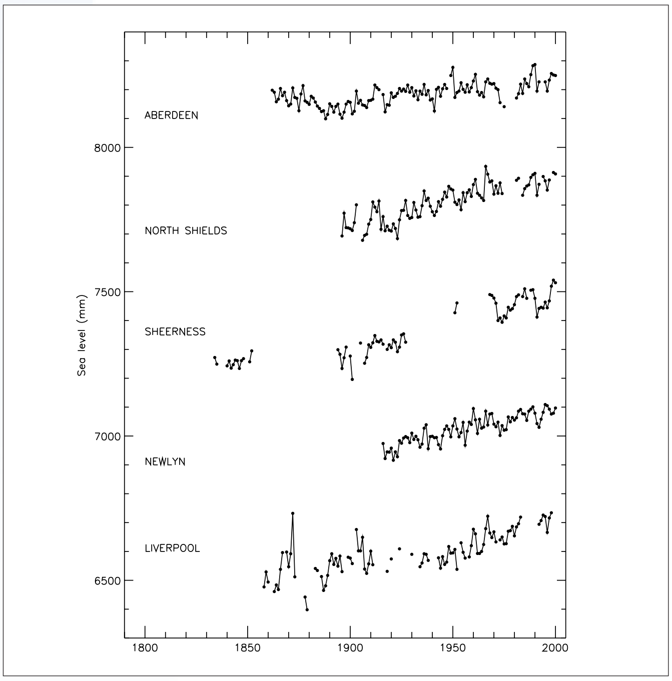

Figure 16: Changes in annual relative sea level (mm scale) recorded by tide gauges at five locations around the UK coastline. Data are unadjusted for natural land movements. Note that each time series has been offset vertically for presentation purposes. [Source: Philip Woodworth].

The heights of waves are dependent on wind strengths over the ocean so, as with gale frequencies, wave heights around the UK are also related to the behaviour of the North Atlantic Oscillation. The information used here comes from a combination of direct measurements of wave heights in UK waters (1960s to present), and inferences drawn from pressure and tide gauge data (1880 to present). These data show large spatial and temporal variability in wave height, the average varying from 0.5 m to 5 m depending on season and location around the UK. Although there were not any trends over the twentieth century as a whole, the wave climate roughened between the 1960s and the 1990s.

Over the northern North Sea, for example, for the period January-March there has been an upward trend in average significant wave height over the last 30 years. The extent of the variability in wave heights from one decade to the next over a wider area of the North Atlantic based on satellite measurements is illustrated in Figure 17, suggesting an increase in average wave height of 10 to 15 per cent around the UK coastline between the 1980s and 1990s. As indicated in the 1999 JERCHIO report, the roughening wave climate over the last 40 years is likely to be a consequence of a change in the strength of the North Atlantic Oscillation.

The roughening wave climate is likely to be a consequence of a change in the strength of the North Atlantic Oscillation.

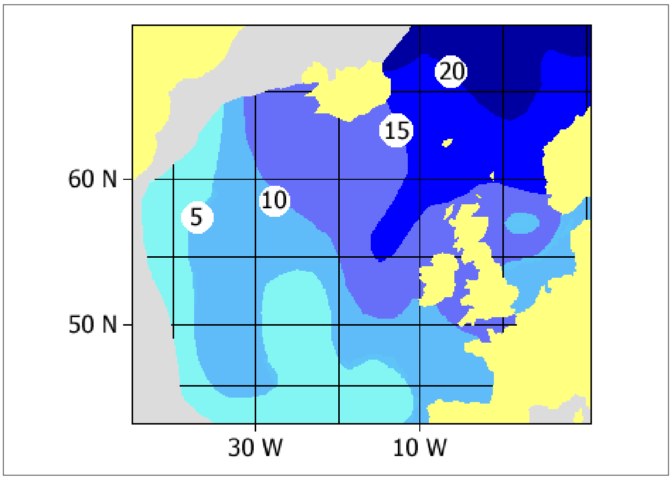

Figure 17: The percentage increase in the significant wave height (i.e., the average height of the highest third of the waves) in the North Atlantic in winter (December-February) between the periods 1985 to 1989 and 1991 to 1996. Note the short periods over which data are averaged. [Source: JERICHO report].

2.6 Average 1961-1990 climate in the UK

The baseline period for the scenarios presented in this report is the conventional 30-year period 1961-1990. All changes in climate are therefore calculated relative to this period [6]. Although a new 30-year normal period has just been completed – 1971-2000 – we continue to use the earlier baseline to ensure continuity with previous studies, including the earlier UKCIP98 scenarios. This choice of baseline means that some of the changes in future climate shown in the maps of Chapters 4, 5 and 6 might be expected already to have occurred. For example, the changes shown in some of the later maps are essentially for the 50-year period from 1961-1990 to 2011-2040 (i.e., “the 2020s”). By year 2002, with measured data available for the 30-year period 1972-2001, we have already reached nearly a quarter-way through this period. The unknown effects of natural climate variability through this period does not allow us, however, to simply infer that the expected changes from today’s (2002) climate to the climate

(6) It should be noted that the recent Third Assessment Report of the IPCC continues to calculate future changes in climate and sea level from the notional year ‘1990’, compared to our notional year ‘1976’ (mid-year of 1961-1990 period). This may lead to small differences between numbers cited by IPCC and in this Report.

of the 2020s are necessarily only about three-quarters of those shown.

To represent the geographic variability of surface land climate in the UK, we use monthly, seasonal and annual spatial grids at a 5 km resolution for the period from 1961 to 2000. These grids have been newly constructed by the Met Office and are illustrated for 1961 - 90 in Figure 18.

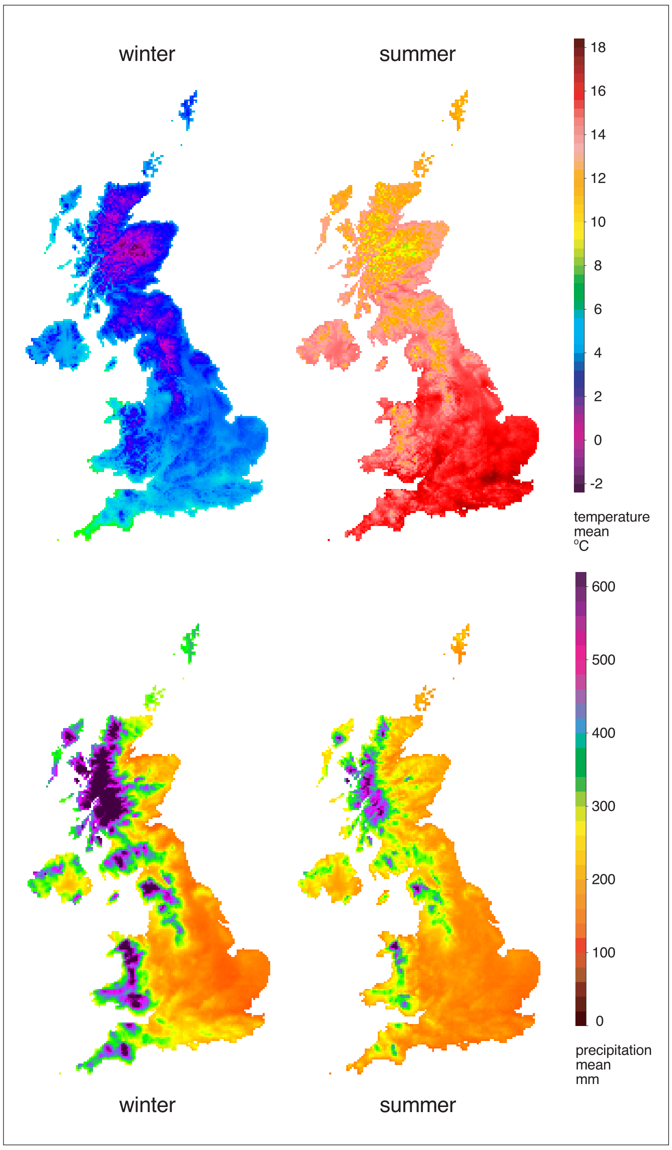

Figure 18: Average observed 1961-1990 winter and summer temperature (°C, top) and precipitation (mm, bottom) in the UK. Data on a 5 km grid.

The data set contains 26 surface climate variables and its construction is summarised in Appendix 7. The data are available under licence from the Met Office and UKCIP02 web sites - see Appendices 7 and 4 for further details. We have used this climate data set, together with our four UKCIP02 climate change scenarios, to create a set of climate scenario data files at 5 km resolution for the three future time periods – the 2020s, 2050s and 2080s – for a sub-set of the 26 variables and at monthly resolution. These scenario data files are also available from the UKCIP02 web site.

2.7 Conclusion

This Chapter has summarised some of the characteristics of global and UK climate over recent centuries, decades and years. This helps us to appreciate both the nature of our present-day climate and also the level of climate variability that recent generations in our country have experienced. These observations of climate variability also allow us to place the scenarios of climate change for the coming century described later in the report in a historical context. It is within this context of year-to-year and decade-to-decade variability in past climate that our environment, our society, and our economy have evolved. Although, of course, we have adapted to some of these aspects of our climate, parts of our society are still vulnerable to occurrences of extreme weather and to large or sustained seasonal climate anomalies. The question for the coming century is not only one of mitigation – to what extent we can slow down the rate of warming? – but, equally important, to what extent we can reduce this vulnerability and adapt to the larger changes in climate, the larger rates of change and the changes in extreme weather, that are likely to occur in the future? The remaining chapters of this report describe what some of these changes may be.

> *Parts of our society are still vulnerable to occurrences of extreme weather and to large or sustained seasonal climate anomalies.*

Chapter 3: Creating Global and UK Climate Change Scenarios

This Chapter introduces the four world scenarios that we use to create the UKCIP02 climate change scenarios. We discuss these world scenarios in terms of future greenhouse gas emissions, atmospheric carbon dioxide concentrations and global-average temperature and compare these results with those reported in the UKCIP98 scenarios. We explain the significance of our choice of assumptions and of models, exploring the consequences of these choices compared to others we could have made, both at a global-scale for temperature and at the scale of the UK for temperature and precipitation. Given the differences between model results, we recommend some simple guided sensitivity exercises for those needing to explore the consequences for specific applications of scientific uncertainties *not* reflected in our UKCIP02 climate change scenarios.

There are two primary factors which determine how human activities change climate - the rate of *greenhouse gas emissions* and other pollutants and the *response of climate* to these emissions. The first of these factors can only be described using a range of scenarios, these scenarios depending on many different assumptions about how the world's population, economy, energy-technology and lifestyles will evolve. The second factor - the climate system response and the resulting regional patterns of climate change - can only be explored through the use of global and regional climate models.

3.1 Greenhouse gas emissions and concentrations

As a starting point for the UKCIP02 climate change scenarios, we adopt four emissions scenarios described in the IPCC Special Report on Emissions Scenarios (SRES). These are related to four different sets of assumptions – or "storylines" – about the key drivers of emissions. The four storylines are summarised in Appendix 5 and are referred to by the IPCC as A1, A2, B1 and B2. We select one emissions scenario from each of the four storylines in such a way as to span a wide and representative range of the future emissions reported in SRES (Figure 19). For the A1 storyline we select the highest emissions variant, labelled A1FI by the SRES team. The cumulative global carbon emissions between 2000 and 2100 for each of these four scenarios are: 2,189 GtC[7] (A1FI), 1,862 GtC (A2), 1,164 GtC (B2) and 983 GtC (B1). We discuss whether we can attach likelihoods to these different scenarios in Box E.

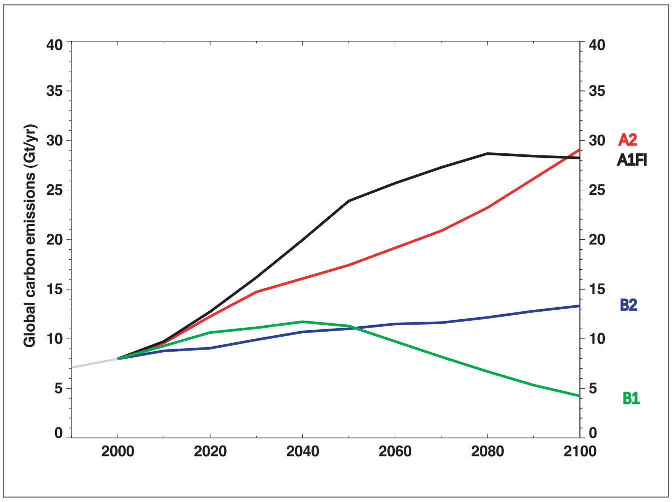

Figure 19: Global carbon emissions from all sources (energy, industry and land-use changes) from 1990 to 2100 for the four scenarios used in this report. Observed values to 2000 are grey. Data refer to the "marker" scenarios reported in the SRES.

New technologies such as this hydrogen-powered car will emerge as one way of reducing greenhouse gas emissions. ©DaimlerChrysler

In order to simulate climate change given these assumed futures, we first need to estimate how the emissions for each scenario will change atmospheric concentrations of the greenhouse gases and other climate-altering pollutants. The carbon dioxide concentrations for the four scenarios we have chosen have been calculated by the IPCC (Figure 20). By 2100, concentrations of carbon dioxide range from about 540 ppm for the B1 scenario (this represents almost a doubling of the pre-industrial concentration of about 280 ppm) to about 920 ppm for the A1FI scenario (here, pre-industrial doubling occurs by about the year 2045). Since carbon dioxide has a long lifetime in the atmosphere (around 100 years), it is well mixed globally and so these global concentrations will also apply to the future atmosphere over the UK.

Although carbon dioxide is the most important greenhouse gas being influenced by human activities, there are others which are substantial contributors to climate change, such as methane and ozone. The atmospheric concentrations of these gases, and also their radiative forcing, are calculated within the Hadley climate model using the SRES emissions as inputs. In addition to greenhouse gases which have a warming effect, human activities also change the concentration of aerosols (small particles) in the atmosphere. The most influential of these are sulphate aerosols, formed chemically in the atmosphere from sulphur dioxide emissions originating from transport, industry and power generation. Sulphate particles form a haze in the lower atmosphere which acts to cool climate, since it scatters sunlight back to space

(7) 1 GtC = 1 giga, or billion, tonnes of carbon; note, 1 tonne of carbon = 3.67 tonnes of carbon dioxide.

which would otherwise reach the surface of the Earth. In addition, sulphate aerosols change the properties of clouds and this also has a cooling effect. Calculation of the concentration of sulphates, and both their direct and indirect cooling effects, is also performed within the climate model. On the other hand, the model does *not* consider the role of black soot in the atmosphere, an active forcing agent originating from fossil-fuel combustion which acts to warm climate.

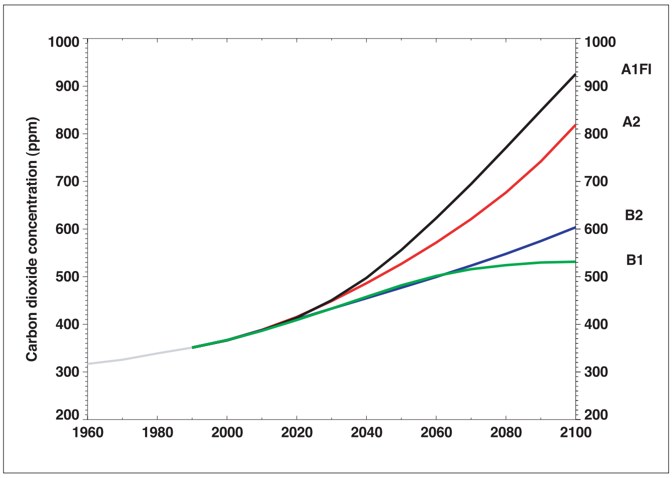

Figure 20: Global carbon dioxide concentration (parts per million) from 1960 to 2100 for each of the four emissions scenarios. Key as for Figure 19. Uncertainties associated with these concentration calculations are not shown. [Source: IPCC, 2001].

3.2 Climate response

The second major factor controlling the extent of human influence on future global climate is the response of the climate system to forcing from human influences, i.e., from greenhouse gases and the other forcing agents described above. The size of this response is not well known and differs between global climate models (see Box D for a brief discussion about how we can summarise these differences). For example, in response to the same emissions scenario (A2), the models assessed in the Third Assessment Report of the IPCC simulate global temperature rises by 2100 of between 1.6ºC and 5.4ºC. The Hadley Centre's most recent global climate model, HadCM3, calculates a rise of about 4ºC for this scenario. We discuss the implications of our choice of model for the UKCIP02 climate change scenarios in Section 3.5. HadCM3 was used to simulate global climate from 1860 to 2100 for all four of our selected emissions scenarios. For the period from 1860 to 1990, the model was driven by observed, or deduced, human-induced changes in greenhouse gases and sulphate aerosols, plus natural changes in volcanoes and solar output. From 1990 to 2100, the model was driven by changes in individual greenhouse gas and sulphate aerosol concentrations, based on the selected A1FI, A2, B1 and B2 emissions. The effects of unpredictable volcanoes or uncertain solar changes in the future were not considered. The model does simulate, however, natural variability generated internally within the climate system and to quantify this effect the model was run three times using the A2 emissions, each time using a different and randomly selected initial condition. Further details about the HadCM3 model and the simulation experiments are provided in Appendix 2.

The changes in global-average surface air temperature from these various model runs are shown in Figure 21. It is noticeable that, despite quite large differences in emissions between the four scenarios (cf. Figure 19), there is relatively little difference between the global temperature changes they produce until after the middle of the century. This is partly

Box D: Measuring the climate response of different models

- The UKCIP98 scenarios applied the label "climate sensitivity" to a measure of how the climate system responds to greenhouse gas, or other, forcing. Sensitivity in this context was defined as the equilibrium global surface air temperature change resulting from an increase of greenhouse gas concentration in the atmosphere equivalent to a doubling of carbon dioxide. In other words, the higher the sensitivity, the more global climate will be perturbed by human influences. Different global climate models yield different values for this index, which is believed to vary depending on how rapidly the climate system is forced.

- Climate sensitivity, as used above, is properly called *equilibrium climate sensitivity,* and can only be determined once the simulated climate has completely equilibrated to the change in greenhouse gas concentration. When using a fully coupled atmosphere-ocean GCM, such as HadCM3, this equilibrating takes a very long time. A more practical index of climate system response is the *effective* climate sensitivity, which can be obtained from non-equilibrium conditions. This value changes over time in the model-simulated climate. The latest range quoted by the IPCC (2001) for the effective climate sensitivity is between 1.7ºC and 4.2ºC.

- A special case of the effective climate sensitivity is the *transient climate response*, defined as the global-average surface air temperature change at the time of carbon dioxide doubling (~year 70) in a transient climate change experiment in which carbon dioxide concentration increases at the rate of 1 per cent per year.

- Since the descriptions of future climate over the UK shown in this report derive from experiments conducted using Hadley Centre models, the four UKCIP02 scenarios implicitly adopt the effective climate sensitivity of the HadCM3 model - a value of 3.0ºC. This compares to the range used in the UKCIP98 scenarios of 1.5º to 4.5ºC.

Box E: How 'likely' are the UKCIP02 climate change scenarios?

The range of global warming by the year 2100 for the four UKCIP02 scenarios is between 2.1ºC and 4.8ºC higher than the 1961-1990 average. These calculations are based on a representative range of emissions scenarios using a single climate model (HadCM3). Other climate models have a different climate response to HadCM3, and hence give a higher or lower estimate of global temperature rise. Is it possible to estimate the relative likelihood of the four UKCIP02 climate change scenarios occurring, given these differences, or the likelihood of other climates being realised that lie outside this range?

As explained in Chapter 7, there are several types of uncertainties that limit our ability to make definitive predictions of future climate, including those concerning future emissions (based on societal choice) and those concerning the climate system response. The SRES team deliberately did *not* assign any probabilities to their storylines or emissions scenarios, the authors not wishing to make what may have been construed as preferential, and possibly self-fulfilling, statements about the future. The IPCC also did not assign confidence limits to their cited 2100 warming range of 1.5ºC to 5.9ºC.

For a number of reasons, however, estimating the possible shape of the probability distribution of future global temperature change is desirable. This cannot yet be done using a fully objective method – and this may never truly be achieved given the subjectivity associated with future emissions scenarios. However, it should be possible to provide users of climate change scenarios and policy-makers with more information than a straightforward range.

Recent analyses have shown that *if* all climate responses and emissions scenarios have equal probability, the output distribution of global warming values is a positively-skewed bell curve. In other words, under these assumptions it is rather *less* likely that global temperature will fall at the upper and lower limits of the cited range than that it will fall towards the middle of the range. Although general qualitative conclusions may be drawn from these types of analyses, the precise results obtained depend critically on a number of key assumptions about which there is as yet no widespread agreement among scientists.

The question of how likely a particular *regional* climate response – such as described in this report for the UK and including variables other than temperature – might be a much harder one to answer and will be the subject of continuing research in the years to come (see Section 9.2). At present therefore we cannot assign a relative probability to each of the UKCIP02 scenarios, or exclude the possibility that the real change will lie outside this range.

because much of the change in climate over the next 30 to 40 years has already been determined by historic emissions and partly because the effects on climate of scenario differences in changes in greenhouse gas and sulphate aerosol concentrations initially offset each other. After 2050, however, the curves diverge more substantially. By 2100, the warming with respect to the 1961-1990 average ranges from 2.1ºC for the B1 scenario to 4.8ºC for the A1FI scenario. The *full* range of global-average temperature changes by 2100 as reported by the Third Assessment Report of the IPCC, using all the SRES emissions scenarios and a number of global climate models from different modelling centres, lies between 1.5ºC and 5.9ºC[8] (see Figure 21). This range is only moderately greater than the range from HadCM3 alone. Attributing probabilities to these different warming rates is not straightforward and the issues involved in trying to do so are discussed in Box E.

Regional temperature and precipitation changes

Although the global-average temperatures shown above provide useful information, they cannot reveal regional climate change responses. We therefore show in Figure 22 the worldwide patterns of change in annual temperature and annual precipitation for the average of the three A2 HadCM3 experiments (the A2 ensemble-average) for the period from 2071 to 2100, i.e., the 2080s. The land clearly warms more

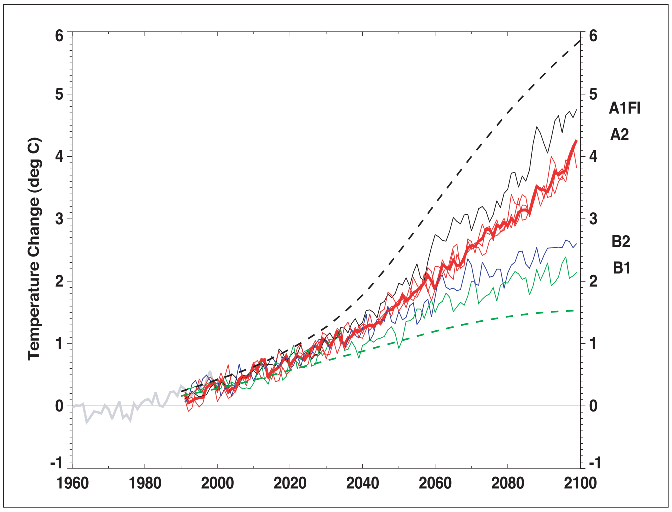

Figure 21: Annual global-average surface air temperature anomalies from 1961 to 2100 relative to the 1961-1990 average (14.0ºC) as observed (grey) and as simulated by the HadCM3 model. Key as for Figure 19. The bold red curve represents the average of the three separate experiments (thin red lines) conducted using the same A2 emissions scenario. The dotted green and black curves represent the full IPCC range of global temperature change when both emissions uncertainties and model uncertainties are considered.

(8) Note: the IPCC quoted changes in temperature with respect to the 1990 value rather than with respect to the 1961-1990 average. Our use of 1961-1990 as the baseline period adds just over 0.1ºC to the quoted IPCC values.

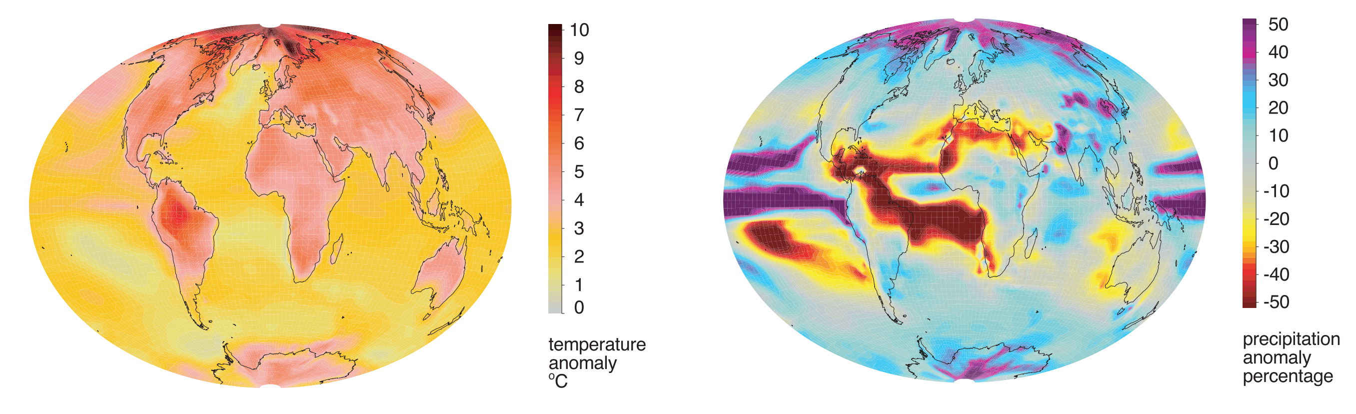

Figure 22: Change in annual average temperature (left) and precipitation (right) for the 2080s period, relative to 1961-1990, for the HadCM3 ensemble-average under an A2 forcing scenario.

than the ocean, and northern high latitudes warm the most – in excess of 6ºC over far northern Russia and Canada. There is no part of the globe which cools. These patterns of temperature change are fairly consistent between climate models, at least in relative terms.

Although *global* precipitation increases as temperature rises – by between 2 and 3 per cent for each degree of warming – changes in the regional distribution of precipitation are more complex and less consistent between models than are the patterns of temperature change. For the HadCM3 model (Figure 22), northern Africa, Central America and north-eastern South America experience substantial drying, along with southern Europe, Australia and the south-east Pacific. In this model, the central Pacific, parts of south-east Asia and northern high latitudes experience a wetter climate. The wetting of high latitudes in both hemispheres, especially in the winter half-year, is one of the more consistent precipitation results across different climate models.

3.3 Regional climate change over the UK

As we have just seen, HadCM3 produces patterns of climate change across the whole surface of the Earth. Changes over the UK could simply have been extracted from these model experiments and used as the basis of our UK climate change scenarios, in the same way as the UKCIP98 scenarios came directly from the HadCM2 version of the global model. The global model resolution is relatively coarse, however – between 250 and 300 km for each grid box for the UK - and the model's representation of some aspects of observed European climate is not as good as we would like. Storm tracks over northwest Europe, for example, are displaced too far south.

The experimental design adopted for the UKCIP02 scenarios therefore utilises a hierarchy of climate models. The output from the coupled ocean-atmosphere HadCM3 experiments provided the boundary conditions to drive a high resolution (~120 km) model of the global atmosphere (HadAM3H), and the outputs from these experiments (called "time-slice" experiments, since they cover the slice of time from 2071 to 2100) in turn provided the boundary conditions to drive the high resolution (~50 km) regional model of the European atmosphere (HadRM3). This "double-nesting" approach improves the quality of the simulated European climate – the position of the main storm tracks, for example, are better located – and also allows the UKCIP02 scenarios to present information with greater spatial detail - 50 km rather than 250 to 300 km. The climate modelling techniques are further described in Appendix 2.

The substantial computing cost of this "double-nesting" method meant that only four regional climate model experiments could be conducted, three for the A2 emissions scenario and one for the B2 scenario. Furthermore, only the periods 1961-1990 and 2071-2100 - the period we refer to as the 2080s – were simulated by the regional model. To derive climate change scenarios for intervening time periods (the 2020s or 2050s), and for climates which would arise if future emissions followed higher (A1FI) or lower (B2 or B1) emissions pathways, we used a commonly-utilised procedure known as *pattern-scaling*. We first used the respective global-average temperature changes for 2071-2100 as the scalar with which to derive three other scenarios for this same period based on the A2 regional patterns[9]. We then used the respective global-average temperature changes for all of the different periods (Table 3) to create climate change scenarios for the two earlier periods for all four scenarios, again based on the A2 regional patterns. The uncertainties associated with this pattern-scaling method are discussed in Section 7.4.

This hierarchy of model experiments, and the derivation of the UKCIP02 scenarios, is illustrated schematically in Figure 23. The diagram indicates that there are a number of potential modelling routes that could translate the SRES emissions (on the left-hand side) to the eventual 50 km climate change scenarios and 5 km climate scenarios for the UK (on the right-hand side). The fact that no modelling centre other than the Hadley Centre has actually conducted the necessary suite of model experiments - including high resolution modelling - means, however, that we were limited in the scenario derivation method we could choose. The implications of this choice are explored in Section 3.5.

(9) Note: we did not use the result of the B2 regional model run for pattern-scaling since we only had 30 years of data for this scenario compared to 90 years (three ensemble members of 30 years each) for A2.

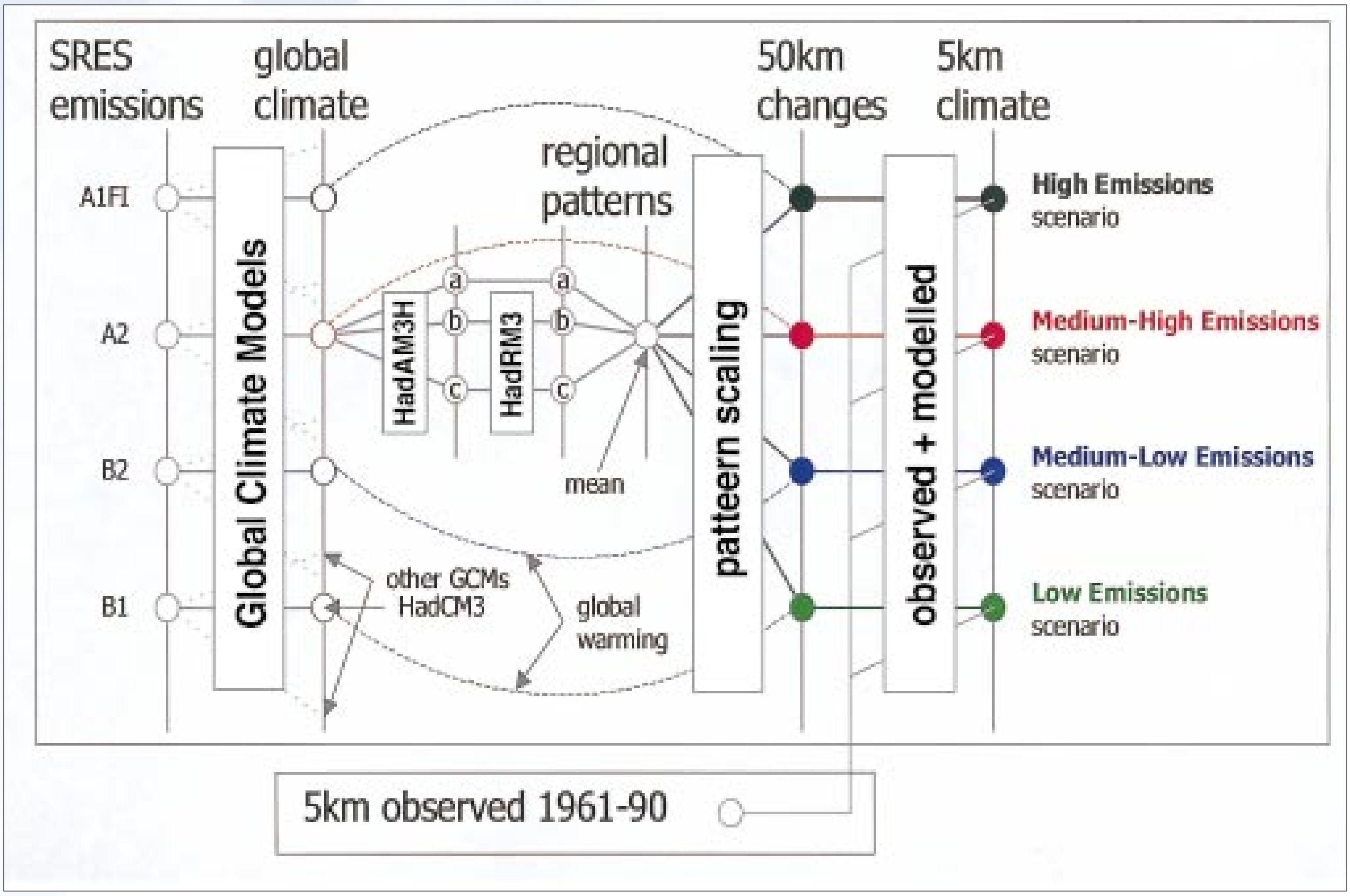

Figure 23: A schematic representation of the model experiment hierarchy used to 'downscale' the global model to a regional scale for the UKCIP02 scenarios.

We henceforth refer to the resulting four UKCIP02 climate change scenarios in terms of their relative greenhouse gas emissions levels: **Low Emissions, Medium-Low Emissions, Medium-High Emissions** and **High Emissions.** The scenario names were chosen to make explicit the link between the respective UKCIP02 scenario and its underlying emissions scenario (Table 2). The report uses colour coding of these names as a visual means of relating the different scenarios to the graphical representation of results, i.e., where lines are shown on graphs they correspond to the adopted colour codes.

With this construction framework established for the four UKCIP02 climate change scenarios, Chapters 4, 5 and 6 proceed to explore the implications of each scenario for the regional climate of the UK. The majority of the analyses presented in these three Chapters use results from the regional model simulations of HadRM3. Some analyses, however - such as those covering a wider area, or examining trends over the whole period from 2000 to 2100 – use results from the coupled global model (HadCM3) or from the intermediate-resolution global atmosphere model (HadAM3H).

UKCIP02 Scenario	SRES Emissions Scenario	Derivation
Low Emissions	B1	HadRM3 ensemble simulation for A2 emissions scaled to the HadCM3 global temperature for B1 emissions
Medium-Low Emissions	B2	HadRM3 ensemble simulation for A2 emissions scaled to the HadCM3 global temperature for B2 emissions
Medium-High Emissions	A2	HadRM3 ensemble simulation for A2 emissions
High Emissions	A1FI	HadRM3 ensemble simulation for A2 emissions scaled to the HadCM3 global temperature for A1FI emissions

Table 2: Naming and derivation of the UKCIP02 scenarios. Although results were available from one regional model experiment for the B2 emissions scenario (30 years of simulated data), we preferred to use the scaled results from the A2 ensemble (90 years of data) to provide more robust statistics.

3.4 Comparison with the UKCIP98 scenarios

Table 3 summarises the differences in carbon dioxide concentrations and global-average temperature changes between the 1998 and the 2002 scenarios. The four UKCIP02 scenarios yield a range of global warming by the period 2071-2100 (i.e., the 2080s) of 2.0º to 3.9ºC. The absolute levels of warming are slightly higher than in the UKCIP98 scenarios (range: 1.1º to 3.5ºC), although the new range is somewhat narrower. The reasons for this are as follows.

The four SRES emissions scenarios used here encompass a higher estimate of future carbon emissions (A1FI) than either of the emissions scenarios used in 1998. In addition, the climate experiments used this time include the effect of sulphate aerosols; in 1998 these were ignored. Since the SRES emissions include scenarios where sulphur emissions *fall* substantially compared to the present day, there will be a reduction in cooling from this source and hence an additional contribution to warming. These two factors help to explain the increase at the lower and upper ends of the warming range compared to the 1998 scenarios.

The reason for the narrower range is that in 1998 we used a wider range of climate responses than was used here. The UKCIP02 climate change scenarios are derived solely from the HadCM3 model, which has an effective climate sensitivity (3.0ºC) close to the middle of the IPCC range (1.7º to 4.2ºC). This explains why the range of warming by the 2020s is very narrow in the UKCIP02 scenarios (only from 0.8º to 0.9ºC) compared to the UKCIP98 scenarios (from 0.6º to 1.4ºC).

3.5 Exploring the implications of scientific uncertainties for future UK climate

We have already stressed that the four UKCIP02 climate change scenarios reveal the effects of uncertainties in future emissions on UK climate, but do not quantify the effects of scientific or modelling uncertainties on future climate change. This situation arises because our scenarios are based on results from just one climate modelling hierarchy – that of the Hadley Centre. The reason for this is that, at the time of design, only in this modelling centre had a set of model experiments for Europe been conducted using regional (high-resolution) climate models forced by SRES emissions scenarios. Our desire to show future changes in UK climate at a spatial resolution higher than the 250-500 km resolution of the various global models has therefore limited our ability to represent quantitatively, at that higher resolution, the effects of scientific uncertainties on future climate.

> *The absolute levels of warming are slightly higher than in the UKCIP98 scenarios.*

The advantages of using results from a 50 km regional model - such as the improved spatial resolution and more credible representation of changes in extreme weather – are therefore offset by the disadvantage of not being able to represent explicitly the effects of scientific uncertainties at this 50 km resolution. Nevertheless, it is important for users of the UKCIP02 scenarios to be fully aware of their limitations (see Appendix 1).

What we *can* do is to explore the range of regional climates over the UK simulated by global climate models other than the Hadley Centre's, at least the broad-scale changes in average climate. A number of other modelling centres around the world have also developed global climate models. Each model has a different structure and each model contains different representations of important climate processes such as clouds, ocean eddies and soil moisture. Each model will therefore simulate a different global climate change and a different regional climate response even when forced by exactly the same emissions scenario. It is important, therefore, to compare the UKCIP02 patterns and magnitudes of climate change with those that would have been generated if we used results from other modelling centres. We would, of course, like to do this at the scale of 50 km, but as of 2001 no other regional models had yet completed the same suite of experiments as the Hadley Centre. Thus we conduct this inter-comparison using coarser-scale results from global climate models[10].

	2020s		2050s		2080s	
UKCIP02	∆T (ºC)	CO_2 (ppm)	∆T (ºC)	CO_2 (ppm)	∆T (ºC)	CO_2 (ppm)
Low Emissions	0.79	422	1.41	489	2.00	525
Medium-Low Emissions	0.88	422	1.64	489	2.34	562
Medium-High Emissions	0.88	435	1.87	551	3.29	715
High Emissions	0.94	437	2.24	593	3.88	810
UKCIP98						
Low	0.57	415	0.89	467	1.13	515
Medium-Low	0.98	398	1.52	443	1.94	498
Medium-High	1.24	447	2.11	554	3.11	697
High	1.38	434	2.44	528	3.47	637

Table 3: Global climate change estimates for three future 30-year periods centred on the decades of the 2020s, 2050s and 2080s, and for various scenarios. Results for the UKCIP98 scenarios are shown for comparison with the UKCIP02 scenarios. All temperature changes are with respect to the 1961-1990 average.

(10) In Section 7.5, we provide an inter-comparison of results from successive versions of the Hadley regional model – HadRM2 and HadRM3 – to illustrate further the model-dependency of aspects of the UKCIP02 scenarios.

Whilst inter-comparison of model results is important and may reveal areas where there are significant differences, or indeed similarities, there is no easy way of attaching higher or lower confidence to the results of one model over another. There are certain basic criteria, however, that can be applied - for example how well each model represents current climate - and these evaluations are undertaken as part of the WMO Coupled Model Inter-comparison Project (CMIP). The new Hadley model, HadCM3, performs well in this exercise. In this section we compare the changes in average UK winter and summer temperature and precipitation from HadCM3 with those from other models used in the IPCC Third Assessment Report (see summary in Table 4). These models have all been used for experiments using the same A2 and B2 emissions scenarios as have been used here. Results from these model experiments have been, or will shortly be, lodged with the IPCC Data Distribution Centre from where they can be obtained (see Appendix 8 for more details).

There is no easy way of attaching higher or lower confidence to the results of one model over another.

Temperature

The simulated changes in average winter and summer temperature for the 2080s for the SRES A2 emissions scenario are shown in Figures 24 and 25 for the nine IPCC climate models. These show differences both in magnitude of change and in geographical pattern. Those models with the most extreme global-scale climate response – MRI (low) and NIES (high)[11] – also show the most extreme temperature changes over the UK in both winter and summer. Within these extremes, however, it is not always the case that the size of the regional temperature response follows the size of the global response. Nevertheless, the magnitude of the HadCM3 temperature responses (three different ensemble members) falls roughly in the middle of the full model range. The patterns of temperature warming across the UK also differ, although more so in winter than in summer. Winter temperature change gradients vary from southeast to northwest (HadCM3), to east to west (NIES), to north to south (PCM). These differences are likely to reflect the different strengths of various feedback processes simulated by different models and also their relative ability to define adequately an anthropogenic signal (harder for models with small responses, for example PCM). For summer, the warming gradients are more similar to each other; only the PCM and CSIRO models differ from the southeast to northwest gradient simulated by HadCM3 and the other models. Model consistency of results is one of the three criteria that we use in this report for assigning relative confidence levels to the headline statements we make about future UK climate in Chapters 4, 5 and 6 (cf. Box B, p.7).

Precipitation

The model-simulated changes in seasonal precipitation also show differences - and some similarities (Figures 26 and 27). All models indicate a wetter UK winter climate, but again the magnitudes and geographical patterns of the wetting vary between models. The NIES model is again the most extreme – by some margin – and this time the PCM model shows the smallest increase in precipitation. The wetting is relatively uniform across the region in several models; HadCM3 tends to reveal a general south to north gradient, however, with the south of the country wetting more than the north. In summer, there is less agreement between the models over the direction of the rainfall change – CCCma and CSIRO, for example, suggest slightly wetter summers – although all models suggest the same south to north gradient such that the south of the UK dries more than the north, or possibly dries slightly while the north of the country gets wetter. The three HadCM3 experiments reveal some of the largest reductions in rainfall – over southern England – of any of the models.

All models indicate a wetter UK winter climate.

It is important to point out that agreement between models is not “proof” that they are correct, merely that given our current state of knowledge and modelling capability all models are telling a similar story. On the other hand, where differences between models are large – and by this we mean larger than

Model Name/Version	Country	Approximate Grid Spacing over the UK (km)	Transient Climate Response (ºC)
CCCma	Canada	340	2.0+
CSIRO Mk2	Australia	360	2.0
CSM 1.0	USA	250	1.6
DOE PCM	USA	250	1.3
MPI/DMI	Germany	250	1.4
GFDL R30c	USA	500	2.0
HadCM3	UK	265	2.0
MRI2	Japan	250	1.1*
NIES-CCSR v2	Japan	490	3.1*

+ The transient climate response for this model is not known. The cited value refers to an earlier version of the model.
* The NIES and MRI2 models were not used by the IPCC in defining their full range of future possible global warming.

Table 4: Some details of the nine global climate models used in the model inter-comparison described in this section. Results from these other models will gradually become available in the public-domain through the IPCC Data Distribution Centre (see Appendix 8). See Box D for a definition of transient climate response.

(11) The NIES and MRI models were not used by the IPCC in defining the full range of future global warming. They are included here for completeness.

might be expected due to purely natural variability of climate – it is unlikely that both models can be correct. As hinted at above, determining which model is more likely to be correct is not a straightforward task.

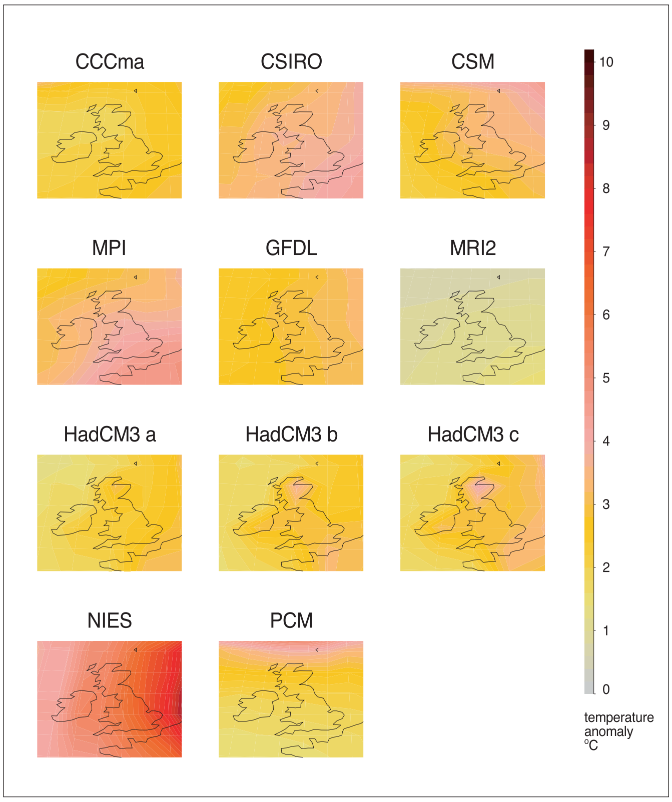

Figure 24: Patterns of change in winter-average temperature across the UK as simulated by nine global climate models for the 2080s for the A2 emissions scenario (the scenario adopted as our UKCIP02 Medium-High Emissions scenario). The three HadCM3 results are for the three ensemble members. The model names are those listed in Table 4.

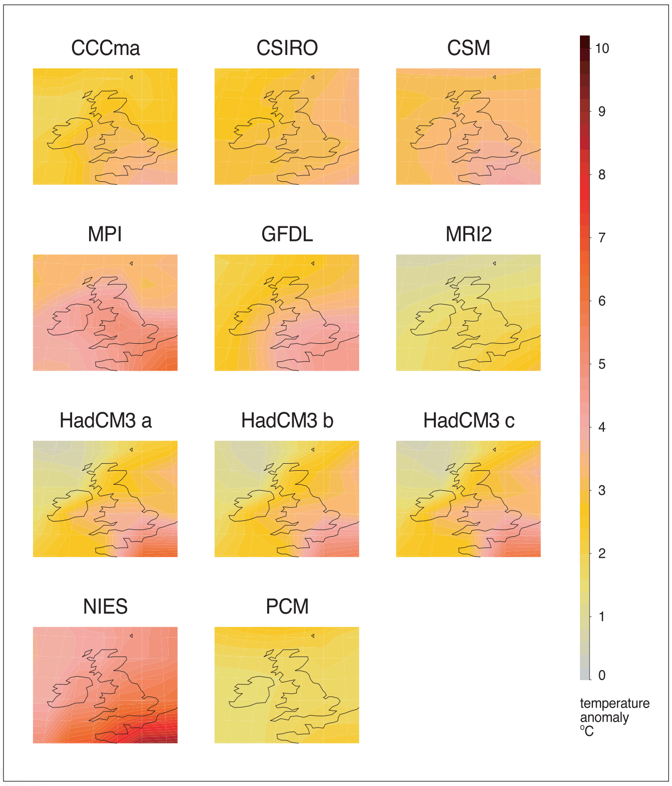

Figure 25: As for Figure 24, but for summer-average temperature.

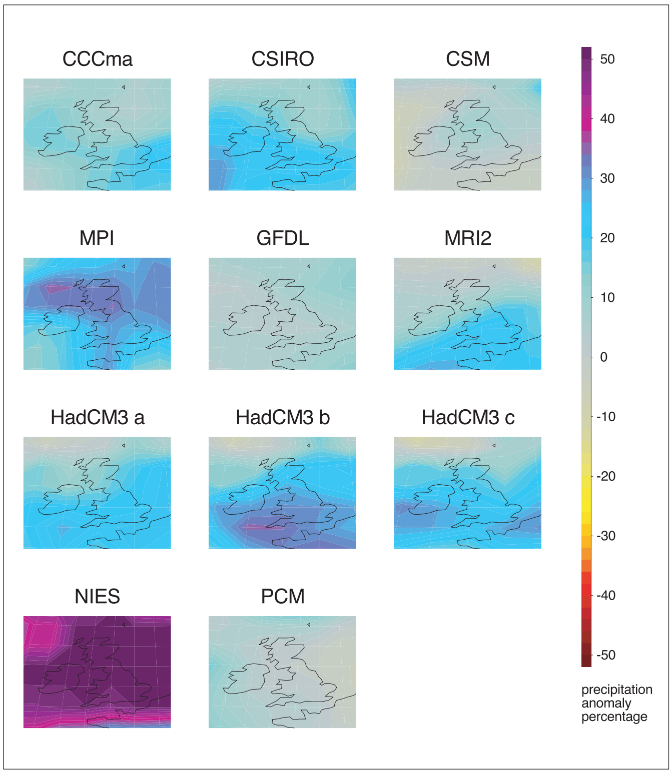

Figure 26: As Figure 24, but for winter-average precipitation

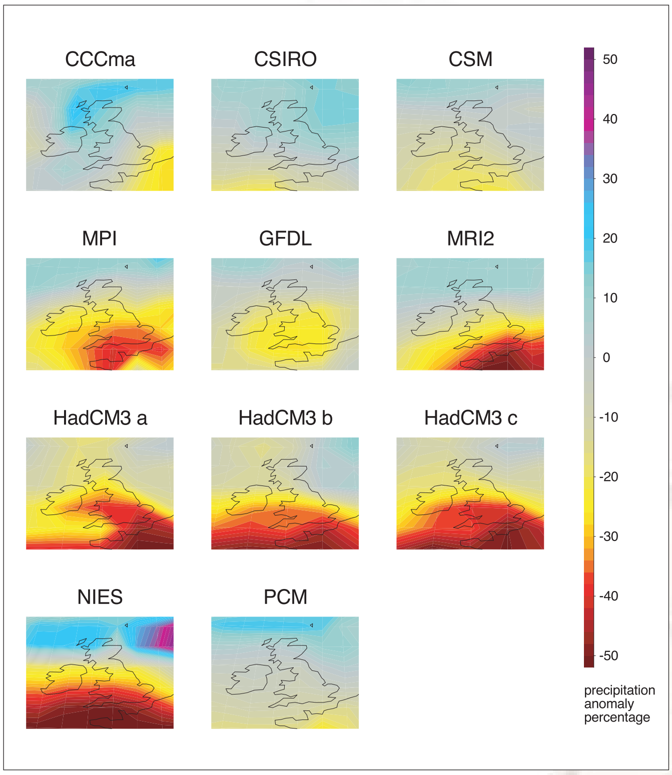

Figure 27: As Figure 24, but for summer-average precipitation.

Because of these differences between model responses over the UK – and we have only illustrated here very simple diagnostics such as change in average seasonal climate – it is important that users of the UKCIP02 scenarios use results from these other model experiments when engaged in research or in applications where representing a wide range of uncertainty is important. This is especially the case when designing operational adaptation strategies (see Appendix 1 for further comments on this point). Many of these other GCM results are or will be available via the IPCC Data Distribution Centre (Appendix 8).

For those who may not be in a position to exploit these additional data sets, at the very least we would suggest some form of guided sensitivity analysis be conducted based on the results shown in Figures 24 to 27. To assist in this activity we summarise the results of the maps in a set of simple scatter plots (Figure 28). When averaged over the UK land area, all the models agree that winters will become wetter and warmer in the UK, a result that is true for both the A2 (our **Medium-High Emissions**) and the B2 (our **Medium-Low Emissions**) scenarios. The strength of the wetting by the 2080s varies, however, from an increase of only a few per cent (PCM and CSM models) to an increase of 30 per cent or more (MPI and NIES models). The models that show the greatest warming globally tend to be the models that show the greatest warming and wetting over the UK in winter. There is not quite the same agreement in summer, although a majority of the models do indicate a modest drying. The range for the A2 scenario is from a few per cent increase in summer rainfall (CSIRO and CCCma models), to a decrease of about 20 per cent (HadCM3, MPI and GFDL). The model used for the UKCIP02 scenarios – HadCM3 – therefore produces results for the UK which are about in the middle of the range for winter, but which are near the extreme of drying for summer.

We would suggest some form of guided sensitivity analysis be conducted.

The results in this section are extracted from global climate model experiments with quite coarse spatial resolution. Our UKCIP02 scenarios, however, are presented at 50 km resolution over the UK and do not reflect any of the uncertainties summarised in Figure 28. As a rough guide we would therefore recommend that studies explore the sensitivity of their particular application by adopting the uncertainty margins summarised in Table 5, which have been derived semi-objectively from the scatter of global model

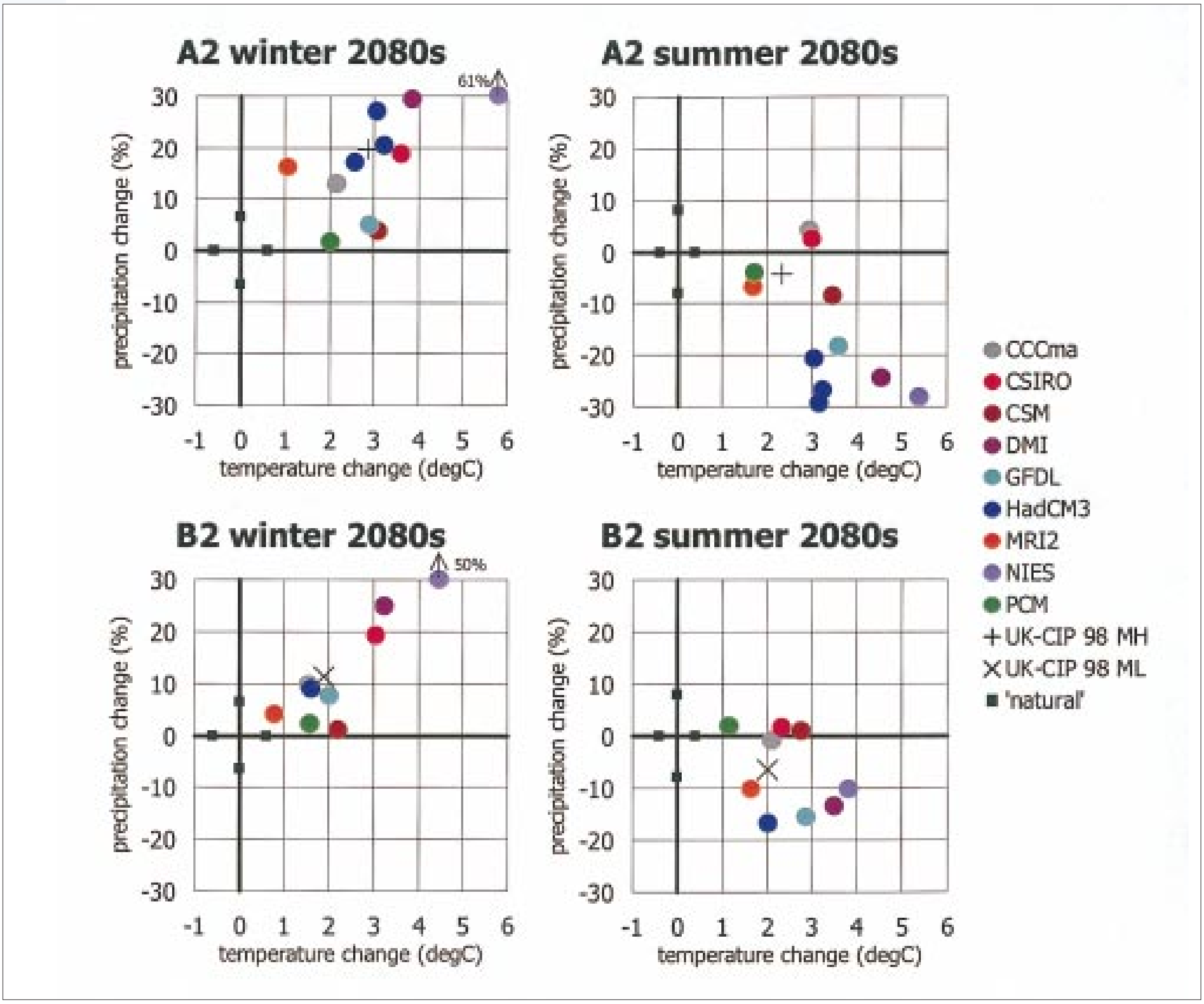

Figure 28: Changes in average winter (left) and summer (right) temperature and precipitation in the 2080s over the UK land area with respect to the average 1961-1990 climate, for the A2 emissions (top) and B2 emissions (bottom) scenarios. Each coloured circle represents the result from a different global climate model (see Table 4 for model details). The dark blue circles represents the model used in this report (HadCM3). The + and X symbols represent the old UKCIP98 Medium-High and Medium-Low scenarios respectively. The black squares close to the origin indicate "natural" climate variability as estimated by the HadCM2 model.

results over the UK. This is not as rigorous an estimate of scientific uncertainty as we would like but, in the absence of other regional model results, it is probably the best guidance we can give.

These margins should be applied to all the *changes* in climate simulated at the 50 km scale for the UK as a first-order approximation for introducing the effects of scientific uncertainties on our description of future UK climate. Note that the range of percentages for precipitation should be added or subtracted from the percentage changes given by the UKCIP02 scenarios. For example, if the UKCIP02 **Medium-High Emissions** scenario change in winter precipitation is +15 per cent for a particular location, and the uncertainty margin from Table 5 is ±20 per cent, a typical uncertainty range to explore would be -5 to +35 per cent, rather than ±20 per cent of 15 per cent (+12 to +18 per cent).

We cannot provide similar guided sensitivity recommendations for all the climate variables presented in Chapters 4, 5 and 6 since not all the IPCC climate models have yet reported all their results to the DDC; this example, nevertheless, gives us an idea about the possible scale of the scientific uncertainties involved.

	Low Emissions	Medium-Low Emissions	Medium-High Emissions	High Emissions
Average Temperature				
Winter (ºC)	±0.5	±1.0	±1.5	±2.0
Summer (ºC)	±0.5	±1.0	±1.5	±2.0
Average Precipitation				
Winter (per cent)	± 5	±10	±15	±20
Summer (per cent)	+10	+15	+30	+40

Table 5: Suggested uncertainty margins to be applied to the UKCIP02 scenarios of **changes** *in average winter and summer temperature and precipitation. Estimates based on the model inter-comparison summarised in Figures 24 to 28. Note: summer rainfall sensitivities are all positive, i.e., the UKCIP02 summer rainfall changes are already perhaps at the drier end of the range.*

Chapter 4: Future Changes in UK Seasonal Climate

This Chapter presents changes in seasonal and annual average climate for the UK for the four UKCIP02 scenarios designed in Chapter 3. Changes in UK daily climate and weather are shown in Chapter 5. For many maps and tables in this, and following, chapters we present changes in climate for three 30-year periods centred on the 2020s (2011 to 2040), the 2050s (2041 to 2070), and the 2080s (2071 to 2100). The changes in climate for each of these periods are calculated as the change in 30-year average climate with respect to the model-simulated climate of the baseline period, 1961 to 1990. The year is divided according to the standard climatological seasons: winter refers to December-January-February; spring to March-April-May; summer to June-July-August; and autumn to September-October-November. We also show examples of changes in the interannual variability of climate within these three periods, and include examples of the possible year-to-year evolution of UK climate throughout the twenty-first century.

For all the maps in this Chapter, we have shown as grey the regions of the UK where the future changes in climate are within (an estimate of) "natural" climate variability, i.e., where the changes are relatively small. Natural variability in this case is defined as one standard deviation of 30-year average climates, estimated from the control model simulations of the HadRM3 model. These estimates of natural climate variability

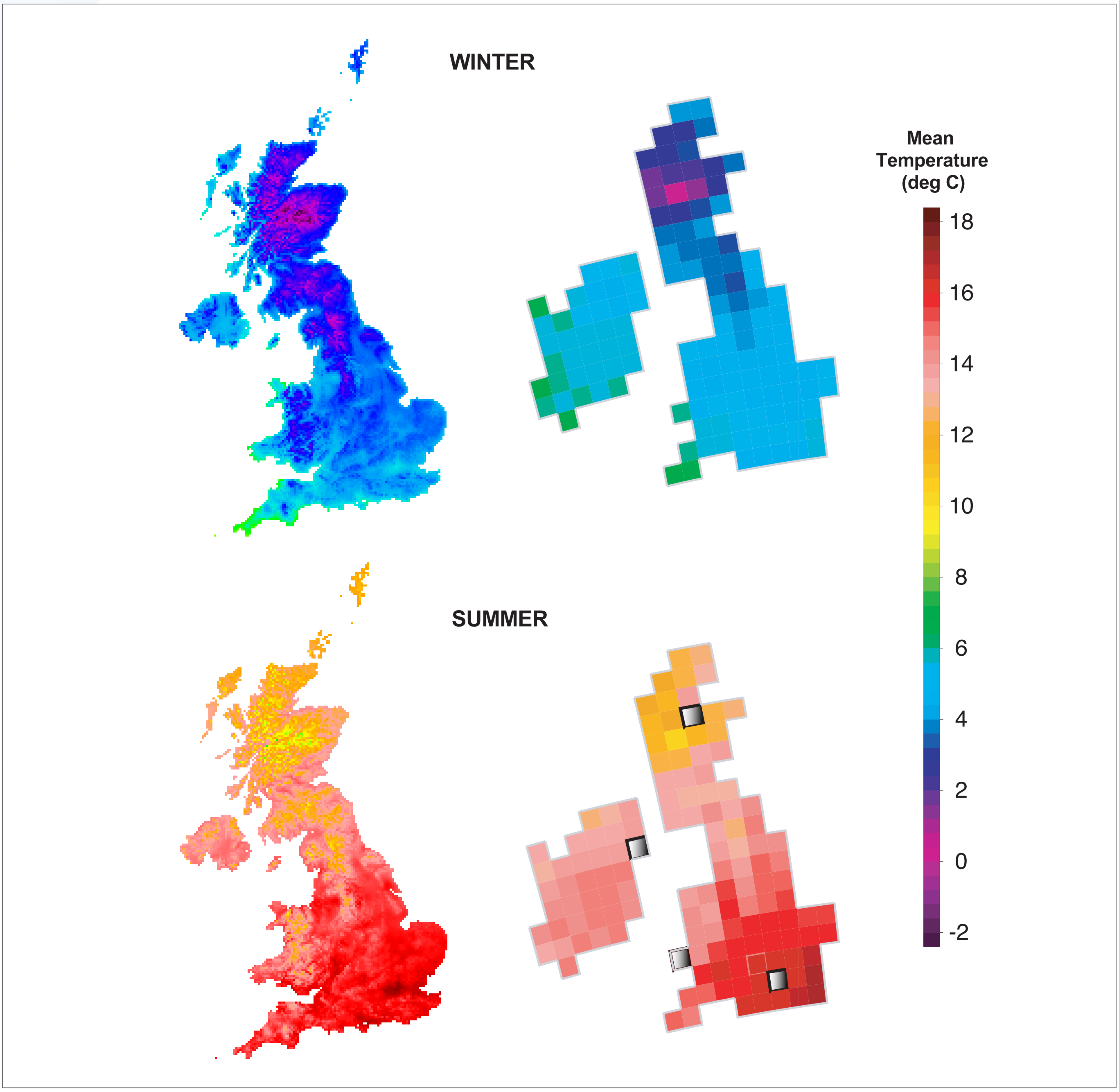

Figure 29: Comparison of average winter and summer temperature for the period 1961-1990 as observed (left) and as simulated by HadRM3 (right). The observed data are plotted on the 5 km grid used in the baseline climate data set (Appendix 7); the simulated data are plotted on the model 50 km grid. The 50 km grid boxes highlighted in the lower right map are the boxes used for detailed analysis in Chapters 4 and 5.

may not of course be entirely accurate, but this method at least enables us to focus attention on areas of the UK where future changes are relatively large, i.e., the coloured areas.

In the final section of the Chapter, we extract a set of headline statements from our analyses and compare them with conclusions from the UKCIP98 scenarios, identifying the major similarities and differences. Further maps and graphics showing additional analyses are available on the UKCIP02 scenarios website, along with links to allow access to the scenario data files for use in research (see Appendix 4).

4.1 How accurate is the climate model?

Before using climate models for constructing climate scenarios, it is important to evaluate their ability to simulate the observed climate for the region in question. We may be less keen on using a model that is unable to simulate current climate accurately than one that can faithfully simulate the main relevant features of observed climate. It is also true, however, that just because a model simulates present climate accurately, this is no guarantee that it will simulate future climate accurately.

There are a large number of diagnostic indicators that can be used to evaluate models. The HadCM3 global model has been part of an international model inter-comparison exercise in which it performs as one of the best models in the world. We show here, however, one simple evaluation of the performance of the *regional* model over the UK. Figures 29 and 30 compare the average winter and summer average temperature and precipitation for the period 1961-1990, as observed and as simulated by the model. The plots are

Figure 30: As Figure 29, but for average 1961-1990 precipitation.

retained on their respective grids to demonstrate the relative differences in these spatial resolutions.

For both variables and both seasons, the model simulates the recent average climate very well, given the limitations imposed by the coarse model grid. The pattern of precipitation decrease from west to east is captured well by the model, and the effects of altitude - obvious in the observed data, for example temperature in central Scotland - are also picked up as well as can be expected by a grid as coarse as 50 km[12]. On the basis of this, and other diagnostic analyses not shown here, we conclude that we have some confidence that the HadRM3 model is able to simulate the basic climatology of the UK reasonably well. Global climate models, from the Hadley Centre or elsewhere will show a very much poorer comparison with observations of temperature or rainfall, due to their coarser resolution.

4.2 Future changes in average temperature

Annual warming rates vary from about 0.1º to 0.3ºC per decade for the **Low Emissions** scenario, to about 0.3º to 0.5ºC per decade for the **High Emissions** scenario. These rates of climate warming over the UK are very similar to the global-average warming rates presented in Chapter 3. In all seasons, and for all scenarios, there is a northwest-to-southeast gradient in the magnitude of the climate warming over the UK, the southeast consistently warming by at least several tenths of a degree Celsius more than the northwest (Figures 31 to 34). The warming in the southeast is especially pronounced in summer, with warming in excess of 4ºC over a large part of southern England and south Wales by the 2080s in the **Medium-High Emissions** and **High Emissions** scenarios. By contrast, winter warming by the 2080s in northwest Scotland ranges from just 1ºC (**Low Emissions**) to 2ºC (**High Emissions**). The slower warming rates in the northwest are likely to be influenced by the weakening of the thermohaline circulation in the North Atlantic (see Section 7.8), which would reduce the ocean heat transport from low latitudes to the ocean off northwest Scotland. The more rapid warming rates in the southeast in summer are likely to be a result of the increased continentality of climate here – drier summers and drying soils leading to larger increases in the sensible/latent heat ratio than in the northwest.

The warming in the southeast is especially pronounced in the summer.

The main conclusions about changes in average temperature are:

- an annual warming by the 2080s of between 1º and 5ºC depending on region and scenario
- greater summer warming in the southeast than the northwest
- greater warming in summer and autumn than in winter and spring

4.3 Future changes in average precipitation

The patterns of change in average precipitation are less consistent between seasons than for temperature (Figures 35 to 38). Winter precipitation increases for all periods and scenarios, although these increases by the 2080s range from 5 to 15 per cent for the **Low Emissions** scenario, to more than 30 per cent for some regions for the **Medium-High Emissions** and **High Emissions** scenarios. With the exception of parts of western Scotland in the 2020s, these increases in winter precipitation are larger than would be expected due to natural variability. For summer, the pattern is reversed and almost the whole country becomes drier, with rainfall decreases over England for the **Low Emissions** scenario of more than 20 per cent, rising to more than 40 per cent for the **High Emissions** scenario. The largest percentage changes in precipitation in both winter and summer are experienced in eastern and southern parts of the country – the changes in northwest Scotland are the smallest (see Section 7.5 for a discussion of possible reasons for this).

River flooding may increasingly be a problem in the winter half of the year © M Robinson.

In spring, precipitation decreases over inland areas of the UK, the largest magnitudes for the **High Emissions** scenario being about 15 per cent around the England-Wales border. There are only modest changes in spring precipitation in the coastal regions and in Northern Ireland, in most cases being less than 5 per cent – effectively representing little change from existing conditions. Autumn displays a southeast-to-northwest gradient in precipitation change, with the southeast drying by between 5 and 20 per cent – depending on scenario - while precipitation in the northwest of Scotland and in Northern Ireland increases slightly under all scenarios. When aggregated over the year, a large proportion of the UK experiences a small reduction in precipitation – less than 5 per cent decrease for the **Low Emissions** scenario, up to a 10 or 15 per cent decrease in some inland areas for the **High Emissions** scenario.

The main conclusions about changes in average precipitation are:

- wetter winters, by up to 30 per cent by the 2080s for some regions and scenarios
- drier summers, by up to 50 per cent by the 2080s for some regions and scenarios
- little change - or slight drying - in the annual total

(12) Future model development in the Hadley Centre will lead to higher resolution models for the UK at 25 km and 10 km; see Section 9.5.

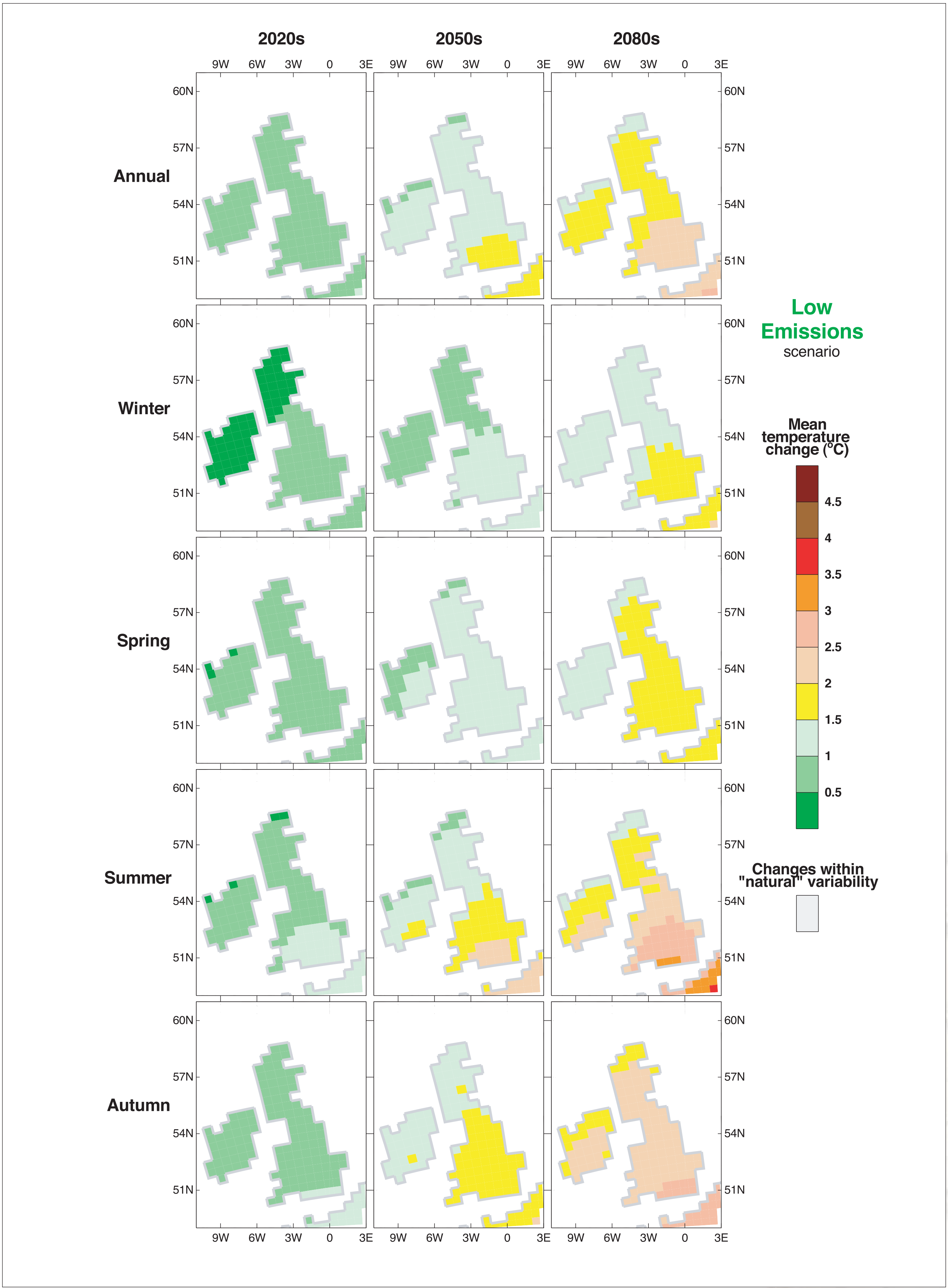

Figure 31: Change in average annual and seasonal temperature (with respect to the model-simulated 1961-1990 climate) for thirty-year periods centred on the 2020s, 2050s and 2080s for the Low Emissions scenario. Grey areas show changes within an estimate of "natural" variability, one standard deviation of model-simulated 30-year average climates.

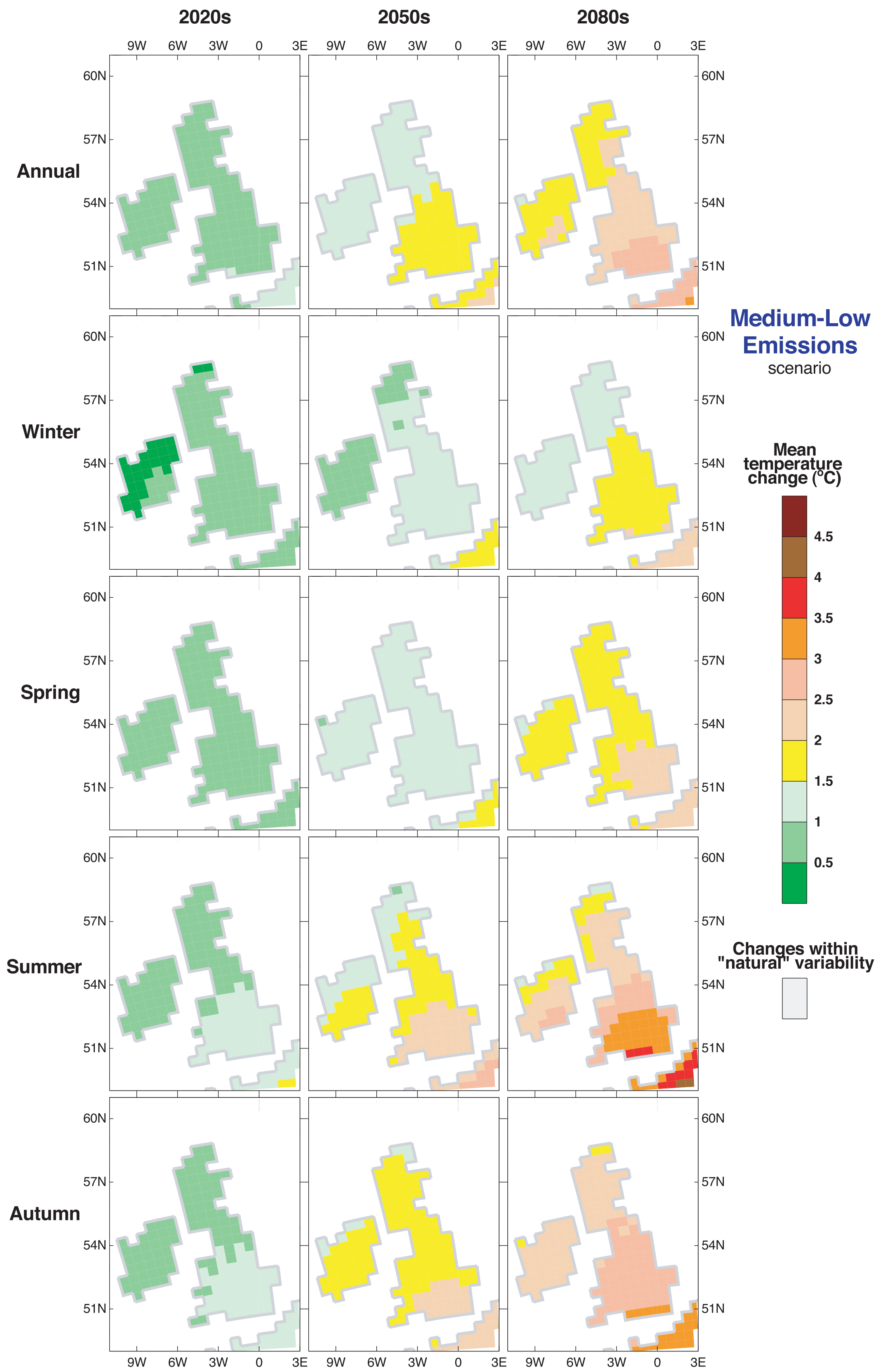

Figure 32: As Figure 31, but for the Medium-Low Emissions scenario.

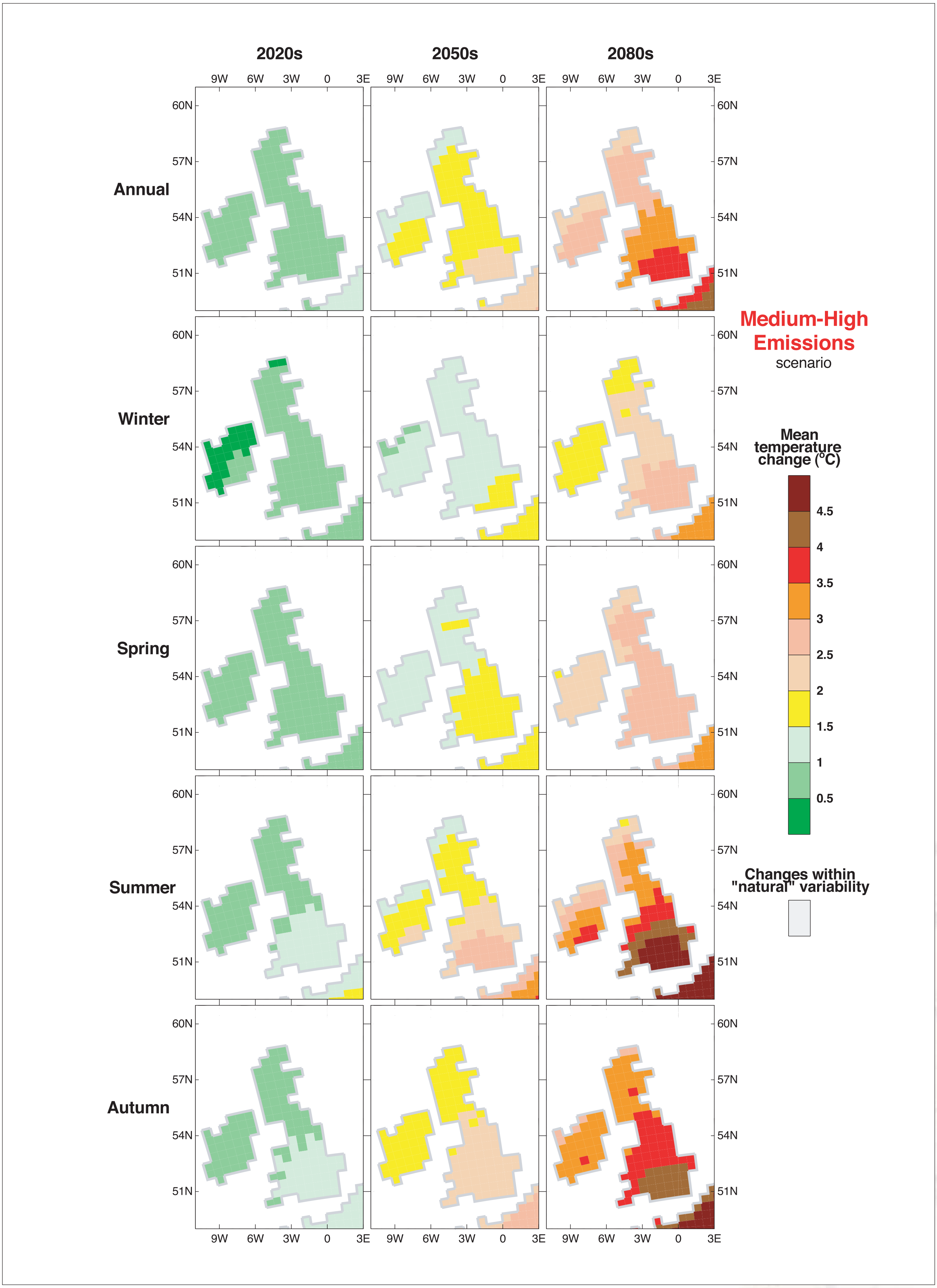

Figure 33: As Figure 31, but for the Medium-High Emissions scenario.

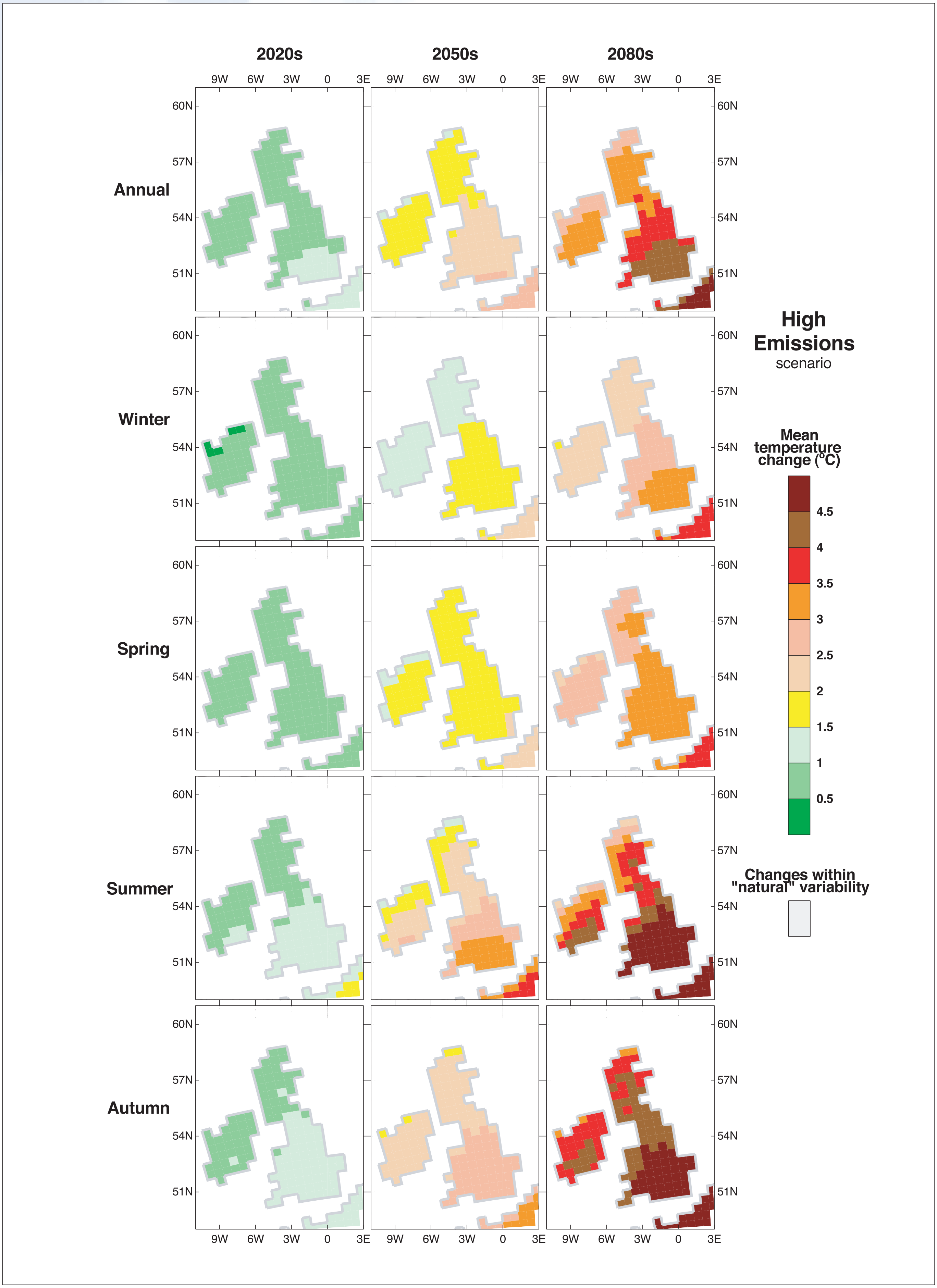

Figure 34: As Figure 31, but for the High Emissions *scenario.*

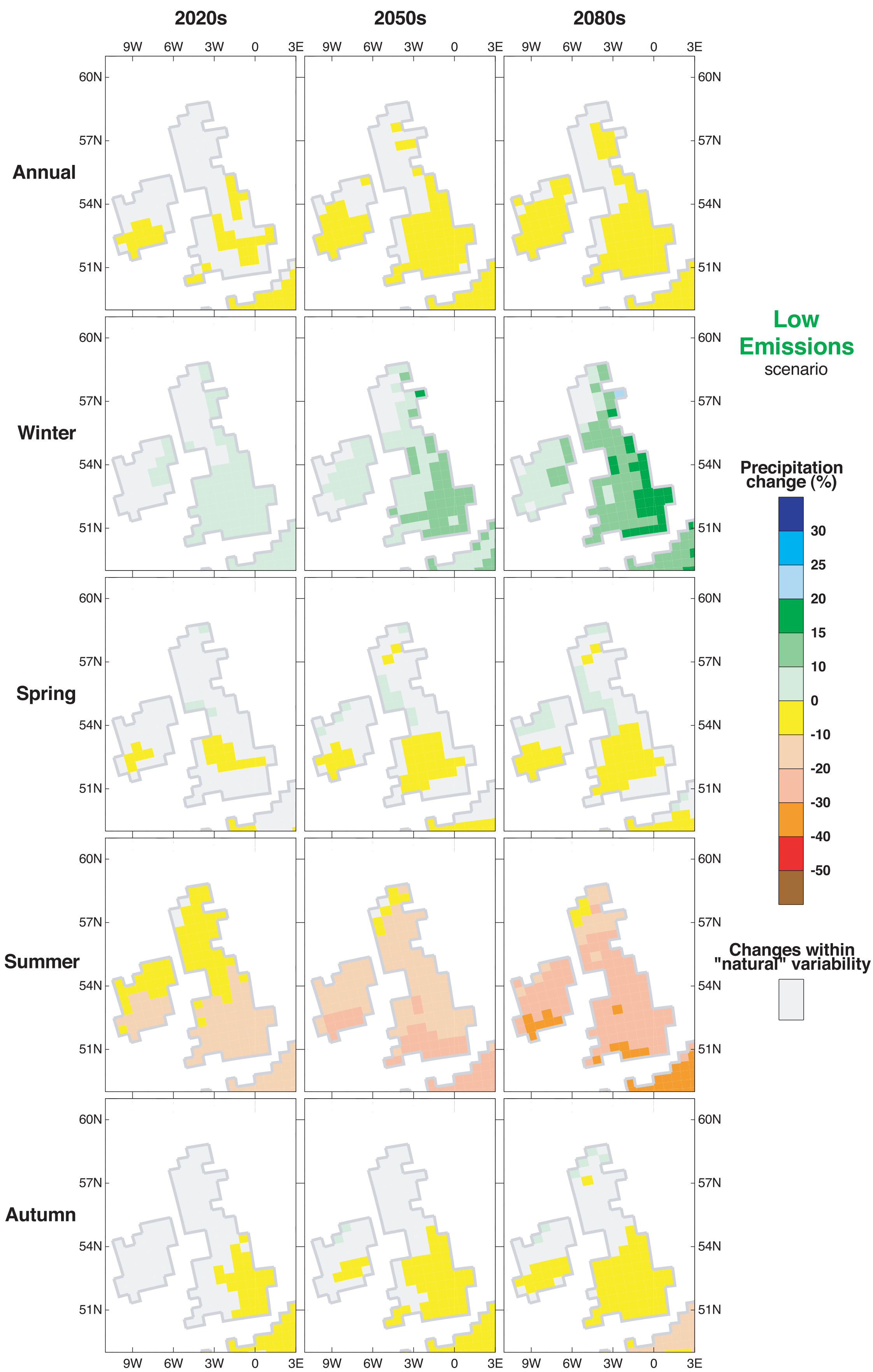

Figure 35: Change in average annual and seasonal precipitation (with respect to model-simulated 1961-1990 climate) for thirty-year periods centred on the 2020s, 2050s and 2080s for the Low Emissions scenario. Grey areas show changes within an estimate of "natural" variability, one standard deviation of model-simulated 30-year average climates. Note the asymmetric scale.

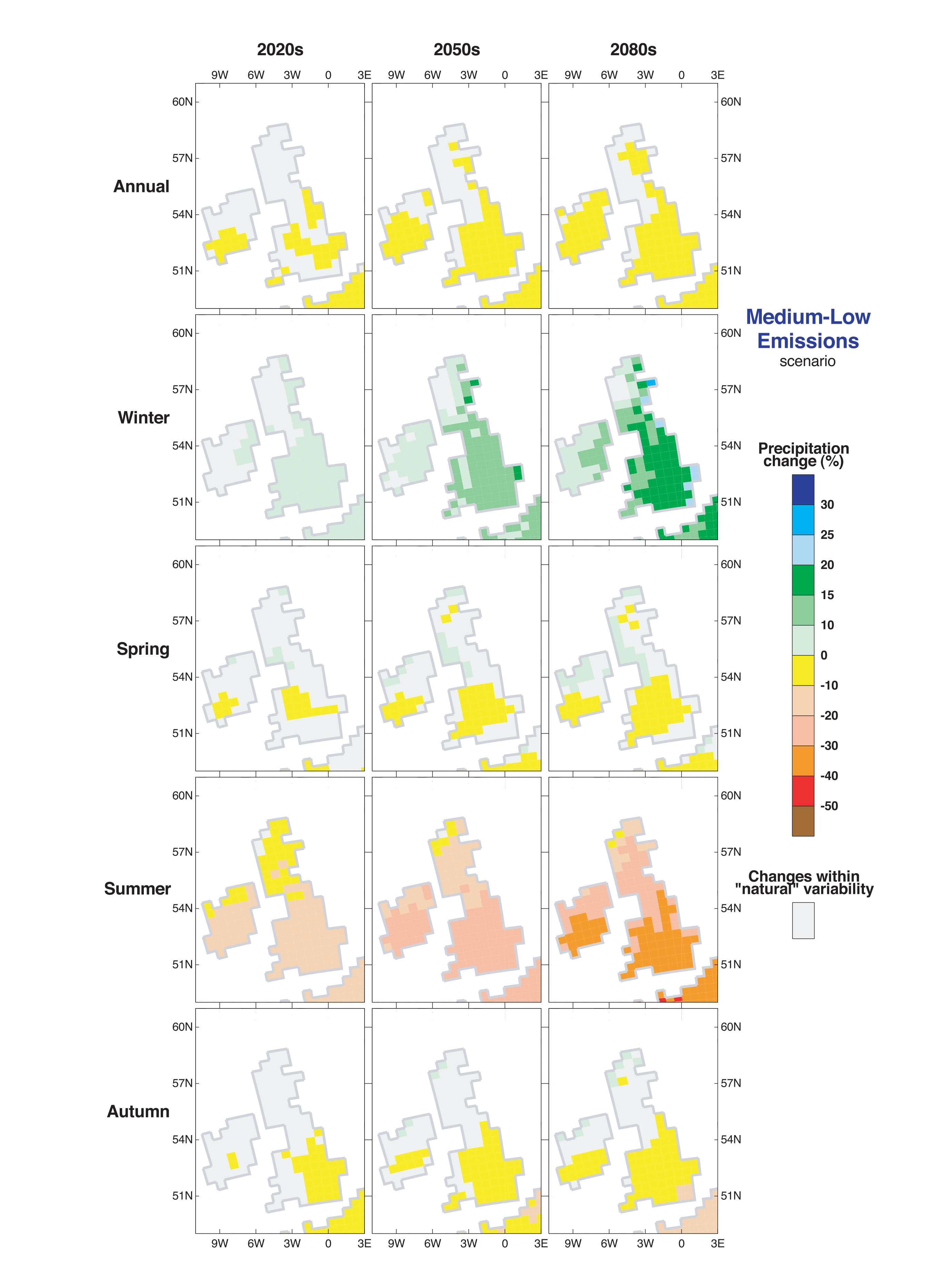

Figure 36: As Figure 35, but for the Medium-Low Emissions scenario.

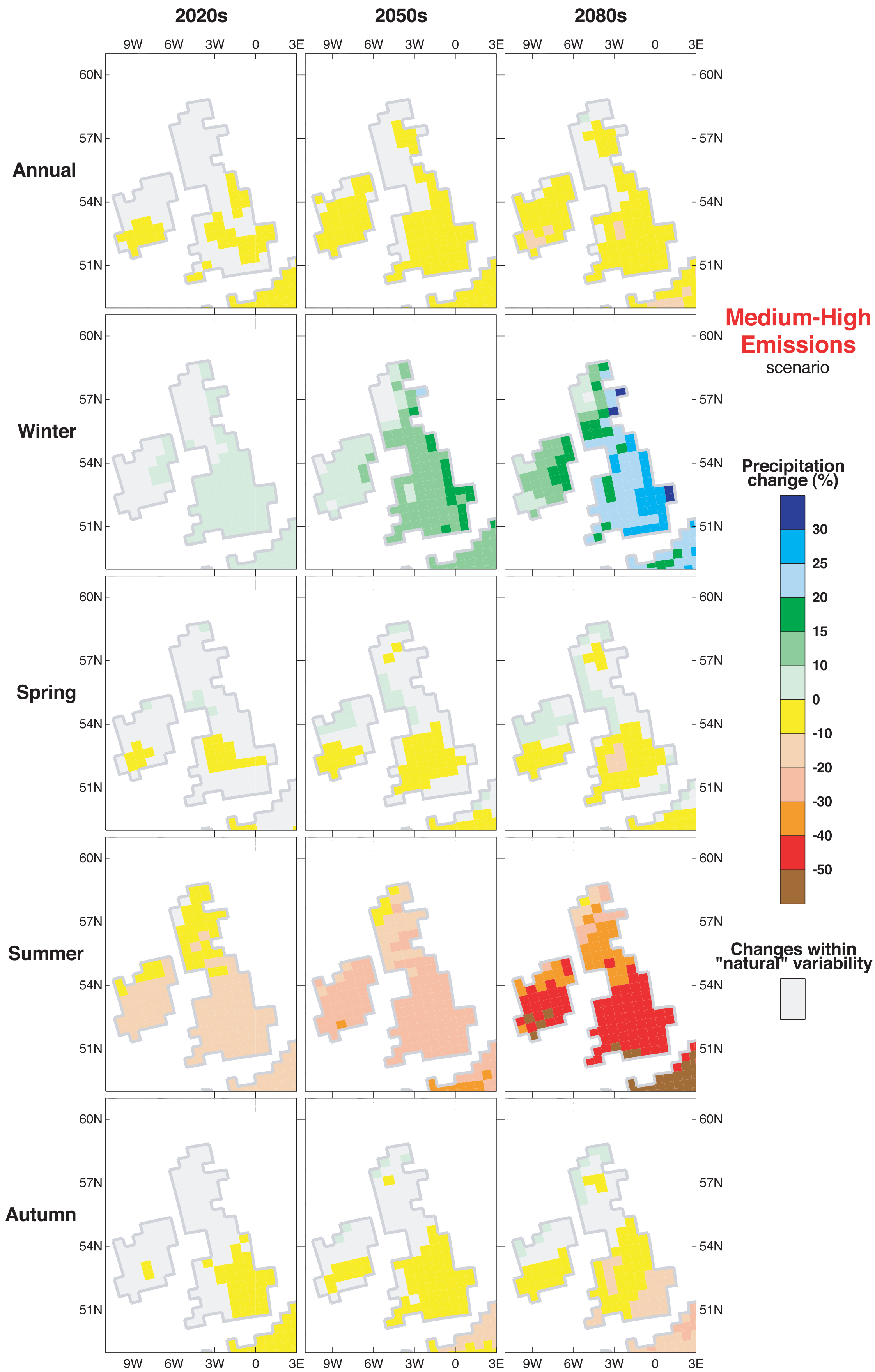

Figure 37: As Figure 35, but for the Medium-High Emissions scenario.

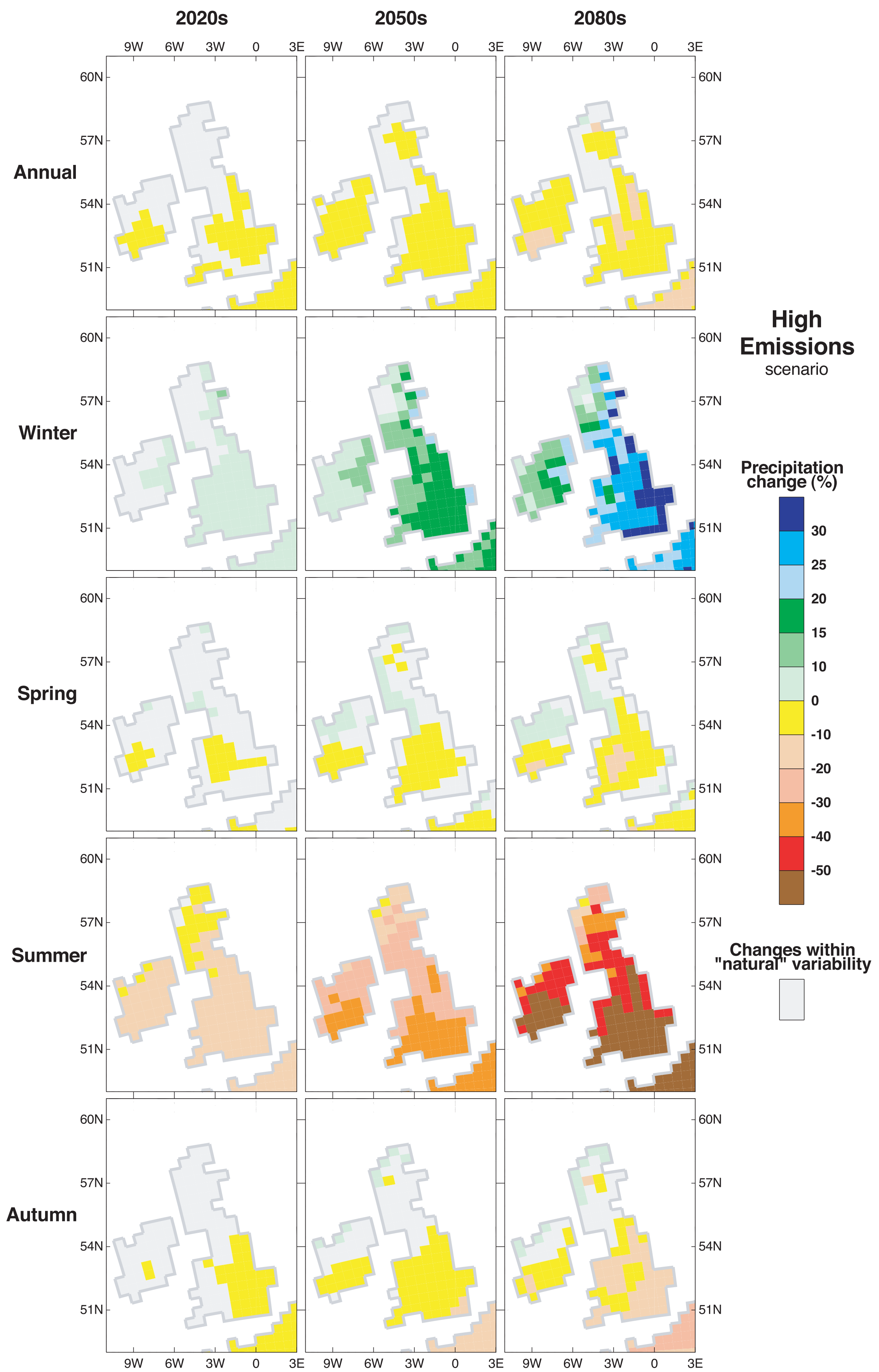

Figure 38: As Figure 35, but for the ***High Emissions*** *scenario.*

4.4 Future changes in average seasonality

These changes in average seasonal temperature and precipitation will affect the seasonality of UK climate. To illustrate such changes we select four grid boxes from the regional climate model representing different climate regimes across the UK (see Figure 29 for their location). These grid boxes are 50 km by 50 km in size so are representing the climate of a locality rather than of a specific place. We refer to them therefore by a county or regional name which best describes their location. Thus "Berkshire" represents the lowlands of south-central England, "Pembrokeshire" represents west Wales, "Inverness-shire" represents the Scottish Highlands, and "County Down" represents coastal Northern Ireland. These same four localities are also used for illustrative purposes in Chapter 5.

The seasonality of climate can be mapped by plotting the average monthly temperature through the year against the average monthly precipitation. This is done in Figure 39 for the four UK localities using observations for the baseline period (1961-90; grey), and then as simulated by the model for the 2080s for the **Low Emissions** and **High Emissions** scenarios. The shape of these polygons reveals the different seasonality of climate across the UK. A long flat polygon - as at Berkshire - indicates large seasonal differences in temperature but little seasonality in precipitation, whereas the more open polygons for western coastal areas (Pembrokeshire) and northern Scotland (Inverness-shire) indicate areas where winters are much wetter than summers.

Drier summers are likely to result in reduced river flow. © M Robinson.

For both scenarios, and for all four localities, future climate moves towards drier summers and wetter winters than at present, indicated by a progressive clockwise tilting of the polygons. As would be expected, the change is more noticeable in the **High Emissions** scenario than in the **Low Emissions** scenario. The polygons also all become more elongated in the horizontal dimension, indicating larger warming in summer than in winter. These shifts in the seasonality of UK climate point towards a more Mediterranean-like seasonal climate regime – in effect a larger differentiation between the summer (warm and dry) and winter (mild and wet) seasons.

4.5 Future changes in inter-annual variability

The previous sections have described changes in average seasonal climate for discrete 30-year periods. It is also important to examine whether the variation in seasonal temperature or precipitation that can be expected to occur from year-to-year also changes as UK climate warms. The size of these year-to-year changes is called the inter-annual variability (IAV) and changes in this quantity can be expressed as a percentage change in the standard deviation of the average seasonal climate. In order to account for long-term trends in the variables over the 30-year periods, such as those due to climate change, the data were de-trended before analysis. Figures 40 and 41 show the changes in inter-annual variability of temperature and precipitation respectively, for the four scenarios and for the 2080s period. Negative changes indicate that a future climate is *less* variable from year-to-year than the present climate, and positive changes indicate a future climate is *more* variable from year-to-year than at present.

Winter and spring temperatures over most of the country become less variable, with northwest Scotland and parts of northwest England and Wales seeing a reduction in IAV of up to 20 per cent. Summer and autumn temperatures become more variable over the whole UK, and this is especially marked in the west of the country. For the **Medium-High Emissions** and **High Emissions** scenarios, the inter-annual variability of summer temperature increases by 25 per cent or more.

Almost the whole country experiences an increase in winter precipitation variability, especially eastern England (Figure 41). In summer, there are mostly decreases in precipitation variability, most marked in the south and west of the country. Only the far north of Scotland experiences an increase in summer precipitation variability. These changes in variability largely reflect the changes in average precipitation shown in Figures 35 to 38; the standard deviation tends to increase as the average increases, and decreases as the average decreases.

Changes in seasonal temperature and precipitation anomalies

We can also examine changes in the variability of climate from year-to-year by plotting the individual seasonal anomalies for model-simulated future years and comparing them with recent extreme seasons that have had a major impact on the UK.

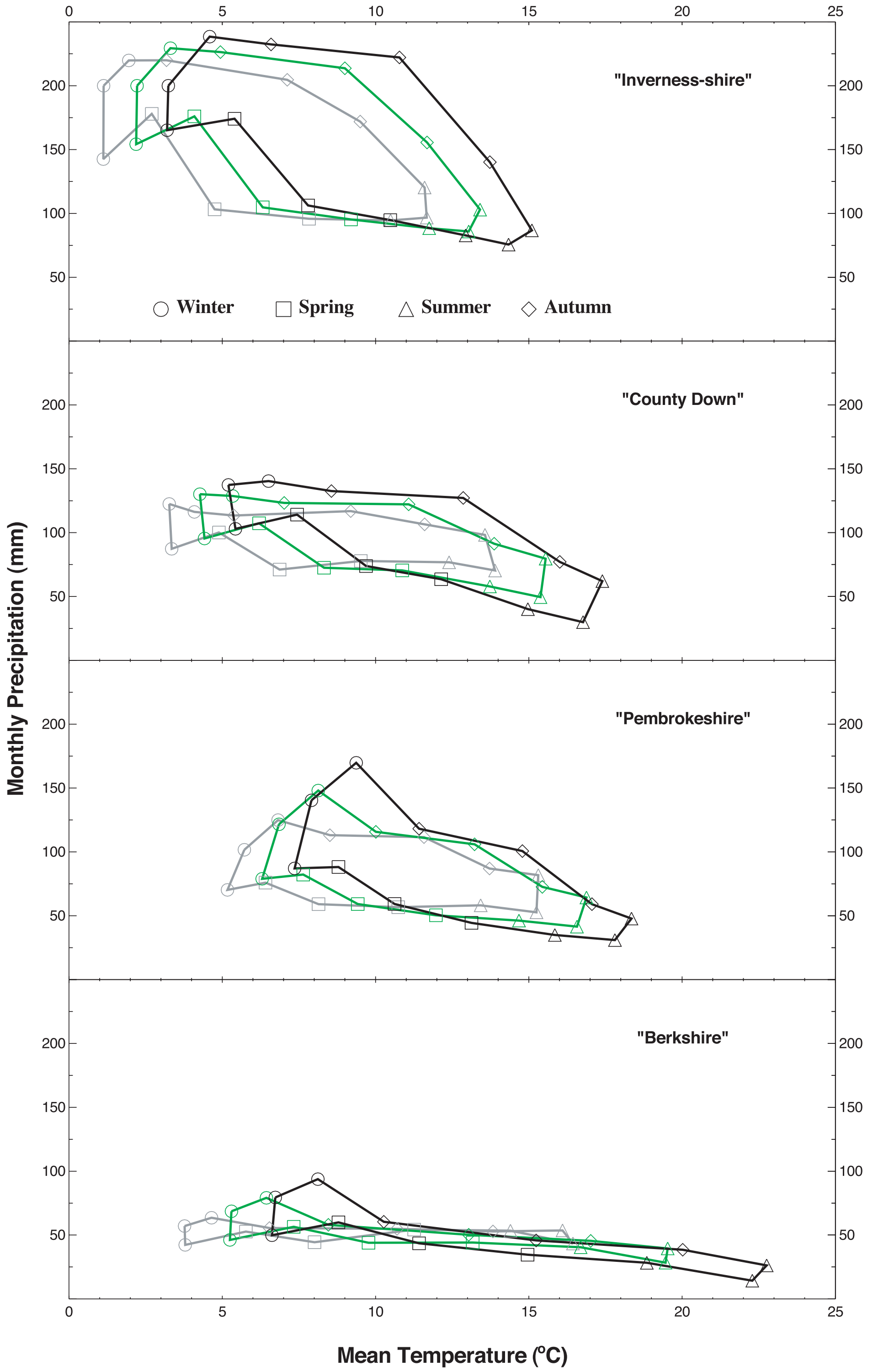

Figure 39: The changing seasonality of UK climate in the future. The seasonal variation in average temperature and precipitation for observed 1961-90 climate (grey), and for the 2080s as simulated for the Low Emissions and High Emissions scenarios. The monthly points are shown by different symbols for each season and these points join up to trace out the climate evolution of an average year.

We do this in Figure 42 for the summer and winter seasons over England and Wales, focusing on our two most extreme scenarios, the **Low Emissions** and the **High Emissions**. We also combine information about temperature *and* precipitation in these individual years. Showing the information this way is important. The occurrence of high temperatures in a summer of low precipitation enhances drought conditions and, for example, contributes to subsidence of structures, while a warm *and* wet winter can result in damp-related health problems and building and flood damage.

Each point in these graphs represents an individual year simulated by the model in the respective future time period. The inter-annual variability of climate is therefore shown by the degree of scatter of the points within each period. This analysis also allows us to relate future changes in climate with recent seasonal anomalies. For example, by the 2080s virtually every summer over England and Wales – whether for the **Low Emissions** or **High Emissions** scenarios - may be hotter and drier than the summer of 2001. For the **High Emissions** scenario by the 2080s, about one summer in three will be both hotter *and* drier than the hot, dry summer of 1995, and nearly *all* summers will be hotter. Roughly one summer in ten will have less than 25 per cent of present-day rainfall. A less extreme change is evident for the **Low Emissions** scenario, for which even by the 2080s few summers would match the dryness of 1976 or 1995. Nevertheless, even for this scenario about two summers in three are as hot as, or hotter than, the summer of 1995.

By the 2080s virtually every summer over England and Wales may be hotter and drier than the summer of 2001.

A similar comparison can be made for the winter season (Figure 42, right panels). For the **High Emissions** scenarios, more than half of the winters by the 2080s will be milder than the recent mild winters of 1989/90 or 1994/95, and about 15 per cent of them will be wetter as well. For the **Low Emissions** scenario, few winters will be as wet as these two recent seasons, but about a third will be as mild or milder. For neither **Low Emissions** nor **High Emissions** scenario will a very cold, dry winter such as 1962/63 occur by the 2050s or 2080s, although it is still possible even for the **High Emissions** scenario that such an extreme winter may occur again sometime over the next few decades (see the 2020s panel).

Changes in the frequencies of selected extreme seasonal climate anomalies are summarised in Table 6 for the **Medium-High Emissions** scenario. For this scenario, a very hot "1995-type" August might be expected to occur six years out of ten by the 2080s and by this period it is unlikely that *any* year would be cooler than the warm year of 1999. For precipitation, very dry summers like 1995 occur in half the years by the 2080s, while very wet winters like 1994/95 occur on average almost once a decade.

4.6 The evolution of temperature and precipitation

The previous sections have presented changes in average UK climate and have drawn attention to changes in the year-to-year variability of climate. This has been shown for three distinct time periods, the 2020s, the 2050s and the 2080s. Although using these discrete 30-year periods is a convenient way to show the changes in map form, in reality climate will be continuously changing from year-to-year, both as a result of natural variability but also because of the underlying long-term trends in climate brought about by human influences on the climate system.

The global model, HadCM3, simulates the continuous evolution of climate on a day-by-day basis throughout the twenty-first century and this enables us to examine transient changes in climate. One possible year-by-year evolution of climate for the **Medium-High Emissions** scenario is shown in Figure 43 for England and Wales and in Figure 44 for Scotland. In these plots just one ensemble member ('a') was used to describe the year-to-year variability. The long-term warming trends in winter and summer temperature are clearly seen for both regions, consistent with the changes in 30-year average climates shown in Figures 31 to 34. The wetting of winters is also evident in both regions, but the drying trend in summer rainfall is much larger over England and Wales than over Scotland. This again is consistent with the changes in average precipitation shown in Figure 35 to 38. The graphs also clearly show the substantial year-to-year and decade-to-decade variability superimposed on top of these trends. This variability is natural, caused mainly by interactions between the ocean and atmosphere in the model; these variations are qualitatively similar to those observed in the real UK climate.

The effect of this natural variability in climate means that there may well be long periods in the future which show relatively little warming, or even cooling for a few years (for example, England and Wales summers during the late 2040s). Similarly, there may be trends in precipitation over a few years which are opposite to those expected according to the average 30-year changes shown earlier. Due to the variability of climate, new records will not be established every year, or even every decade. There may be long periods when no new records are established but, conversely, several records may fall in the space of a few years. Although we can simulate the overall variability of these quantities reasonably well, we are not yet able to model the long-term course of natural variability, so we cannot predict the future climate for specific years - although forecasts for one to ten years hence may soon be possible; see Section 9.7. The years in which climate records are broken in England and Wales will clearly *not* be those precise years indicated in Figures 43 and 44.

	2020s	2050s	2080s
Mean Temperature			
A hot '1995-type' August (+3.4ºC)	1	20	63
A warm '1999-type' year (+1.2ºC)	28	73	100
Precipitation			
A dry "1995-type" summer (37 per cent drier than average)	10	29	50
A wet "1994/95-type" winter (66 per cent wetter than average)	1	3	7

Table 6: The percentage of years experiencing various extreme seasonal anomalies across the southern UK (England and Wales) for the Medium-High Emissions scenario. Simulated by HadCM3.

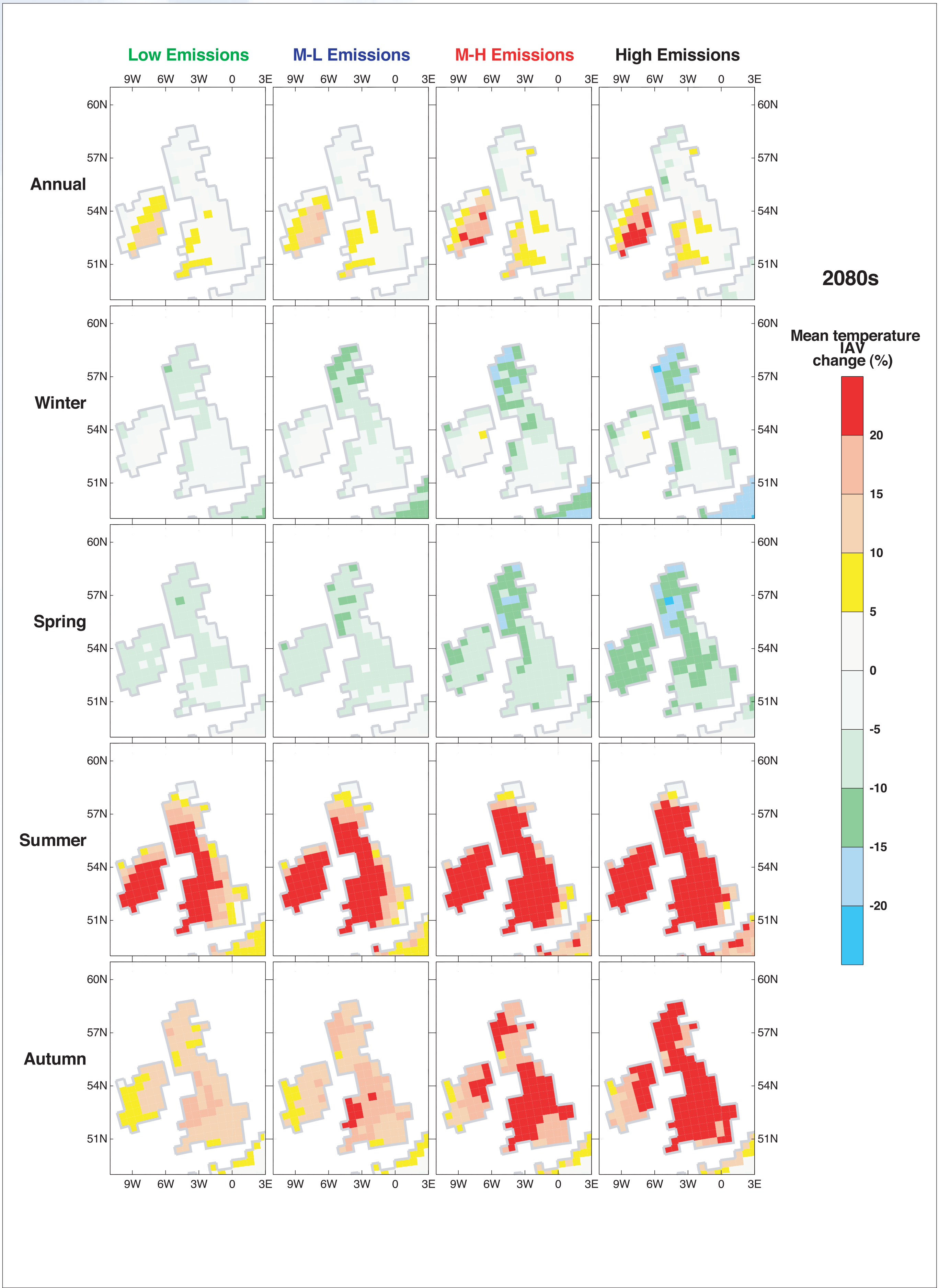

Figure 40: Relative changes in the inter-annual variability of annual and seasonal temperature for the 2080s and for the four scenarios. Changes are the percentage change in standard deviation, with respect to 1961-1990. Data were detrended before analysis.

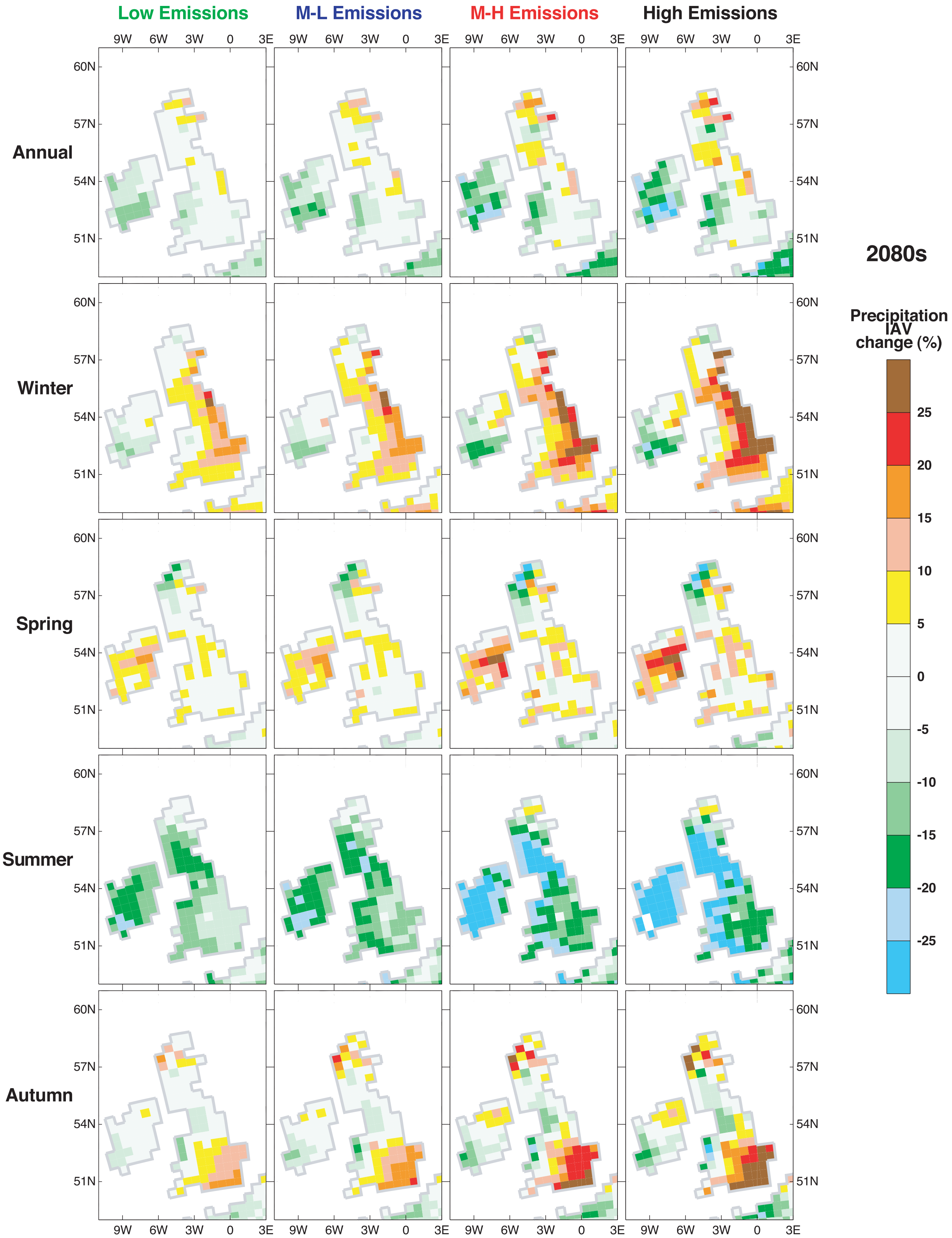

Figure 41: As Figure 40, but for precipitation.

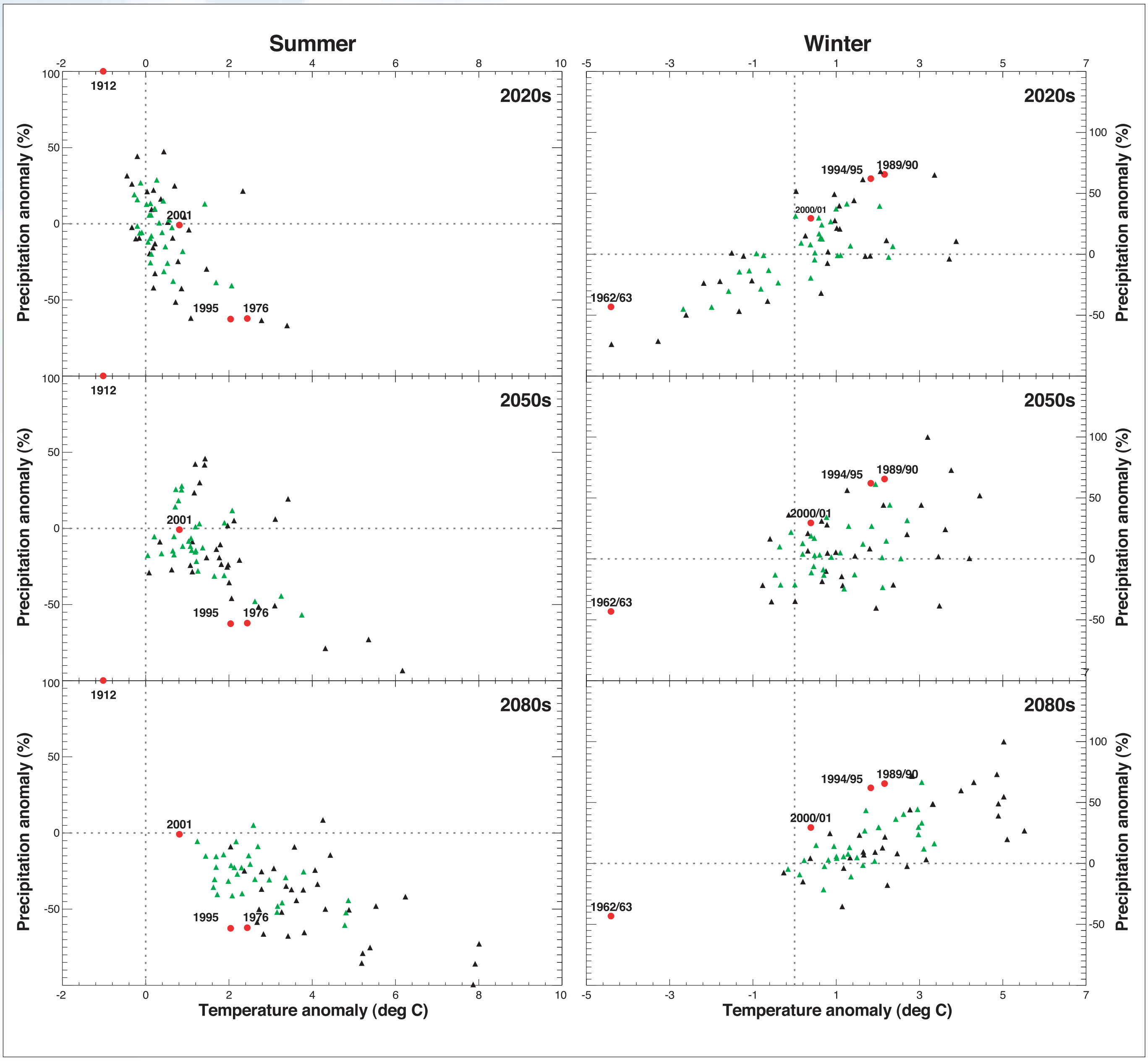

Figure 42: Plot of HadCM3-simulated England and Wales Precipitation versus Central England Temperature for three time-slices for the High Emissions (black triangles) and Low Emissions (green triangles) scenarios. Left = summer; Right = winter. Red dots indicate observed anomalies for the exceptional summers of 1912, 1976 and 1995, along with summer 2001 for reference, and the exceptional winters of 1962/63, 1989/90 and 1994/95, along with winter 2000/01 for reference.

4.7 Future changes in other surface variables

Until now we have restricted our comments to just average temperature and precipitation. The patterns of change over the UK for selected additional climate variables which are directly modelled by the regional model are shown in Figures 45 to 50 for the annual average, for the four seasons and, usually, for all four scenarios.

These maps only show changes for the 2080s however; changes for the 2050s and 2020s are not shown here. Also, in one or two cases, only results for the **Medium-High Emissions** scenario are shown. This selection is not only for reasons of space but because, as explained in Chapter 3, we only have direct model output from HadRM3 for the **Medium-High Emissions** scenario and for the 2080s period (i.e., 2071-2100); our results for the other time-slices and the other scenarios are scaled from these 2080s **Medium-High Emissions** scenario patterns.

In order to obtain rough estimates of the changes for the 2020s and 2050s, or for the other three scenarios for the 2080s, it is possible to use the scaling factors shown in Table 7 and apply them to the changes shown for the **Medium-High Emissions** scenario for the 2080s from the map. For example, Figure 49 shows the change in snowfall rate for four scenarios for the 2080s. To estimate change in snowfall rate for the **Medium-Low Emissions** scenario in the 2050s for a grid box in north-west Wales, take the **Medium-High Emissions**-2080s change from the map (about -70 to -75 per cent) and multiply by the **Medium-Low Emissions**-2050s factor in Table 7, i.e., 0.50. The **Medium-Low Emissions**-2050s change for this box is therefore about -35 to -38 per cent.

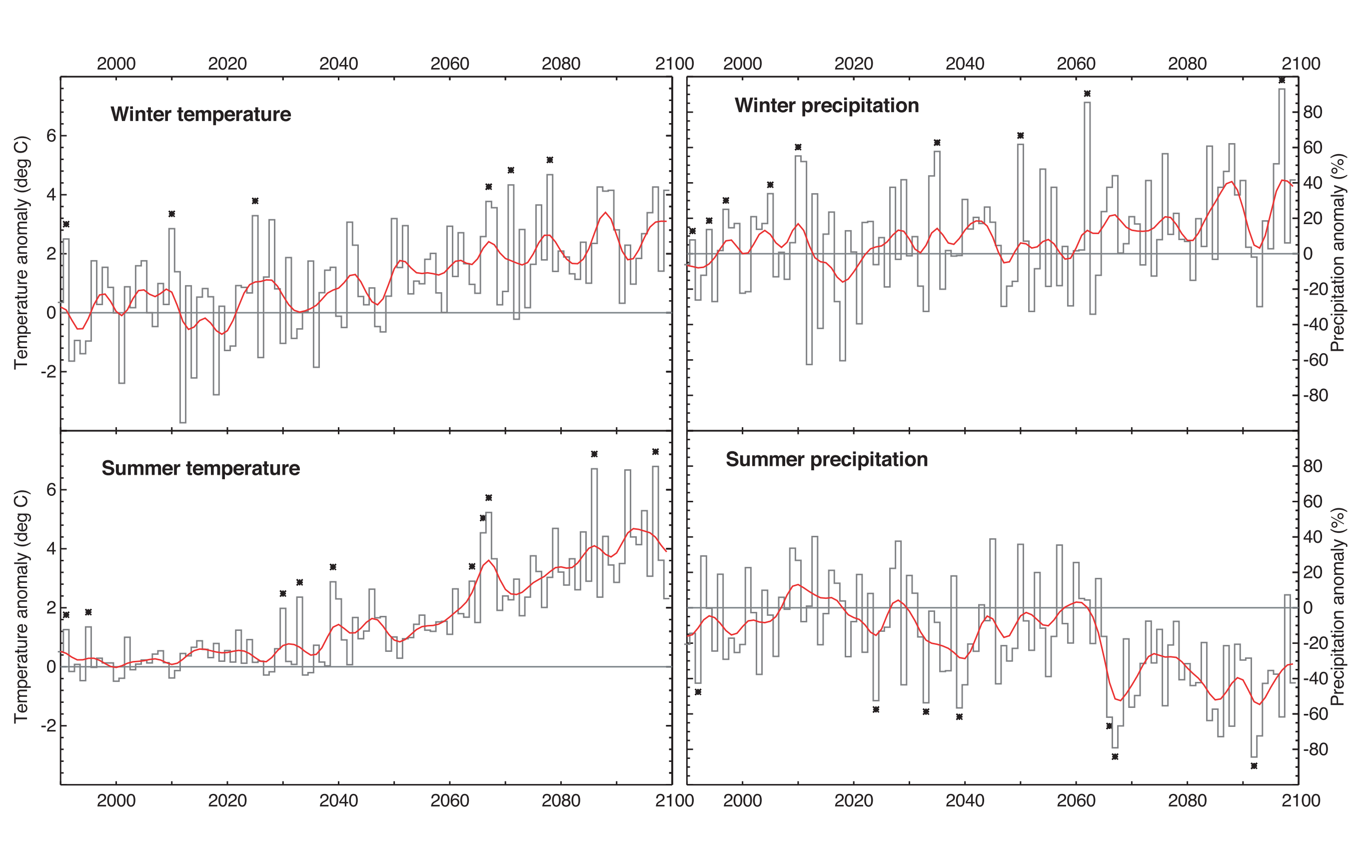

*Figure 43: One possible evolution (HadCM3 ensemble member 'a') of winter and summer mean temperature (left panel) and precipitation (right panel) from 1990 to 2099 for England and Wales for the Medium-High Emissions scenario. The seasonal anomalies are calculated with respect to average 1961-1990 climate. The stars show the years in which the model simulates new warm, dry or wet record seasonal anomalies. Smooth curves emphasise variations on time-scales greater than 10 years. Important note: these data must **not** be interpreted as forecasts for specific calendar years.*

Diurnal temperature range

Changes in diurnal temperature range – daytime minus night-time temperature – are closely related to changes in cloudiness. Clear days generally have a higher diurnal range of temperature than cloudy days. As climate warms, there is a slight decrease in the diurnal temperature range in winter over nearly the whole country; this is consistent with warmer, wetter and cloudier winters. In summer, however, the diurnal temperature range increases across all scenarios and, again, over nearly the entire country (Figure 45). For the **Medium-Low Emissions** scenario, for example, the summer diurnal range increases by more than 1ºC only in south-central England, but for the **High Emissions** scenario such increases are experienced over nearly the whole country, the exceptions being the coastal margins of Scotland and Northern Ireland. This increase in summer diurnal temperature range is likely to be due to reduced cloudiness leading to greater day-time insolation.

These changes may be summarised as follows - nights warm more than days during winter; days warm more than nights during summer. Nevertheless, this diurnal pattern of warming will still lead to milder summer evenings – each 1ºC of warming of summer nights equates on average over southern Britain to more than an hour shift in the diurnal cycle; temperatures currently experienced at 7.00pm would be experienced well after 8.00pm. With the 3º to 4ºC night-time warming for the **High Emissions** scenario by the 2080s, a 7.00pm temperature on an average summer evening at present would be experienced at 11.00pm. During spring and autumn there are smaller changes, with the northwest experiencing decreases in diurnal range and the southeast experiencing increases.

Cloud cover and short-wave radiation

Changes in cloud cover and solar radiation are important for a variety of reasons, including health, agriculture and tourism. Our scenarios suggest large decreases in summer cloud cover over the whole country, but especially in the south. Reductions in the south of England by the 2080s are about 10 per cent in the **Low Emissions** scenario, but are as large as 25 per cent or more in the **High Emissions** scenario (Figure

Time-slice	Low Emissions	Medium-Low Emissions	Medium-High Emissions	High Emissions
2020s	0.24	0.27	0.27	0.29
2050s	0.43	0.50	0.57	0.68
2080s	0.61	0.71	1.00	1.18

Table 7: Multiplying factors for conversion from 2080s Medium-High Emissions scenario to other scenarios and time-slices.

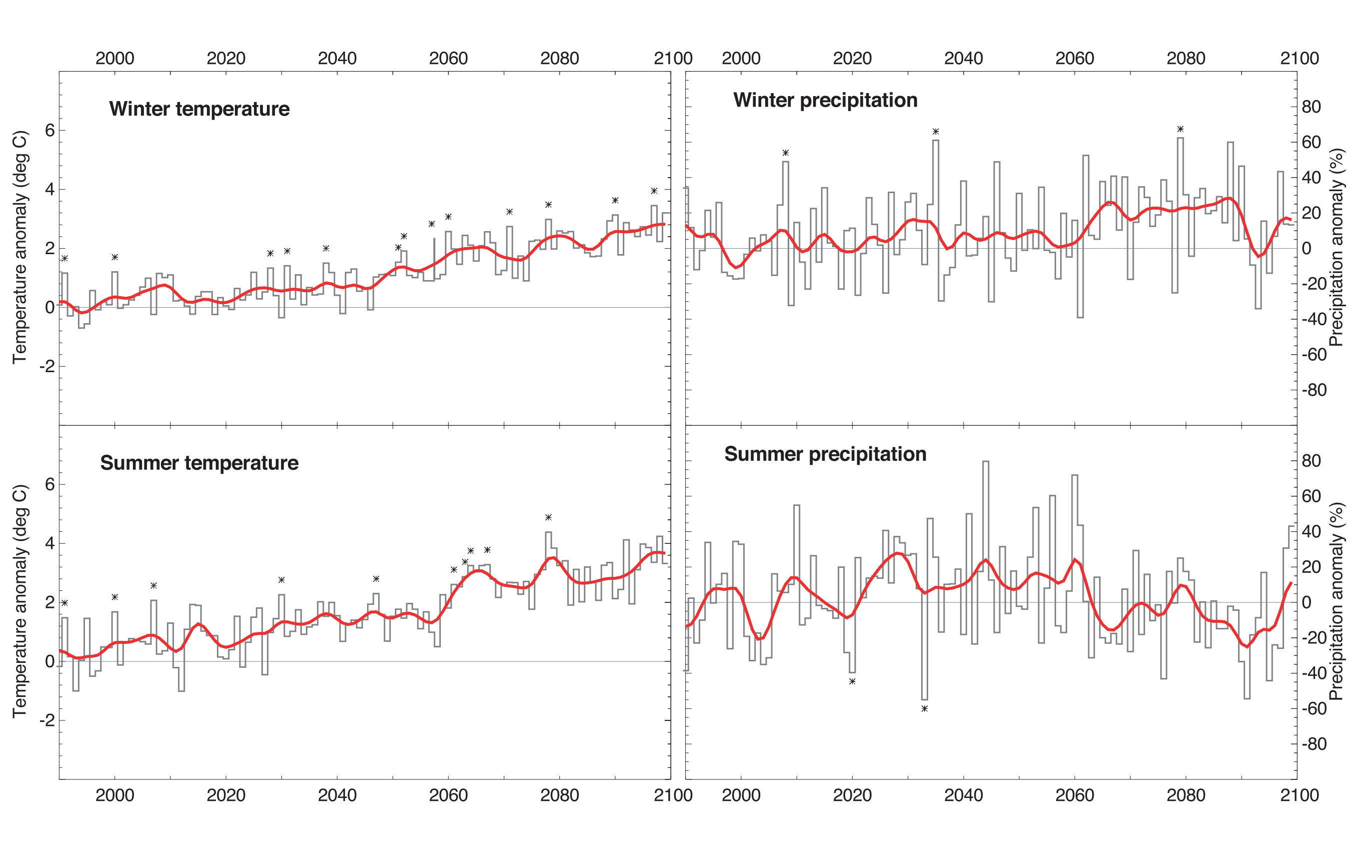

Figure 44: As Figure 43, but for Scotland.

46). Cloud cover increases slightly in winter – by no more than 2 or 3 per cent – over most of the country. In spring and autumn, cloud cover decreases over all but northwest Scotland (where changes are within natural variability), but the largest decrease is in the southeast of England. Averaged over the whole year, by the 2080s cloud cover decreases by up to 10 per cent depending on region and scenario. UK climate therefore becomes correspondingly more sunny in summer and solar radiation during this season increases by 10, 20 or even 30 Wm^{-2} over southern parts of the country (not shown). These changes are consistent with the patterns of precipitation change across the country, and also consistent with the changes in diurnal temperature range noted above.

Relative humidity

Specific humidity increases in the future in all seasons and scenarios, but the warmer temperatures mean that relative humidity *decreases* throughout the year and for all scenarios in all but a few areas of northern Scotland (Figure 47[13]). In winter, these reductions in relative humidity are only a few per cent, but in summer they can amount to up to 10 per cent or more by the 2080s, especially in England and Wales for the **Medium-High Emissions** and **High Emissions** scenarios. Relative humidity decreases over the whole UK in the summer, but this change is especially strong over southern England and south Wales with reductions in relative humidity of more than 10 per cent. Spring and autumn show smaller decreases than in summer, again with a north-south gradient. This gradient is slightly larger in the autumn than the spring. For the year as a whole, relative humidity decreases by between 1 and 8 per cent, depending on region and scenario.

Relative humidity decreases throughout the year and for all scenarios.

Average wind speed

Wind is driven by the pressure gradient across the country. When this gradient is high, winds are strong. Only small changes in pressure gradient are simulated by the model for spring and autumn. For these seasons average wind speed - the modelled 10-minute wind speeds averaged over a whole season - are little changed from today. In winter - when most severe winds occur - the pressure gradient across the country is simulated to tighten and stronger winds are experienced in southern and central Britain, but no higher than present in Scotland or Northern Ireland (Figure 48). Since the northwest of the UK is currently windier than the southeast in winter, this pattern of change implies a weakening of the winter differences in average wind speed across the country.

The largest increases in average wind speed in both winter and summer seasons occur along the south coast of England – here, increases in winter wind speed by the 2080s are between 4 (**Low Emissions**) and 10 (**High Emissions**) per cent; in summer the increases are smaller. For other coastal areas in summer, however, average wind speeds decrease

(13) Note that on these maps, the change in relative humidity refers to the number of percentage points relative humidity changes by. For example, if the current mean relative humidity is 70 per cent, a change of –10 per cent on the map means the future humidity is 60 per cent and not 63 per cent (i.e., a drop of [10 per cent of 70 per cent] = 7 per cent).

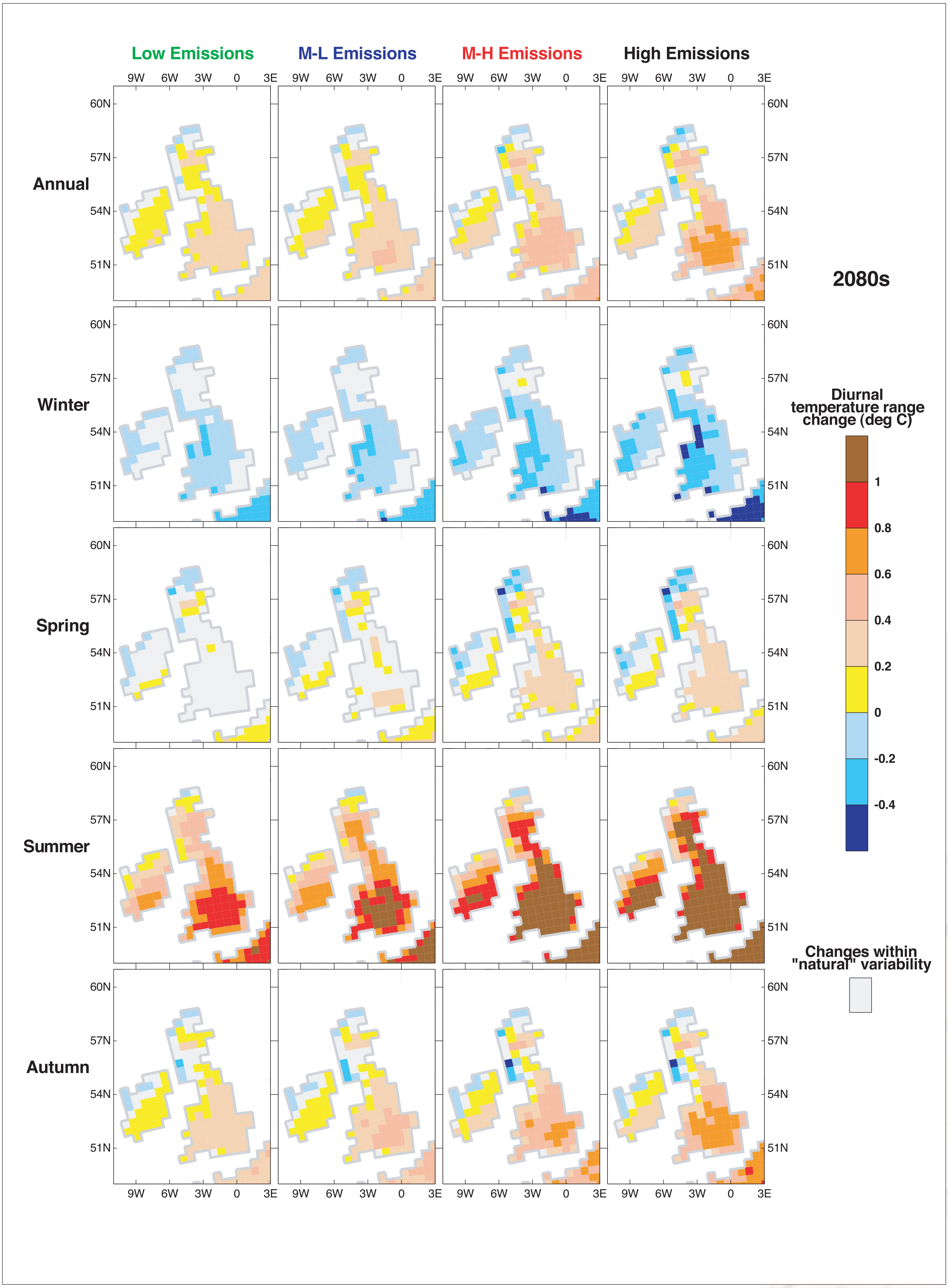

Figure 45: Change in average annual and seasonal diurnal temperature range (wrt 1961-1990) for the four scenarios for the 2080s. Grey areas show changes within an estimate of "natural" variability, one standard deviation of model-simulated 30-year average climates. The resolution of the HadRM3 model output is 50 km by 50 km. To convert data to other time-slices see Table 7.

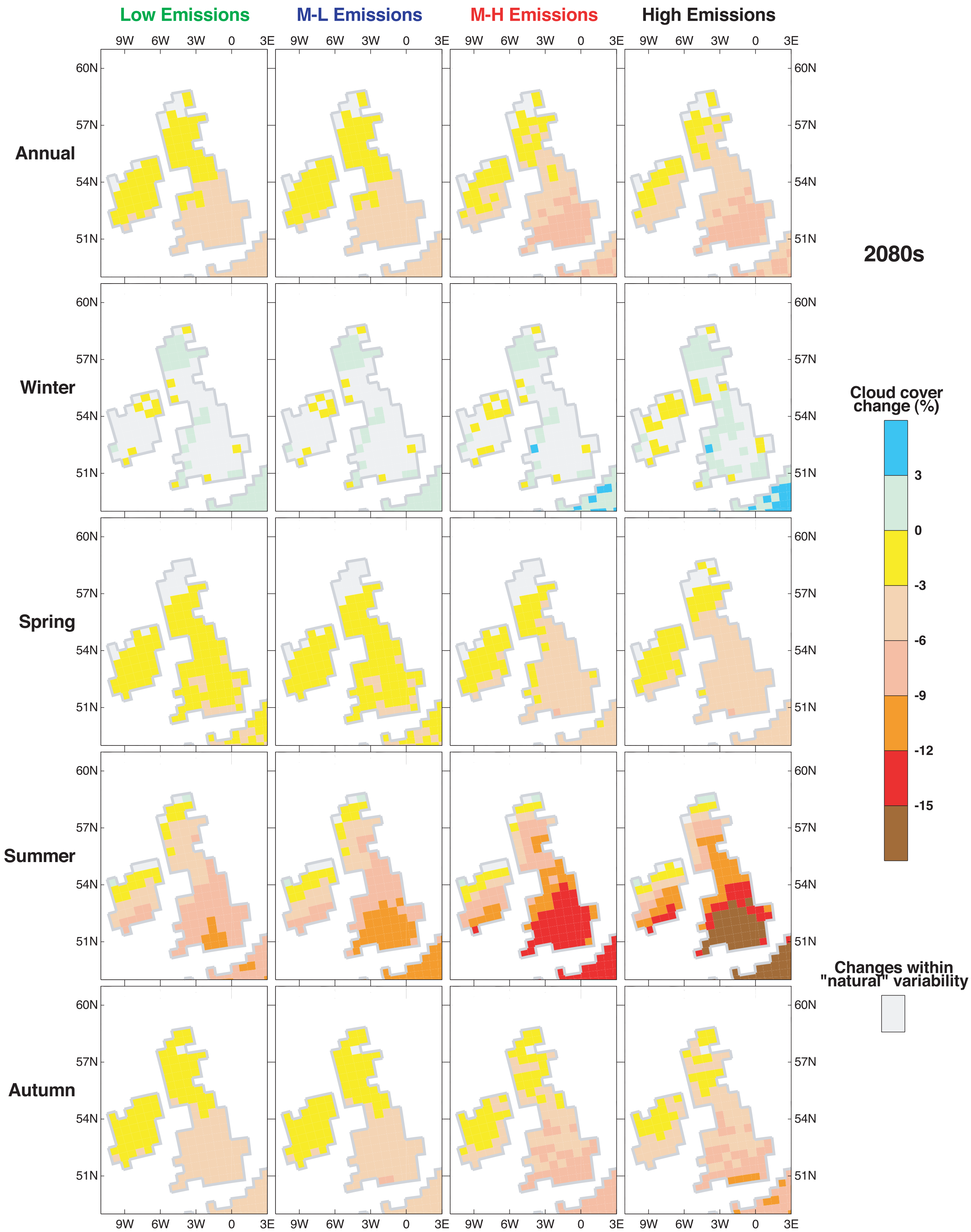

Figure 46: As Figure 45, but for percentage change in cloud cover.

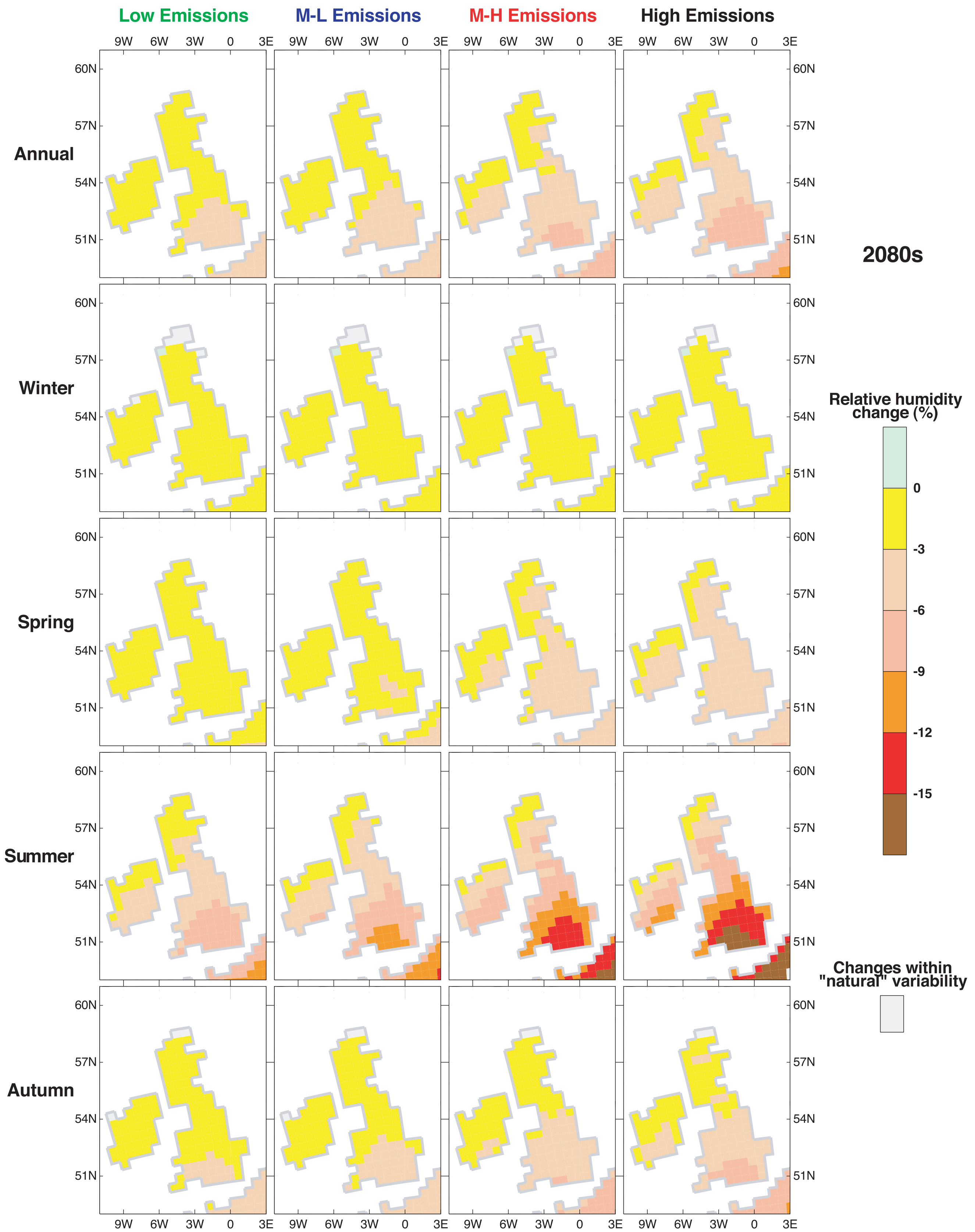

Figure 47: As Figure 45, but for percentage change in relative humidity.

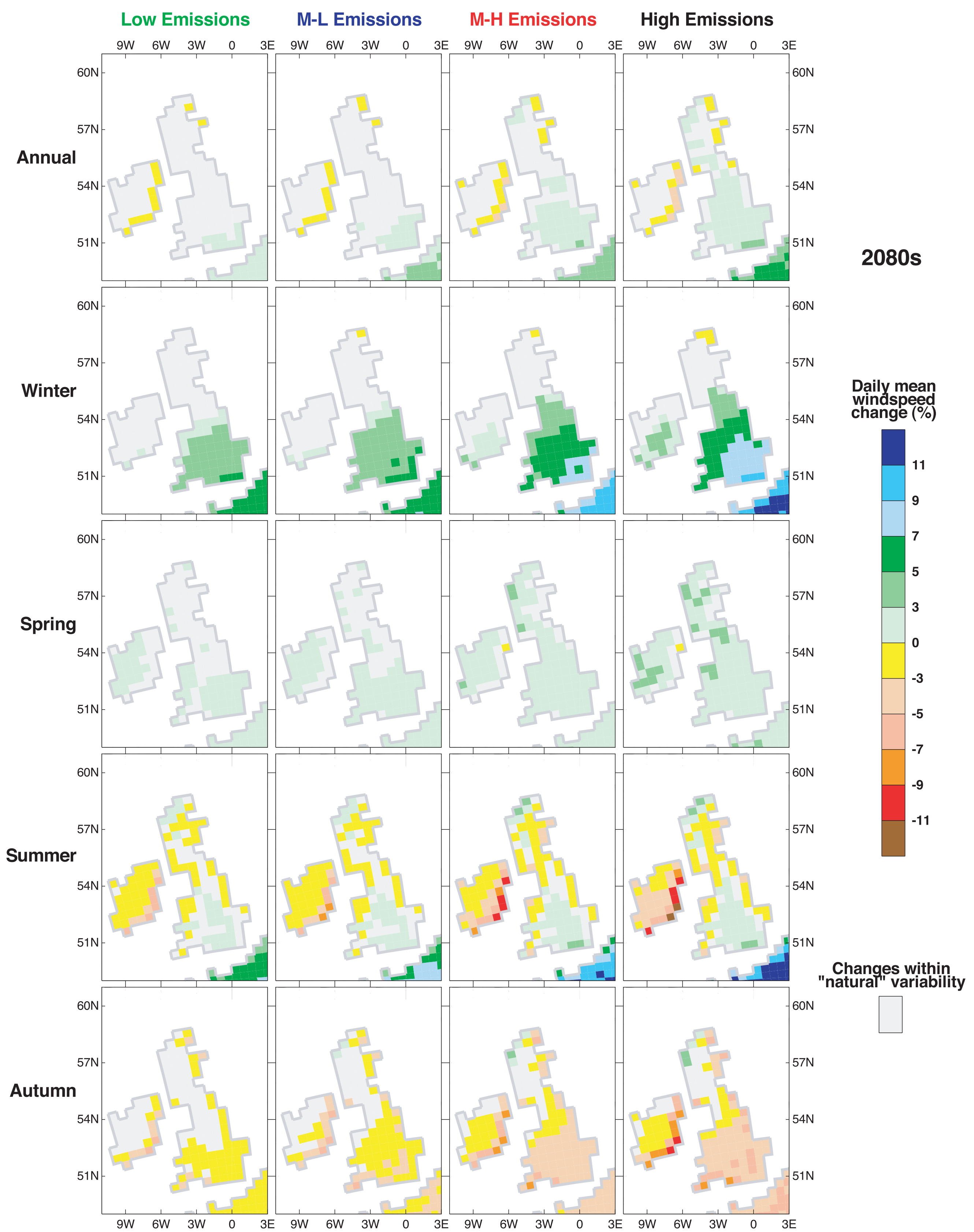

Figure 48: As Figure 45, but for percentage change in average wind speed.

slightly, while summer wind speeds inland increase by a correspondingly small amount. Summer average wind speed in Northern Ireland decreases quite substantially. In spring, changes are small, but autumn appears to see a decrease over England of up to 5 per cent. This is consistent with the sunnier, drier autumns indicated above.

It must be noted, however, that the consistency between different models and the physical representation within HadRM3 are not sufficient to be able to attach any level of confidence to wind speed. The changes in wind speed described above should be interpreted with this in mind, and certainly more caution should be taken when using these results than when using, for example, those for temperature and precipitation.

Snowfall
Although we have shown changes in total precipitation, for some physical and social systems changes in snowfall or snow cover will be equally, or even more, important. We show here changes in the average winter snowfall for the 2080s and for the four scenarios (Figure 49) – most snow of course falls in winter so these seasonal changes are very similar to the annual change. Snow amounts are defined as a depth of water, i.e., the depth of water collected when the snow is completely melted. As a rough guide, the depth of solid snow is about twelve times greater than the depth of snowmelt water, although this changes with humidity and temperature.

Snowfall totals decline substantially over the whole UK and for all scenarios.

The pattern of snowfall change reflects the variations in elevation across the UK, since snowfall is very strongly related to altitude. Snowfall totals decline substantially over the whole UK and in all scenarios, with the largest percentage reductions around the coast and in the English lowlands. For the **Medium-High Emissions** and **High Emissions** scenarios these reductions reach 90 per cent or more implying that for these scenarios by the 2080s these areas will rarely receive any snowfall (Table 8). By the 2080s, large areas of the UK are likely to experience quite long sequences of snowless winters, especially for the **Medium-High Emissions** and **High Emissions** scenarios. In relative terms, the Scottish Highlands and parts of Northern Ireland experience the smallest reductions, but even here total snowfall by the 2080s might only be 50 per cent or less of present-day totals.

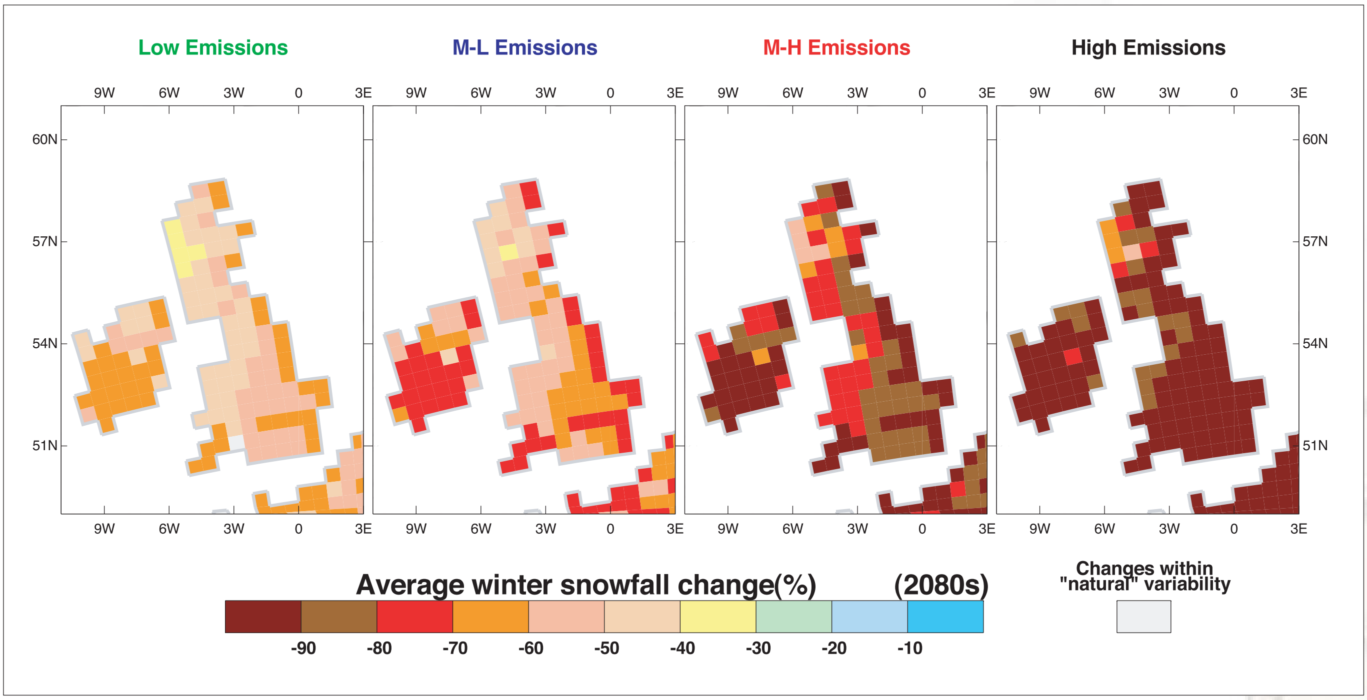

Figure 49: Change in average winter snowfall (per cent) for the four scenarios for the 2080s.

Grid Box	Average winter snowfall (mm water equivalent) 1961-1990	2080s	Change from 1961-1990 to the 2080s (per cent)
"Berkshire"	5.4	0.3	-94
"Pembrokeshire"	6.6	0.9	-86
"Inverness-shire"	75.0	25.5	-66
"County Down"	10.5	2.4	-77

Table 8: Average winter snowfall (mm of water equivalent) simulated for the baseline period and for the 2080s for the Medium-High Emissions scenario. The four individual grid boxes in HadRM3 selected for this analysis as those shown in Figure 29.

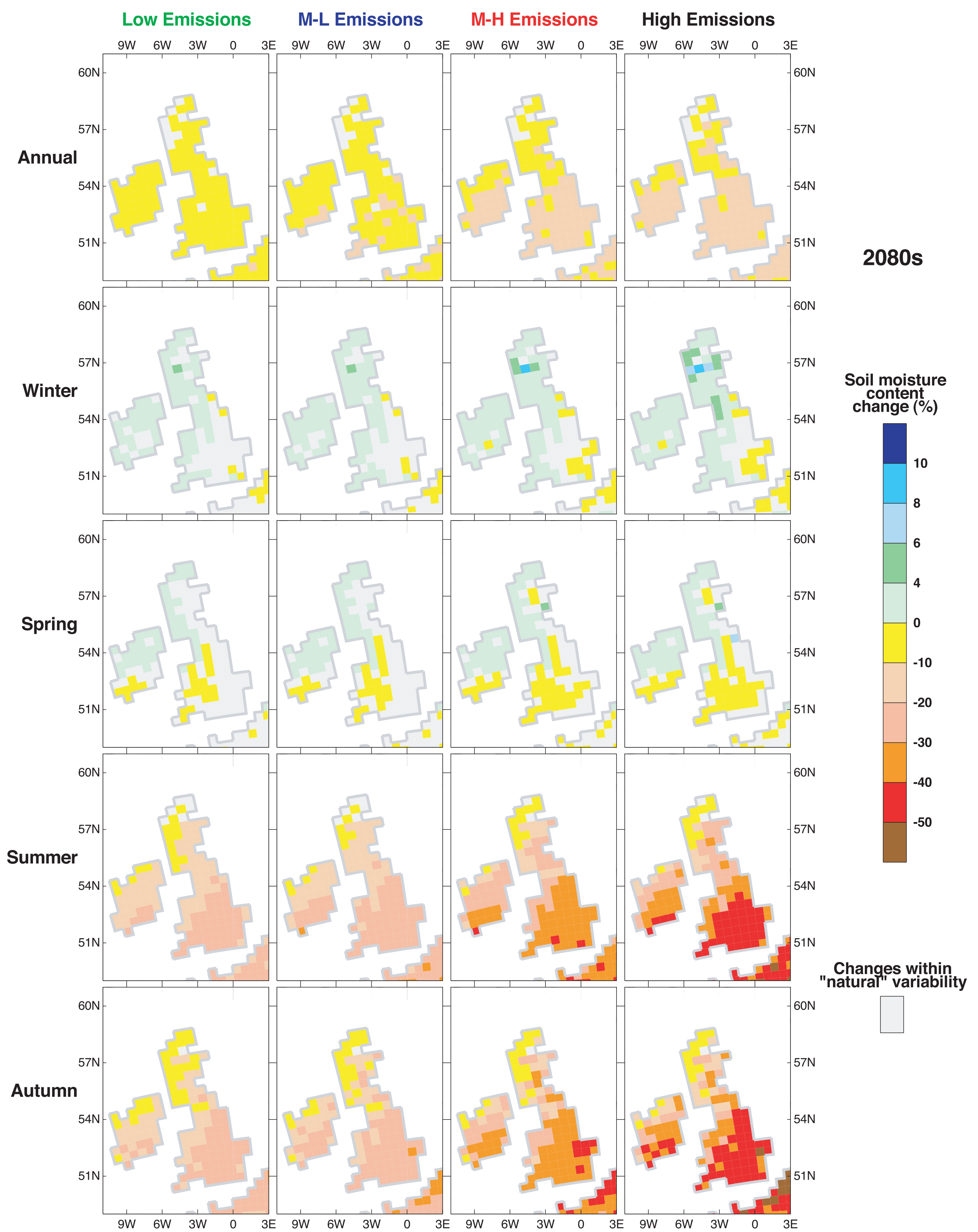

Figure 50: As Figure 45, but for percentage change in soil moisture. Note the asymmetrical scale.

Soil moisture

Changes in soil moisture – important for agriculture, flooding and building stability - are dependent on changes in precipitation, temperature, evaporation, wind speed and radiation. In this report soil moisture is defined as the amount of moisture in the root zone, i.e., moisture available for evapo-transpiration. The model does not include an interactive vegetation scheme, so vegetation remains constant as climate changes.

In summer the whole country experiences a decrease in average soil moisture.

Both annually and in summer, the whole country experiences a decrease in average soil moisture, with the highest summer reductions - 40 per cent or more by the 2080s - occurring in the **High Emissions** scenario in southeast England (Figure 50). These reductions are halved for the **Low Emissions** scenario. In winter, the scenarios show a slight increase in moisture content over most of Scotland, little change over Northern Ireland and Wales, and by the 2080s for the **High Emissions** scenario a decrease of up to 10 per cent over England. In spite of increased winter precipitation over England, higher temperatures and reductions in relative humidity mean that winter evaporation increases and soil moisture levels fall relative to the present. Soil moisture changes in autumn are similar to those in summer – both pattern and magnitudes – indicative of the long time taken to restore soil water levels following increasingly dry and hot summers.

4.8 Future changes in derived surface variables

This section summarises changes in a number of other important climate variables that, although not output directly by the climate models, can be derived from simulated variables.

Depression tracks

The weather of the UK is dominated in winter by depressions moving in from the North Atlantic. These are often called “lows”, or even “storms”, although storm is a rather ambiguous word since it is also used to mean thunderstorms, quite a different phenomenon. We identified and tracked low pressure areas using the pressure fields from the intermediate resolution global model - HadAM3H. A track with its lowest pressure below 1000 hPa was classed as a depression. The number of all such depressions crossing the UK in an average winter increases from about five for the present climate to about eight for the **Medium-High Emissions** scenario by the 2080s (Figure 51). This is mainly due to a shifting southward of the depression tracks from their current position, resulting in a strengthening of the winter winds over the south of England (cf. Figure 48). The probability of an individual low pressure system being a “deep” depression - defined when the central pressure is less than 970 hPa - does not change by the 2080s but, since there are more depressions overall, there are more frequent deep depressions. These “deep” depressions increase in frequency in winter by about 40 per cent for the **Medium-High Emissions** scenario by the 2080s. In the summer, the pattern is reversed, with depressions over the UK in the 2080s falling, on average, from five to four per season. There is little significant change in depression frequency or intensity in autumn or spring.

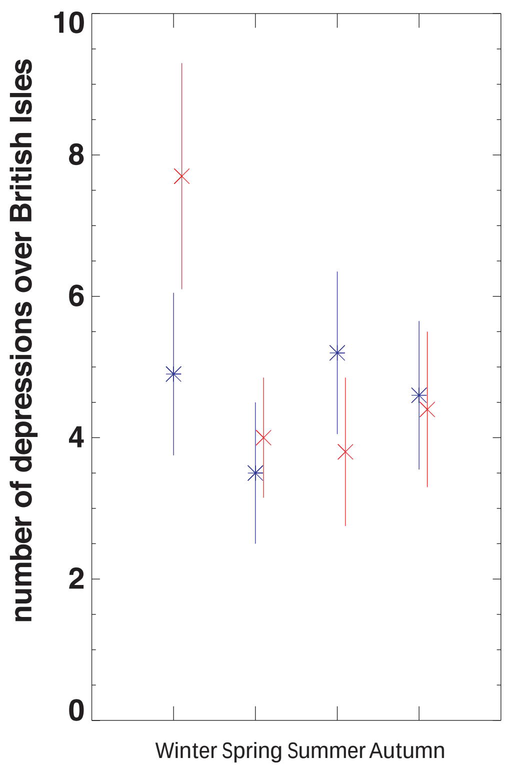

Figure 51: Average absolute number of depressions per season (lowest pressure <1000 hPa) across the British Isles for the baseline period (blue: 1961 to 1990) and for the Medium-High Emissions scenario by the 2080s (red). Crosses are the 30-year average and the bars show one standard deviation either side of the average.

North Atlantic Oscillation

A further consequence of the changing pressure patterns that cause changes in storm tracks across the British Isles is a change in the behaviour of the North Atlantic Oscillation (NAO). As explained in Chapter 2, the NAO is a measure of the westerliness of winter weather - a high NAO index means a windy, wet but mild winter. Although for many applications it will be more useful to employ scenarios of changes in *these* direct aspects of UK winter weather – wind speed, precipitation and temperature - the NAO index is also useful for some impact studies. Simulated changes in the NAO index give an indication of the change in the likely weather patterns over the north Atlantic. For the **Medium-High Emissions** scenario (Figure 52), the future trend is for an increase in the NAO index, although the year-to-year variability (not shown) in the index is large. This increase in this decadal NAO index becomes significant – i.e., larger than “natural” variability – by the 2050s. On the basis of present-day relationships between the NAO and UK winter weather, this suggests that UK winters will become more “westerly” in nature - milder, windier and wetter - which is consistent with the model results presented earlier in Figures 31 to 39, 42 to 44, 48 and 51.

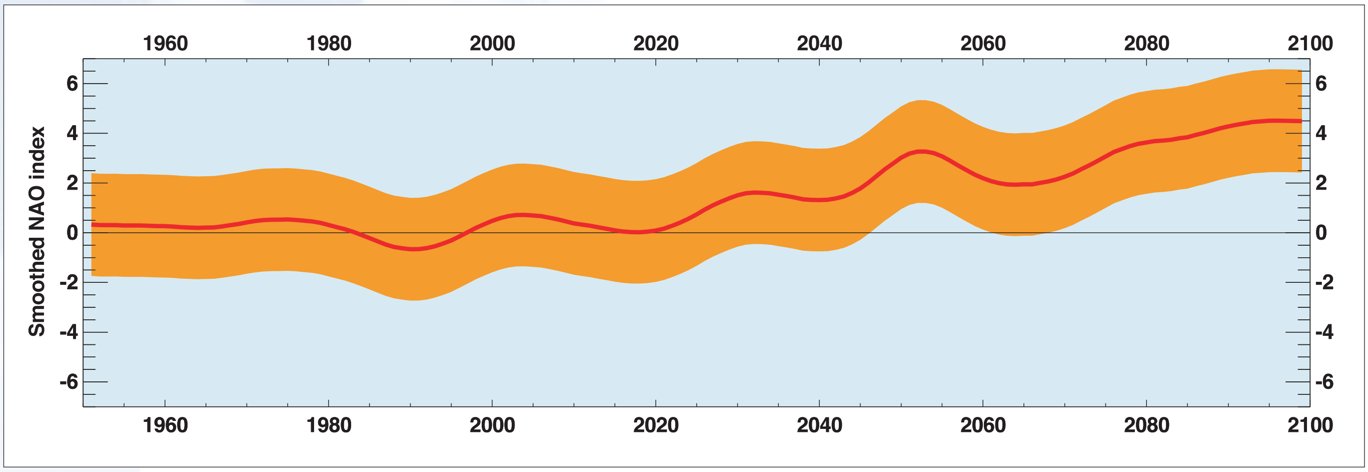

Figure 52: Simulation of future changes in an index of the winter North Atlantic Oscillation with respect to the 1873-1998 observed average for the ensemble-mean Medium-High Emissions scenario. The orange shading is a measure of the range due to natural variability (± 2 standard deviations of the three-member ensemble), i.e., the NAO is significantly different from the baseline at the 5 per cent level where the bottom edge of the shading is above the zero line. Data are smoothed to emphasise variations on time-scales of 30 years [Source: Tim Osborn].

Lightning

The frequency and severity of lightning can have important impacts on a number of activities, for example on the security of electricity supplies. The climate model does not simulate lightning directly, so we have derived lightning flashes using relationships established in weather forecasting. These are mainly based on the velocity of updrafts. Daily data from the regional climate model are used for the summer season when lightning is most prevalent. Based on the **Medium-High Emissions** scenario, the peak lightning flash rate in a convective event is expected to more than double by the 2080s over parts of southwestern England, the region which experiences the greatest change. The number of estimated thunderstorms, however, decreased by about a half by the 2080s, meaning that the overall number of lightning strikes per year will remain about the same. Over Scotland and Northern Ireland, little change was simulated in the amount of lightning per thunderstorm.

Fog

The number of days with fog was calculated from changes in relative humidity simulated by the regional climate model. This calculation was made using a relationship derived from weather forecasting. For the **Medium-High Emissions** scenario by the 2080s, some 20 per cent fewer fog days in winter might be expected across all areas of the UK.

4.9 Qualitative summary and comparison with the UKCIP98 scenarios

This Chapter has presented changes in average seasonal and annual climate for the UK for the four UKCIP02 scenarios. The analyses have relied primarily on the experiments conducted with the HadRM3 regional model – results extracted from 90 years (three ensemble simulations of 30 years each) of simulated future climate for the 2080s for the SRES A2 emissions scenarios, scaled to construct patterns of change for the 2020s, 2050s and 2080s for the **Low Emissions, Medium-Low Emissions, Medium-High Emissions** and **High Emissions** scenarios. In places, results from the coupled global model and the intermediate resolution atmospheric global model have also been used. Table 9 summarises the main highlights of this Chapter, expressed in qualitative terms only. The third column indicates the relative level of confidence in each of these statements (cf. Box B in Chapter 1). Note that we have not assigned confidence levels to fog, lightning or wind. Changes in lightning and fog were derived from empirical relationships between observed variables and it is impossible to assign confidence in whether these relationships will hold under a changed climate. We can only assume they do in the absence of any other information. For wind, the results are highly uncertain and we cannot even assign a Low Confidence level to this variable.

For wind, the results are highly uncertain and we cannot even assign a Low Confidence level to this variable.

The broad level of consistency between the UKCIP02 and UKCIP98 scenarios is indicated in the final column of Table 9. The main differences between the scenarios in terms of average climate are as follows:

- The UKCIP02 scenarios show slightly larger warming rates over the UK than the 1998 scenarios, especially for the **Low Emissions** scenario. This is partly because we use a model with a higher effective sensitivity for *all* the 2002 scenarios and partly because we now consider the effects of changing (falling) sulphate aerosol concentrations.

- The UKCIP02 scenarios suggest that summers become drier across the *whole* of the UK – not just in England and Wales - and by a larger amount than in the 1998 scenarios.

- The UKCIP02 scenarios suggest different patterns of change in average wind speed compared to the 1998 scenarios. These changes in wind speed are still relatively small, however, and it remains the case that we have little confidence in the simulated changes in the UK wind regime.

Variable	**UKCIP02 Scenarios**	**Relative Confidence Level**	**Consistency with UKCIP98**
Temperature	• Annual warming by the 2080s of between 1º and 5ºC depending on region and scenario	H	✘
	• Greater summer warming in the southeast than in the northwest	H	✔✔
	• Greater night-time than day-time warming in winter	L	✔
	• Greater warming in summer and autumn than in winter and spring	L	✔
	• Greater day-time than night-time warming in summer	L	✔
Precipitation	• Generally wetter winters for the whole UK	H	✔✔
	• Substantially drier summers for the whole UK	M	✘
Seasonality	• Precipitation: greater contrast between summer (drier) and winter (wetter) seasons	H	✔✔
	• Temperature: summers warm more than winters	L	✘
Variability	• Years as warm as 1999 become very common	H	✔✔
	• Summers as dry as 1995 become very common	M	✔✔
	• Winter and spring precipitation becomes more variable	L	✔
	• Summer and autumn temperatures become more variable	L	✔
Cloud cover	• Reduction in summer and autumn cloud, especially in the south, and an increase in radiation	L	✔
	• Small increase in winter cloud cover	L	✔
Humidity	• Specific humidity increases throughout the year	H	✔✔
	• Relative humidity decreases in summer	M	✔
Snowfall	• Totals decrease significantly everywhere	H	**n/a**
	• Large parts of the country experience long runs of snowless winters	M	**n/a**
Soil moisture	• Decreases in summer and autumn in the southeast	H	**n/a**
	• Increases in winter and spring in the northwest	M	**n/a**
Storm tracks	• Winter depressions become more frequent, including the deepest ones	L	**n/a**
North Atlantic Oscillation	• The NAO tends to become more positive in the future – more wet, windy, mild winters	L	**n/a**

Table 9: Summary statements of the changes in average seasonal UK climate for the UKCIP02 climate change scenarios for which we can attach some confidence. Quantitative statements are deliberately avoided; see the Chapter for detailed numbers. Relative confidence levels: H = high; M = medium; L = low. The qualitative consistency of these statements with the UKCIP98 scenarios is indicated in the last column by: ✔✔ *= highly consistent,* ✔ *= some consistency,* ✘ *= some differences,* ✘✘ *= inconsistent, n/a = little or no analysis in UKCIP98.*

Chapter 5: Future Changes in UK Daily Climate

5.1 Daily data and analyses

The UKCIP98 climate change scenarios presented changes in UK climate primarily at monthly, seasonal and annual time-scales. A few examples were given of changes in daily weather distributions, but these were derived from coarse resolution global model simulations. Due to their finer spatial resolution, regional climate models are generally able to represent more faithfully than global models the statistical character of observed daily weather. *Changes* in the daily characteristics of weather - including extreme weather events such as heatwaves, intense precipitation and strong winds - may also therefore be better simulated by regional models than by global models.

This Chapter presents daily weather scenarios for precipitation, average, maximum and minimum temperature and average wind speed, extracted from the three HadRM3 ensemble experiments with A2 emissions and, where appropriate, pattern-scaled to represent our four UKCIP02 scenarios and three time-slices. The analyses examine changes in frequency of occurrence of events[14] of given magnitudes using the *quantile* or *percentile method* and also by showing *return periods* - the average elapsed time between events of a given magnitude. We also examine changes in the probabilities of certain threshold values being exceeded at a selection of locations. Details of the methodologies used are given in Box F. For each variable, a combination of maps and probability plots provide a picture of the changes in frequency and magnitude of "extreme" daily weather.

Data

We have used 90 years of daily data from the control experiments made with HadRM3 – representing 1961 to 1990 climate - and 90 years of daily data from the same model forced with the SRES A2 emissions scenario for the 2080s. The 90 years were obtained from three 30-year ensemble members. Results for the **Medium-High Emissions** scenario were obtained from analysis of daily data simulated directly by the regional model. Where we show maps of the changes in occurrence for the other three scenarios - **Low Emissions**, **Medium-Low Emissions** and **High Emissions** – these are scaled from the analysis obtained from the **Medium-High Emissions** scenario (see Section 7.4 for a discussion about pattern-scaling). It should be noted that the scenarios presented here are derived exclusively from regional model data and are for areas of the country representing 50 km by 50 km grid boxes. The absolute numbers of this model-simulated daily "weather" will therefore differ from daily weather observed at specific meteorological stations.

5.2 Future changes in daily precipitation extremes

How accurate is the model?

As indicated in Section 4.1, it is important to have some appreciation of the performance of the climate model by evaluating how well it simulates aspects of current observed climate. This is perhaps even more important when we come to consider the model's representation of daily weather.

Figure 53 shows one such diagnostic – histograms of the changes in the probability that different daily precipitation totals are exceeded on any given day for four standard UK precipitation sub-regions – eastern Scotland, Northern Ireland, southeast England and southwest England. The observed bars are based on about 60 years of recent data (~1931-1990) and the model bars on 90 years of simulated 1961 to 1990 data. Each sub-region consists of between 6 and 15 HadRM3 grid boxes. Daily precipitation is averaged over all grid boxes within each region and then the probability of exceedence from these data can be compared directly with regional observations.

In all regions, the model performs better in summer than in winter. Indeed, only for eastern Scotland are the observed and model results in summer significantly divergent, and here mostly for intensities greater than about 15 mm. For the winter season, the model tends to overestimate the intensity of the heaviest events, especially over southwest England and eastern Scotland. For example, in eastern Scotland in winter the event with a probability of 1 per cent (i.e., the event that will occur about once per 100 days, or once per season on average) has an intensity of about 21 mm according to the model, but the observed figure is 16 mm. Despite this winter bias, Figure 53 suggests that overall the model has genuine skill in reproducing aspects of the observed daily precipitation distribution of sub-regions of the UK. The Bibliography to this report provides further references to literature that has evaluated other aspects of the performance of the HadRM3 model and its precursors.

The model has skill in reproducing aspects of the observed daily precipitation distribution.

Quantile analysis

The quantile analysis yields the change in the number of days with "intense" precipitation (Figure 54). This method allows the definition of "intense" to vary across the country. For example, under baseline conditions, an intense winter day's precipitation is between 35 and 45 mm in northwest Scotland, but only about 20 mm in southeast England. In winter, nearly the whole country experiences an increase in the number of intense precipitation events, with a maximum increase of more than 1.5 extra events in an average winter for southwest Scotland and southwest Wales for the **Medium-High Emissions** and **High Emissions** scenarios by the 2080s. This compares to between only 1.0 and 1.5 such events per season in these areas currently, i.e., roughly a doubling of intense precipitation frequency by the 2080s for these scenarios.

(14) In this Chapter, an "event" is defined as a weather phenomenon measured over a 24-hour period, thus a 24-hour precipitation total, a maximum or minimum temperature within a 24-hour period, or the daily-average wind speed. There are of course many other definitions of "extreme" weather that could be considered.

Box F: Analysing daily data

Quantile/percentile method

The daily data values for each grid box were first sorted into ascending order. For precipitation, the "extreme" seasonal threshold amount was defined as the value reached that provides the uppermost 10 per cent (or 90th quantile) of the total seasonal precipitation, i.e., the maximum daily precipitation threshold that, above which, delivers 10 per cent of the average total. Daily totals greater than this magnitude are defined as "intense" events. The definition of what constitutes an intense event therefore varies between grid boxes and between seasons. To define what "intense" means at any given grid box, model-simulated daily precipitation data for the baseline period for that box were analysed. For example, consider Location X with a 90th quantile threshold of 25 mm, and 810 daily totals that exceeded 25 mm during the 90 years of simulated 1961-90 climate. This is an annual average of 9 "intense" daily precipitation amounts per year. If at Location X we saw 15.5 such events occur on average each year (i.e., an increase of 6.5) by the 2080s, there has been a 70 per cent increase in "intense" precipitation frequency. If we repeated the above exercise for Location Y in a drier part of the UK, the "intense" daily precipitation threshold might only be, say, 15mm. We could nevertheless see how the frequency of this threshold amount altered with climate change.

For daily-average temperature and wind speed, "extreme" threshold values were defined as the 90th *percentile* of daily ranked events for each season. The daily data were sorted into ascending order as before, but the threshold is merely defined as that temperature or wind speed which is exceeded on 10 per cent of days.

Return period method

The return period is defined as the average elapsed time between events of a given magnitude. The statistics which allow estimation of the return period were derived from each variable's daily frequency distribution, i.e., the number of times different values of temperature, precipitation and wind speed occur over the 90-year period. These statistics were used to produce a theoretical distribution of the most extreme values. For the temperatures a normal distribution was fitted by season to obtain the temperature thresholds associated with given return periods. Daily-average wind speed and precipitation do not follow the normal distribution very closely, so an alternative (the Gumbel distribution) was used for these. For all variables, the created distributions allowed simple reading-off of the values which defined the events which could be expected, on average, once every X years.

This procedure was carried out for the baseline period and for the 2080s. If the baseline 10-year return period daily-average wind speed for Location X is 15 ms^{-1}, for example, and with climate change the threshold velocity increases by 50 per cent, then the new 10-year return period daily-average wind speed is 22.5ms^{-1}.

Return periods should not be used to imply that a given event only occurs with the regularity stated. Two events, each of which have an estimated return period of 10 years say, can quite often occur in the same year or in successive years. Return period refers to the *average* elapsed time between events of a given magnitude. For this reason it may also be helpful to think of the 10-year return period event as the event that has a 10 per cent chance of occurring in a given year; or a 2-year return period event has a 50 per cent chance of occurring in a given year.

Probability of exceedence

The return period method involves creating relationships between event magnitude and the frequency of occurrence. Plotting out the model data which form these relationships before they are fitted with theoretical distributions provides a useful estimate of the frequency of occurrence of given "extreme" daily weather events. These are plotted as "cumulative probability" plots for the three variables we examine for four HadRM3 grid boxes. These boxes are those selected in Chapter 4 to represent different climate regimes in the UK - lowland England ("Berkshire"), coastal Wales ("Pembrokeshire"), coastal Northern Ireland ("County Down"), and highland Scotland ("Inverness-shire"). The resulting 50 km resolution provides more realistic estimates of probabilities of extreme weather thresholds for a given locality than if we had averaged grid boxes for whole regions or for the UK as a whole. It should be noted, however, that these grid box analyses still represent "weather" over an area of 2,500 km^2 and events of the same probability as simulated by the model are likely to be more severe in the real climate for specific point locations.

Wetter winters are partly the result of an increase in the frequency of wet days – most especially over eastern England – but also because of an increase in the intensity of wet events. This behaviour is consistent with the increased total winter precipitation - but similar cloud cover - shown in Chapter 4. In spring, coastal areas and Northern Ireland show slight increases in intense event frequencies, while there are small decreases over the interior of England. Intense rainfall events become rather less frequent in summer just about everywhere, whilst in autumn the changes are small and rather variable in pattern. This contrast between winter and summer in the future changes in frequency of intense precipitation

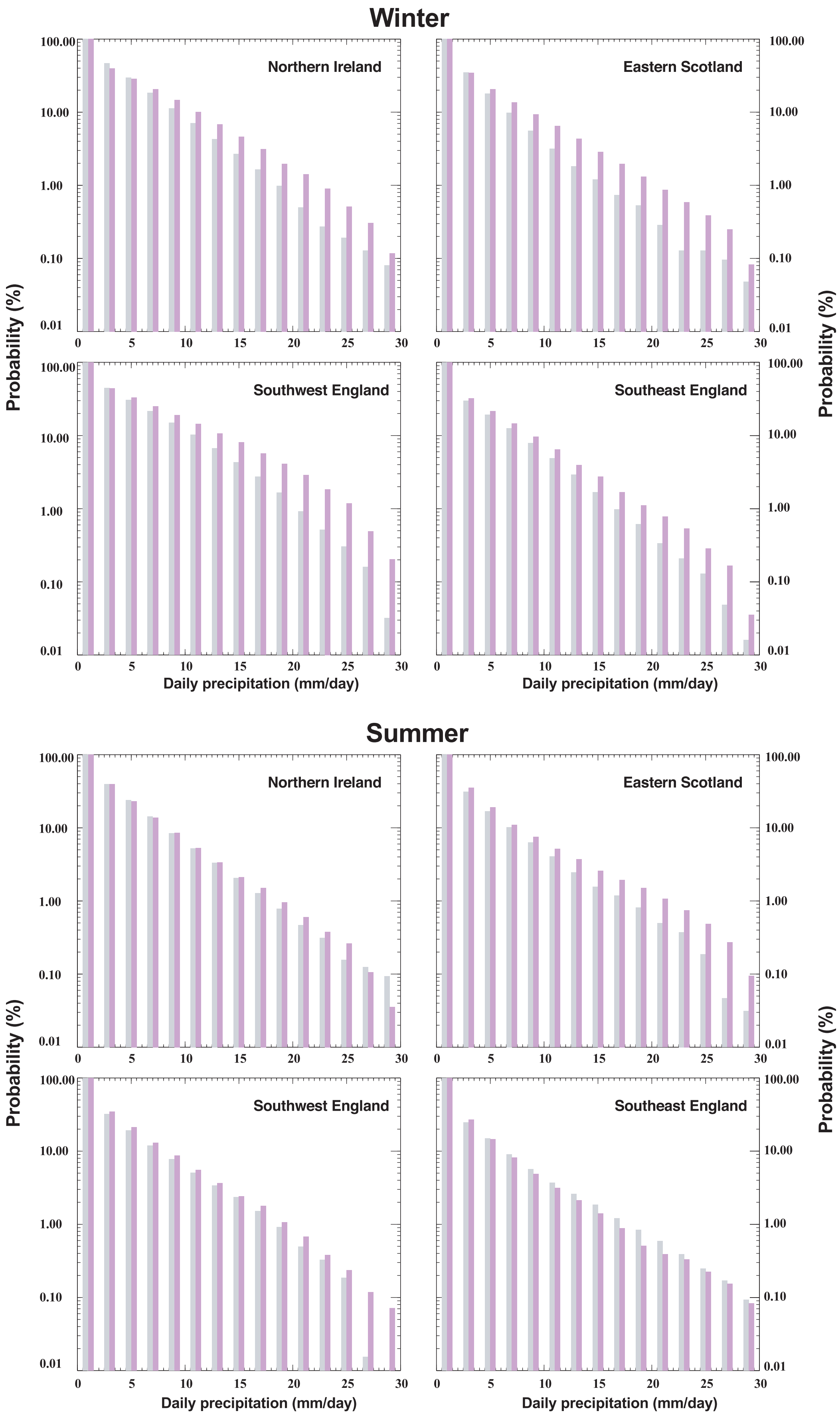

Figure 53: Comparison of observed (grey bars) and model-simulated (purple bars) probabilities of exceedence of daily precipitation totals for four standard UK precipitation sub-regions for the recent few decades. The probability expressed is the probability of the event being exceeded on any given day in each season. Note: the inverse of probability is the return period – for example, a probability of occurrence of 1 per cent (p=0.01) is equivalent to a once-in-100 day event, or roughly once-per-season.

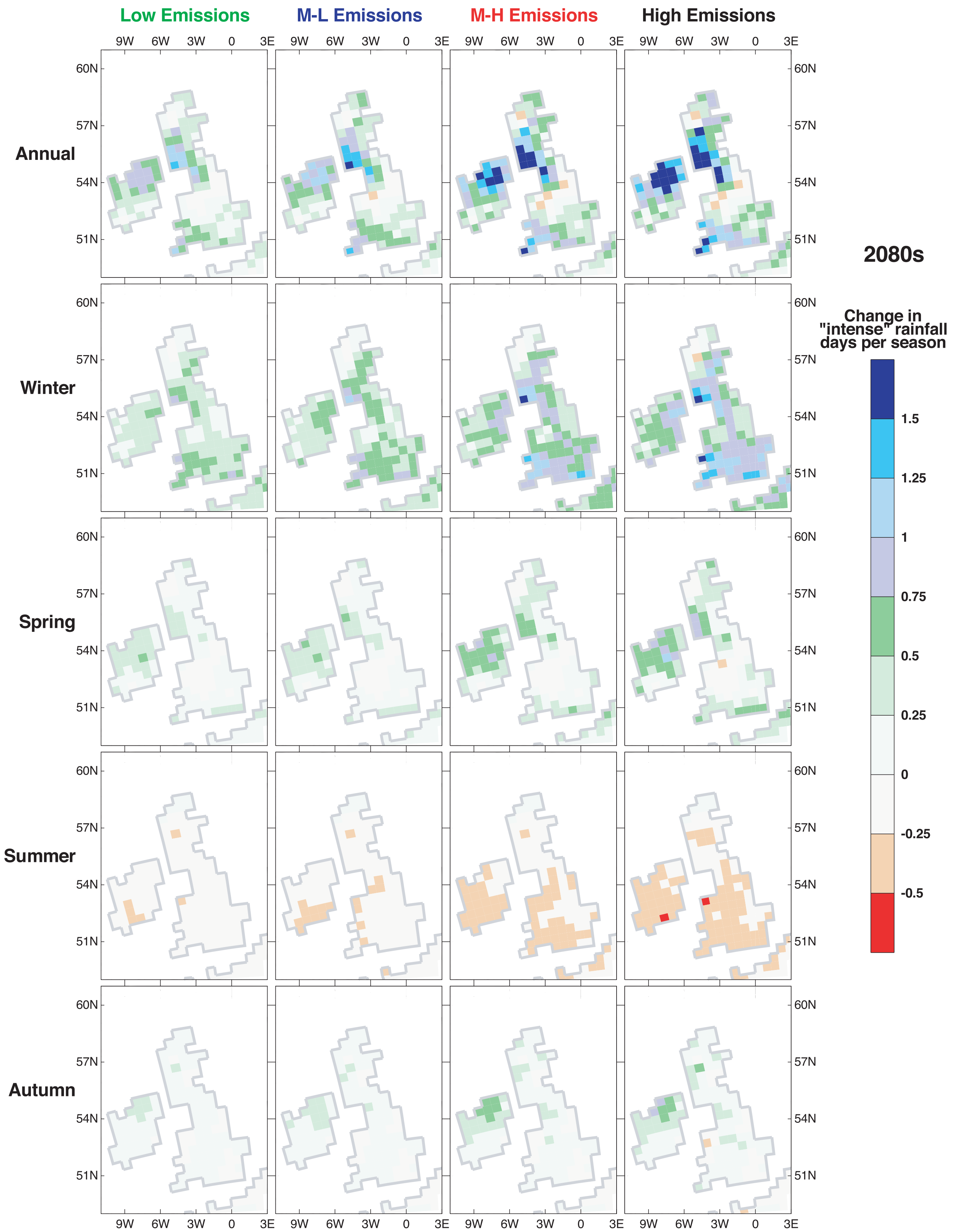

Figure 54: Change in the number of "intense" precipitation days in an average season for the four scenarios for the 2080s.

events is consistent with the observed trends over the last few decades shown in Chapter 2.

Return period analysis

When physical structures are designed to cope with a "once in n-year event", it is conventionally assumed that the magnitude of such an event is constant. As climate changes, this assumption will not hold. The "once in 2 year" daily precipitation amount varies across the country under baseline conditions, ranging from about 50 mm in highland Scotland to between 20 and 25 mm in southeast England in winter. Figure 55 shows the percentage change in this amount which can be expected on average to occur once every two years for the 2080s. Since the analysis is based on only 90 years of data, the pattern of change from grid box-to-grid box is rather variable, but the overall picture is clear. In winter, all of the UK apart from northwest Scotland experiences an increase in the magnitude of the two-year event; in some areas - southeast England and southeast Scotland - the increase is more than 20 per cent for the **Medium-High Emissions** and **High Emissions** scenarios. Parts of northwest Scotland experience a slight decrease in the magnitude of this return period event. During summer, the pattern is inverted with the 2-year daily rainfall intensity falling by between 10 and 30 per cent. In spring and autumn the changes are generally small. These patterns are consistent with the frequency changes shown in Figure 54.

We also examined changes in intensity for return periods greater than two years, but with only 90 years of available model-simulated data the detailed geographical patterns of these lower-frequency statistics become increasingly dominated by "noise". The large-scale patterns and per cent changes in amount, however, are generally repeated for all return periods up to the number of years of available data. For example, the amount of daily rainfall that at present could be expected to occur on average once in every 20 winters in southeast England, increases by between 15 and 30 per cent (depending on scenario). This is similar to the percentage increases in the 2-year event shown in Figure 55.

We will need to adapt to wetter winters with more intense rainfall. © P A Photos.

Intense precipitation probabilities

We next show, for the **Medium-High Emissions** scenario only, changes in the probability that different daily precipitation totals are exceeded on any given day. We show the results of this analysis at two different spatial scales – in Figure 56 for the same four UK sub-regions as evaluated against observations in Figure 53, and in Figure 57 for the same four individual HadRM3 grid boxes we selected in Chapter 4 for detailed analysis (see Figure 29 for their location). In Figure 56, the averaging procedure is different than for Figure 53, since the exceedence curves are calculated for each grid box in the region and then these curves are averaged to produce one regional curve. Hence Figure 57 is an example of one of the individual grid box curves in each region and gives an indication of how representative the information in Figure 56 may be for other boxes in the respective regions.

Unlike the return period analysis contributing to Figure 55, here we do *not* fit theoretical distributions to the model data. The changes shown are not therefore robust for the most extreme events because of poor sampling at the tails of the distribution; this is particularly true for the individual grid box analyses. A probability of 1 per cent for a precipitation amount corresponds to a frequency of about one day per season, on average, when this total is exceeded. 0.1 per cent corresponds to a total exceeded about once every ten years. The graphs are cut off at this low probability since there are only 90 years of data and at lower frequencies than this the plots become too unstable.

Probabilities of the heaviest daily events in winter increase for all four sub-regions and they decrease for all regions in summer (Figure 56). This is consistent with the direction of the seasonal changes in average precipitation shown in Figures 35 to 38. Changes in the probability of exceedence are generally larger for the two southern regions than for eastern Scotland and Northern Ireland, and in the south are generally larger in summer than in winter. For southeast and southwest England, for example, there are increases in the most extreme winter precipitation intensities of about 3 to 4 mm per day, yet in summer the most extreme intensities decrease by 10 mm per day or more.

If we examine the simulations for individual 50 km grid boxes (Figure 57) rather than the average across regions, the magnitudes of the model-simulated extreme precipitation intensities increase. For the **Medium-High Emissions** scenario in central-south England ("Berkshire"), the probability that any given winter day by the 2080s will have precipitation in excess of 20 mm is about 2 per cent, compared to about 1 per cent for present climate (Figure 57, bottom right). For "County Down", the probability of the same intensity event occurring in winter increases from about 3 to 4 per cent. Again, a different pattern emerges for summer, as shown by the dashed lines in Figure 57. A decrease in average summer rainfall across the whole UK translates into a decrease in the probability of given intense daily rainfalls, at least over southern England ("Berkshire") and west Wales ("Pembrokeshire"). For the two northern grid boxes, the probability of the very heaviest summer events actually *increases* slightly. Note that if the scale of analysis was reduced further, to a point location for example, the magnitudes of the extremes would be even higher – but the model is not capable of simulating such localised extremes.

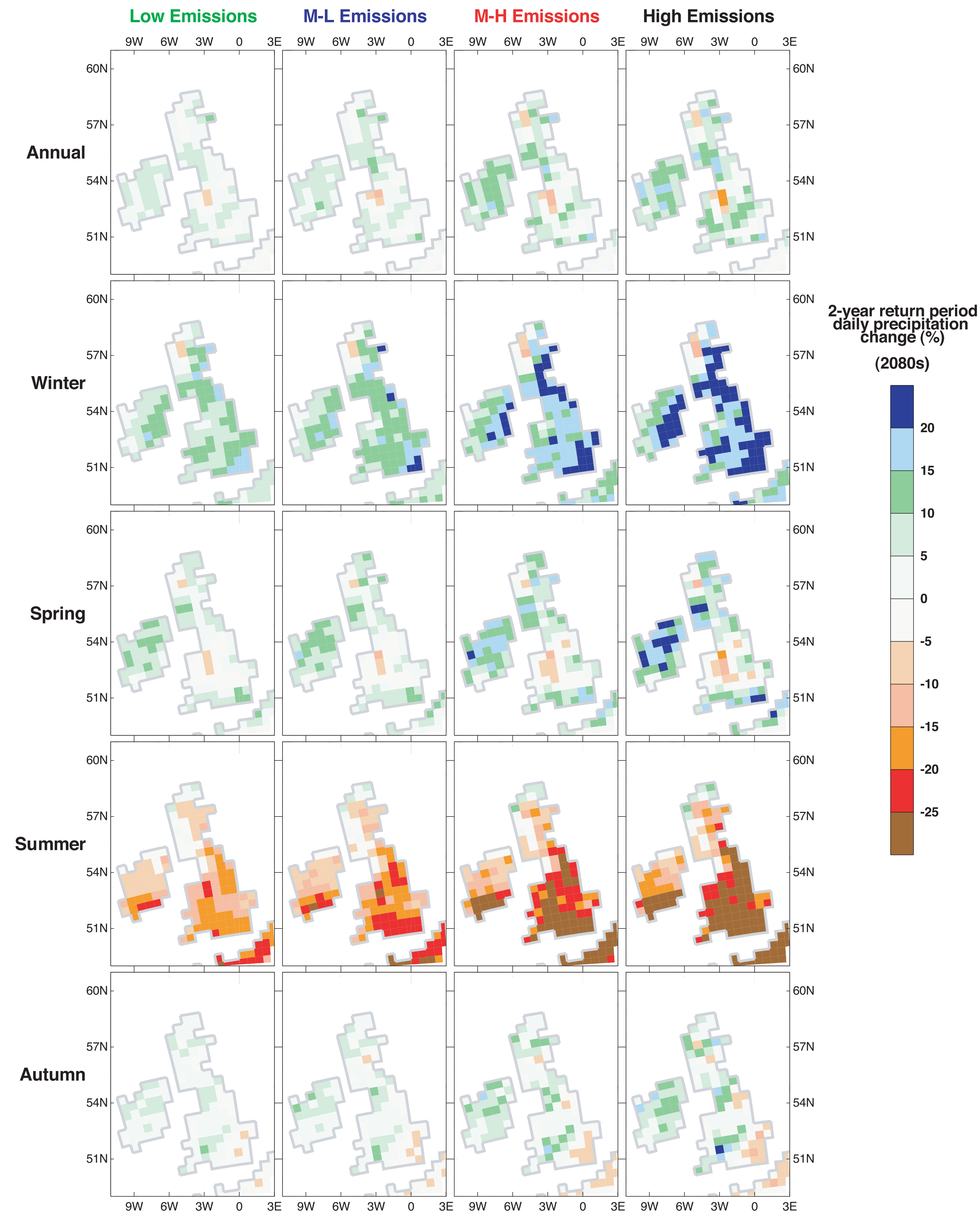

Figure 55: Change in the daily precipitation amount which for the 2080s can be expected, on average, once every 2 years. This is equivalent to the change in the intensity of the precipitation event which has a 50 per cent chance of occurring in a given year.

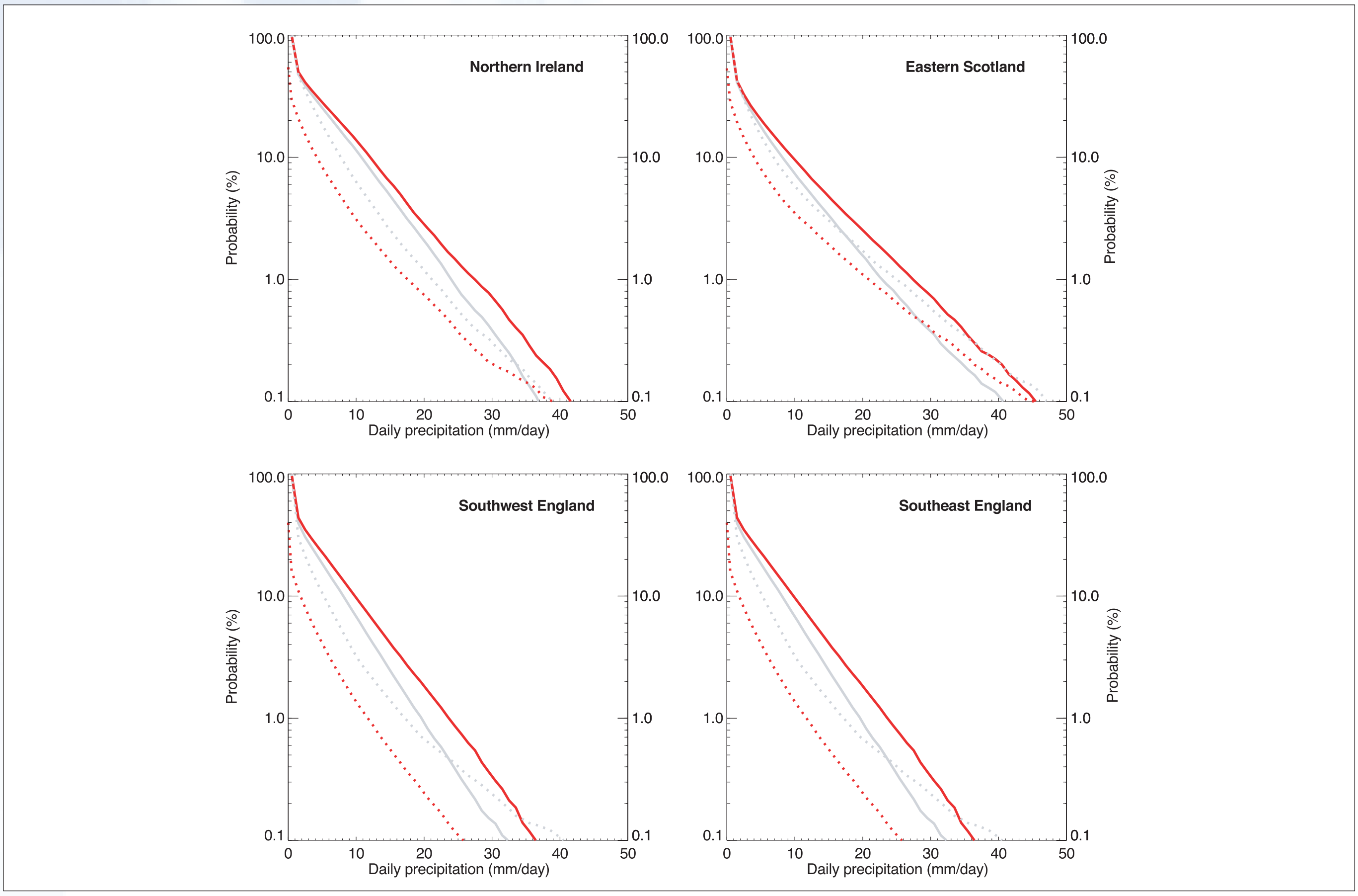

Figure 56: The probability of exceedence of daily precipitation totals for four UK sub-regions for the modelled baseline (grey) and for the Medium-High Emissions scenario for the 2080s (red). The probability expressed is the probability of the event being exceeded on any given day for summer (dashed lines) and winter (solid lines).

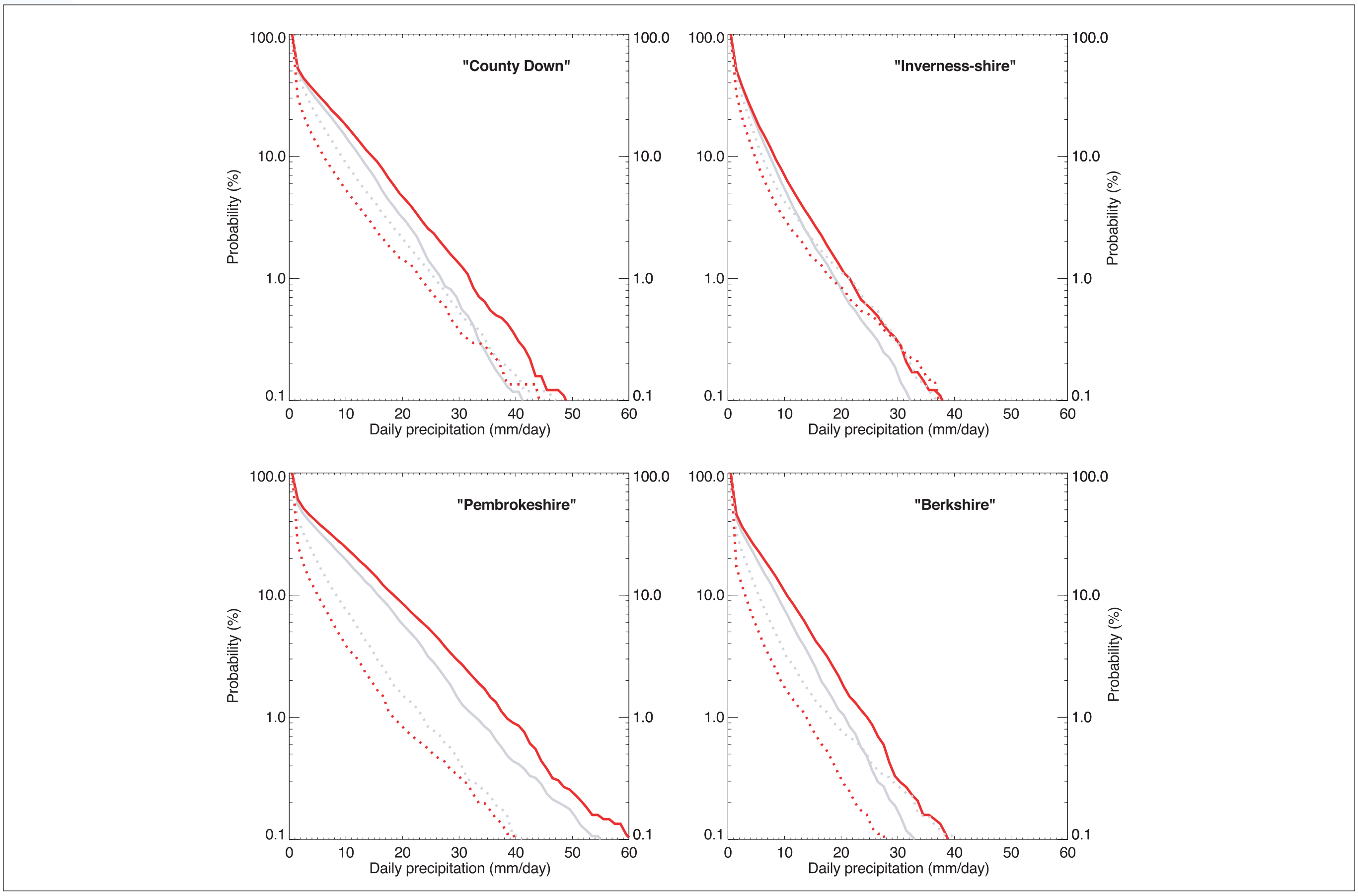

Figure 57: As Figure 56, but for four individual HadRM3 grid boxes.

5.3 Future changes in daily temperature extremes

How accurate is the model?
As with daily precipitation, we provide an example diagnostic to illustrate the model's performance in reproducing the observed frequency distribution of daily temperatures. In this case, the observed data set we use is the standard daily Central England Temperature series for the period 1961 to 1990 – both daily maximum and daily minimum. Note that since the temperatures are averaged across the whole Central England region, they are less extreme than those recorded at individual meteorological stations - for example those quoted in the media during heat waves or cold spells.

The locations and broad shapes of the observed distributions are generally well-simulated by the model. The most obvious deficiencies for day-time temperatures (Figure 58) are that the model slightly overestimates the highest maxima in autumn and does not quite reproduce the coldest days in winter. For night-time temperatures (Figure 59), the model somewhat overestimates the frequency of extreme values (both low and high minima) in spring and autumn and more noticeably overestimates high minima in summer, i.e., the model generates some unrealistically warm summer nights. Nevertheless, these biases are relatively small and the HadRM3 model has generally performed well in reproducing these observed temperature distributions.

The HadRM3 model has generally performed well in reproducing these observed temperature distributions.

Percentile Analysis
The 90th percentile daily-average temperature modelled for the baseline period 1961 to 1990 was used to define "extremely" warm days, annually and by season, i.e., the daily-average temperature which is exceeded, on average, on 10 per cent of days. We use daily-average temperature as it implicitly includes both warm days and warm nights. For southeast England, this threshold for the baseline is about 11ºC in winter and about 23ºC in summer; the corresponding figures for Scotland are about 7º and 17ºC.

The changes in these temperature thresholds by the 2080s are shown in Figure 60. In winter, there is a strong southeast to northwest gradient in the magnitude of these changes. In the northwest of Scotland, an "extremely" warm winter day will be about 2ºC warmer than at present (i.e., daily mean about 9ºC rather than 7ºC) for the **High Emissions** scenario, whereas in the southeast "extremely" warm winter days will be about 3ºC warmer. In summer, the gradient in the changes is from southwest to northeast. An "extremely" warm summer day (i.e., the 90th percentile day) in the southwest of England increases by between 4º and 7ºC, depending on scenario. In this region, a 24-hour-average summer temperature of 30ºC or more might be expected on average once every ten days by the 2080s for the **High Emissions** scenario.

This analysis can also be shown in terms of how many additional "extremely" warm days occur on average per season, but just using the baseline period to define the threshold temperature (Figure 61). More than 20 extra days occur on average in summer for the **Medium-High Emissions** and **High Emissions** scenarios by the 2080s, with the exception of northwest Scotland where between 10 and 15 extra "extremely" warm days occur. For most of the country, however, this increase in warm day frequency represents more than a 200 per cent increase since, by definition, the current 90th percentile temperature occurs about nine times in an average summer. In winter, the largest increases in warm day frequency occur along the southern coast of England, implying mild winter days currently experienced in these regions will become proportionately much more frequent than elsewhere in the country.

In winter, the largest increases in warm day frequency occur along the southern coast of England.

Extreme event probabilities
We now examine changes in probabilities of daily *maximum* and *minimum* temperatures. The probability of exceedence of a given maximum temperature for a large region, for example the standard Central England Temperature region, is likely to be lower than for individual 50 km grid boxes. Figures 62 and 63 confirm this. For example, the baseline summer daily maximum CET with a 1 per cent probability is about 30ºC, compared with about 33ºC for the smaller area of "Berkshire".

Much warmer, drier summers will lead to water shortages and reduced crop yields

Figure 63 shows the exceedence probabilities for daily maximum temperatures for our four chosen 50 km grid boxes, or "county-scale" localities. For probabilities greater than about 1 per cent, the model baseline simulates the observations very well, so we can be more confident about this part of the plots. In "Pembrokeshire", for example, there is currently a probability of about 3 per cent that 25ºC will be

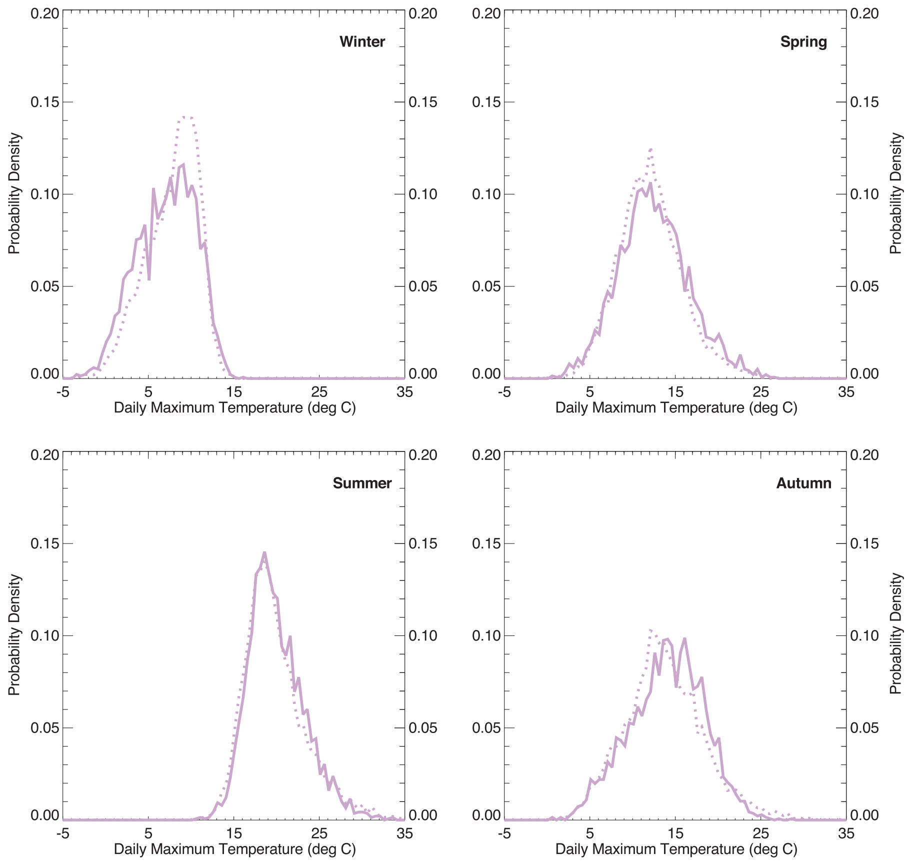

Figure 58: Comparison of model-simulated (dotted line) and observed (solid line) 1961 – 1990 frequency distributions of daily maximum temperature over the Central England region for four seasons.

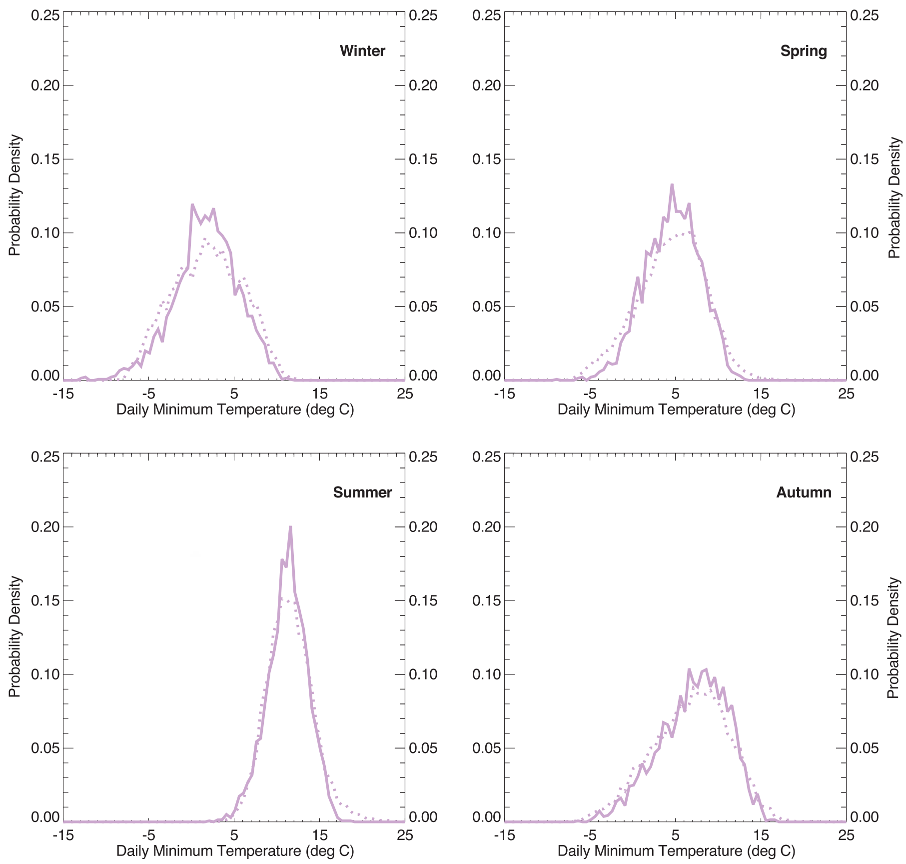

Figure 59: As Figure 58, but for daily minimum temperature.

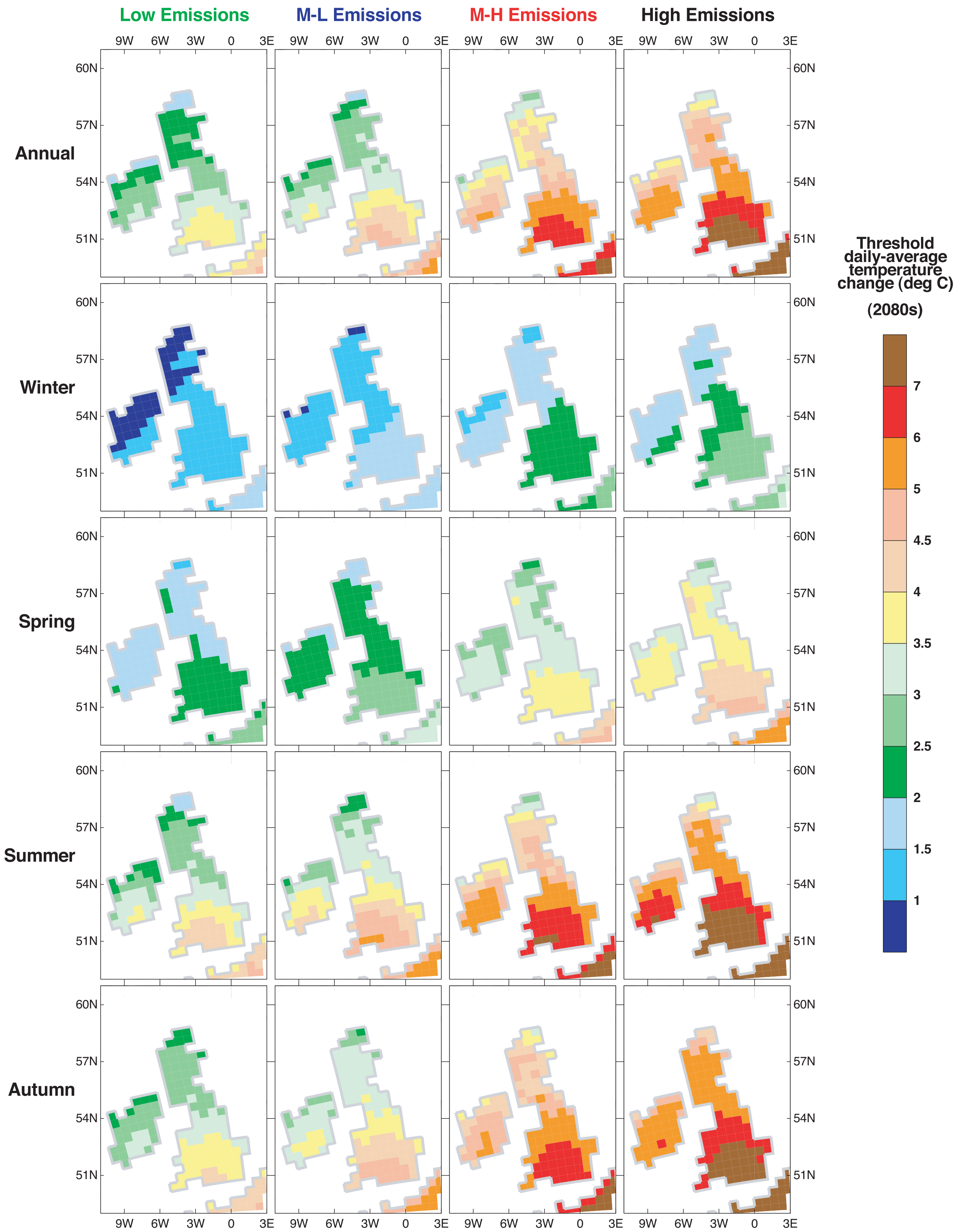

Figure 60: Change by the 2080s in the daily-average temperature threshold which constitutes an "extremely" warm (90th percentile) day.

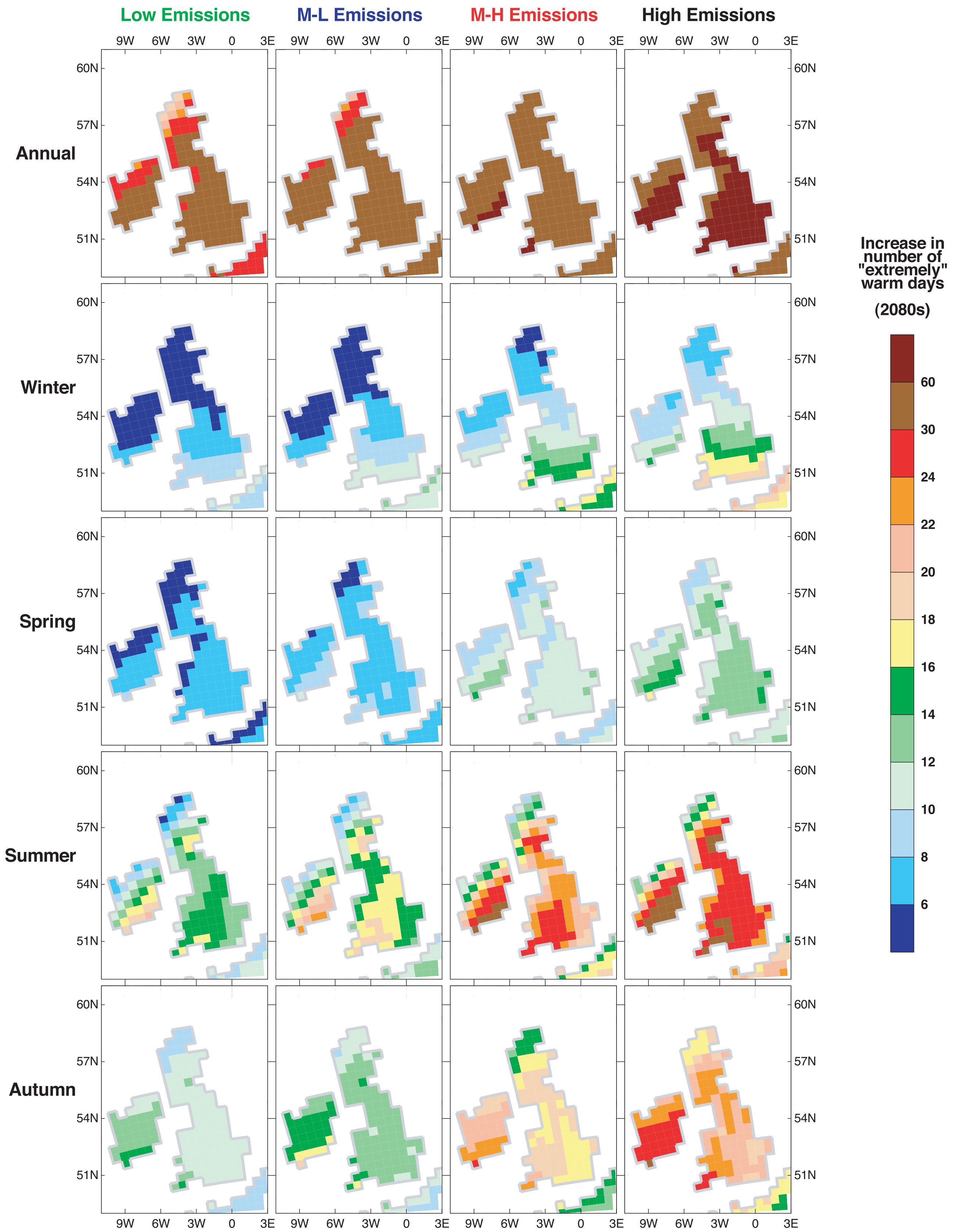

Figure 61: Change by the 2080s in the average number of "extremely" warm days per season (defined as 90th percentile threshold temperature for the period 1961 to

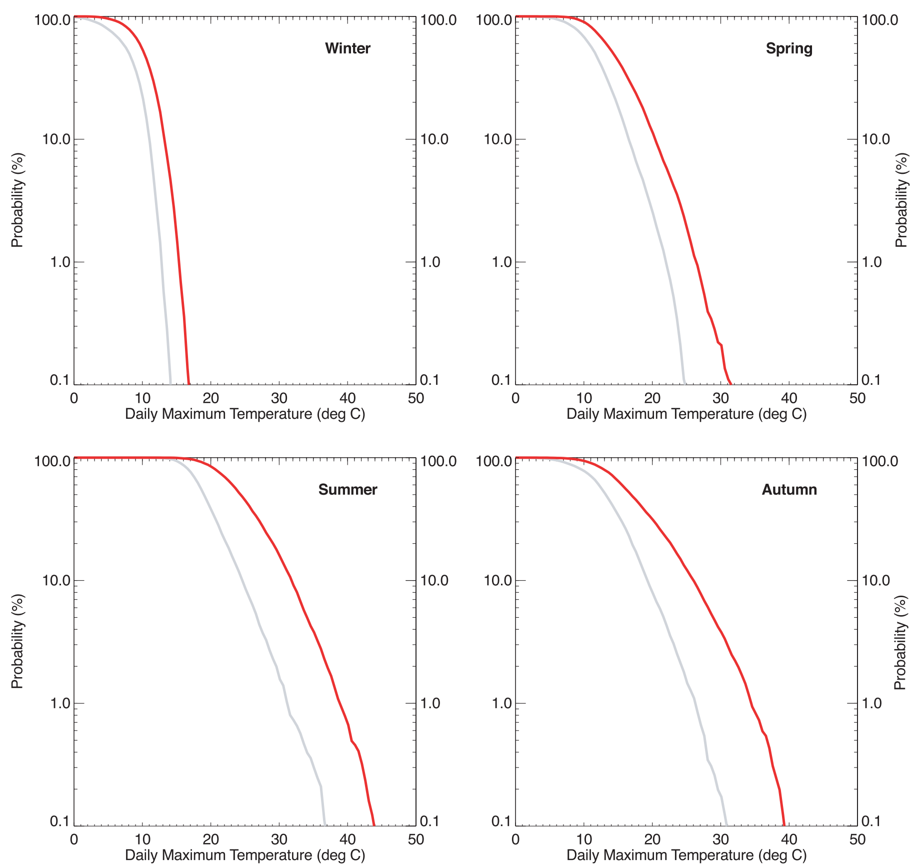

Figure 62: The probability of exceedence for daily maximum temperature for the Central England Temperature region for the modelled baseline (grey) and for the Medium-High Emissions scenario for the 2080s (red). The probability expressed is the probability of the event being exceeded on any given day in the respective season.

exceeded on any given summer day. By the 2080s under the **Medium-High Emissions** scenario, this is expected to rise to about 20 per cent, i.e., between once or twice a week.

Caution should be exercised in interpreting temperatures in absolute terms at probabilities below 1 per cent. Here, we are more confident about the *changes* between baseline and scenario than we are about the absolute magnitudes themselves. For example, the ten-year daily summer maximum (0.1 per cent) in “Berkshire” is only about 35ºC at present, not the 39ºC as simulated in the model baseline (grey dotted line in Figure 63, bottom right). We do not, therefore, expect the temperature in Berkshire to reach 46ºC one summer day in every ten by the 2080s, but we *do* expect the once-in-ten year temperature to be about 7ºC higher than the present, as shown in Figure 63 by the difference between red and grey dotted lines at the 0.1 per cent probability. On the basis of current observations and model simulations therefore, a day-time summer temperature might be expected to exceed about 42ºC in lowland England once a decade by the 2080s.

A day-time summer temperature might be expected to exceed about 42ºC in lowland England once a decade by the 2080s.

Figure 64 shows a similar plot with the probability that the minimum temperature will fall *below* a given threshold on any given day. For “Inverness-shire”, for example, a minimum below -5ºC is currently expected on 15 per cent of winter days. By the 2080s this is likely to have fallen to 4 per cent for the **Medium-High Emissions** scenario. Note that these are night-time minima for the scale of the 50 km grid box and much lower local minima can occur in reality, especially in terrain as varied as central Scotland. As indicated above, for probabilities below 1 per cent we have more confidence in the differences between model-simulated baseline and 2080s temperatures than we have in the absolute values. In “Inverness-shire”, the once-in-ten year event (0.1 per cent) by the 2080s is likely to be about 6ºC higher than a similar frequency event currently.

5.4 Future changes in daily-average wind speed

Wind pressure is proportional to the square of the wind speed; at high wind speeds seemingly small changes can have major impacts on physical structures. In this section we examine the changes in the distribution of daily-average wind speeds, to complement the analysis in Chapter 4 which examined changes in the seasonal-average wind speed. Of course, even daily averages of wind speed are still averages over relatively long periods when considering the variability of the wind from minute-to-minute, but the model statistics based on daily *maximum* wind speeds (i.e., the maximum modelled 10-minute gust) were too unstable to be analysed with any confidence. Instead, we advise use of empirical relationships to obtain statistics at a shorter time-scale than the daily-

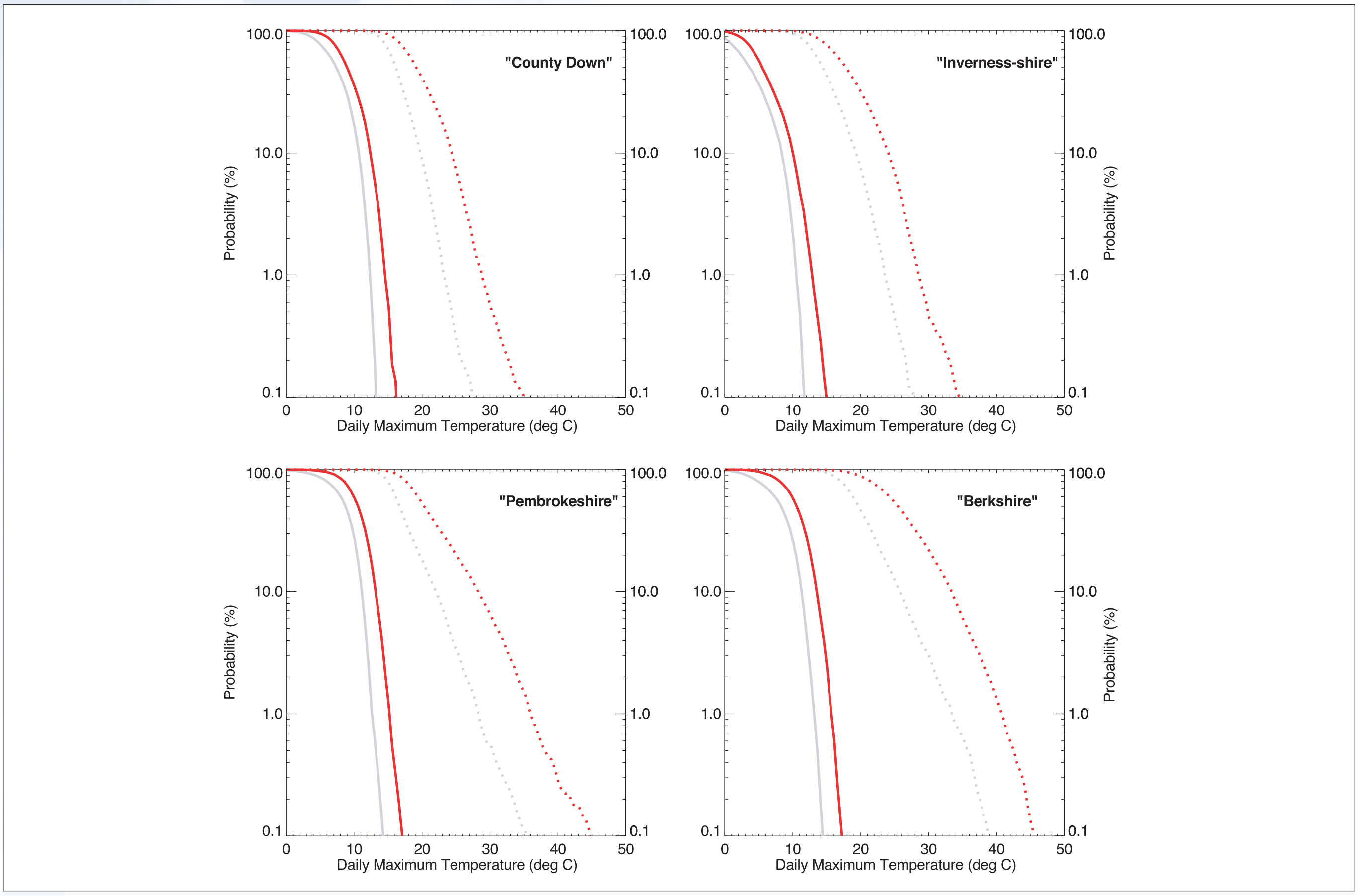

Figure 63: The probability of exceedence of daily maximum temperature for four HadRM3 grid boxes for the modelled baseline (grey) and for the Medium-High Emissions scenario for the 2080s (red). The probability expressed is the probability of the event being exceeded on any given day in summer (dashed lines) and winter (solid lines).

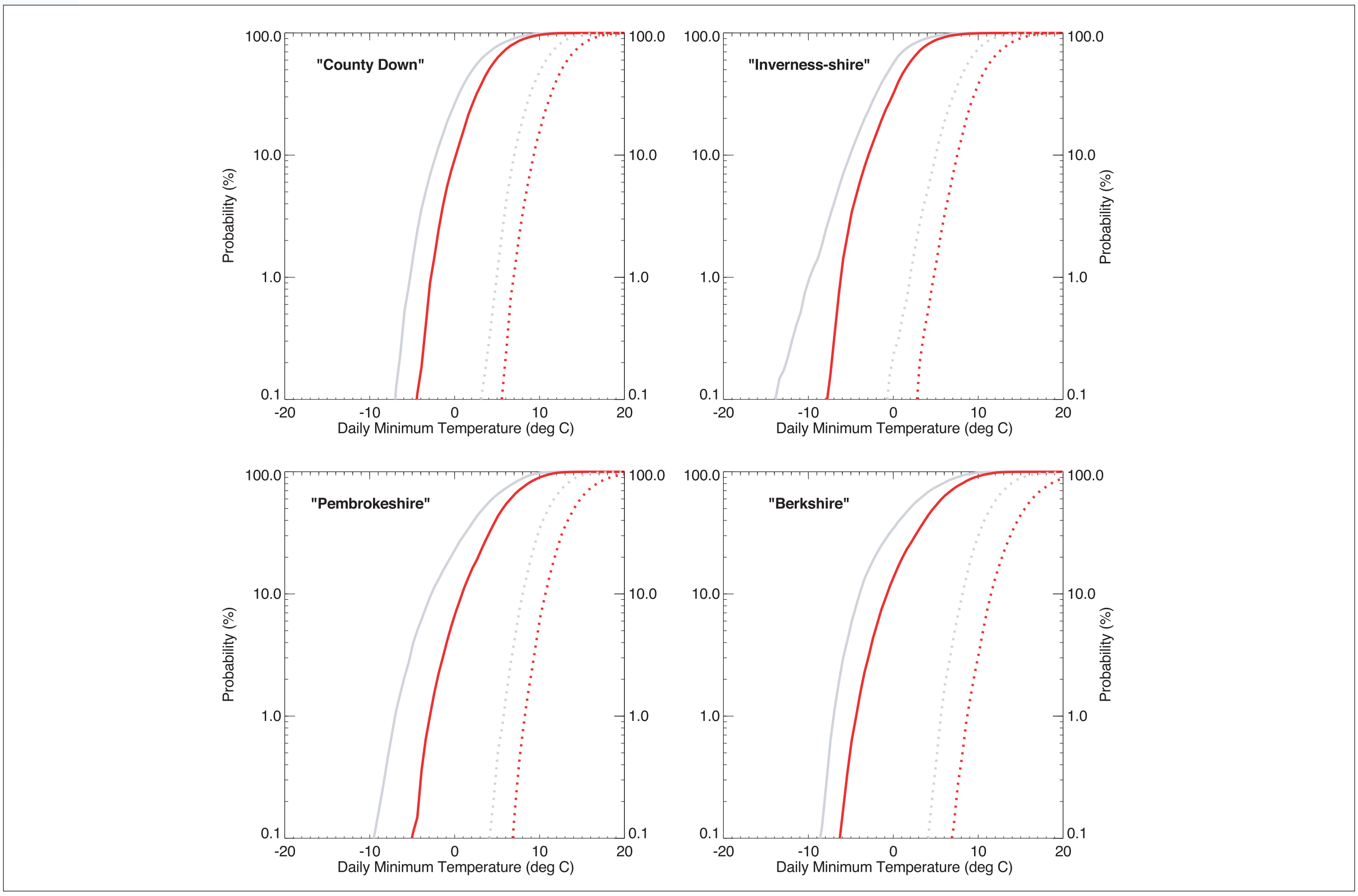

Figure 64: As Figure 63, but for the probability of daily minimum temperatures falling below *given thresholds.*

averages shown here. For example, observed relationships suggest that the maximum hourly-average wind speed is

Changes in wind extremes are uncertain. © M. Robinson.

about 30 per cent higher than the daily-average wind speed. The maximum gust, which may occur only for a few seconds, is typically about twice the daily-average wind speed. We have no evidence to suggest that these empirical relationships will change greatly in the future.

Return period analysis

Figure 65 shows the percentage change in the strength of the 2-year return period daily-average wind speed. This is the daily-average wind speed that might be expected to occur in any given winter with a probability of 50 per cent. Again, the pattern is rather noisy, but the general picture is for an increase in wind speed in winter, especially in the south of England by between 2 and 6 per cent (depending on scenario), and a decrease in wind speed in summer of between 2 and 10 per cent, except in southern England and northern Scotland where little change is expected. The changes in spring and autumn are rather small; in autumn there are small decreases in wind speed in England, Wales and Northern Ireland and small increases in Scotland. As with the daily precipitation analysis, the signal becomes noisier as the return period is lengthened, but the patterns and magnitudes of percentage change in daily-average wind speed remain broadly similar to those shown in Figure 65 for these lower-frequency events. For example, the daily-average wind speed that could be expected in southeast England on one winter day every 20 years increases by between 2 and 6 per cent (depending on scenario) relative to the current 20-year event velocity. This is similar to the 2-year percentage increase shown in Figure 65.

In conclusion, the patterns shown in Figure 65 are broadly consistent with the seasonal-average wind speed changes presented in Chapter 4. These changes seem to be partly driven in the HadRM3 model by a southward movement across the UK of the average winter depression tracks. Climate models remain rather poor at simulating small-scale and high intensity wind speeds, however, and relatively low confidence should be attached to these results. Further research would be extremely useful in this area.

5.5 Future changes in other variables using daily data

Thermal growing season length

The length of the thermal growing season is defined in the same way as in Chapter 2 (see Box G), but this time using model-simulated daily-average temperature data rather than observed. For the baseline period, typical average growing season lengths ranged from around 150 days in the Scottish Highlands to more than 250 days in the southwest of England. By the 2080s (Figure 66), the length of the thermal growing season extends in all parts of the country and under all scenarios. Much of England and Wales sees an increase of between 40 and 100 days per year in the growing season, depending on scenario, and the corresponding lengthening in western Scotland is between 20 and 60 days. Since these are average figures, it is likely that occasional years with year-round thermal growing seasons will occur in southern England well before the 2080s. It must be noted, however, that the definition of growing season used here is the *thermal* growing season; it is dependent only on temperature and does not take account of water availability nor day-length. Although the temperatures may be acceptable for year-round plant growth, the drier summers coupled with the same daylight hours as today's means in reality many plants may not grow all year round.

The length of the thermal growing season extends in all parts of the country and under all scenarios.

Heating "degree days"

The number of heating "degree days" (HDD) in a year gives an indication of the amount of time, and by how much, the temperature is below a given baseline (see Box G). HDD are especially important because organisations have a legal obligation to maintain a minimum temperature within a building. Knowing the possible changes in the number of HDD is therefore useful for energy and facilities managers and may be used to show the possible changes in the pattern of energy demand for buildings. Under model-simulated baseline conditions, each year on average has between about 2100 and 2300 HDD in southern England and between about 3000 and 4000 HDD in Scotland.

As climate warms, the number of heating degree days decreases.

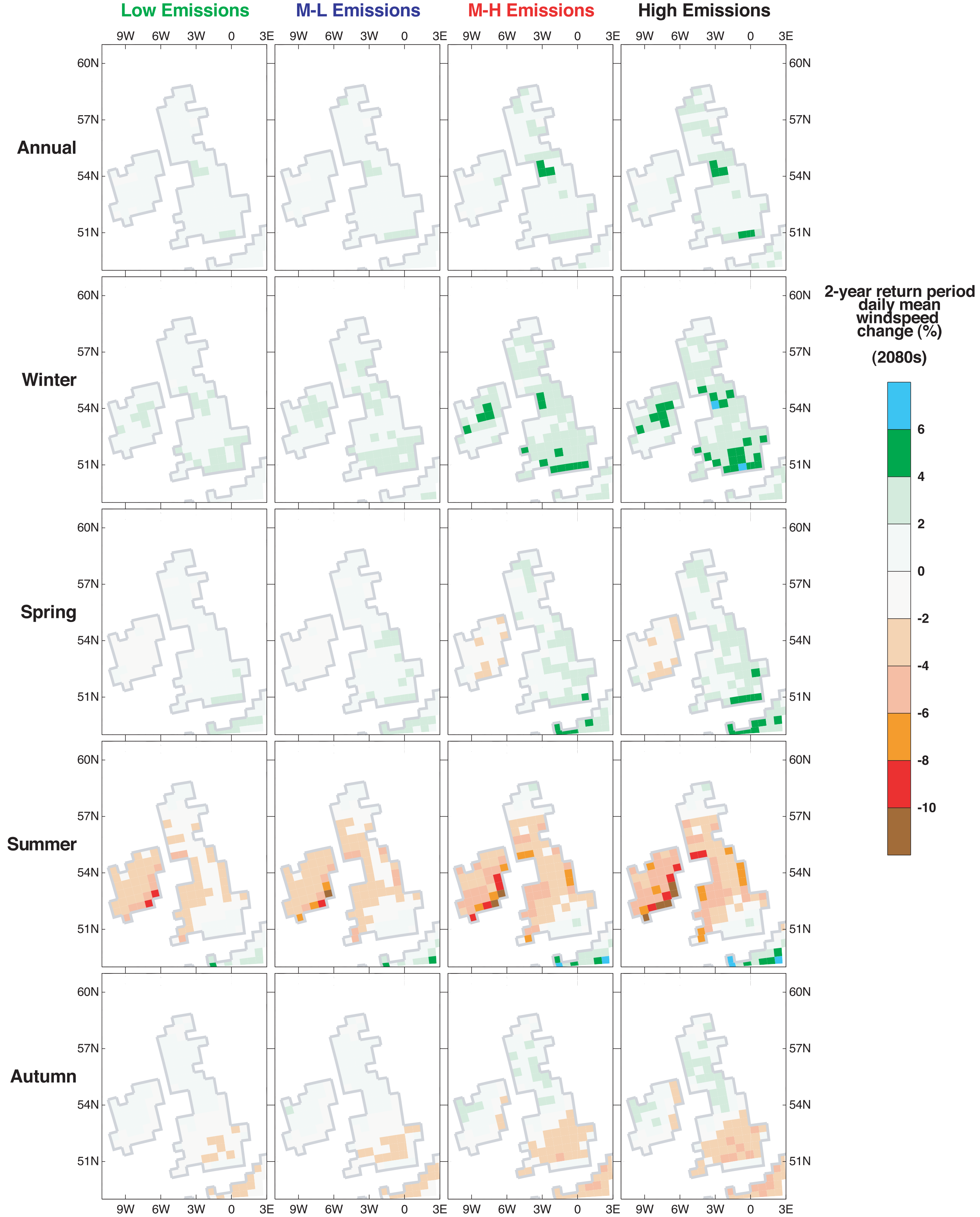

Figure 65: Per cent change for the 2080s in the daily-average wind speed which can be expected, on average, once every 2 years.

Box G: Definitions

Thermal growing season length
The length of the thermal growing season is defined as the longest period within a year that satisfies the twin requirements of: (i) beginning at the start of a period when daily-average temperature is greater than 5.5°C for five consecutive days; and (ii) ending on the day prior to the first subsequent period when daily-average temperature is less then 5.5°C for five consecutive days.

Heating "degree days"
The method used here is that adopted by the Met. Office and is explained in the Energy Efficiency Booklet 7 published in 1988 by the Energy Efficiency Office. The baseline standard is a daily-average temperature, Tmean - usually estimated as the average of the minimum and maximum temperatures for that day - of 15.5ºC. Therefore,

$$HDD = 15.5 - Tmean$$

and is summed for all days in a year, ignoring negative values. For example, if Tmean on one day is 10.5ºC, then there are 5 heating degree-days for that day. The formula for HDD is correct for cases when both the maximum and minimum temperatures are below the base. If this is not the case, various weighted increments are used to correct the basic equation.

Cooling "degree days"
There is no officially designated base temperature; in this report we have used 22ºC on the basis of building energy management practice. Thus,

$$CDD = Tmean - 22$$

which is summed for all days in the year, ignoring negative values. The formula holds when both the maximum and minimum temperatures are above 22ºC; in other cases weighted increments are used.

As climate warms, the number of heating "degree days" decreases as shown in Figure 67. Reductions in absolute terms are fairly uniform over the country, although somewhat larger over Scotland and northern England. In relative terms, the reductions are largest in the south in the **High Emissions** scenario, but over Scotland, where this figure takes on greater importance because of higher energy demand, the reductions are likely to be between 15 and 35 per cent, depending on scenario.

Cooling "degree days"
Cooling "degree days" (CDD; see Box G) fulfil a similar

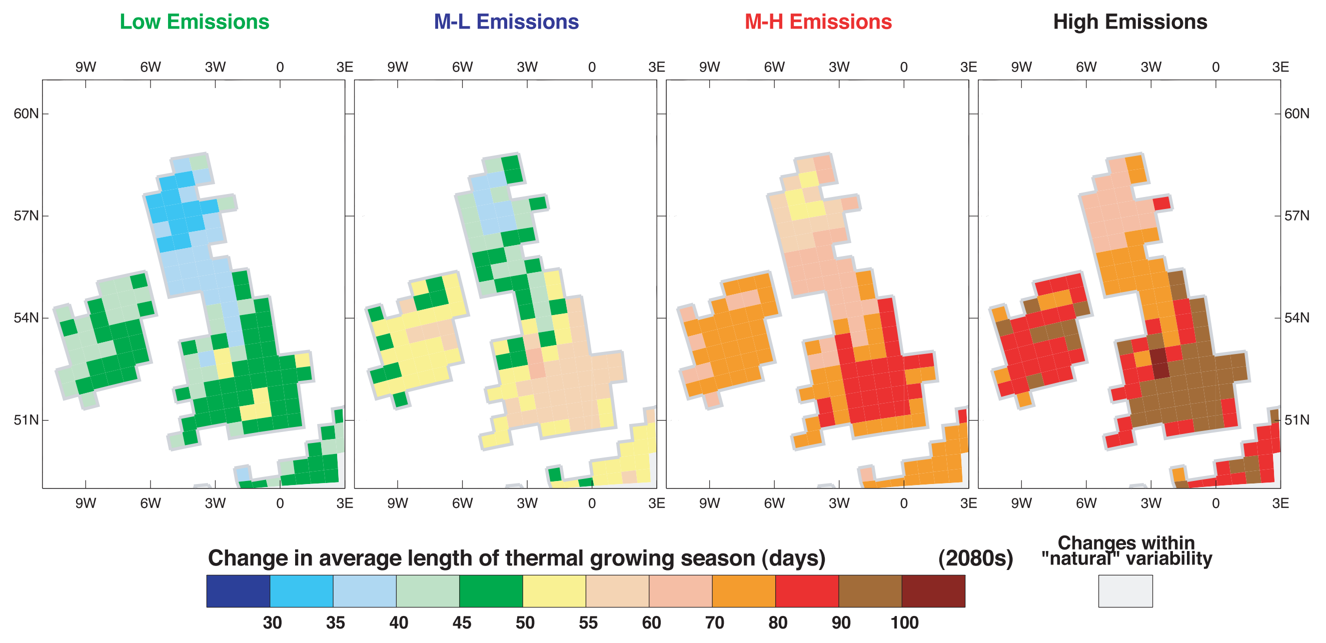

Figure 66: Change for the 2080s in the average thermal growing season length (days) with respect to the 1961-1990 baseline period. See Box G for definition.

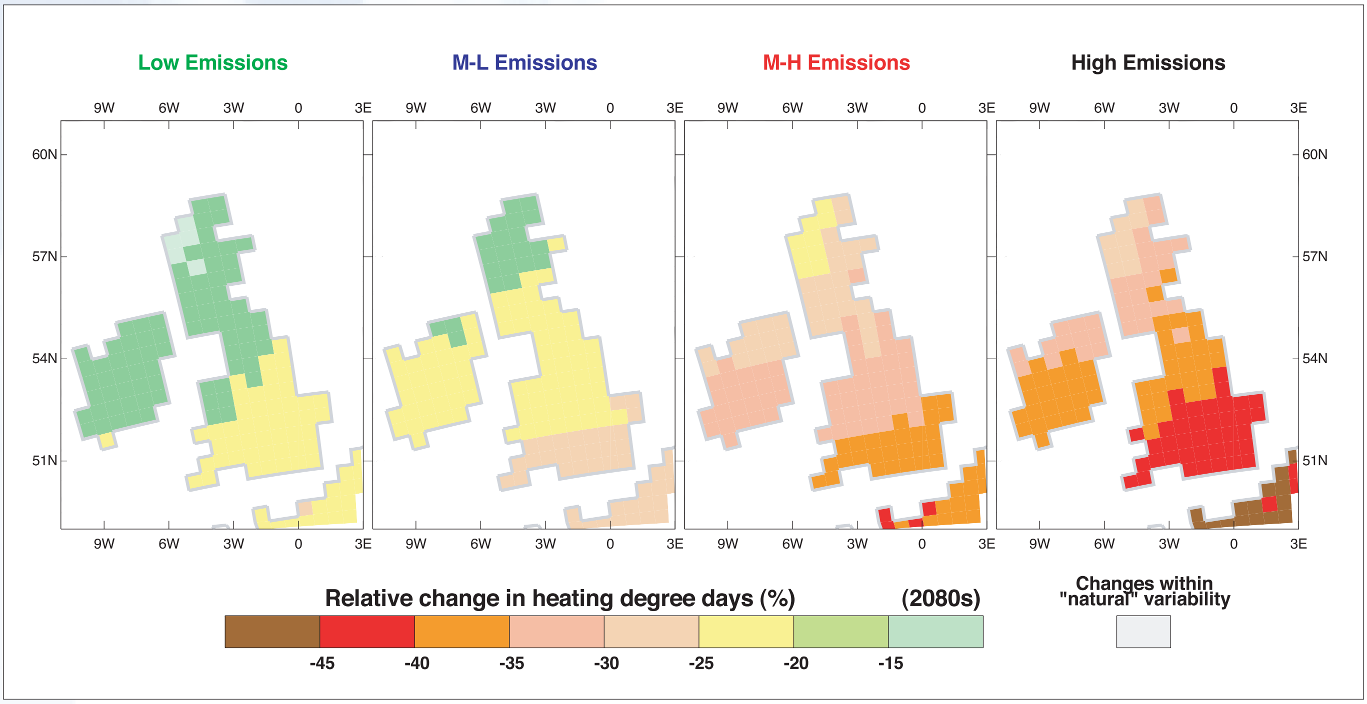

Figure 67: Per cent change by the 2080s in the average number of heating "degree days" with respect to the model-simulated 1961-1990 baseline period

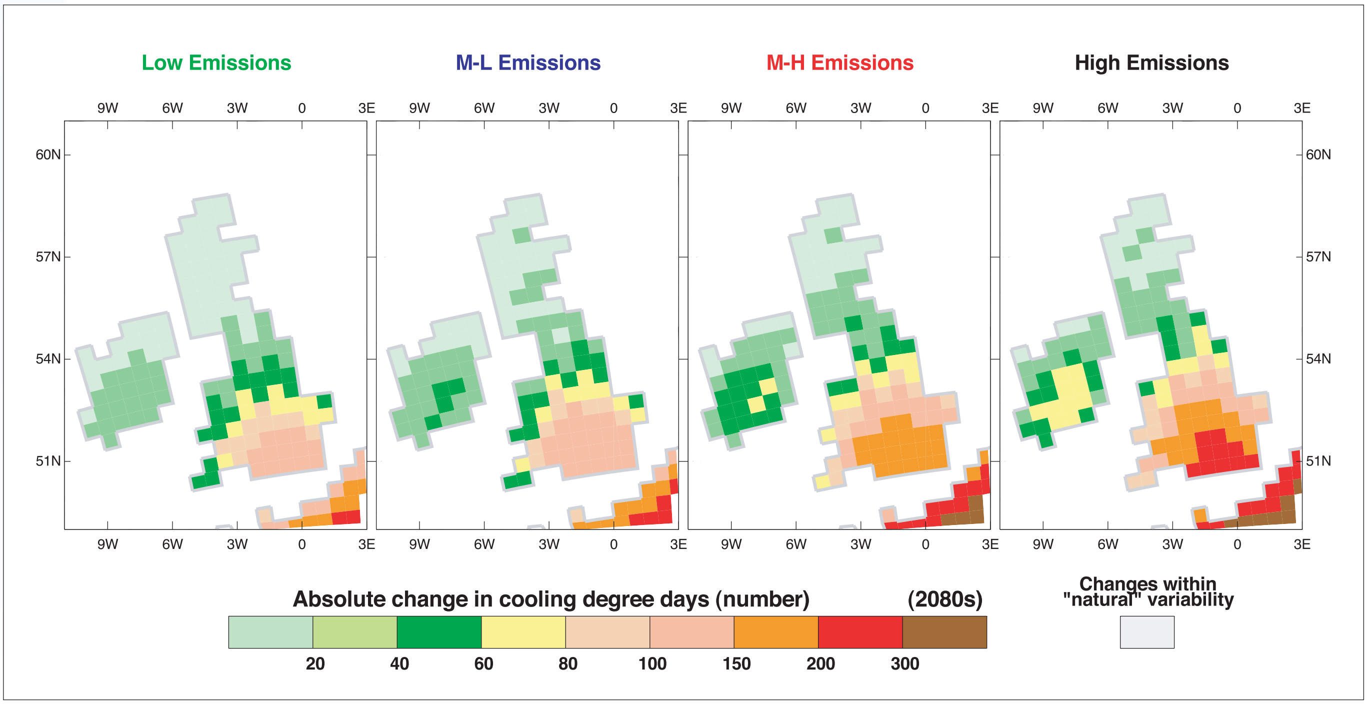

*Figure 68: Change by the 2080s in the average number of cooling "degree days" with respect to the 1961-1990 baseline period. Note the non-linear scale and that, unlike Figure 67, this map shows **absolute** changes*

function to HDD, but are less widely used since the cooling energy consumption (for example from air-conditioning) is not so well correlated with CDD. Cooling "degree days" are a more common statistic in other countries, but we may expect their use to become more prominent in the UK in the future. For the model-simulated baseline period, Scotland averaged only between about 20 to 50 CDD per year, while southern England experienced between about 310 to 330 CDD. As climate warms, CDD increase everywhere as shown in Figure 68. Over southern England by the 2080s, CDD increase by between 100 and 250 depending on scenario; this represents an increase of between about 30 and 80 per cent. Over Scotland and Northern Ireland, increases are smaller – between 10 and 40 CDD – but then these regions rarely experience any cooling degree days under present climate and the percentage changes are correspondingly much larger.

5.6 Qualitative summary and comparison with the UKCIP98 scenarios

This Chapter has presented changes in some aspects of "extreme" daily weather over the UK for the four UKCIP02 scenarios. The analyses have relied exclusively on the experiments conducted with the HadRM3 regional model – results extracted from 90 years of simulated future climate for the 2080s for the SRES A2 emissions scenarios, pattern-scaled where appropriate to construct patterns of change for the 2020s, 2050s and 2080s and for the **Low Emissions**, **Medium-Low Emissions**, **Medium-High Emissions** and **High Emissions** scenarios**.**

Table 10 summarises the main conclusions of this Chapter, expressed in qualitative terms only. As in Chapter 4, the relative confidence level of each of these statements is indicated. For wind, the results are highly uncertain and we cannot even assign a Low confidence level to this variable. The consistency of these UKCIP02 conclusions with those obtained from the UKCIP98 scenarios is indicated in the final column.

Variable	**UKCIP02 Scenarios**	**Relative Confidence Level**	**Consistency with UKCIP98**
Precipitation intensity	• Increases in winter	H	✔
Temperature extremes	• Number of very hot days increases, especially in summer and autumn • Number of very cold days decreases, especially in winter	H H	**n/a** **n/a**
Thermal growing season length	• Increases everywhere, with largest increases in the southeast	H	✔
Heating "degree-days"	• Decrease everywhere	H	✔✔
Cooling "degree-days"	• Increase everywhere	H	✔✔

Table 10: Summary statements of the changes in daily weather extremes for the UK for the UKCIP02 climate change scenarios. Quantitative statements are deliberately avoided; see the Chapter for detailed numbers. Relative confidence levels: H = high; M = medium; L = low. The qualitative consistency of these statements with the UKCIP98 scenarios is indicated in the last column by: ✔✔ = highly consistent, ✔ = some consistency, ✘ = some differences, ✘✘ = inconsistent, n/a = little or no analysis in UKCIP98.

Chapter 6: Future Changes in Sea Level and UK Marine Climate

6.1 Future changes in global sea level this century

Changes in global-average sea level are an important consequence of changes in global temperature, mainly arising through thermal expansion of ocean water and through the melting of mountain glaciers. Table 11 shows the globally-averaged sea-level rise with respect to the 1961-1990 average calculated using the Hadley Centre models for each of the four UKCIP02 scenarios and for the three 30-year periods – the 2020s, 2050s and 2080s. The differences in sea-level rise between the four scenarios are small during the first half of the twenty-first century, but thereafter the projections start to diverge. By the 2050s, the HadCM3 range is only from 14 to 18 cm, yet by the 2080s this range has widened to 23 (**Low Emissions** scenario) to 36 cm (**High Emissions**).

The IPCC in their Third Assessment Report also calculated global sea-level changes for the same emissions scenarios as used here, but using different models with different representations for the atmosphere and ocean and for the mass balance of land ice such as the Greenland and Antarctic ice-sheets. We show this wider range of calculations in Table 11 and, graphically, in Figure 69. For the UKCIP02 **High Emissions** scenario, for example, the IPCC range of sea-level rise for the 2080s is from 16 to 69 cm, compared to a HadCM3 calculation of 36 cm. The conclusion to be drawn from these analyses is that although sea level will undoubtedly rise as the planet warms, there is still a great deal more to understand about the complex dynamic and thermodynamic interactions of ocean, atmosphere and ice-sheets before we can reduce the differences between these estimates. It is important to note that the full range of global sea-level change used in this chapter – from 9 to 69 cm by the 2080s – results from a combination of *both* emissions uncertainty and scientific uncertainty. This contrasts with the climate changes shown in Chapters 4 and 5 where the differences between scenarios resulted *only* from emissions uncertainty.

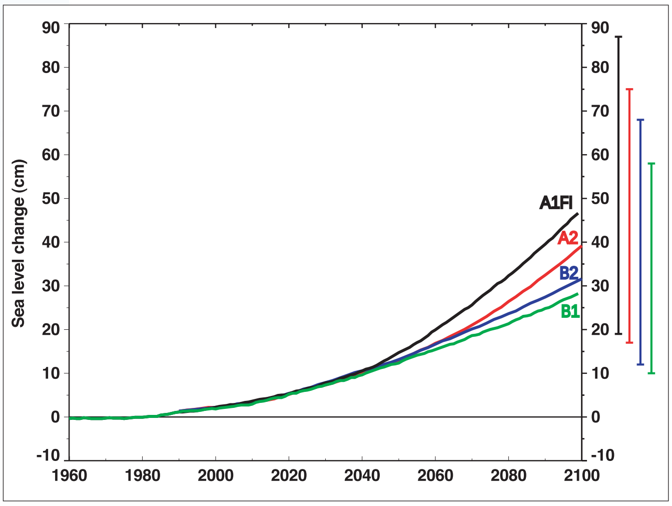

Figure 69: Global sea-level change (wrt 1961-1990 average) plotted from 1960 to 2100. Time series show the HadCM3 results. Range bars to the right show the full IPCC range for each emissions scenario by 2100, the result of using different climate models and different values for ice melt parameters.

The global rise in sea-level used in the UKCIP02 scenarios – even including the IPCC range - are generally smaller than those cited in the UKCIP98 report, especially at the upper end of the range. The IPCC range for the **High Emissions** scenario by the 2080s is from 16 to 69 cm, compared to 99 cm quoted for the UKCIP98 High scenario. The differences between the 1998 and 2002 reports are rather smaller for the other three scenarios. This situation arises despite the larger global temperature increases in the UKCIP02 scenarios compared to those published in 1998 (see Chapter 3). Improvements in the model representation both of ice melt and of ocean heat uptake result in sea level being rather *less* sensitive to global temperature change than previously calculated.

The majority of sea-level rise by 2100 occurs due to thermal expansion of ocean water.

As indicated below, a number of different factors will contribute to changes in sea level brought about by climate change. These different contributions are shown in Figure 70 for the HadCM3 calculation of the **Medium-High Emissions** scenario. The majority of sea-level rise by 2100 occurs due to thermal expansion of ocean water, with the melting of land ice in mountain glaciers and in the Greenland ice-sheet contributing smaller amounts. Over the next 100 years, it is thought that warmer temperatures and increased precipitation over Antarctica may actually result in a slight expansion of the Antarctic ice sheet, contributing to a *fall* in sea level of approximately the same magnitude as the contribution melting ice over Greenland makes to the *rise* in sea level. The long-term contribution these massive ice-sheets might make

UKCIP02 Scenario	2020s (cm)	2050s (cm)	2080s (cm)
Low Emissions	6 (4 – 14)	14 (7 – 30)	23 (9 – 48)
Medium-Low Emissions	7 (4 – 14)	15 (7 – 32)	26 (11 – 54)
Medium-High Emissions	6 (4 – 14)	15 (8 – 32)	30 (13 – 59)
High Emissions	7 (4 – 14)	18 (9 – 36)	36 (16 – 69)

Table 11: Global-average sea-level change (cm) relative to the 1961-1990 average for the four UKCIP02 scenarios as calculated by the Hadley Centre models. Figures in brackets are the IPCC range associated with the same SRES emissions scenarios we have used in UKCIP02; we term these our 'low' and 'high' estimates for each scenario, with the HadCM3-derived values adopted as our 'central' estimates. Note that the values we cite for the 2080s are somewhat less than the quoted IPCC values for 2100 since we are averaging over the period 2071-2100.

to sea-level rise beyond 2100 is discussed in Section 6.2 below. Note that the melting of floating sea ice – for example in the Arctic Ocean - does not contribute to a change in sea level, although it may affect ocean circulation patterns by altering the density of ocean water (see Section 7.8).

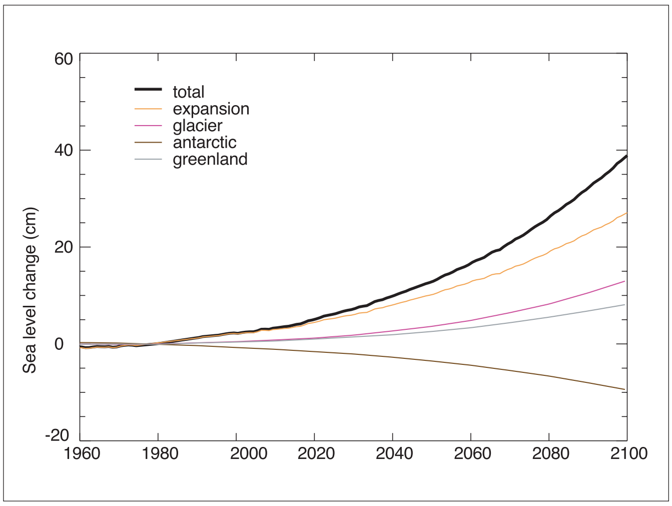

Figure 70: The contribution to sea-level change from different sources for the Medium-High Emissions scenario as modelled by HadCM3 for the period 1960 to 2100.

6.2 Future changes in global sea level in the long-term

The above calculations relate to changes in sea level that may occur over the next hundred years. There are certain characteristics of the oceans and ice-sheets, however, that mean that we may already have "committed" ourselves to much larger changes in sea level over longer time-scales.

The thermal expansion of ocean water

The additional heating of the ocean surface caused by the enhancement of the greenhouse effect will gradually penetrate down to deeper ocean layers, causing progressive expansion of deeper (and colder) waters. This penetration takes many centuries and so also therefore does the expansion of ocean water. Figure 71 shows an illustration of the effect of this slow ocean response to heating. The sea-level rise due to thermal expansion alone (no ice melt was allowed) was calculated in a climate model experiment during which time carbon dioxide concentration in the atmosphere was increased at the rate of one per cent per year. By Year 70 the concentration had doubled and was thereafter held constant in the model atmosphere. After about Year 120 little further global warming occurred. Despite this, sea level in the model carried on rising for many hundreds of years. This analysis illustrates that even once we have stabilised concentrations of greenhouse gases in the atmosphere, with global surface temperature stabilising a few decades later, there remains an inescapable "commitment" to a further substantial rise in sea level over many centuries.

Even once we have stabilised concentration of greenhouse gases there remains an inescapable 'commitment' to a further substantial rise in sea level over many centuries.

The thermal expansion component of climate-induced sea-level rise over the twentieth century is estimated to be about 5 cm. It has been calculated that due to historical emissions of greenhouse gases we are already committed to a further eventual rise in global sea level of about one metre due to thermal expansion alone. This would occur even if climate change itself was halted within a few decades, something that

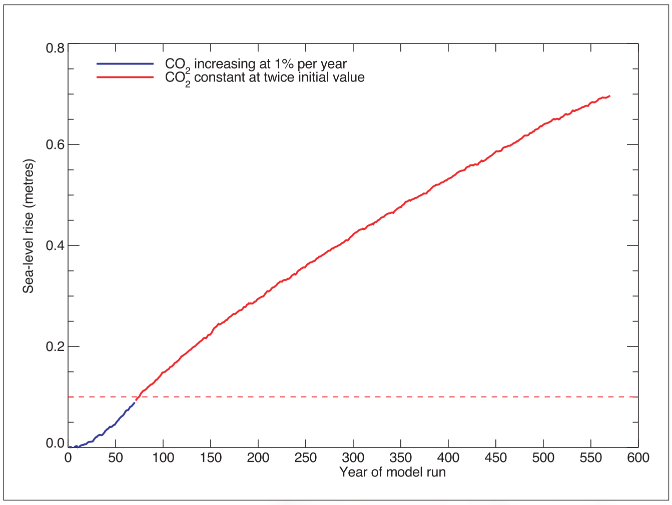

Figure 71: The long-term commitment to global sea-level rise through thermal expansion. In this model experiment from the Hadley Centre, sea level continues to rise for several centuries even though there are no further changes in greenhouse gas concentrations after Year 70, and little further rise in global temperature after about Year 120. The red dotted line indicates sea-level rise at the point of stopping carbon dioxide concentration increases.

would require an almost instantaneous reduction of 60 per cent in global greenhouse gas emissions and which is not presently conceivable. This eventual rise in sea level of a metre or so would take several centuries to materialise, this example illustrating the long time-scales involved in the behaviour of the climate system.

Greenland ice-sheet

Of the large ice-sheets, Greenland is probably the most vulnerable to global warming. According to the IPCC Third Assessment Report, if a local warming over the Greenland region of 3ºC or more were sustained for millennia, then models of the Greenland ice-sheet suggest that eventually it could melt completely. If the sustained local warming were 5.5ºC or more, the Greenland ice sheet is predicted to contribute about three metres to sea-level rise over the next 1,000 years. For a larger warming of 8ºC, it could contribute as much as six metres to global sea-level rise over this period. For our **Medium-High Emissions** scenario, the warming over Greenland by the 2080s just about reaches 5ºC (see Figure 22).

East Antarctic ice-sheet

The latest findings presented by the IPCC (IPCC, 2001) state that for the East Antarctic ice-sheet to disintegrate as a result of surface melting, a local warming over Antarctica of 20ºC or more would be required. This warming is greater than that simulated for even the most extreme scenario for the coming century and *much* greater than the local warming in the UKCIP02 **High Emissions** scenario by the 2080s. Furthermore, the period over which this melting would occur is expected to be at least 10,000 years. The associated rise in sea level would be tens of metres.

West Antarctic ice-sheet

It is possible, however, that a much more rapid rise in sea level than suggested in the UKCIP02 scenarios could occur should the West Antarctic ice-sheet disintegrate. This might arise from an interaction between warming, sea-level rise and ice calving and melt. The West Antarctic ice-sheet is unlike Greenland or the East Antarctic in that it is grounded below sea level and is therefore potentially unstable. If it were to disintegrate completely, global sea level would eventually rise by about five metres.

Predictions about the contribution of the West Antarctic ice-sheet to sea-level rise are difficult and uncertain for at least two reasons. First is the complexity of processes determining the stability of this ice-sheet and, second, is the uncertain relationship between changes caused by climate change in the accumulation of snow and in the discharge of ice. In particular, the effects of natural millennial-scale trends in climate on this relationship are very uncertain. It appears unlikely that the West Antarctic ice-sheet will contribute much to sea-level rise in the present century, but over following centuries higher discharge rates from the ice-sheet might increase its contribution to global sea-level rise to between 30 and 50 cm per century. It is important to note, however, that the rapidity of the West Antarctic ice-sheet disintegration may depend upon the warming rate over the next century, which is already being determined by our present emissions of greenhouse gases.

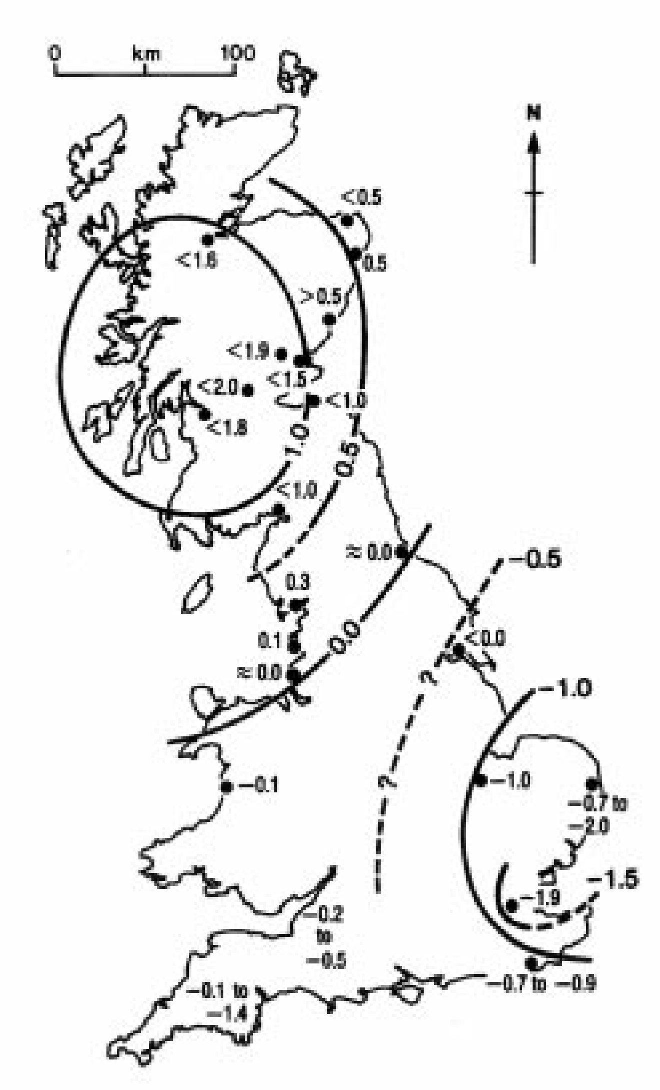

Figure 72: Estimates of present (late Holocene) rates of relative land changes (mm/yr); positive values indicate relative land uplift, negative values are relative land subsidence. Contours are drawn by eye. Effects of sediment consolidation are not included [Source: Ian Shennan, 1989].

6.3 Future changes in regional sea level

The change in the average level of the sea relative to the land will not be the same everywhere because of natural land movements and regional variations in the rate of climate-induced sea-level rise.

The main reasons for regional land movements in the UK are on-going readjustment of the land to the de-glaciation that followed the last ice age and localised sediment consolidation brought about, for example, by groundwater extraction. In consequence of the former factor, much of southern Britain is sinking and much of northern Britain is rising relative to the sea (Figure 72). This means that the relative, or net, change in average sea level around the UK coastline will vary, even if the climate-induced change in sea level were the same everywhere. This is illustrated in Table 12 for various regions of the country for the two most extreme UKCIP02 scenarios. The effects of sediment consolidation are not included in these regional estimates, since they are highly localised and can vary over relatively short stretches of coastline.

These regional differences in sea-level rise can vary by up to ±50 per cent of the change in the global-average.

Regional variations in climate-induced sea-level rise occurs because the warming of ocean water is not uniform and neither therefore is the expansion of ocean water. Changes in ocean circulation and atmospheric pressure will also affect the distribution of sea-level rise. These regional differences in climate-induced sea-level rise can be quite substantial and can vary by up to ±50 per cent of the change in the global-average. In principle, therefore, we should take these regional variations into account in our UK sea-level rise scenarios. However, apart from one or two regions of the world's oceans – mostly in the Southern Hemisphere – there is little agreement between different models about these regional patterns of sea-level rise. We have therefore decided to use only the global-average rise as the basis for the UKCIP02 scenarios. For sensitivity studies, however, it is advisable to consider changes in sea level for each scenario that are ±50 per cent of those shown in Table 11, including those for the full IPCC range. One should also of course factor in the natural rates of land movement, as illustrated in Table 12.

	Regional Isostatic Uplift (+ve) or Subsidence (-ve)(mm/yr)	Net Sea-level Change 2080s (cm) Relative to 1961-90	
		Low Emissions scenario	High Emissions scenario
NE Scotland	+0.7	1	61
SE Scotland	+0.8	0	60
NE England	+0.3	6	66
Yorkshire	-0.5	15	75
East Midlands	-1.0	20	80
Eastern England	-1.2	22	82
London	-1.5	26	86
SE England	-0.9	19	79
SW England	-0.6	16	76
Wales	-0.2	11	71
Northern Ireland	n/a	~9	~69
NW England	+0.2	7	67
SW Scotland	+1.0	-2	58
NW Scotland	+0.9	-1	59
Orkney & Shetland	n/a	~9	~69
Global-average	**n/a**	**9**	**69**

Table 12: Rates of vertical land movement due to isostatic adjustment for Wales, regions of Scotland and the administrative regions of England [Source: estimated from Ian Shennan, 1989]. Relative sea-level change is also shown for the 2080s with respect to the 1961-1990 period (i.e., including 110 years of assumed future land movement) using the low estimate for the Low Emissions (9 cm global rise) and the high estimate for the **High Emissions** *scenario (69 cm global rise). Note: land movement data not available for Northern Ireland and Orkney & Shetland.*

6.4 Future changes in extreme sea levels and coastal flooding

The century-scale rise in average sea level may threaten some low-lying unprotected coastal areas, yet it is the extremes of sea level - storm surges and large waves - that will cause most damage. Future changes in extreme sea levels are therefore of great concern, although the uncertainties in modelling such changes remain very large.

Storm surges

Storm surges are temporary increases in sea level, above the level of the astronomical tide, caused by low atmospheric pressure and strong winds. They occur in shallow water regions, such as on the continental shelf around the UK and, in some places, their height may be increased by the funnelling effect of the coastline. The surges are most damaging when they occur at high tide; regular flooding around much of the UK coast is only prevented by flood defences. Future changes in the extreme sea levels associated with storm surges will occur if there are changes in the number, location, or strength of storms and also, of course, as a result of increases in average sea level.

Regional climate models cannot yet produce simulations of storm surge height directly because they do not have an ocean component. Instead, the atmospheric winds and pressure from the regional model (HadRM3) have been used to drive a separate high-resolution (30 km) model from the Proudman Oceanographic Laboratory (POL) of the shelf seas around the UK. Statistical distributions have been fitted to the simulated extreme storm surges and these allow estimates to be made of changes in the 50-year return period storm surge heights, i.e., the surge that has a two per cent chance of occurring in any given year. The height of storm surges simulated by the surge model are generally below those measured using tide gauges, although this is not surprising given that the surge model averages over a 30 km region, while tide gauge measurements are made at a single coastal location. Nevertheless, the geographical pattern of simulated surges for present-day climate, with elevated values at the southern end of the North Sea, compares well with the observations and provides some confidence in the model simulations.

Using the POL surge model and HadRM3, changes in storminess alone suggest that the largest increases in surge height around the UK coastline might occur off the southeast coast. In contrast, a *decrease* in the storm surge height is simulated for the Bristol Channel, although the 30 km resolution of the storm surge model means that we have much less confidence in the results for narrow channels like this. When the rise in global-average sea level for the central estimate of the **Medium-High Emissions** scenario is included in this analysis – an additional 30 cm - the increase in the height of the 50-year return period extreme water level, relative to present day, is also raised by this amount. For impact and adaptation studies it is also necessary to include *relative* sea level brought about by vertical land movements (cf. Table 12).

The simulated changes in the 50-year return period water levels around the UK coastline when all three factors are included - change in storminess, rise in global sea level and vertical land movements - are shown in Figure 73 for three different global sea-level rise scenarios. The largest rise in surge height, up to 1.4 m for the High Emissions scenario high estimate, occurs along the southeast coast of England, which experiences both the largest change in surge height due to changes in storms (see above) and also the one of the largest regional subsidence rates (Figure 72). It is important to note, however, that the modelling uncertainties involved here are

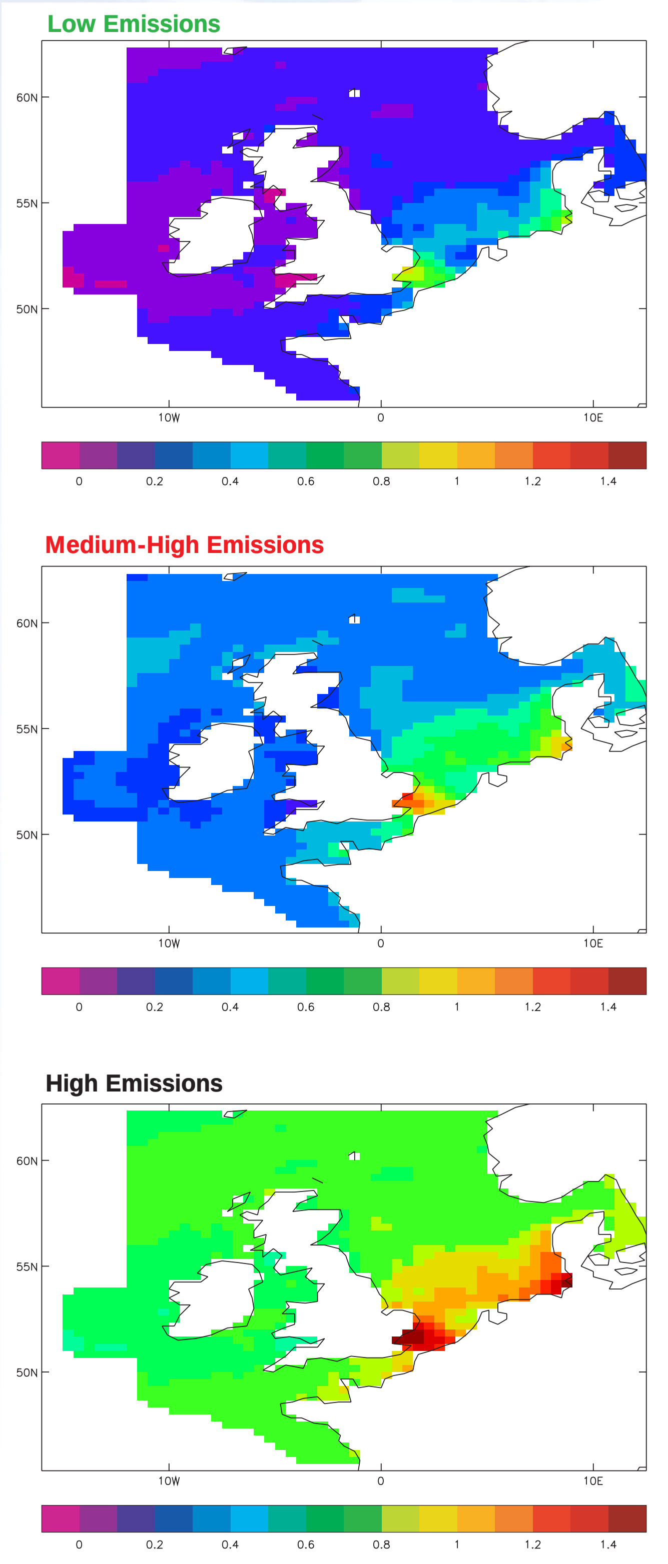

Figure 73: Change in 50-year return period surge height (metres) for the 2080s for three different scenarios. The combined effect of global-average sea-level rise, storminess changes and vertical land movements (from Shennan, 1989) are considered. (Top) Low Emissions scenario (low sea-level rise estimate; 9 cm); (Middle) Medium-High Emissions scenario (central estimate; 30 cm); (Bottom) High Emissions scenario (high estimate; 69 cm).

very large. Different patterns and magnitudes of change in surge height to those shown in Figure 73 can be produced either by using changes in climate extracted from a different climate model to HadRM3, or by using the same changes in climate but applying them to a higher resolution (12 km) surge model. Earlier modelling work completed using the 12 km POL surge model, for example, found that the rise in the 50-year return period surge height off southeast England was much less than that shown in Figure 73. We have relatively little confidence in these patterns and magnitudes of change in storm-surge height.

To demonstrate how the water levels associated with storm surges of other return periods will change in future we have considered in greater detail the results at an example port, Immingham, on the east coast of England for the **Medium-High Emissions** scenario (Figure 74). The graph shows water levels plotted against the average time between their occurrence (return period). For example, currently a water level of 1.5 m would be expected once every 120 years on average (green line and black curve). Under the **Medium-High Emissions** scenario for the 2080s, this level could occur once every seven years; a seventeen-fold increase in frequency (green line and red curve). Another implication of Figure 74 is that a water level that occurs, on average, once every 50 years at present might occur as often as once every three years by the end of the century.

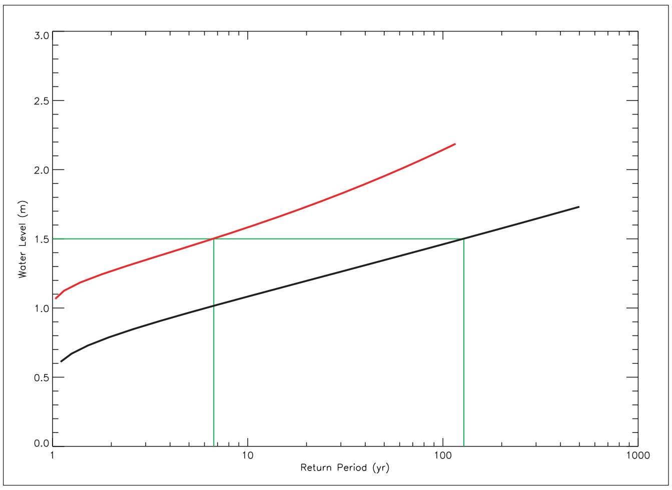

Figure 74: Change in high water levels associated with different return periods for Immingham in the east of England. Black line is current (1961-1990) regime; red line is for the 2080s for the Medium-High Emissions scenario, using the central sea-level rise estimate (30 cm). Storminess changes and vertical land movements also considered. The green lines show the changes in return period for an example water level (1.5 m) under climate change.

We have also investigated how using the full IPCC range of sea level changes for the 2080s (9 and 69cm, Table 11) alters the frequency of the present-day "once-in-50-year" surge event, using the changes in storminess from the **Medium-High Emissions** scenario. When the lowest future sea-level rise is used (9cm; **Low Emissions** – low estimate), this magnitude surge event occurs, on average, once every 10 years by the end of the twenty-first century. When the largest future sea-level rise is used (69cm; **High Emissions** – high estimate), the storm surge is predicted to occur more often than once a year. This event could become even more frequent if the local climate-induced sea-level rise is larger than the global-average (Section 6.3), or if storminess changes from the **High Emissions** scenario were used in the model simulation.

Wave heights

Understanding how wave heights may change as climate warms is important; waves can cause damage to coastlines, including coastal defences, and can be hazardous to shipping and offshore structures. The heights of offshore waves depend on the strength of the wind and on both the distance and the length of time over which the wind acts on the ocean surface. In addition, swell waves can travel vast distances away from the windy region in which they were generated so that strong winds on the western side of the Atlantic can affect the heights of waves in UK coastal waters. In future, because average wind speeds and wind extremes are expected to change (for example, see Figure 76 below), the height of offshore waves around the UK could also change.

Coastal wave height is a function both of local water depth and of the strength of offshore waves. If offshore waves increase in height, this extra energy will be transmitted directly to coastal defences only if there is already a fairly deep water-path leading to these defences. Where the water is fairly shallow in the coastal zone, the extra wave energy is dissipated before reaching the shoreline, although this may lead to additional offshore erosion and greater shoreline vulnerability. Even if offshore waves do *not* increase in height, sea-level rise will lead to locally deeper water in the near-shore zone and therefore lead to greater wave energy being transmitted to the shoreline. This would increase the risk of breaching or overtopping coastal defence structures.

Sea-level rise will lead to locally deeper water and to greater wave energy being transmitted to the shoreline.

Pressure on coastal defences from rising sea level is already increasing.
© M Robinson.

Wind direction is also important in determining shoreline vulnerability. Changes in wind direction may lead to increased exposure to offshore energetic waves and hence greater erosivity even if the wave climate itself does not change. The worst-case scenario for the near-shore zone would be an increase in average sea level, an increase in local tidal high waters, combined with an increase in wind speed and changes in local wind direction such that exposure to offshore waves is increased.

Changes in offshore wave climate and wind direction are not well quantified and we present no quantitative estimates in this report. The few modelling studies that have tried to quantify these effects have not been conclusive and vary widely from model-to-model. Equally, on the basis of observational evidence we know that the role of the North Atlantic Oscillation in influencing wave heights is important (see Section 2.5), and our scenarios suggest that the Oscillation may tend towards higher (more westerly) index values in the future (Section 4.8). More detailed studies in the future will use winds from long regional climate model simulations to drive detailed models of ocean waves around the UK.

6.5 Future changes in surface marine climate

Climate conditions at sea are vital for shipping, for offshore industries and for those marine species which can only survive in a narrow range of temperature. We show here changes in just two aspects of marine climate around the shores of the UK - average annual sea-surface temperature and the two-year return period daily-mean wind speed.

Sea-surface temperature

All regions show an increase in the temperature of coastal waters, with the shallowest seas such as the southern North Sea and English Channel warming the most – by more than 3ºC by the 2080s under the **Medium-High Emissions** and **High Emissions** scenarios (Figure 75). This 3ºC warming of surface water off the coast of southeast England is equivalent to about a three-month extension to the duration when sea temperatures in this part of the UK reach, or exceed, the present August-September average of about 16ºC. Thus by the 2080s, average sea-surface temperatures would exceed the current mid-August to mid-September maximum for the five-month period from mid-June to mid-November. In contrast, the waters of the Atlantic Ocean northwest of Scotland warm by less than 1ºC for the **Low Emissions** scenario by the same period.

All regions show an increase in the temperature of coastal waters.

Daily-average wind speed

Changes in wind speeds over ocean areas will be an important factor driving the changes in extreme sea levels analysed above. Figure 76 shows the change in 2-year return period daily-average wind speed over the seas around the British Isles; it is the same analysis as shown in Figure 65, but only over the ocean. The areas off the south and east coasts of England see the largest wind speed increases in winter and spring, between 2 and 8 per cent by the 2080s depending on scenario. Around most of the rest of the British Isles, however, there are few changes in these seasons. In summer and autumn, the wind speed decreases as climate warms, especially off the west coast of the British Isles where reductions are up to 10 per cent. These patterns are consistent with the drier, more settled summers and more southerly winter depression tracks under conditions of climate change described in Chapter 4.

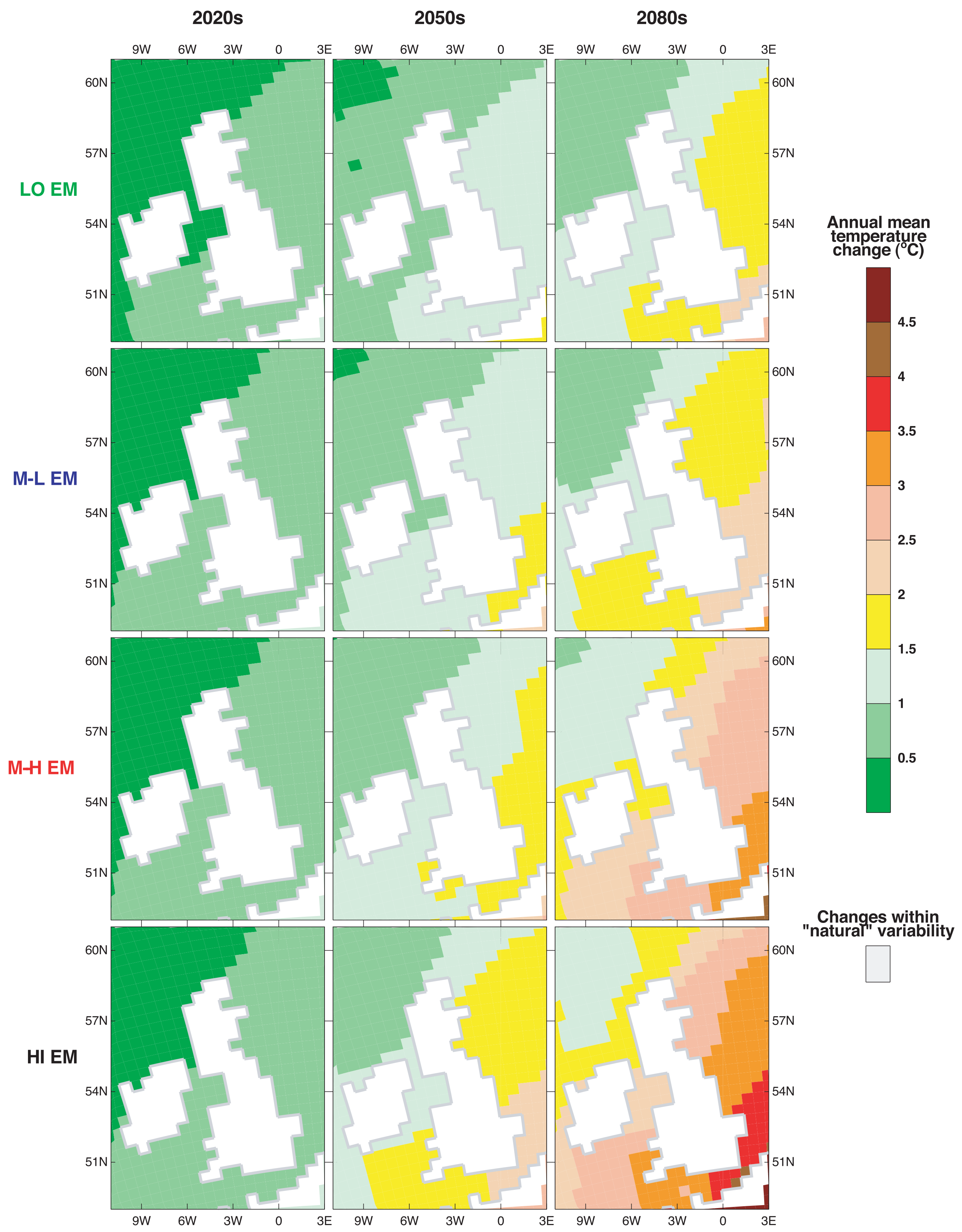

Figure 75: Changes in annual average sea-surface temperature by the 2020s, 2050s, and 2080s (wrt model-simulated 1961-1990 average) for the four scenarios; results from the regional model HadRM3.

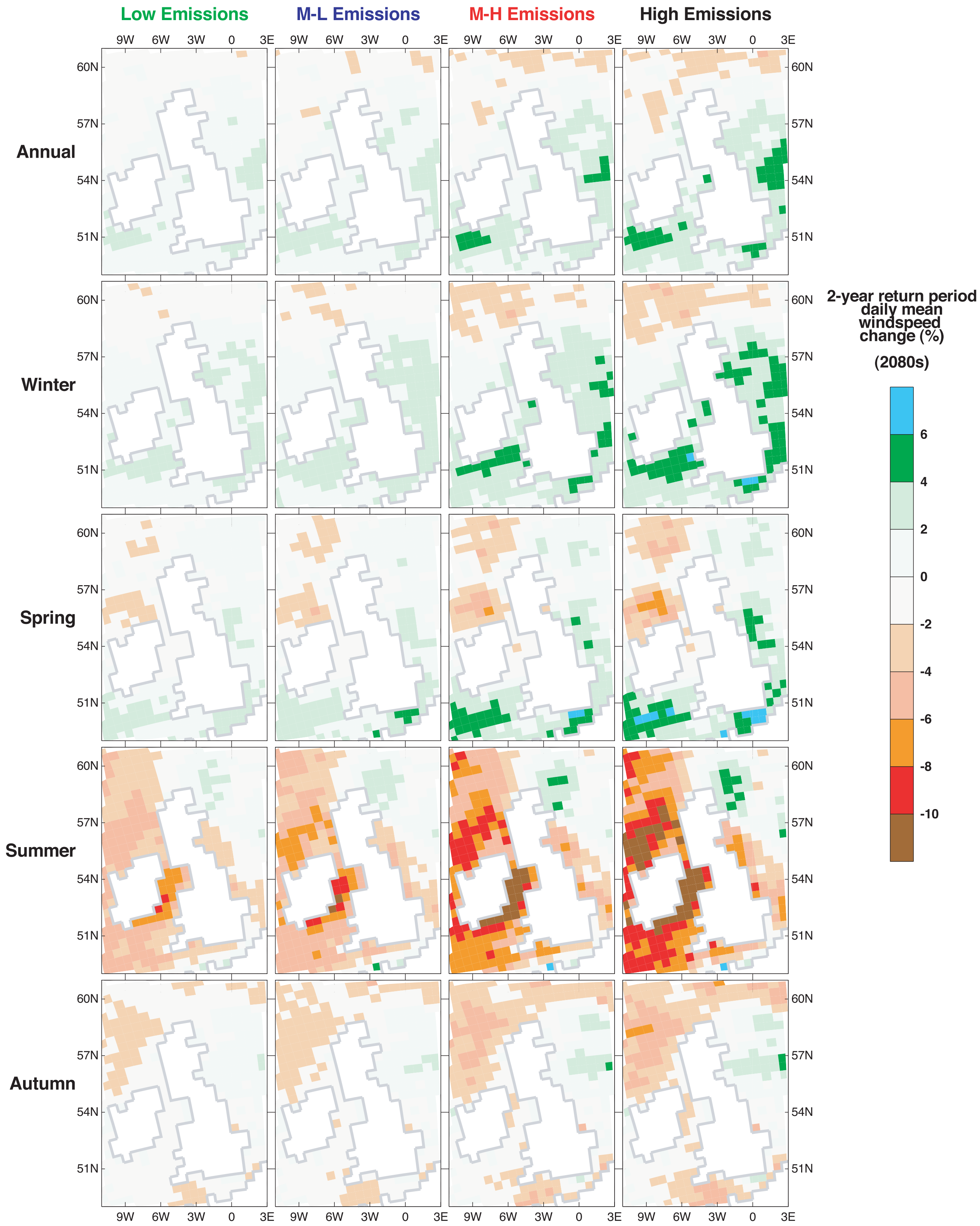

Figure 76: Per cent change for the 2080s in the daily-average wind speed which can be expected, on average, once every 2 years.

6.6 Qualitative summary and comparison with the UKCIP98 scenarios

This Chapter has presented changes in sea level, extreme water levels and average marine climate in UK coastal waters for the UK for the four UKCIP02 scenarios. The analyses have relied on experiments conducted with the HadCM3 and HadRM3 models, on the storm surge model from POL, and on the results from the IPCC Third Assessment Report. Table 13 summarises the main highlights of this Chapter, with relative confidence levels being attached to each headline. For wind, the results are highly uncertain and we cannot even assign a Low confidence level to this variable. The consistency of these conclusions with those derived from the UKCIP98 scenarios is indicated in the final column.

Variable	UKCIP02 Scenarios	Relative Confidence Level	Consistency with UKCIP98
Global-average sea level	• Will continue to rise for several centuries, and probably longer	H	✔
	• The West Antarctic ice-sheet will contribute relatively little to sea-level rise in the present century	H	✔
	• Will increase by the 2080s by between 9 and 69cm	M	✗
UK sea-level change	• Continuation of historic trends in vertical land movements will introduce significant regional differences in *relative* sea-level rise around the UK	H	✔
	• Will be similar to the global-average	L	**n/a**
Extreme sea levels	• For some coastal locations and some scenarios, storm surge return periods by the 2080s will reduce by an order of magnitude	M	✔
	• Changes in storminess, sea level and land movement mean that storm surge heights will increase by the greatest amount off southeast England	L	**n/a**
Marine climate	• Sea-surface temperatures will increase around all UK coasts	H	**n/a**

Table 13: Summary statements of the changes in sea level and marine climate for the UKCIP02 climate change scenarios. Quantitative statements are deliberately avoided; see the Chapter for detailed numbers. Relative confidence levels: H = high; M = medium; L = low. The qualitative consistency of these statements with the UKCIP98 scenarios is indicated in the last column by: ✔✔ = highly consistent, ✔ = some consistency, ✗ = some differences, ✗✗ = inconsistent, n/a = little or no analysis in UKCIP98.

Chapter 7: Uncertainties and Wider Issues

7.1 Uncertainties in scenarios of climate change

As explained in Chapter 3, the climate change scenarios presented in this report are based on four plausible, self-consistent descriptions of how the world may change in the future. For each description of the future, quantitative estimates of future greenhouse gas and aerosol precursor emissions are made using energy-economy models. These quantitative emissions profiles are then used to drive a hierarchy of climate models – global to regional – that simulate the ensuing changes in climate.

There are therefore several different stages in this process of climate scenario construction, with different methods being used and different assumptions being made at each stage. The uncertainties associated with each stage are not only different in magnitude, but also different in nature. The most important of these stages are perhaps the following:

- derivation of future global emissions;
- calculation of how these emissions will affect atmospheric concentrations;
- calculation of the radiative forcing (the warming or cooling effect) these concentration changes will produce;
- calculation of how large-scale climate will respond to the change in radiative forcing;
- calculation of how local-scale climate will respond to the large-scale changes;
- the natural variability of the climate;
- feedbacks between climate change, the carbon cycle and atmospheric chemistry.

We say a few words below about the uncertainties associated with each of these stages. Some of these comments are then elaborated at greater length later in this Chapter, being illustrated with specific examples. We examine uncertainties associated with climate change scenario production rather than give specific guidance on how to handle risk and uncertainty in decision-making. This latter can be obtained from the joint UKCIP-Environment Agency-DEFRA guidance for decision-makers, due to be published in the first half of 2002.

Uncertainty about *future emissions* arises because we do not know with any confidence how populations, economies, energy technologies, and other social factors that influence greenhouse gas emissions will change in the future. As explained in Chapter 3, we adopt a range of possible world futures using those created by the IPCC Special Report on Emissions Scenarios. See Section 7.2 for further discussion.

Uncertainty in the *concentration of greenhouse gases and aerosols* in the atmosphere arises because we do not fully understand the fate of the emissions. To what extent are these emissions: 1) absorbed by sinks (vegetation and the oceans in the case of carbon dioxide); 2) deposited on the ground; or 3) converted into other species through interaction with other chemicals in the atmosphere (this process is important for sulphate aerosols, ozone and methane)? For example, the atmospheric concentration of carbon dioxide calculated by 2100 for the SRES A2 emissions scenario (UKCIP02 **Medium-High Emissions** scenario) using a number of different carbon cycle models ranges from about 700 ppm to 1100 ppm. Even this wide range does not take into account changes in the carbon cycle that occur as a result of climate change (see Section 7.3). For comparison, the climate modelling used as the basis of this report uses a single carbon dioxide concentration profile for the **Medium-High Emissions** scenario which reaches 820 ppm by 2100.

Although the additional *radiative forcing* produced by increases in greenhouse gas concentrations is reasonably well known (i.e., with small uncertainty), that due to changing aerosol concentrations is very uncertain. In particular, the indirect cooling effect of sulphate aerosols on climate, due to the modification of cloud properties, is poorly known; the Hadley Centre model upon which our scenarios are based gives an estimate for this effect roughly in the middle of the range from a number of models.

The *response of large-scale climate* to a given change in radiative forcing is different for different global models. For example, the global temperature rise from 1990 to 2100 for the SRES A2 emissions scenario is 1.5ºC in the least sensitive model reported in the IPCC Third Assessment Report, but 5.3ºC in the most sensitive. For the HadCM3 model used as the basis of this report, the rise is about 4ºC. The corresponding range for global precipitation change is about 1 to 8 per cent from the least to the most sensitive models; the rise in HadCM3 is 3 per cent. At a regional scale, differences between models are even greater, at least for some variables, as illustrated in Section 3.5. At present we have no agreed way of attaching probabilities to the results from these models, although research to quantify some of these uncertainties and generate probabilistic forecasts is underway and is described in Section 9.2.

This report has made use of the Hadley Centre *regional climate model* to generate descriptions of future UK climate at a 50 km spatial resolution. This regional model is one way of "downscaling" the coarse resolution of the global model to spatial scales more useful for impacts assessments. Although the Hadley Centre model is the only one to have yet been used to make regional simulations over the UK from the SRES emissions scenarios, there are different regional models from other centres which will be used in the future. In addition, a range of alternative statistical methods could be used. Each of these different approaches would yield different results at the local scale, and the uncertainties associated with downscaling have not been systematically assessed. A new European programme, PRUDENCE, will tackle this issue over the next few years. Some further discussion of this point is provided in Sections 7.5 and 7.6.

There is clearly more work to be done in quantifying the various uncertainties associated with future climate and subsequent sections summarise some recent work. The UKCIP02 scenarios do not claim to cover the complete range of uncertainty in future climates; users may wish to use additional climate scenarios if they are undertaking comprehensive studies. The IPCC Data Distribution Centre (Appendix 8) provides a starting point for identifying such additional scenarios.

The UKCIP02 scenarios do not claim to cover the complete range of uncertainty in future climates.

7.2 Emissions uncertainties

All of the published SRES emissions scenarios are termed "non-intervention" scenarios[15], being based solely on different assumptions about population, economic growth and energy futures. The range of their cumulative global carbon emissions from 1990 to 2100 extends from less than 800 GtC to more than 2500 GtC. The emissions scenarios underpinning the **High Emissions** and **Low Emissions** scenarios (SRES A1FI and B1 respectively) clearly span a substantial part of the possible future anthropogenic emissions range (Figure 77). The effect of possible climate policy interventions on these emissions profiles, and hence on climate, is discussed in Chapter 8. The SRES maintains that it is not possible to attach objective probabilities to these different emissions futures, although there are formal subjective methods available to do so. This report does not attempt to employ such methods and simply presents the four scenarios as an indication of the range of possible climate futures.

One of the uncertainties associated with future climate stems from unknown future carbon emissions – our choices about methods of transport, for example, will influence such emissions. © M Robinson.

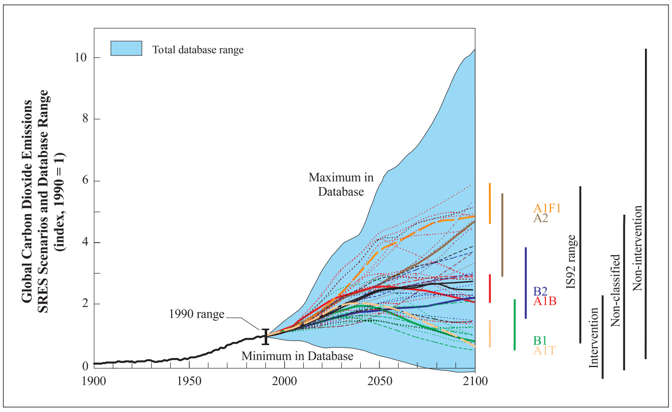

Figure 77: The range of published global carbon emissions scenarios out to 2100 (blue shaded), together with the emissions ranges calculated by the IPCC SRES (coloured bars on right hand side). The emissions used as the basis for the UKCIP02 scenarios are the bold coloured curves for A1FI, A2, B2 and B1; A1T and A1B scenarios are not used in this report. [Source: SRES, 2000]

7.3 Feedbacks from the carbon cycle and atmospheric chemistry

The Hadley Centre climate model used as the basis for the UKCIP02 scenarios, and the other global climate models whose results are shown in Section 3.5, include many interactions between various components of the climate system in the oceans, atmosphere and on land. A version of the Hadley Centre model has been developed which, uniquely, allows the effect of climate change on the carbon cycle, and its feedback into climate, to be included. This model has not been used, however, in deriving the UKCIP02 scenarios presented in this report because this feedback has only recently been included in the climate model for the first time. There remains substantial uncertainties about many of the processes represented.

Results from the model version which includes an interactive carbon cycle show that, as the world warms, microbial activity in soils accelerates and they emit more carbon dioxide. By about the middle of the century, they emit more carbon than they absorb, and hence act as a net source of carbon dioxide rather than (as now) a net sink. The model also shows that in some parts of the world, particularly northern South America, rapid warming and large reductions in rainfall cause existing forests to die back and their carbon is returned to the atmosphere. On the other hand, increases in atmospheric carbon dioxide concentration will fertilise large areas of northern forests and these will grow faster, taking up more carbon dioxide from the atmosphere. The exchange of carbon between atmosphere and ocean is also perturbed by human-induced climate change. The net result of all these interactions between climate and the carbon cycle is a substantial increase in atmospheric carbon dioxide concentrations, reaching 1120 ppm by 2100 for the A2 emissions scenario, compared to 820 ppm when this interaction is not included. The size of global warming by 2100 is also increased, from 4ºC to 5.5ºC. Figure 78 shows the effect that this biospheric feedback might have on UK

(15) Scenarios which do not *include explicit implementation of climate policies such as the UNFCCC or the Kyoto Protocol.*

climate; temperatures by the 2080s under the **Medium-High Emissions** scenario would be more than 2ºC higher than in a simulation with no such feedback (cf. Figure 33).

A further feedback arises when the reactions between chemical species in the atmosphere are modified as climate changes, particularly as the amount of water vapour in the atmosphere increases. Recent work with the Hadley Centre

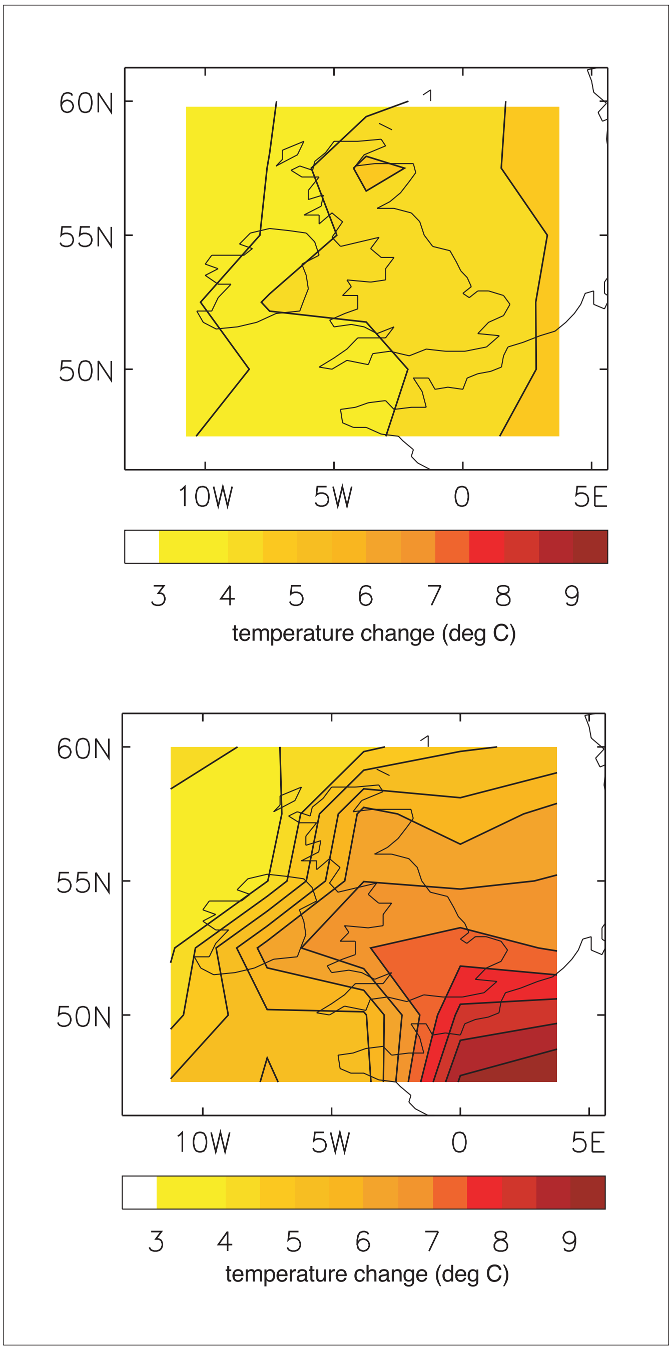

Figure 78: Changes in UK winter (top) and summer (bottom) average temperature (ºC) by the 2080s for versions of the Hadley Centre model with an interactive carbon cycle. The A2 emissions scenario is used in each case.

model shows that global-average concentrations of both methane and ozone will rise less quickly and, because these are important greenhouse gases, this will act to slow climate change – perhaps by a few per cent. The lower concentrations of these species under conditions of climate change are mainly due to the increase in water vapour, which in turn produces more of the oxidants which remove methane. Of course, these climate-induced chemical changes, illustrated in Figure 79, will also be important when estimating how pollution levels over the UK may change through the century.

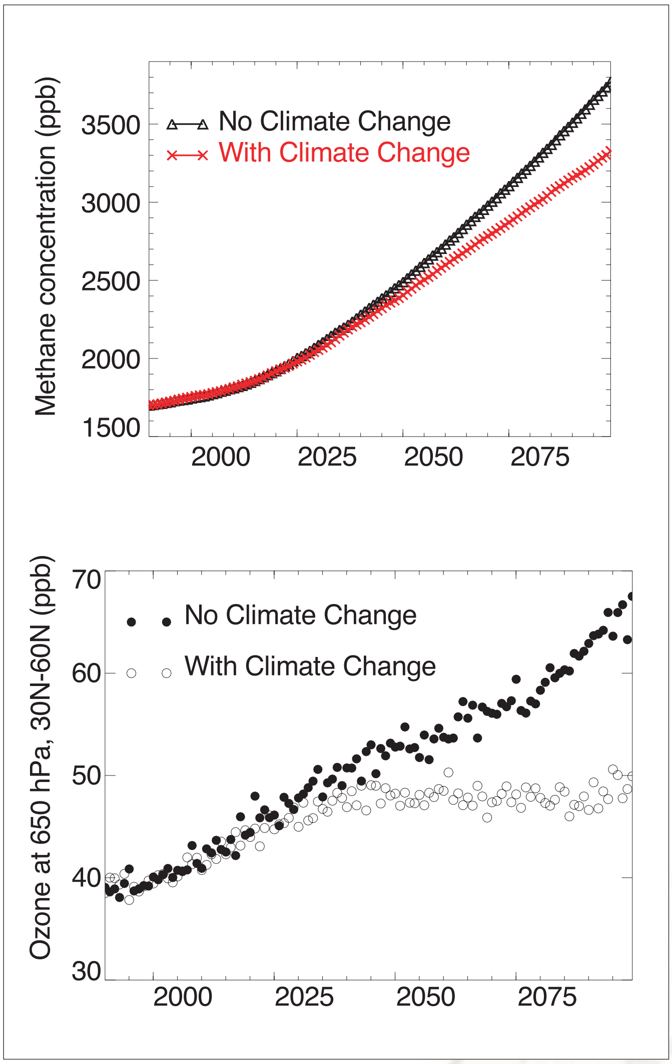

Figure 79: Simulations of the global-average atmospheric concentration of methane (top) and ozone at about 5 km altitude (bottom), calculated from IPCC SRES A2 emissions with and without the feedback from climate change.

The net effect of these two feedbacks – the carbon cycle and atmospheric chemistry - would likely be a larger warming of UK climate. Work continues to improve their representation in climate models, and hence the confidence we may have in the model results, so that these interactive processes can be included in future UKCIP scenarios.

7.4 Uncertainties due to the method of pattern-scaling

The climate change patterns for each time-slice in the **Low Emissions**, **Medium-Low Emissions**, **Medium-High Emissions** and **High Emissions** scenarios are derived from a single master set of patterns. The master set of patterns is the average of results from three climate change simulations made by HadRM3 using the A2 emissions scenario for the period 2071 to 2100. Although the *patterns* associated with each scenario and time-slice are therefore the same, the *magnitudes* are different. In each case the master pattern is multiplied by the amount of global warming experienced at that time and for that scenario, as calculated by the global model (HadCM3; see Table 7 in Chapter 4 for these scaling factors). For the 2080s, for example, if the magnitude of the climate change patterns in the **Medium-High Emissions** scenario is 100 units, the magnitudes of the Low Emissions, **Medium-Low** and **High Emissions** scenarios are about 61, 71, and 118 units respectively.

Scaling climate model results in this way is a convenient solution to the scarcity of model experiments - especially regional climate model experiments - that have sampled the range of climate prediction uncertainties, in particular uncertainties caused by different emissions scenarios. Pattern-scaling methods were originally developed over ten years ago for equilibrium experiments performed with atmosphere-only GCMs. Since then, these methods have become widespread in impact and integrated assessments and have been used with results from coupled ocean-atmosphere global models. Although this method has not been widely applied to results from regional climate model experiments, that is at least partly due to the relative scarcity until recently of such experiments.

All pattern-scaling applications rely on a number of key assumptions:

- the simulated anthropogenic climate change patterns are a function of global temperature;
- the patterns are independent of the history of greenhouse gas forcing;
- the anthropogenic climate change signal can be adequately defined from climate model results.

Assessments of the pattern-scaling technique have concluded that it is reasonable to make these assumptions for the present generation of GCMs. Our brief assessment of the application of the technique to HadRM3 is presented in Figure 80. We compared the average temperature and precipitation changes for the 2080s from the **Medium-Low Emissions** scenario (obtained by scaling the patterns from the HadRM3 A2 simulations by the global warming under the B2 emissions scenario) and a single HadRM3 B2 simulation.

The differences between the **Medium-Low Emissions** and B2 changes are generally small for temperature and in some seasons for precipitation (Figure 80). The B2 winter precipitation change, however, is significantly less than the scaled A2 change over most of England and in autumn the two scenarios contain a different sign of change (albeit of relatively small magnitude) over most of the same region. The differences arise from a combination of the internal variability of the climate system and from errors introduced by pattern-scaling. A larger set of model experiments would be needed to quantify the relative contribution of these two factor to the expressed differences. The latter factor forms an additional source of scientific uncertainty. In the absence of much larger samples of climate model experiments to draw upon - whether global or regional - pattern-scaled climate change scenarios are likely to continue to be widely used in impacts and integrated assessments. It is therefore important to consider, or to assess where possible (for example in the case of the B2 scenario here), this aspect of uncertainty when applying pattern-scaled climate scenarios.

7.5 Uncertainties due to model development

We illustrated in Section 3.5 the different model responses over the UK for a set of global climate models and we emphasised that these differences help us identify the extent of scientific uncertainties on descriptions of future UK climate. The different model patterns included responses from successive versions of the Hadley Centre global model, HadCM2 (ca. 1994-1995; used as the basis of the UKCIP98 scenarios) and HadCM3 (ca. 1999-2000; used as the basis of the UKCIP02 scenarios). Here, we explore the implications of modelling uncertainties for the high resolution versions of these models, HadRM2 and HadRM3. This further illustrates the importance of appreciating scientific uncertainty when interpreting differences between alternative climate change scenarios.

Although the HadRM2 regional model results were not available at the time the UKCIP98 scenarios were prepared, subsequent work translated one of the UKCIP98 scenarios – the Medium-High – into higher resolution results by driving the HadRM2 model with boundary conditions for the 20-year period 2081-2100 from the respective HadCM2 experiment (the IS92a GGa2 simulation). Results from this 50 km simulation were subsequently used in the report for the Scottish Executive, *“An exploration of regional climate scenarios for Scotland”* and, from 2000 onwards, the results have been openly available through the Climate Impacts LINK Project. Here, we contrast the patterns of change in seasonal temperature and precipitation in the HadRM2 and HadRM3 experiments and explore reasons for these differences.

The results of these two experiments are not *precisely* comparable for three reasons. The time periods are slightly different (2081-2100 in HadRM2 versus 2071-2100 in HadRM3); the HadRM2 patterns derive from just one experiment, whereas the HadRM3 patterns are the average of an ensemble of three experiments; and the emissions scenarios used are different. For HadRM2, the emissions scenario was the old IPCC IS92a scenario which results in lower greenhouse gas concentrations by the end of the century compared to the SRES A2 scenario used as the basis of the HadRM3 experiments. Furthermore, no account was taken of the effects of sulphate aerosols in the HadRM2 experiment. Nevertheless, the global-average warming for the period 2081-2100 in the driving global model HadCM2 (about 3.2ºC) was very similar to that for the 2071-2100 period in the driving model for the HadRM3 experiments which used the A2 emissions scenario (about 3.3ºC; cf. Table 3). Despite this similarity in global warming, the patterns of climate change over the UK are very different between these two successive model versions.

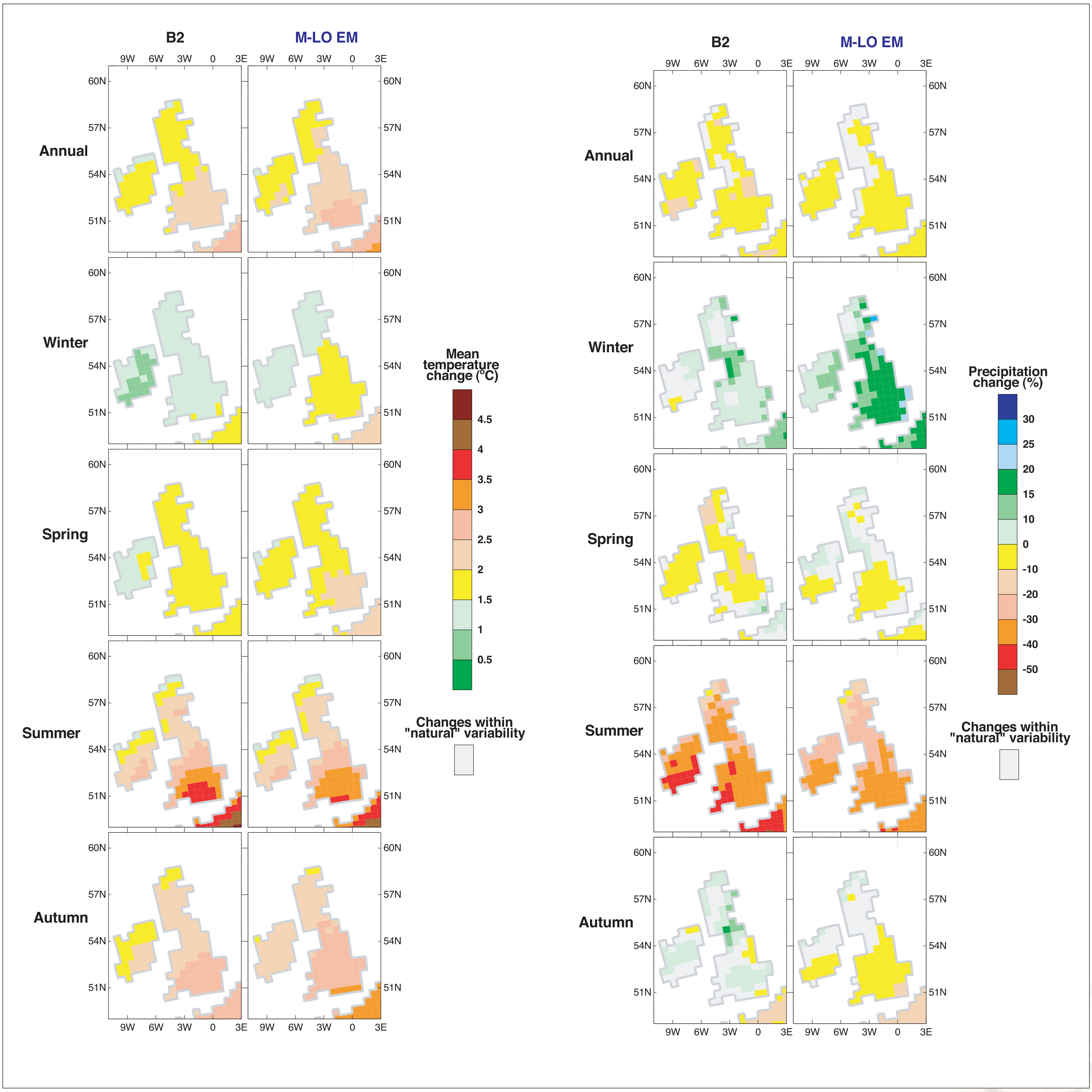

Figure 80: Comparison of 2080s seasonal and annual changes in average temperature (left panel) and precipitation (right panel) obtained directly from a HadRM3 B2 emissions simulation (left columns) and obtained for the Medium-Low Emissions scenario through pattern-scaling the A2 emissions simulations (right columns).

Temperature changes in summer and autumn are quite similar between the model versions (Figure 8, left), but the winter and spring warming in HadRM2 is much larger than in HadRM3 and both these seasons in HadRM2 exhibit secondary warming maxima over Scotland. Precipitation changes between the experiments are even more divergent (Figure 81, right), with only winter showing broadly similar magnitudes and patterns, although even here the north-south gradient of change is more pronounced in HadRM2 than in HadRM3 resulting in a small winter drying over northern Scotland. In the other seasons, both spring and autumn become much wetter in HadRM2 compared to HadRM3, and in summer the severe drying over England in the HadRM3 simulation is moderated in the HadRM2 experiment, while Scotland actually becomes wetter.

Part of these differences might be accounted for by internal climate variability as simulated by the driving global models – in effect we are comparing one 20-year period with three independent 30-year periods and different initial conditions in the model experiments can lead to non-trivial differences in simulated climate change (see Section 7.7). This is very unlikely to explain all of these differences, however, and so plausible explanations for some of these differences can also be inferred from the different simulated changes in mean sea level pressures and associated large-scale flow patterns (Figure 82).

These large-scale circulation changes are very different between models in all seasons and are larger for HadRM2 than HadRM3. In winter, HadRM2 simulates strongly

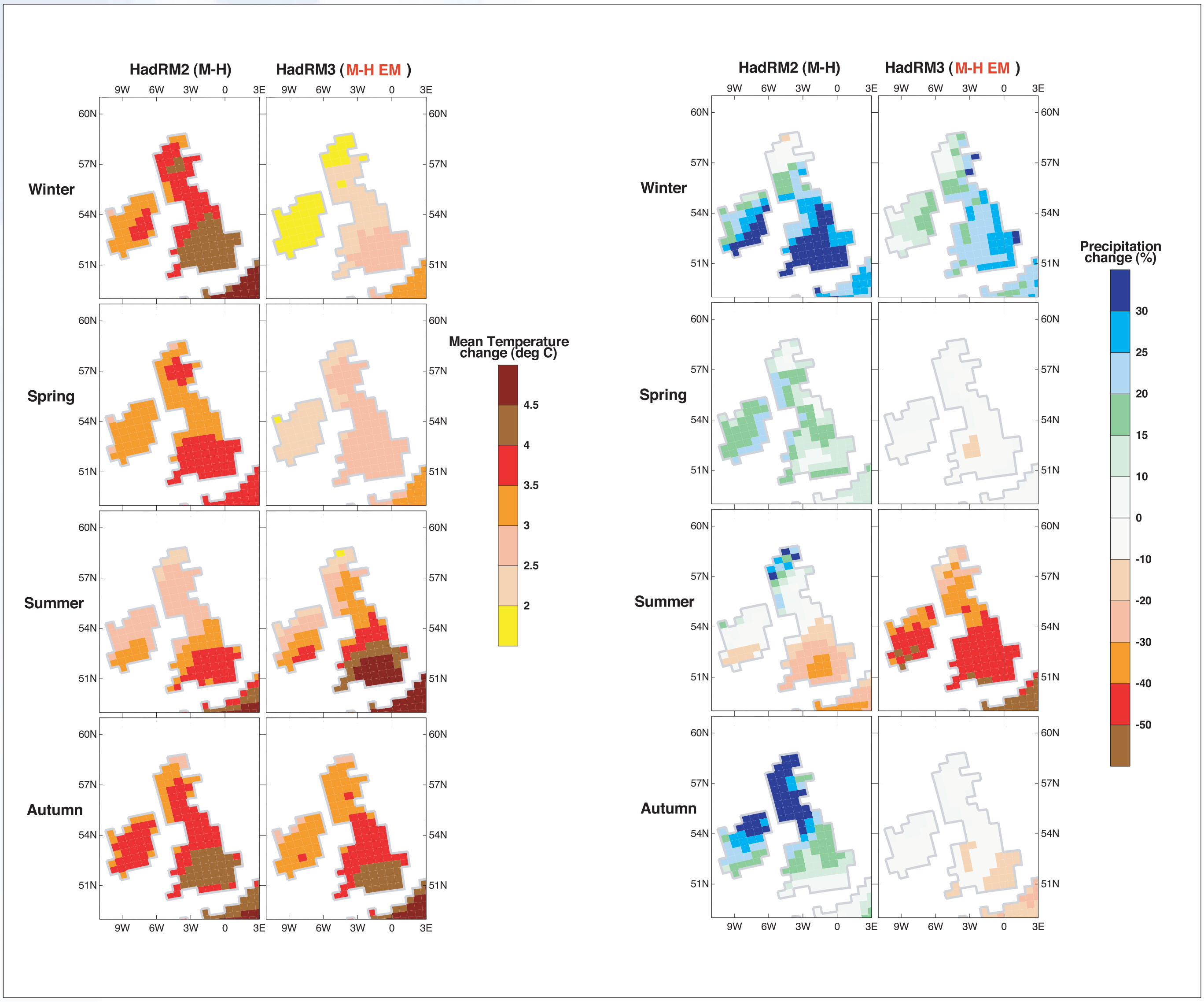

Figure 81: Changes in average seasonal temperature (left panel) and precipitation (right panel) for the 2080s from the old HadRM2 experiment (left columns) and from the three-member ensemble HadRM3 experiment (right columns) used as the basis of the UKCIP02 Medium-High Emissions scenario. See text for further explanation.

increased southerly flow, as opposed to smaller increases in westerlies in the south and reduced south-westerlies in the north simulated in HadRM3. HadRM2 will thus introduce in winter an influx of warm moist air advected into the British Isles not seen in HadRM3, thus contributing to the warmer temperatures and greater precipitation increases in HadRM2 compared to HadRM3 (cf. Figure 81). In summer, in HadRM2 there is a strong increase in north-westerly flow over much of the UK, whereas in HadRM3 this occurs more weakly over Scotland and over southern England is replaced by a weakening of the summer south-westerly flow. These changes in summer circulation contribute to the summer rainfall increases over northwest Scotland in HadRM2 (cf. drying in this region in HadRM3) and the larger warming and drying over southern England in HadRM3 compared to HadRM2. Spring and autumn see enhancements of, respectively, south-westerly and westerly flow in HadRM2 which, compared to the rather weak changes in circulation simulated by HadRM3 for these seasons, contribute to the much larger increases in precipitation in spring and autumn for HadRM2 compared to HadRM3.

These results provide some insight into the importance of scientific uncertainty.

These results provide some insight into the importance of scientific uncertainty for creating regional climate change scenarios. Although many general features of the simulated UK changes are similar between the two models (for example, overall increases in temperature, and wetter winters and drier summers over most of the country) these can be modulated locally and seasonally by the simulated changes in circulation which may vary substantially from model-to-model and, as in this case, from model version to model version. These differences should be appreciated when using the 50 km resolution UKCIP02 scenario data in applications which may be sensitive to the direct or indirect influence of variables whose simulated changes are highly model-dependent, for example atmospheric circulation, as demonstrated here, cloud cover and wind speed (see also Appendix 1 for further guidance).

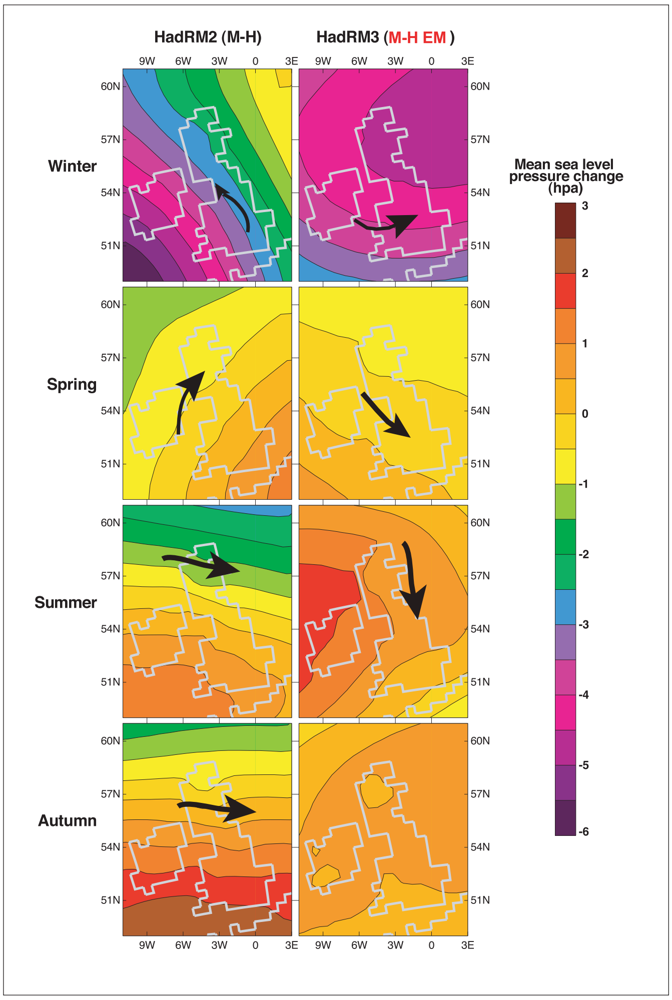

Figure 82: As Figure 81, but for average mean sea level pressure. Arrows show direction of large-scale flow.

7.6 Uncertainties due to changes of scale

Many impact and adaptation studies need climate scenarios at spatial resolutions of less than 100 km. However, most global climate models produce data at 300 – 500 km resolution. Uncertainty hence arises from the need to fill in the missing regional detail. This process is known as "downscaling" and involves accounting for a range of influences on climate at sub-GCM grid-scales arising from the effects of mountains, coastlines, lakes and inland seas, heterogeneity in land surface cover and smaller-scale processes in the atmosphere. The downscaling can be achieved using either dynamical or statistical approaches, or a mixture of the two. Dynamical downscaling involves using a climate model at higher resolution than the GCM, driven by the lower-resolution conditions provided by the global model, as we have done in this report. Alternatively, a statistical downscaling (SDS) approach can be used in which relationships calibrated from observations are used to infer relationships between GCM outputs and local climate. Tools which carry out this process, for example "weather generators", are available in the public domain; see inside back cover for details.

More research is needed to quantify and reduce uncertainties associated with downscaling.

In principle, the uncertainty associated with downscaling can be estimated by applying different methods to the same GCM scenario. Only a few such studies have been published to date, focusing on comparisons between the RCM and SDS approaches. The two methods are found to perform with similar skill in simulating variability within present climate, but produce significant differences in estimates of future changes. These differences can arise from a failure of SDS to account for physical feedbacks which play an important role in climate change, but are excluded from the SDS equations because they are weak predictors of natural variability. However, many RCMs do not supply feedbacks to the parent GCM either. Alternatively, different results can occur because RCMs fail to reproduce the observed inter-variable relationships used to calibrate the SDS equations. A third possibility is that inter-variable relationships simulated by RCMs may change in response to physical climate feedbacks, whereas SDS is based on the assumption that relationships found in present-day climate remain unchanged in future.

More research is needed to quantify and reduce uncertainties associated with downscaling. The future is likely to involve greater use of dynamical techniques as access to RCMs is improved by more widespread availability of suitable computing resources. Nevertheless, there is likely to remain a role for SDS for the foreseeable future because exclusive reliance on dynamical methods is unlikely to cover all applications. For example a mixed dynamical-statistical approach will be appropriate for some applications requiring information below the resolution of RCMs - typically about 50 km at present.

7.7 The effects of natural variability

A further source of uncertainty about defining future climates arises from the effects of natural climate variability. For a given period in the future (for example, 2041-2070) natural variability could conspire to either reinforce the underlying human-induced change (for example an increase in UK winter precipitation could make conditions even wetter), or could counteract it (making the wetting less pronounced). It is therefore important to consider natural variability in studies on impacts of, and adaptation to, climate change. Unfortunately we cannot predict this natural variability of climate deterministically over these long time-scales and are unlikely to be able to do so for some considerable time. It is reasonably straightforward - albeit expensive - to quantify this aspect of future climate by running an ensemble of experiments, each starting at different initial conditions in the ocean-atmosphere system. This method of examining natural variability was used in the UKCIP98 report and is also reported here.

The effects of natural variability become larger as the spatial scale decreases.

The effects on changes in average climate

The effects of natural variability become larger as the spatial scale decreases. We can examine the effects of natural variability on average UK climate in two ways – by examining the differences that exist between the three ensemble members of the model experiments forced with the A2 emissions scenario, and by examining the differences in 30-year average climates simulated in the long "control" (unforced) experiment using the global model. In these analyses we are analysing 30-year average climate variability that results from internal ocean-atmosphere variability; we are not examining the additional natural variability induced by changes in solar or volcanic forcing of the climate system. These analyses therefore probably underestimate slightly the real world natural variability. It should also be noted that these are estimates of natural variability derived from a single climate model – HadCM3 - and not from observations.

We show the effects of natural variability on average UK climate in Figure 83. The intra-ensemble differences indicate the relative contribution of human-induced climate change and natural climate variability to the climate changes presented in this report. Little variation between ensemble members suggests that most of the change is human in origin; large variations between the members suggests natural climate variability dominates. The scatter of the black dots in the Figure show the estimate of variability in UK climate when not influenced at all by human activities. One can see that natural temperature variability is larger in winter than in summer, but that for precipitation the opposite applies. By the 2020s, winter temperature and precipitation changes, and summer precipitation changes, are almost indistinguishable from natural variability. Summer temperatures, on the other hand, are well distinguished from naturally varying climates by the 2020s. By the 2080s, the changes in both variables andseasons are much greater than could be expected from natural variability.

This analysis of natural variability in average 30-year climates has at least two important implications for using climate change scenarios at this regional level. First, the average of the results from analysed ensemble members should be used to give the best estimate of future human-induced climate change, rather than estimates extracted from a single ensemble. Second, even when using ensemble-average changes, a better appreciation of the full range of multi-decadal natural climate variability is warranted before interpreting the impacts of such changes. Failure to appreciate the relative magnitudes involved may cause one to attribute the effects on physical or social systems of *both* human-induced climate change and natural climate variability *as if* they were the effects of human-induced climate change alone.

The effects on changes in transient climate

Natural climate variability is even more important on the time-scale of a year to a decade. We can illustrate this using the England and Wales winter precipitation record. From 1950 to 2000 we plot the observed series (Figure 84), but from 2000 onwards we show the results from the global model for each of the three ensemble experiments based on the SRES A2 emissions (our **Medium-High Emissions** scenario), but starting the historical forcing with different initial conditions.

The three future time series of winter precipitation are very different from year-to-year and from decade-to-decade, indicating that the *precise* evolution of precipitation decade-by-decade over the next 50 years is much more dependent on the forces shaping internal climate variability than on the human forcing of climate. All three simulations nevertheless suggest a long-term trend towards wetter winters. As noted in Chapter 4, there may be periods in the future where records for wetness or dryness are broken every few years, but some periods lasting decades where no new records are established.

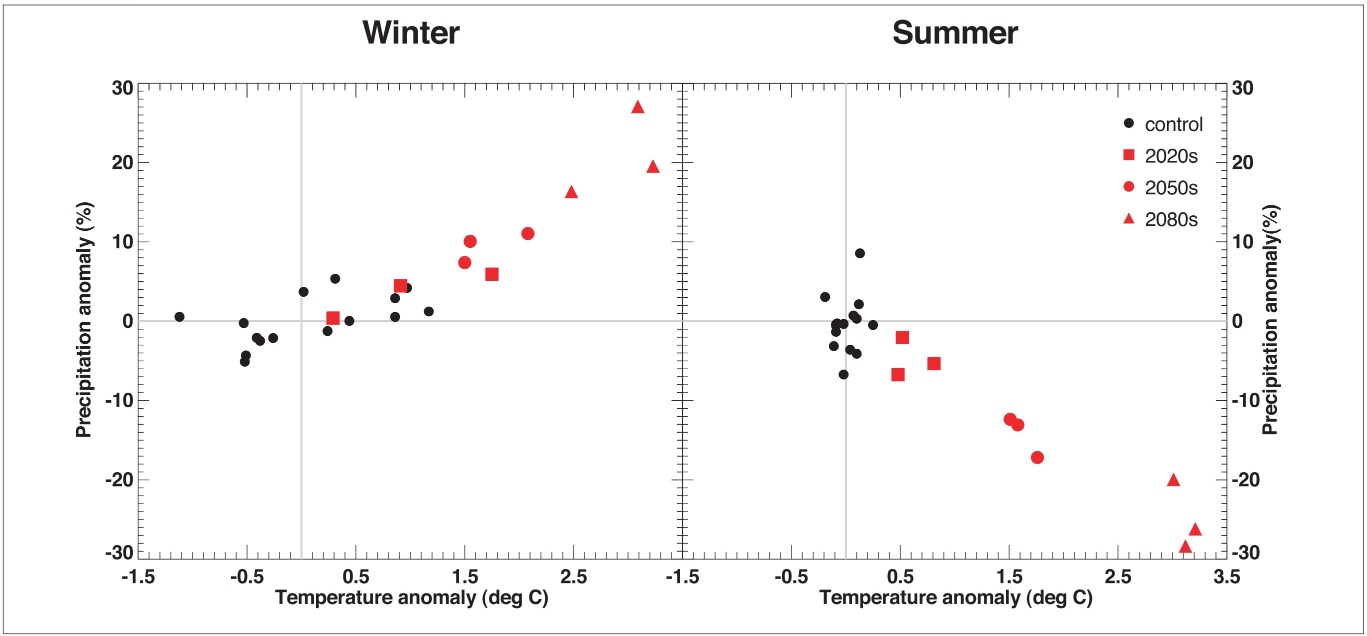

Figure 83: Average 30-year winter and summer climates for the UK land area expressed in terms of average temperature and precipitation. The black dots show climates extracted from the 240-year "control" simulation using HadCM3; these represent naturally varying climates. The red symbols represent climates for three future time periods – the 2020s (squares), 2050s (circles) and 2080s (triangles) – for the Medium-High Emissions scenario. Each circle/square/triangle represents a different ensemble member.

This illustrates the problem - for example for flood defence planners - of adapting to a long-term trend in climate, whilst at the same time managing the substantial, and still largely unpredictable, year-to-year and decade-to-decade natural variability of climate. Although at present we cannot predict precipitation one to ten years ahead, there are encouraging signs that this may soon be possible (see Section 9.7), and this capability may allow this problem to be tackled.

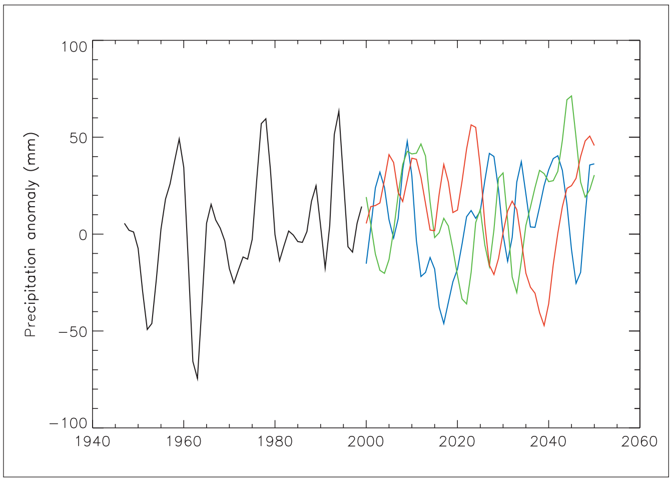

Figure 84: England and Wales winter precipitation: observed for 1950-2000 (black) and three possible future evolutions for 2000-2050 for the UKCIP02 Medium-High Emissions scenario using different initial conditions (colours)

7.8 Possible changes to the Gulf Stream

The climate of the UK is greatly influenced by its proximity to the ocean and, in particular, by the characteristics of the circulation in the Atlantic Ocean. The relative mildness of UK winters is, in part, due to warm water transported to northwest European coasts by the Gulf Stream, and its northeastward extension, the North Atlantic Drift. The Gulf Stream is driven partly by surface wind patterns and partly by differences in density caused by spatial variations in temperature and salinity. The density-driven component is part of a larger ocean circulation, known as the "thermohaline circulation" (THC). Surface water in two areas of the north Atlantic, near Labrador and in the Greenland Sea, is cooled mainly by cold winds from the Arctic, and sinks to the ocean floor (the so-called "deepwater formation"). The cold water then moves equatorward deep in the ocean. To replace the water removed from the north Atlantic by this current, warmer water is drawn up from the Gulf of Mexico, across the North Atlantic, and up to areas west of the UK and northwest Europe. This is a very simplified picture, but it includes the main features.

The formation of deepwater could be reduced by a reduction in the density of north Atlantic surface waters, for example by a large input of fresh water at the surface. If this occurs, it could lead to a reduction, or even a shutdown, of the THC, including the Gulf Stream, with a marked decrease in the warm water transported by the Gulf Stream. It is believed that a modification, or even a shutdown, of the THC occurred around 11 200 years ago at the end of the last Ice Age, when temperatures in northwest Europe may well have cooled by 5ºC within only a few decades. This was caused by a sudden discharge of fresh water from the melting of a large ice sheet over North America, resulting in a cool period, the Younger Dryas, which persisted for over 1000 years. Currently, the Greenland ice sheet is more stable and a repeat performance is unlikely to recur in the short-to-medium term. Freshwater input, however, could also come from melting sea ice, and from increased precipitation over the deepwater formation areas, which may be outcomes of human-induced climate change.

Have we any recent evidence that the thermohaline circulation is weakening? The main source of cold dense water for the THC is the Greenland-Norwegian seas, from where it flows over the under-water ridge that lies between Scotland and Greenland. The Faeroe Bank channel is the deepest pass through the ridge and a third of the total overflow into the North Atlantic passes through this channel. Not only has this overflow become warmer and less salty over time, but the volume passing through the Faeroe Bank channel is estimated to have decreased by at least 20 per cent (about 0.5 Sverdrups) since 1950.

New observations of the flux of very cold water, which amounts to two-thirds of the total flux through the channel, show the recent trend (Figure 85). If this diminishing source of North Atlantic deepwater has not been compensated by an increased flow through the Denmark Strait - between Iceland and Greenland - or from sources in the Labrador Sea, the consequence must be a weakening of the global thermohaline circulation. We do not yet know for sure whether this compensating flow has occurred.

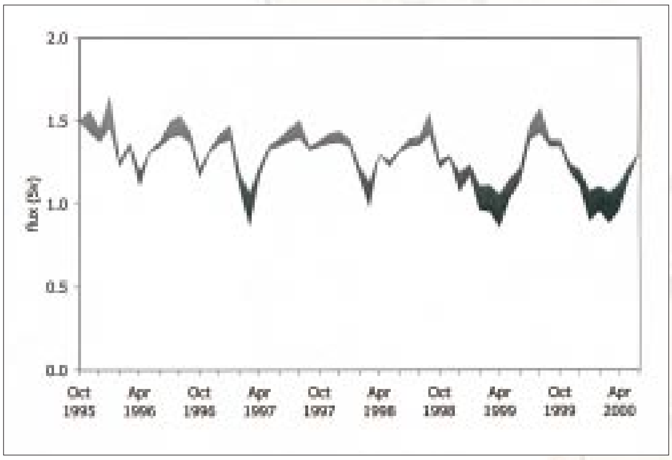

Figure 85: The flux of very cool water (less than 0.3°C) through the Faeroe Bank Channel from November 1995 to June 2000 (in Sverdrups, where 1Sv = $1x10^6$ cubic metres of water per second). The shaded range of the curve is an indication of the uncertainty in the observations. [Source: Bill Turrell].

What does the climate model predict for the future of the North Atlantic thermohaline circulation? When the model is run with no human influences on climate, the THC exhibits no long-term trend although it is variable from decade-to-decade (cf. 'control', Figure 86). When greenhouse gas concentrations are increased, it steadily decreases under all the four UKCIP02 scenarios, declining by about 25 per cent by 2100. A shut-down of the THC is therefore *not* predicted by

HadCM3 over the next century, although further analysis shows that one of the two deepwater formation areas - that near Labrador - does appear to cease operating.

The Hadley Centre model's ocean resolution is better than in most climate models and its simulation of current ocean circulation is good. Results of similar experiments - albeit using an earlier emissions scenario - using other climate models have been compared by the IPCC. They find that most models do indeed show a weakening of the THC, but no model shows a shut-down by 2100. Nevertheless, the IPCC also point out that a weakened THC appears to be less stable and under these conditions a future shut-down might therefore become more likely. Note that, although even a reduced THC means that the Gulf Stream brings less heat to the UK, increased greenhouse gas heating greatly exceeds this cooling effect; for example, all of the average seasonal temperature changes shown in Chapter 4 for the four UKCIP02 scenarios indicate a warming of UK climate, and not a cooling. It must be emphasised that all the results presented in Chapters 4, 5 and 6 include the effect of the weakening THC. In the terms of the relative confidence levels introduced in Chapter 1, we state with medium-to-high confidence that although the strength of the Gulf Stream may weaken in the next 100 years, it is unlikely that this would lead to a cooling of UK climate over this time-scale.

Although the strength of the Gulf Stream may weaken in the next 100 years, it is unlikely that this would lead to a cooling of UK climate over this time-scale.

Understanding the behaviour of the thermohaline circulation is nevertheless an active area of research, both in the UK and abroad. For example, a new six-year thematic research programme on rapid climate change and the North Atlantic has just been launched in the UK by the Natural Environment Research Council.

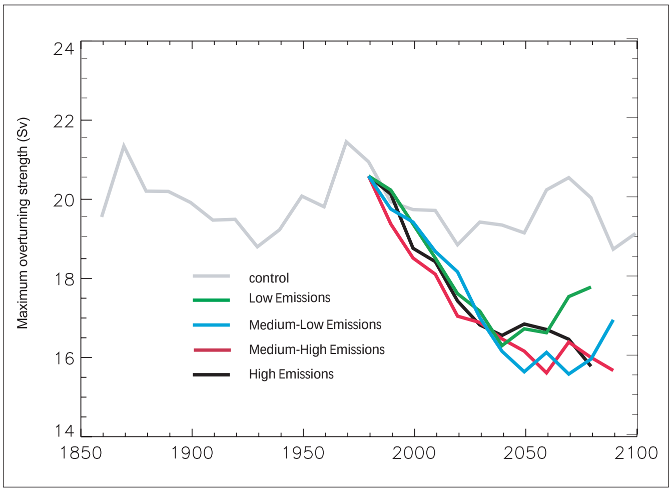

Figure 86: The strength of the North Atlantic thermohaline circulation (in Sverdrups, where 1Sv = $1x10^6$ cubic metres of water per second): grey = no change in greenhouse gases; colours = with observed changes in greenhouse gases to 1990, and thereafter for the four SRES emissions scenarios as shown.

Chapter 8: Mitigation Scenarios

8.1 Introduction

The UKCIP02 climate change scenarios are based on a range of emissions scenarios which in turn result from different descriptions of how the world might develop during the century to come – the so-called SRES storylines (see Appendix 5). None of these descriptions of the future includes reductions in greenhouse gas emissions achieved as a consequence of specific climate protection policies or measures. The differences in emissions between scenarios result solely from different assumptions about rates of economic and population growth, and about changes in energy consumption and the carbon intensity of the energy system.

How might the descriptions of future UK climate presented in this Report be different if specific mitigation measures were implemented worldwide? We know, for example, that progress is being made on the design and implementation of the Kyoto Protocol, which seeks specific emissions reductions by developed countries by the time of the first commitment period of 2008-2012, with aspirations for further reductions thereafter.

The direct effect on global climate of full implementation of the first commitment period obligations of the Kyoto Protocol will be small.

8.2 The Kyoto Protocol

The direct effect on global climate, and hence on regional UK climate, of full implementation of the first commitment period obligations of the Kyoto Protocol on its own will be small. If there were no further emissions reduction targets negotiated for subsequent commitment periods the effect of the Protocol on global temperature by the year 2100 would be a reduction of only 0.2ºC at the very most. This gain is modest for three reasons. First, only developed countries currently have reduction targets for the first commitment period of the Protocol. Second, even for these developed countries, the stated emissions reductions under the existing terms of the Protocol are relatively small – a net reduction of about 5 per cent below 1990 levels[16]. Third, the inertia within the climate system means that, in any case, we are committed to a significant amount of future climate change as a consequence of past and current emissions.

The importance of the Kyoto Protocol for controlling rates of future climate change, however, should be viewed in other ways. Commitment to achieve the initial goals of the Protocol by the period 2008-2012 is likely to have two further beneficial, but as yet impossible to quantify, effects on global climate. First, the implementation of the Protocol as specified *now* will make it much more likely that emissions reduction targets for later commitment periods will be negotiated and implemented. These later emissions reduction commitments may be larger and/or involve a wider group of countries and hence offer the prospect of achieving even larger global emissions reductions. Second, notwithstanding the success or otherwise of these later commitments under the Protocol, the global framework agreed at the recent Conferences of the Parties to the UN Framework Convention on Climate Change (COP6.5 and COP7) for achieving emissions reductions by 2008-2012 can only increase the chances of the relatively low emission SRES B1 or SRES B2-type worlds occurring. In other words, if we were discussing the UKCIP02 scenarios in probabilistic terms (cf. Box E, p18), then it would be true to say that the ratification of the Kyoto Protocol would tend to make the **Low Emissions** and **Medium-Low Emissions** climate scenarios rather *more* likely than if no ratification occurred – but of course we cannot say how much more likely.

8.3 Stabilisation of greenhouse gas concentrations

Another approach to considering the effects of mitigation policies on future climate is to consider the effect of stabilising concentrations of carbon dioxide and other greenhouse gases in the atmosphere. Climate would in fact continue to warm for several decades beyond such a stabilisation date before eventually warming no further, yet sea level would continue to rise for several centuries or more (see Section 6.2). Two stabilisation targets often cited are atmospheric carbon dioxide concentrations of 550 parts per million (ppm; about twice the pre-industrial concentration) and 750 ppm (about twice today's concentration).

Responding effectively to climate change will involve many areas of life.
© M Robinson.

Our understanding of the carbon cycle tells us that, in order to stabilise concentrations at either of these levels, global carbon

(16) The current operation of the Protocol, after the COP7 negotiations at Marrakesh, will result in a reduction of less than 2 per cent in actual emissions from 1990 levels, owing to flexible mechanisms and the exclusion of the USA.

emissions would eventually have to be reduced by some 60-70 per cent relative to 1990 levels. There is no unique emissions pathway to achieve these magnitudes of reduction and the rapidity of the reductions required depends both on the stabilisation level and on the eventual date by which stabilisation should be achieved. Nevertheless, the IPCC have shown indicative profiles of global carbon emissions over the next 250 years which could result in eventual stabilisation at these two carbon dioxide concentration levels.

The climate effects of these two emissions profiles were explored using the second generation Hadley Centre model (HadCM2). In these experiments, stabilisation of carbon dioxide concentrations at 550 ppm and 750 ppm was achieved, respectively, by about the years 2150 and 2250. The increase in global-average temperature relative to the present-day (1961-1990) was limited eventually to about 2ºC under the 550 ppm stabilisation pathway, and to about 3ºC under the 750 ppm pathway. Regional changes in climate occurred more slowly than under the respective non-mitigation scenario, which in this case was IS92a (i.e., the UKCIP98 Medium-High scenario), an emissions scenario somewhere between SRES B2 and A2 from which we derive our UKCIP02 **Medium-Low Emissions** and **Medium-High Emissions** scenarios. Figure 87 shows that, in this example, warming over the UK by the 2080s reaches between 2º and 3ºC in the unmitigated case (UKCIP98 Medium-High scenario), compared to about 1.5º to 2ºC with emissions leading to 750 ppm stabilisation and compared to only about 1º to 1.5ºC with emissions leading to an eventual stabilisation at 550 ppm.

This illustrates that stabilisation of greenhouse gas concentrations, resulting from mitigation measures, *will* lead to reductions in regional UK climate change relative to scenarios in which no mitigation measures were implemented. The size of these reductions in the rate and magnitude of climate change depends both on the stabilisation concentration and its timing, and also on the unmitigated scenario against which we are comparing it. In fact, if we compare a 550 ppm stabilisation scenario against our UKCIP02 **Low Emissions** scenario then the changes in climate occurring by the 2080s are almost the same (although we cannot here compare the effects of these two scenarios on climate beyond 2100). This similarity in climate change out to 2100 occurs because it matters little to the climate system how this 550 ppm carbon dioxide concentration is achieved. It could equally occur as a result of a B1-type world (the basis of our UKCIP02 **Low Emissions** scenario, which yields about 540 ppm by 2100; see Figure 20) in which *no* deliberate mitigation measures are implemented, or as a result of, say, an SRES A2-type world (the basis of our UKCIP02 **Medium-High Emissions** scenario) in which specific mitigation measures that lead to a 550 ppm carbon dioxide concentration by the end of the century *are* implemented.

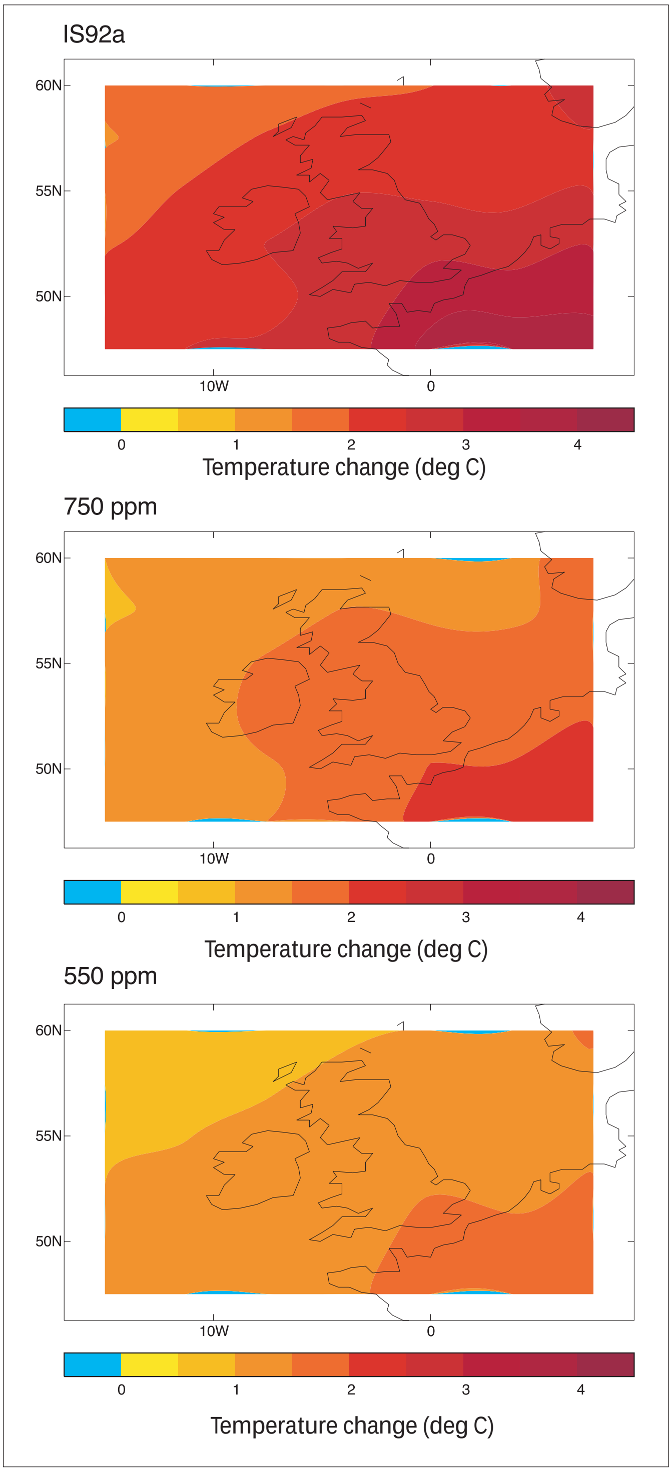

Figure 87: Average annual temperature rise (degC) over the British Isles by the 2080s, relative to the 1961-1990 average, for: IS92a emissions (top; UKCIP98 Medium-High scenario); emissions designed to ultimately stabilise carbon dioxide concentrations at 750 ppm (middle); and emissions designed to stabilise concentrations at 550 ppm (bottom). All results are from HadCM2 global climate model.

Chapter 9: Further Work and Developments in Research

9.1 Additional data analyses from HadRM3 experiments

This report describes changes in average seasonal climate and shows changes in the distributions of daily-average weather quantities such as temperature, precipitation and wind speed. Daily averages for a number of other quantities are also available for the HadRM3 experiments - three simulations of 1961-1990 climate and four simulations of 2071-2100 climate, three assuming the SRES A2 emissions (our **Medium-High Emissions** scenario) and one assuming the SRES B2 emissions (our **Medium-Low Emissions** scenario). These daily data can be obtained from the Climate Impacts LINK Project web site (see inside back cover), although many of the data remain to be fully analysed.

Sub-daily averages

The time-step used in the regional climate model is 5 minutes. In principle, data could have been saved and archived at this rate, but the amount of storage required would have been too great. For some periods and quantities, however, data has been saved at hourly intervals. These simulated data have not yet been validated against observations to assess their credibility on time-scales of say, 6 hours, 3 hours or even 1 hour. If such data validate well then studies could be carried out to reveal simulated changes in very short (hourly) time-scale weather extremes.

Derived quantities

There are often requirements for changes in meteorological quantities which are not calculated directly by the model. A few such examples – lightning, fog, storm-tracks, etc. - have been shown in this report, but there are a number of others – for example hail or temperature inversions - which could be generated from the model data using algorithms derived, for example, from weather forecasting.

Spatial downscaling

Although the spatial resolution of the scenarios presented in this report is the highest that has currently been produced, we have also interpolated the 50 km climate change monthly data onto the observed 5 km climate data set as described in Appendix 7. These 5 km data files are available through the UKCIP02 website. Note that this is not downscaling in the precise sense of the word, since the climate *change* information is still resolved only at 50 km resolution. While this simple approach may be sufficient for some applications, some studies require descriptions of future climate that include representations of daily weather, or that need to be at finer, or irregular, spatial scales - for example a small river catchment of, say, 5 km^2, or for individual point locations. In such cases, statistical downscaling techniques at present are the only option to translate model-simulated daily data on the 50 km grid down to finer resolutions. Some downscaling techniques can also be used in conjunction with weather generators (see below).

Weather generators

The daily data generated by the HadRM3 model represent simulated daily "weather" on a 50 km grid, rather than the conventional description of weather as observed at a specific meteorological station. Daily weather data from the regional model will therefore possess different statistical properties from an observed weather series, even if the model simulation were "perfect". Caution needs to be exercised therefore before using simulated daily weather from HadRM3 experiments directly in environmental simulation models or as the basis for engineering design. In most cases, further manipulation of the 50 km HadRM3 data may be necessary to derive sufficient approximations to observed daily weather for such applications.

> *Weather generators can produce surrogate daily weather sequences over a large number of years representing future climate at a point location.*

One approach to such manipulation uses changes in the *distribution* of model-simulated quantities (for example daily maximum temperature mean and variance) as input, along with observed daily data, to a stochastic weather generator. The weather generator would then be able to produce surrogate daily weather sequences over a large number of years representing future climate at a point location. Such surrogate weather sequences may then be used more appropriately with environmental simulation models. Two examples of public-domain weather generators (the LARS Generator and the Statistical Down-Scaling Model), which may be used in conjunction with Hadley Centre model output, can be found at web sites listed on the inside back cover. Weather generators have certain limitations of course, such as their inability to always adequately reflect inter-decadal climate variability, and they are also based on the assumption that the relationship between large-scale circulation and local weather remains the same in the future as it has been over the period of historical measurements.

Unique local factors

Each of the 50 km grid boxes in HadRM3 uses characteristics appropriate to the average terrain being represented. There will often be small areas within a grid box which have quite different characteristics from the average and for which the grid box data will not be representative. An example would be for a large city, where changes (for example in night minimum temperatures because of the "heat island" effect) in climate may be quite different to the surrounding countryside. To create climate change scenarios that represent the effects of cities, small lakes and mountains, etc., would require specific scenarios to be developed using more complex methods. It would also ideally require a fully integrated land use model that would allow land surface characteristics to alter as land use changed, either as a result of the change in climate or as a result of human developments.

9.2 Probabilistic predictions of future climate

Considerable efforts are being made to reduce the uncertainty in descriptions of future climates, for example by building better climate models, as described below. These scientific uncertainties can never be completely eliminated, however, and uncertainties associated with future emissions will likely remain irreducible (see below). It is important therefore to quantify as best we can the uncertainties that remain, opening up the possibility for probabilistic predictions of future climate that can be used in risk assessment and risk management.

Work already published by Hadley Centre and the University of Oxford evaluated the performance of the climate model in simulating climate change over the last 100 years, and applied the uncertainties arising from this evaluation to model simulations over the next 50 years. This method assumed that the errors are approximately linear; however this becomes less likely as the simulation extends beyond a few decades. The method is also more suited to looking at uncertainties in global quantities – such as global-average temperature – rather than those that affect climate change simulations at smaller scales. In principle, however, these techniques can be applied to regional quantities and this work is now beginning.

Uncertainties in model simulations arise because of the way processes in the atmosphere, ocean and over land are represented in the model. These parameterisations are derived from experimental measurements - for example of cloud properties - but these measurements themselves are subject to a range of uncertainty. One technique to be used by the Hadley Centre in the future to quantify uncertainty is to build a large number of different climate models, each using a different, but plausible, representation of a number of climate processes. Each of these models will then be used to make a climate prediction for a given emissions scenario. Using, say, two different representations for each of the ten most important representations in the model at the same time will effectively generate 1024 (2^{10}) different climate models, and hence 1024 different predictions. Simulated climate from each of these models will be compared against observed climate for a recent period, say 1950 to 2000, and the models which do not validate acceptably will be rejected. From experiments such as these, it should be possible to express the predictions of a required climate quantity for a given emissions scenario in probability form. It would then be possible to make statements such as 'if emissions grow at X per cent per year, the probability of England and Wales winter precipitation increasing by 20 per cent by 2050 is Y per cent', or 'the probability of North Sea sea-level rise exceeding 50cm by 2100 is Z per cent' (see the hypothetical example in Figure 88).

It should be possible to express the predictions of a required climate quantity for a given emissions scenario in probability form.

Ultimately, probability-type predictions can also be extended to the regional climate model. As a starting point for this work, in a collaborative project called PRUDENCE (part-funded by the EU) a number of European regional climate models will be driven using the same output from the HadCM3 global model. This will enable the range of uncertainty generated by different regional downscaling methods to be examined and quantified. Similar regional climate model inter-comparisons are also being planned for other parts of the world.

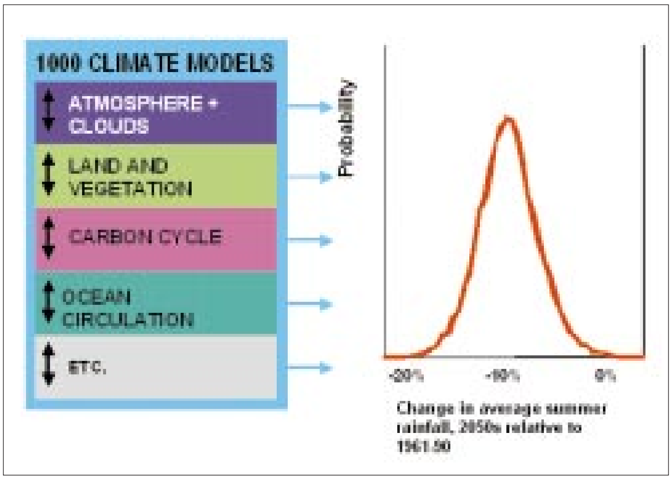

Figure 88: A schematic diagram showing how the most important representations in the climate model will be varied between plausible limits to create a large number of climate models, which will then be used to generate a probabilistic prediction of climate change. The hypothetical example shown in this Figure is for change in summer rainfall.

9.3 Emissions scenarios

Even if the above developments using climate models are successful, *fully* probabilistic and unconditional statements about future climate will only be achievable if efforts are made to develop probabilistic descriptions of future greenhouse gas emissions - and other human or natural forcing of the climate system. This may well prove an insurmountable task. Future greenhouse gas emissions are intimately tied to developments in energy technology, demography, geo-politics, lifestyle choices and changes in cultural values. None of these factors is predictable in any deterministic way, although some progress is being made in developing stochastic predictions of future changes in global population. Unknown future emissions may therefore remain an irreducible uncertainty affecting climate predictions. As mentioned earlier, however, the change in climate out to around the 2030s is broadly similar for all four SRES emissions scenarios; at least over this period of time climate change descriptions are not particularly sensitive to this source of uncertainty.

Unknown future emissions may remain an irreducible uncertainty affecting climate predictions.

The SRES emissions scenarios used as the basis for this report are unlikely to be updated or replaced by a similar comprehensive study by the IPCC for some time to come. Other emissions scenarios will continue to be generated by a variety of organisations using different assumptions about the future. For example, in 2001 Shell International published two alternative world energy scenarios that described two different pathways to 2050, both of which resulted in carbon dioxide concentrations of about 550 ppm by 2050. Few of these new scenarios, however, including the Shell ones, are likely to fall significantly outside the range of emissions quantified in the SRES report – the B1 and A1FI marker emissions scenarios used here were designed deliberately by the SRES team to span a large portion of the viable range of future greenhouse gas emissions out to 2100. The choice of emissions scenarios on which to base a set of climate scenarios is likely to remain a matter of judgement, and hence a contentious process for the foreseeable future.

9.4 Development of the Hadley Centre global environmental model

Development of the next generation climate model, known as the Hadley Centre global environmental model (HadGEM), is underway. This model will have latitude and longitude resolutions in the atmosphere twice those of the HadCM3 model used as the basis for the UKCIP02 scenarios and will slice the atmosphere into twice as many layers. Both these improvements will allow a number of physical processes (for example boundary layer clouds and convection) to be represented more explicitly in the model. The ocean model will also be improved with 40 levels and a resolution of 1º by 1º latitude/longitude. HadGEM will require about ten times the computing power required by HadCM3 and could generate up to eight times the volume of data. The model will represent climate processes in the atmosphere, ocean and land more comprehensively than HadCM3. It will also be able to include - as options - the carbon-cycle and atmospheric chemistry feedbacks referred to in Section 7.3, and other biogeochemical feedbacks (for example methane emissions from permafrost and hydrates and sulphur emissions from the oceans) when credible representations become available. Climate change estimates made using this model will still, of course, be dependent on future greenhouse gas emissions scenarios (as described above).

9.5 An improved UK regional climate model

The 50 km Hadley Centre regional climate model used in this report (HadRM3) will shortly be run in combination with regions of improved (25 km) resolution for some UK islands too small to be resolved at 50 km. The next generation of the atmospheric regional climate model – HadRAM1 - will be based on the improved global model, HadGEM1. HadRAM1 will have a spatial resolution of 10 km and be "double nested". This means that it will be driven by output from the 50 km regional model which is itself driven by output from the global model. The 50 km version of the model will also be improved to include an ocean component, i.e., it will be a coupled atmosphere-ocean regional model (denoted HadCRM1). It will also benefit from new scientific understanding assembled as part of the IPCC Fourth Assessment due in 2007 and, possibly, from any new emissions scenarios (but see above). The aim is to use HadRAM1 as the basis for the next UKCIP climate scenarios tentatively scheduled for 2006.

9.6 Marine climate change scenarios

This UKCIP02 report concentrates mainly on climate change over land (although see Chapter 6). It is intended that a separate report *"Marine climate change scenarios for the UK"* will be published in due course. This will include more information about changes in sea-surface temperatures, sea-level rise and storm surges, building on what is already included in this report. It will also deal with changes in wave climate and model changes to the shelf-seas around the UK, for example changes in salinity, temperature and currents from the ocean surface to the ocean floor. These scenarios will be aimed at users such as fisheries, offshore operators, sea-bed cable operators, marine biologists, conservationists and coastal engineers and managers. In each case, separate wave and shelf-seas models (already in use operationally) will be driven by data from the regional climate model.

9.7 Decadal climate forecasting

Even in the absence of any human perturbation of the climate system, or in changes to external forcing agents such as the sun or volcanic "dust", climatic conditions vary from year-to-year and from decade-to-decade. This variability (or "chaos") is caused by natural internal fluctuations in the climate system, mainly due to the interaction between ocean and atmosphere, and is simulated, albeit imperfectly, by climate models. To ensure that climate change scenarios are describing human-induced climate change more than they are representing the effects of natural climate variability, model results are usually averaged over a long period - 30 years in this report - and where possible averaged over an ensemble of simulations.

Until recently, it was thought that the variability of the climate system over a period of 1-10 years (known as "decadal variability") was random and unpredictable. Research, however, has shown the potential for predictability over this time period. Analysis of observations of sea-surface temperatures (SSTs) have identified modes in the ocean which retain their identity for a decade or more while they are transported, for example, from the east coast of America to Scotland. If climate models can forecast SSTs successfully, then the well-established links between SST and aspects of UK climate - for example the warmth or wetness of winters - could lead to predictability at time-scales from a season to perhaps a few years ahead.

Progress has been made in a Hadley Centre project, and elsewhere, to provide such predictions on an operational basis. It is now possible to assimilate ocean and atmospheric observations into the model in order to provide initial conditions for worldwide climate forecasts. The skill of the forecasts will not always be high and will also vary from place-to-place. There is already evidence, however, that predictability beyond the seasonal time-scale will sometimes be possible. The typical level of skill in such predictions - and its variability - is currently being assessed, following which it is planned to produce experimental forecasts for the first decade of the twenty-first century. Prospects for future improvements in skill, arising from improved ocean observing networks and better climate models, will also be investigated.

There is evidence that predictability beyond the seasonal time-scale will sometimes be possible.

If further research demonstrates that broad changes in climate - such as the run of mild winters in the late 1980s/early 1990s - are predictable in this sense, then the availability of this sort of forecast could be of considerable benefit. Not only would it allow medium-term adjustments to operational planning, but it would also allow longer-term strategic planning, in anticipation of larger climate changes in the future due to human-induced global warming, to be designed more robustly. For example, it would be useful for a water company to know in 2010 that, despite a scenario of *reduced* precipitation over southern UK for the middle of the century, three or four years in the middle of the 2010s decade might actually experience *greater* than average amounts of precipitation. Research at the Hadley Centre and at various UK universities, through the Coupled Ocean Atmosphere Processes and European Climate (COAPEC) Programme of the Natural Environment Research Council and other initiatives, is aimed at demonstrating this potential and realising it on an operational basis.

Bibliography and Literature Sources

Alcock, G., Rickards, L. [eds.] (2001) Climate of UK waters at the millennium: status and trends. IACMST Information Document No.9, SOC, Southampton, 48pp.

Collins, M., Tett, S.F.B., Cooper, C. (2001) The internal climate variability of HadCM3, a version of the Hadley Centre coupled model without flux adjustment. Climate Dynamics 17: 61-81.

Durman, C.F., Gregory, J.M., Hassell, D.C., Jones, R.G., Murphy, J.M. (2001) A comparison of extreme European daily precipitation simulated by a global and regional climate model for present and future climates. Quart. J. Royal Meteor. Soc. 127: 1005-1015.

Flather, R., Baker, T., Woodworth, P., Vassie, I., Blackman, D. (2001) Integrated effects of climate change on coastal extreme sea levels Unpublished POL Internal Document No. 140, Proudman Oceanographic Laboratory, Bidston, UK.

Hansen, B., Turrell, W. R., Østerhus, S. (2001) Decreasing overflow from the Nordic seas into the Atlantic Ocean through the Faroe Bank channel since 1950. Nature 411: 927-930.

Harrison, J., Winterbottom, S., Johnson, R. (2001) Climate change and changing snowfall patterns in Scotland. Scottish Executive Central Research Unit Report, Edinburgh, 60pp.

Hulme, M., Jenkins, G.J. (1998) Climate change scenarios for the UK: scientific report. UKCIP Technical Report No. 1, Climatic Research Unit, Norwich, UK, 80pp.

Hulme, M., Lu, X., Crossley, J. (2001) An exploration of regional climate change scenarios for Scotland. Scottish Executive Central Research Unit, Edinburgh, 50pp.

IPCC (2000) Special report on emissions scenarios (SRES): A special report of Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, 599pp.

IPCC (2001) Climate change 2001: the scientific basis. Cambridge University Press, Cambridge, UK, 881pp.

JERICHO (1999) JERICHO: Joint evaluation of remote sensing information for coastal and harbour organisations. Final report. [authors] Cotton, P.D., Carter, D.J.T., Allan, T.D., Challenor, P.G., Woolf, D., Wolf, J., Hargreaves, J.C., Flather, R.A., Bin, L., Holden, N., Palmer, B. BNSC Earth Observation LINK Programme, UK.

Johns, T.C., Ingram, W.J., Johnson, C.E., Jones, A., Mitchell, J.F.B., Roberts, D.L., Sexton, D.M.H., Stevenson, D.S., Tett, S.F.B., Woodage, M.J. (2001) Anthropogenic climate change for 1860 to 2100 simulated with the HadCM3 model under updated emissions scenarios. Hadley Centre Technical Note 22, being revised for publication.

Jones, P.D., New, M., Parker, D.E., Martin, S., Rigor, I.G. (1999) Surface air temperature and its changes over the past 150 years. Reviews Geophysics 37: 173-199.

Jones, P.D., Reid, P.A. (2001) Assessing future changes in extreme precipitation over Britain using regional climate model integrations. Int. J. Climatol. 21: 1337-1356.

Levermore, G. (2000) Building energy management systems: applications to low-energy HVAC and natural ventilation control, 2nd ed., E & FN Spon, 519pp.

Lowe, J.A., Gregory, J.M., Flather, R.A. (2001) Changes in the occurrence of storm surges around the United Kingdom under a future climate scenario using a dynamic storm surge model driven by the Hadley Centre climate models. Climate Dynamics 18: 179-188.

Mitchell, J.F.B., Johns, T.C., Eagles, M., Ingram, W.J., Davis, R.A. (1999) Towards the construction of climate change scenarios. Climatic Change 41: 547-581.

Murphy, J.M. (2000) Predictions of climate change over Europe using statistical and dynamical downscaling techniques. Int. J. Climatol. 20: 489-501.

Osborn, T.J., Hulme, M., Jones, P.D., Basnett, T.A. (2000) Observed trends in the daily intensity of United Kingdom precipitation. Int. J. Climatol. 20: 347-364.

Parker, D.E., Folland, C.K., Jackson, M. (1995) Marine surface temperature: observed variations and data requirements. Climatic Change 31: 559-600.

Shennan, I. (1989) Holocene crustal movements and sea-level changes in Great Britain. J. Quaternary Science 4: 77-89. [an updated version of the Shennan vertical land movement data set used in this report is to be shortly published]

SNIFFER (2000) The development of temperature indices for Scotland and Northern Ireland, SNIFFER Report, Edinburgh, UK.

Stott, P.A., Tett, S.F.B., Jones, G.S., Allen, M.R., Mitchell, J.F.B., Jenkins, G.J. (2000) External control of twentieth century temperature by natural and anthropogenic forcings. Science 15: 2133-2137.

UKCIP (2000) Climate Change: Assessing the impacts - identifying responses. The first three years of the UK Climate Impacts Programme [eds:] McKenzie Hedger, M., Gawith, M., Brown, I., Connell, R., and Downing, T.E. UKCIP Technical Report. UKCIP and DETR, Oxford. 168pp.

UKCIP (2001) Socio-economic scenarios for climate change impact assessment: a guide to their use in the UK Climate Impacts Programme. UKCIP, Oxford, UK, 123pp.

Van Engelen, A.F.V., Buisman, J., IJnsen, F. (2000) A millennium of weather, winds and water in the Low Countries. [In:] Jones, P.D., Ogilvie, A.E.J., Davies, T.D., Briffa, K.R. (2001) History and climate: memories of the future? Kluwer, New York, USA

Vaughan, D.G., Spouge, J.R. (2002) Risk estimation of collapse of the West Antarctic Ice Sheet. Climatic Change 52: 65-91.

Vellinga, M., Wood, R.A. (2002) Global climatic impacts of a collapse of the Atlantic thermohaline circulation. Climatic Change (in press)

WASA (1998) Changing waves and storms in the north-east Atlantic? Bull. Amer. Meteor. Soc. 79: 741-760.

Wigley, T.M.L., Raper, S.C.B. (2001) Interpretation of high projections for global-mean warming. Science 293: 451-454.

Wood, R.A., Keen, A.B., Mitchell, J.F.B., Gregory, J.M. (1999) Changing spatial structure of the thermohaline circulation in response to atmospheric CO_2 forcing in a climate model. Nature 399: 572-575.

Woodworth, P.L., Tsimplis, M.N., Flather, R.A., Shennan, I. (1999) A review of the trends observed in British Isles mean sea level data measured by tide gauges. Geophysical J. Int. 136: 651-670.

Appendix 1: An Introductory Guide to Choosing and Using Climate Change Scenarios

Purpose

This short guide summarises some of the issues connected with choosing and applying climate change scenarios when conducting vulnerability, impact or adaptation studies for scoping, research or policy applications. It is *not* intended as a comprehensive guidance document on how such studies should be conducted, nor does it cover *all* of the issues – and certainly not in depth - associated with the choice and use of climate scenarios. It does provide important background information, however, for those considering using the UKCIP02 climate change scenarios in quantitative studies. Guidance on handling climate change uncertainty in decision-making will shortly be published by UKCIP and will provide further information on using scenarios to make decisions about adaptation.

Applying climate scenarios

1. This report presents four scenarios of climate change for the UK at 50 km resolution. The scenarios reflect (at least in part) uncertainty due to future emissions (by using four possible widely-different emissions futures), and uncertainty due to natural variability (by using results from three climate model experiments with different initial conditions). However, because the only existing high-resolution simulations of future climate for the new IPCC SRES emissions scenarios come from one model (that at the Hadley Centre), the scenarios do not reflect uncertainties associated with modelling the response of the climate system to emissions. This "scientific uncertainty" is illustrated by showing results (at a lower resolution) from a number of other global climate models (GCMs), each of which will have a different representation of the processes in the climate system (see Section 3.5). (Even this may not cover the complete range of uncertainty, as the response of the real climate system may lie outside this range).

2. We cannot attach any probability to future emissions scenarios and we have not attached probabilities to the climate response from different models. Hence the four UKCIP02 climate change scenarios, and the additional GCM results, are all of unknown relative probability. Faced with a large number of different climate change scenarios, how do users estimate changes in the impacts of interest or design robust climate change adaptation strategies?

3. Methodologies for estimating the impacts of climate change and for conducting adaptation studies have been the subject of many reports in the past. Users are advised as a starting point to read the following:

- Chapter 13 of the IPCC Third Assessment WG1 report (Mearns,L.O., Hulme,M., Carter,T.R., Lal,M., Leemans,R. and Whetton,P.H. (2001) *Climate scenario development* pp.739-768 in, Climate change 2001: the scientific basis (eds.) Houghton,J.T., Ding,Y., Griggs,D.J., Noguer,M., van der Linden,P.J., Dai,X., Maskell,K. and Johnson,C.A. (eds.) (2001) Contribution of WG1 to the IPCC Third Assessment, Cambridge University Press, Cambridge, UK, 944pp.)

- Chapter 3 of the IPCC Third Assessment WG2 report (Carter,T.R., La Rovere,E.L., Jones,R.N., Leemans,R., Mearns,L.O., Nakicenovic,N., Pittock,A.B., Semenov,S.M. and Skea,J. (2001) *Developing and applying scenarios* pp.145-190 in, Climate change 2001: impacts, adaptation and vulnerability (eds.) McCarthy,J., Canziani,O., Leary,N.A., Dokken,D.J. and White,K.S., Contribution of WGII to the IPCC Third Assessment, Cambridge University Press, Cambridge, UK, 1032pp.).

- The *"Guidelines on the use of Scenario Data for Climate Impact and Adaptation Assessment"* prepared by the IPCC Task Group on Scenarios for Climate Impact Assessment (TGCIA; this can be downloaded from: http://ipcc-ddc.cru.uea.ac.uk/cru_data/support /guidel nes.html).

4. For a general scoping study, using the four UKCIP02 scenarios, or even the highest and lowest, may be adequate to frame the extent of the problem, to decide if a more detailed investigation is necessary. For developing new research methodologies it may even be sufficient to use just one or two scenarios to test the appropriateness of different techniques. For applications with major policy recommendations or specific design criteria in mind, however, users should investigate the impact of a wider range of climate change scenarios than are provided by this UKCIP02 Report. Table 5 (p25) suggests some initial adjustments to apply to the UKCIP02 scenarios to capture some of this range. Such an approach will reveal (again, at least in part) the extent of uncertainty in the response to climate change, and hence in the adaptation strategy which might be required. (Users may go even further, and investigate the response using a number of different impacts models, to each of which they apply a wide range of climate change scenarios, thus exploring the uncertainty due to emissions, due to climate change science and due to estimating impacts responses, but this further step is outside the remit of this Report).

5. Where a climate change study has implications for large infrastructure investments, for example in water resources, flood defences, transport networks, then the relative credibility of each of the various available climate change scenarios may have to be investigated more thoroughly. Some ways of doing this are discussed below.

Investigating different climate models

6. Although we have no formal way of ascribing credibility to

each model, there are a number of tests which could be applied which might suggest greater or lesser confidence in these different results. The IPCC Task Group on Scenarios for Climate Impact Assessment (TGCIA) stipulates that, in order for a model to be included in the Data Distribution Centre (see Appendix 8), it must:

- be a fully coupled ocean-atmosphere GCM
- be documented in the peer review literature
- have performed a multi-century control run, to demonstrate that it is stable
- have participated in the second Coupled Model Inter-comparison Project (CMIP2)

and the model experiments must:

- be documented (at least in an internal report)
- be historically forced from 1900, and run to 2100
- consider both greenhouse gas and aerosols in a single experiment

They also suggest a number of other criteria which are deemed desirable or preferable.

7. The IPCC does not involve itself with analysing the performance of individual models. The availability of data from a particular climate model from the IPCC Data Distribution Centres (DDC) does not imply that IPCC has given it any “seal of approval”. All such models have been documented and have been entered into international inter-comparison exercises, but their acceptance by the DDC does not imply the model has necessarily performed well in model inter-comparisons.

8. In addition to these IPCC criteria, therefore, the global climate models could be examined using a number of other, more quantitative, criteria, for example:

- is the resolution of the model acceptably good?
- does it consider greenhouse gases individually, rather than as a carbon dioxide equivalent?
- does it treat both direct and indirect aerosol radiative forcing?
- have a number of experiments been performed with different initial conditions, in order to quantify the influence of natural variability?
- is daily data available?
- how many quantities are output from the model experiment? There is a wide core set of variables in the IPCC DDC, but this may not cover everyone's requirements.
- how does the model's simulation of average long-term climate compare to observations, on a range of spatial and temporal scales (from seasonal means to daily distributions), for the quantities of importance in the specific impact study?
- how well does the model reproduce the transient climate change since the middle of the last century, compared to observations?
- how well does the model simulate substantial changes in palaeoclimates, for example that of the Holocene Maximum some 6,000 years ago when the Earth was about 1ºC warmer than today, or the last ice-age some 21,000 years ago when the Earth was about 8 degrees cooler?
- is the literature in which the model details been published peer reviewed at a high standard?
- in addition to CMIP2, have the model or its components taken part in other international inter-comparison exercises, for example PMIP (palaeoclimatology), PILPS (land surface processes), AMIP2 (the atmospheric component of the model), OCMIP (oceans), etc.?
- how well did the model, or its components, perform in these inter-comparison exercises?
- is the data (required variables and time resolution) easily available?

9. It may be the case that the impact on the particular sector or system being investigated is not sensitive to whether high (50 km) or low (300 km) spatial resolution scenarios are used, in which case the conclusion may be drawn that the extra resolution offered by RCMs is not warranted. In other cases, however, the ability of RCMs to take account of processes operating on smaller scales will lead it to make a simulation of climate change on the GCM scale which is different (and in which we have more confidence) to the simulation of climate change from the driving GCM. These differences may lead to different estimates of climate change impacts.

10.It is worth noting that the change in climate expected by about the 2030s is broadly similar for all of the future emissions pathways. This is because first, much of the climate change over the next few decades has already been prescribed by historical emissions and, second, because in the early years emissions pathways do not diverge as much as later in the century. The implication of this is that, if the time horizon of impacts to be studied is up to the middle of the century, uncertainty in future emissions is of minor importance relative to scientific uncertainties. Using scenarios other than the UKCIP02 scenarios therefore becomes still more important.

11. The Earth's climate system is very complex and there is much we do not understand about it. Even representations of what we do understand in climate models are limited by resolution dictated by available supercomputing power. We are confident that simulations from climate models will improve, i.e., they will represent more accurately the changes which will occur in the real climate system. This is because more research will lead to a fuller understanding of processes in the climate system, which in turn (together with the availability of bigger supercomputers and smarter techniques) will lead to better models. We will also be able to constrain more tightly the simulations through model validation, particularly using changes over past decades - this test will of course become more rigorous the more the climate actually changes. These improvements, however, imply that successive generations of climate scenarios may sometimes vary significantly.

12. The improved resolution of RCM simulations is an important step forward. Since RCMs are driven by GCMs, however, the broad-scale changes they show depends in part on that of the GCM. A good example of this is the difference between the two RCM scenarios shown on p84 in Section 7.5. In the previous RCM simulation (from HadRM2), summer rainfall *increased* over northern Scotland, but in the current UKCIP02 scenarios using HadRM3, summer rainfall *decreases* over the whole of the UK. The reason for this difference lies in part with the different circulation (air flow) changes predicted by HadCM2 (the GCM used in UKCIP98) and HadCM3 (used in this report).

13. Although we are confident that climate model simulations will improve with time, this improvement will not be rapid, and over the next decade or more considerable uncertainty will continue to be attached to descriptions of future climates. It is for this reason that research is being directed towards probabilistic descriptions of future climate, where uncertainty is accepted and then quantified, as described in Section 9.2, p94. The more fundamental uncertainties associated with unknown future global emissions are unlikely to be reduced with time.

Conclusion

14. Adaptation strategies should be flexible enough to cope with differences between different climate models and between successive generations of climate scenarios. They should recognise that there are already a number of changes in future climate in which we have high confidence, at least in the direction of change, for example in the long-term for the UK, temperatures will increase, winter precipitation will increase and sea level will rise (see Tables 9, 10 and 13 of this report). Any adaptation measures designed on such changes should prove to be robust, although they may not be optimal and may require adjustment over time and as climate model simulations improve.

15. In the final analysis, however, when designing adaptation strategies, an element of expert judgement will be called for, as in all decision-making in the face of uncertainty. Ideally such judgements should include consultation with scientists who have worked with climate models and with climate observations, who understand first-hand their strengths and limitations in specific applications, but who can also take a pragmatic view about the needs of using the best information at any given time to inform decision-making.

Appendix 2: The HadCM3, HadAM3H and HadRM3 Models and Experiments

Global climate models

The HadCM3 climate model has been developed in parallel with weather forecasting models over a number of decades and is a sophisticated tool for simulating global climate. The model is based on the known laws of physics describing the transport of mass (including moisture) and energy; these equations are solved at intervals (typically 30 minutes) at a number of points forming a grid over the globe. In the HadCM3 model this grid is 2.5º in latitude by 3.75º in longitude; this corresponds to about 265 km by 300 km over the UK. There are 19 vertical levels through the atmosphere. Figure A.1 shows the model domains schematically.

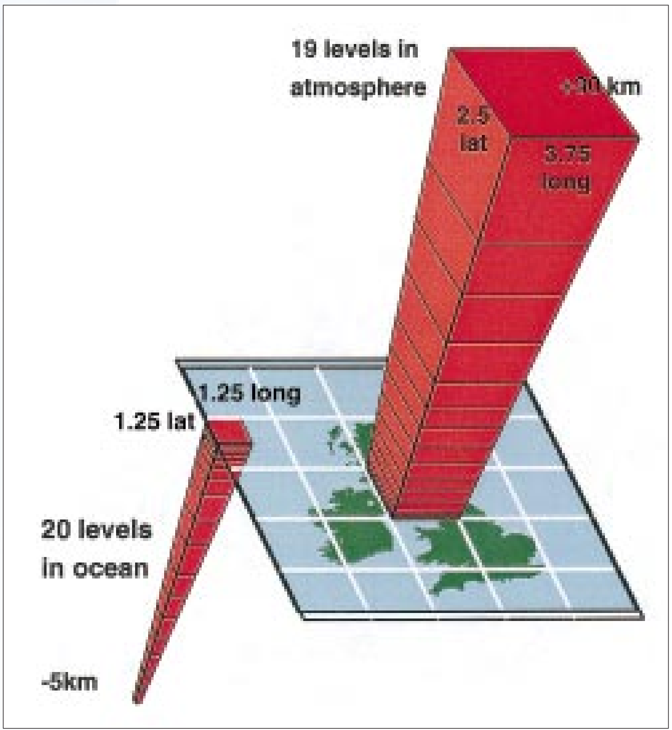

Figure A.1: Schematic representation of the environment around the British Isles in HadCM3.

A climate model has to represent the ocean as well as the atmosphere - not just the continuous transfer of heat, water and momentum across the air-sea interface, but the ocean currents that transport vast amounts of heat between the equator and the poles. Atmospheric models are now successfully coupled to deep ocean models to allow the transient changes in climate to be properly modelled.

The ocean part of HadCM3 has 20 vertical levels and a horizontal resolution of 1.25º latitude by 1.25º longitude. In a significant development from the earlier HadCM2 model used in the UKCIP98 scenarios, HadCM3 does not need to use "flux adjustments" to force the model simulations to match reality. In addition, the radiative effects of greenhouse gases other than carbon dioxide are explicitly represented in HadCM3, another major development over earlier models which usually could only represent carbon dioxide.

Calculating climate change due to an increase in greenhouse gases would be much more straightforward were it not for the consequential effects on climate which follow an initial warming. These effects are known as "feedbacks" and they can act either to amplify the initial change or to reduce it. The melting of sea-ice, for example, will reduce the amount of sunlight reflected and thus enhance the warming in high latitudes - a positive feedback. A warmer atmosphere will "hold" more water vapour (a powerful greenhouse gas) and this too will act as a positive feedback. The greatest uncertainty in model simulations comes from these feedbacks and in particular from possible changes in the behaviour and characteristics of clouds in a warmer world - we do not even know if this particular feedback overall will be positive or negative.

Stages in climate predictions

Predicting climate in the future is a multi-stage process. First, scenarios are constructed of future human-related emissions of the main greenhouse gases. These come from energy-economy models that take account of such factors as growth in population, energy demand and technological change. Appendix 5 describes the emissions scenarios used in this Report. Second, human-related carbon dioxide emissions are translated into atmospheric concentrations using carbon cycle models. The natural carbon cycle involves the transfer of vast amounts of carbon between the atmosphere, the terrestrial biosphere and the oceans; the latter is by far the largest reservoir. Although carbon dioxide emissions due to human activities are only a small fraction of the natural cycle, they have led to more than a 30 per cent increase in carbon dioxide concentrations since pre-industrial times.

Carbon-cycle models estimate the amount of anthropogenic emissions that will be taken up by the ocean and by the land biosphere, and hence the amount retained in the atmosphere. Since the effective lifetime of carbon dioxide in the atmosphere is about 100 years, its atmospheric concentration responds only very slowly to changes in emissions. This is unlike gases such as methane whose concentrations respond to changes in emissions much more quickly. Only emissions reductions greater than about 60 per cent would prevent carbon dioxide concentrations from rising in the future. Such a large reduction would be needed because even past emissions have not yet been fully reflected in current concentrations. For other greenhouse gases, such as methane, future concentrations are calculated using models that represent chemical reactions in the atmosphere.

Finally, climate change experiments can be conducted using the climate model described above. The model is run for many hundreds of (simulated) years to provide a "control" climate unperturbed by any external influences. Starting from an arbitrary point in the control run, the model is then forced with increases in greenhouse gas and aerosol concentrations.

The starting point nominally represents the middle of the nineteenth century when any human influences would have been negligible (specifically the year 1860 was chosen as the start year to allow comparisons with global temperature observations). Over the period from 1860 to 1990 observed changes in greenhouse gases and aerosols are used to simulate changes in climate to date. From 1990 onwards, a number of scenarios of future changes in greenhouse gases and aerosols are used. An important part of the process is model validation against observed data; work on this for HadCM3 and HadRM3 is currently in progress at the Hadley Centre and in the Climatic Research Unit at UEA.

Ensemble simulations

The model simulations of future climate change could depend upon the choice of which point in the control run increasing greenhouse gas concentrations are introduced. For this reason, three identical model experiments, with the same historical changes and the same future changes in greenhouse gases and aerosols, are initiated from three different points on the control run. This experimental design is known as an "ensemble" of simulations. The underlying long-term climate change simulated by each of these model experiments is very similar, showing that the initial condition is not important to the long-term change. However, there are significant year-to-year and decade-to-decade differences between the ensemble members due to natural internal climate variability, particularly at a regional level such as the UK (see Figure 84). For this reason, results from the three members of the ensemble are pooled, as has been done in this Report, to reduce the "noise" of natural variability and hence to give a better estimate of the changes in climate averages and weather statistics.

Aerosols

Climate can also be affected by a number of other agents in the atmosphere in addition to greenhouse gases; important amongst these are small particles (aerosols). These are suspended in the atmosphere and reflect solar radiation back to space, thus having a cooling effect on climate. In addition to this direct effect, aerosols can also change climate by increasing the reflectivity and longevity of clouds; these indirect effects are at least as important as the direct effect. Although there are no measurements to show how these influences on climate have changed over the past 150 years, there *are* estimates of how sulphur dioxide emissions have risen. There are also future estimates of such emissions (the SRES scenarios) and these are used in a sulphur cycle model to calculate the accompanying rise in sulphate aerosol concentrations. In HadCM3, and in the regional model HadRM3, the sulphur cycle which generates sulphate particles from sulphur dioxide, and their transport and removal by deposition and rain, are all included interactively. This allows both the direct and indirect effects of aerosols to be represented in the model.

The effects on climate of sulphur emissions are very uncertain, however, due to a number of factors. First, the SRES emissions scenarios all show long-term declines in global sulphur emissions, resulting in a reduction of aerosol cooling relative to 1995. The net effect on climate by 2100 of such reductions in aerosol concentrations is therefore a *warming* relative to 1995. Second, more recent sulphur cycle models generate a lower sulphate burden per tonne of sulphur dioxide emissions. Furthermore, the radiative effect of the sulphate particles in more sophisticated radiation models is smaller than previously calculated. Above all, the short lifetime of sulphate particles in the atmosphere means that they should be viewed as introducing only a temporary masking effect on the underlying warming trend due to the long-term increase in greenhouse gas concentrations.

Regional climate models

Most processes in the atmosphere, ocean and on land which determine climate (cloud formation and development, for example) take place at scales much smaller than those resolved in HadCM3. The UKCIP02 scenarios make extensive use of the regional climate model HadRM3, which has a horizontal resolution of 0.44º latitude by 0.44º longitude (approximately 50 km), and a time step of 5 minutes. HadRM3 takes boundary conditions from coarser resolution global model simulations and provides a higher spatial resolution of the local topography (for example Figure A.2) and more realistic simulations of fine-scale weather features. The advantage of this approach is that it adds physically-based high-resolution information to the results of GCM experiments. It is also important to remember that although regional models have an improved representation of smaller-scale processes than GCMs, they still exhibit systematic errors due to imperfect representation of *even* smaller-scale features. A regional model still depends on good quality results from the driving global model; an inaccurate global model will result in inaccurate results from a regional model.

Figure A.2: The topography of the HadRM3 climate model over the UK.

Between the global coupled ocean-atmosphere model and the regional model, a global model of the atmosphere alone (HadAM3H) was used. HadAM3H has twice the spatial resolution of the coupled model, i.e., about 150 km by 150 km. HadAM3H was run for a “reference” period (1961-1990), driven by observations of sea-surface temperature (SST) and sea-ice for that period. A second run (2071-2100, labelled the 2080s) was driven by *changes* in SST and sea-ice predicted by HadCM3, added to the observations. The use of this intermediate resolution model, together with observed SST, resulted in a more realistic simulation of the North Atlantic storm track than would have been the case from the global coupled model alone. Wind, temperature and humidity output from the 1961-1990 and 2071-2100 runs of HadAM3H were then used to drive HadRM3 at its lateral boundaries.

This procedure was carried out three times using the SRES A2 emissions scenario to generate three ensemble members (a, b and c) from HadRM3. The results from these experiments were then used to infer future climates for other emissions scenarios and other time-slices through applying a pattern-scaling technique (see Section 7.4).

Appendix 3: Improvements in the 2002 Scenarios Compared to the 1998 Scenarios

Climate change scenarios for the UK were prepared for the Department of the Environment in 1991 and in 1996 as part of the work of the Climate Change Impacts Review Group (CCIRG) and, in a significantly improved version, for the UK Climate Impacts Programme in 1998. The UKCIP98 scenarios provided a more explicit quantification for the UK of four alternative climate change scenarios. Analyses were also presented in UKCIP98 for a wider range of variables on a wider range of time-scales than presented in CCIRG91 and CCIRG96. The UKCIP02 scenarios again introduce further improvements compared to the 1998 scenarios in several respects:

- The four UKCIP02 climate change scenarios are explicitly linked to the four different and coherent storylines of future changes in global socio-economic conditions and population published by the IPCC in 2000 – A1, A2, B1 and B2. The four 1998 climate change scenarios were derived from two less coherent scenarios of population and fossil fuel use – IS92a and IS92d - and linkages between the climate and non-climate scenarios were more tenuous.

- The climate models used for the UKCIP02 scenarios - HadCM3, HadAM3H and HadRM3 - are more sophisticated than the earlier model used for the 1998 scenarios – HadCM2. The later models explicitly represent the different greenhouse gas species and contain an improved representation of the oceans and vegetation.

- The UK land area is represented in the UKCIP02 scenarios by 104 grid boxes with model output analysed at monthly and daily resolution, compared to just four grid boxes in the 1998 scenarios with mostly monthly data analysed. This allows a much more detailed regional and temporal analysis of extreme daily weather events in the new scenarios.

- The UKCIP02 scenarios are accompanied by a new, 5 km resolution observed climate data set for the UK covering the period 1961 to 2000 at monthly time-steps and representing 26 separate climate variables. The 1998 scenarios used an older 10 km resolution data set for the period 1961 to 1990 representing just 11 climate variables.

The main differences in the climates described by the UKCIP02 and UKCIP98 scenarios are as follows:

- The UKCIP02 scenarios show slightly larger warming rates over the UK than the 1998 scenarios, especially for the **Low Emissions** scenario. This is partly because we use a model with a higher effective sensitivity is being used for *all* the scenarios and partly because we now consider the effects of changing sulphate aerosol concentrations.

- The UKCIP02 scenarios show a higher atmospheric concentration of carbon dioxide for the **Medium-High Emissions** and **High Emissions** scenarios than in the equivalent 1998 scenarios. This is mainly because these scenarios assume higher global emissions of carbon dioxide during the twenty-first century.

- The UKCIP02 scenarios show slightly smaller rates of sea-level rise than the 1998 scenarios, especially for the **High Emissions** scenario. This is because improvements in the way the thermal expansion of ocean waters and land glaciers are modelled suggest that sea-level rise is slightly less sensitive to global warming than was the case four years ago.

- The UKCIP02 scenarios suggest that summers become drier across the *whole* of the UK – not just in England and Wales - and by a larger amount than in the 1998 scenarios.

- The UKCIP02 scenarios suggest different patterns of change in average wind speed compared to the 1998 scenarios. These changes in wind speed are still relatively small, however, and it remains the case that we have little confidence in the simulated changes in the UK wind regime.

- The UKCIP02 scenarios include a more comprehensive analysis of changes in some aspects of extreme weather and extreme water levels than the 1998 scenarios. Since these changes derive from a higher resolution model that simulates extreme weather better than the global model used for this purpose in 1998, we have more confidence in these results reported here than in those reported in the 1998 report.

Appendix 4: The UKCIP02 Scenario Data Files and Web Site

The UKCIP02 Report presents a selection of the available analyses of future climate change scenarios in graphical form. However, users may wish either to see more plots and maps which do not appear here for reasons of space, or access the raw data for use in climate impacts or adaptation studies. Both these needs are met by the comprehensive website at: **www.ukcip.org.uk/scenarios/**.

Most of the data available via the website conform to the resolution of the maps presented in this Report (50 km) and follow the resolution of the original model output. In addition, for some variables we have an observed climate data set at 5 km resolution for the UK. This high-resolution data set was used to create a set of *climate scenarios* for these variables by simply interpolating the 50 km changes in climate generated by the model to match the 5 km spatial scale of our observed baseline climate data. Data files may be transferred by FTP following completion of an online license form.

Table A.1 gives details of the variables which have data available on the website and the resolution available. The data are in regular-grid format and can be downloaded as text files. "Climate scenarios" refer to absolute values of UK monthly climate for four scenarios and three time-slices. "Climate change scenarios" refer to the changes from the 1961-1990 baseline in UK monthly climate for four scenarios and three time-slices.

The original monthly data, as well as daily data files from the HadRM3 A2 and B2 experiments, are available through the Climate Impacts LINK project, along with HadCM3 GCM (300 km) data and associated global-mean changes in sea level, temperature and carbon dioxide concentration. LINK can be accessed either through the UKCIP site or at: **www.cru.uea.ac.uk/link/**.

Variable	Code	Model-Simulated 1961-1990 Climate (50 km)	Climate change Scenarios (50 km) 2020s, 2050s, 2080s	Climate Scenarios (5 km) Monthly Averages 2020s, 2050s, 2080s	Climate Scenarios (5 km) Monthly Timeseries 2011-2100
Maximum temperature (ºC)	TMAX	Y	Y	Y	N
Minimum temperature (ºC)	TMIN	Y	Y	Y	N
Daily mean temperature (ºC)	TEMP	Y	Y	Y	Y
Total precipitation rate (mm/day)	PREC	Y	Y	Y	Y
Snowfall rate (mm/day)	SNOW	Y	Y	N	N
10 m wind speed (m/s)	WIND	Y	Y	Y	N
Relative humidity (%)	RHUM	Y	Y	Y	N
Total cloud in longwave radiation (fraction)	TCLW	Y	Y	Y	N
Net surface longwave flux (Wm^{-2})	NSLW	Y	Y	N	N
Net surface shortwave flux (Wm^{-2})	NSSW	Y	Y	N	N
Total downward surface shortwave flux (Wm^{-2})	DSWF	Y	Y	N	N
Soil moisture content (mm)	SMOI	Y	Y	N	N
Mean sea level pressure (mb)	MSLP	Y	Y	N	N
Surface latent heat flux (Wm^{-2})	SLHF	Y	Y	N	N
Specific humidity (g/kg)	SPHU	Y	Y	N	N

Table A.1: Variables contained in the UKCIP02 scenario monthly data files available on the UKCIP web site. These data are available for all four UKCIP02 scenarios.

Appendix 5: The SRES Emissions Scenarios

In 1997, the IPCC set up an expert group to prepare a Special Report on Emissions Scenarios (SRES), which was published in 2000. It describes, quantitatively, present-day global and regional emissions of greenhouse gases, and other pollutants (for example sulphur dioxide and carbon monoxide) which can indirectly influence climate. The scenarios also describe how these emissions could change over the coming century in the absence of any "interventionist" policies designed specifically to reduce greenhouse gas emissions. These scenarios of future emissions are derived from four "storylines", each of which describes a possible future world (Table A.2). Three variants are created for the A1 world.

Storyline	Description
A1	Very rapid economic growth; population peaks mid-century; social, cultural and economic convergence among regions; market mechanisms dominate. Subdivisions: **A1FI** – reliance on fossil fuels; **A1T** – reliance on non-fossil fuels; **A1B** – a balance across all fuel sources
A2	Self-reliance; preservation of local identities; continuously increasing population; economic growth on regional scales
B1	Clean and efficient technologies; reduction in material use; global solutions to economic, social and environmental sustainability; improved equity; population peaks mid-century
B2	Local solutions to sustainability; continuously increasing population at a lower rate than in A2; less rapid technological change than in B1 and A1

Table A.2: A brief description of the SRES storylines used for calculating future greenhouse gas and other pollutant emissions.

Each storyline was quantified by using up to six different energy-economy models to convert the description of the future world into a greenhouse gas emission rate. This resulted in a total of 40 scenarios of greenhouse gas emissions over the next hundred years being created. One "marker" scenario was chosen by the SRES group to represent each of the six storylines. The scenarios chosen for this Report were the markers for the A1FI, A2, B1 and B2 worlds; this choice represents very nearly full range of projections for future greenhouse gas emissions.

The climate-focused SRES scenarios can be explicitly linked with the much broader-scope UK-oriented scenarios produced by the Foresight Programme of the UK Office of Science and Technology and published in early 1999. The Foresight Futures are principally socio-economic in nature and provide four storylines each describing a markedly different set of social, political, economic and institutional circumstances. Socio-economic scenarios for the UK based on the Foresight work were published by UKCIP in June 2001, with more explicit descriptions of the regional and sectoral detail required for climate impacts studies. These are framed in the same thirty-year timescales as the climate change scenarios to allow common use. The Environment Agency have also adopted this same generic scenario framework for their recent work on forecasting water demand, although using a different nomenclature (see Table A.3).

By deriving the UKCIP02 climate change scenarios from the original four IPCC SRES storylines, these future climates for the UK can be sensibly linked to descriptions of future worlds and a different future UK, where these descriptions are expressed in terms of non-climate variables. For UKCIP studies the UKCIP02 climate change scenarios should be used in conjunction with the four UKCIP non-climate futures, published in May 2001 in *"Thinking Ahead: socio-economic scenarios for climate change impact assessment"*.

SRES Storyline	OST Foresight Scenario	UKCIP Socio-economic Scenario	Environment Agency Scenario	UKCIP02 Climate change Scenario
B1	Global Sustainability	Global Sustainability	Gamma	**Low Emissions**
B2	Local Stewardship	Local Stewardship	Delta	**Medium-Low Emissions**
A2	Provincial Enterprise	National Enterprise	Alpha	**Medium-High Emissions**
A1FI	World Markets	World Markets	Beta	**High Emissions**

Table A.3: Links between various socio-economic futures and the UKCIP02 climate change scenarios.

Appendix 6: Glossary of Technical Terms [17]

adaptation. Changing behaviour, institutional arrangements or economic activity to adapt to either direct or indirect consequences of climate change. See **mitigation**.

aerosols (sulphate) Microscopic droplets or solid particles in the atmosphere. They affect the thermal properties of the atmosphere by absorbing and scattering radiation and by aiding cloud formation.

AGCM. Atmospheric General Circulation Model. This does not explicitly model the ocean, but imports the outputs relating to the ocean (e.g. sea-surface temperature) from observations and AOGCMs as boundary conditions. HadAM3H is the AGCM used for the UKCIP02 scenarios. GCM can also be an acronym for Global Climate Model.

AOGCM. Atmosphere-Ocean Coupled Global Circulation Model. AOGCMs model dynamically the coupled atmosphere-ocean system. HadCM3 is the AOGCM used for the UKCIP02 scenarios.

baseline. The thirty-year period 1961-1990, relating to either observed data or model-simulated data. This period is used as the reference from which future changes in climate are calculated.

climate change scenario. A coherent and internally-consistent description of the *change* in climate by a certain time in the future, using a specific modelling technique and under specific assumptions about the growth of **greenhouse gas** and other emissions and about other factors that may influence climate in the future.

climate scenario. A description of possible future *climates* rather than possible future *changes* in climate. Climate scenarios usually – although not always – combine observations about present-day climate with estimates of the change in climate, for example from **climate change scenarios**.

control experiment. A model experiment in which greenhouse gas concentrations are kept constant.

downscaling. The process of reducing coarse spatial scale model output to smaller scales.

effective climate sensitivity. Similar to **equilibrium climate sensitivity**, but obtained from non-equilibrium conditions, and therefore changes with time. The latest range quoted by the IPCC (2001) for the effective climate sensitivity is between 1.7º and 4.2ºC. A special case of effective climate sensitivity is the **transient climate response**.

ensemble. A set of simulations (each one an ensemble member) made by the same model, using the same emissions scenarios but initialised at different points on the **control experiment**. The difference in climate between ensemble members is a measure of the natural **internal climate variability**.

equivalent CO_2 concentration. The concentration of CO_2 which would cause the same amount of **forcing** as a given mixture of CO_2 and other **greenhouse gases**.

flux adjustment. Artificial adjustments applied to climate model output to force it to match reality. These are *not* needed in the models used to produce the UKCIP02 scenarios.

forcing (radiative). Altering the heat balance of the earth-atmosphere system. Human-induced climate forcing occurs principally by increasing the concentration of atmospheric **greenhouse gases** and **aerosols**.

greenhouse gas. A gas which "traps" energy radiated by the Earth within the atmosphere. Carbon dioxide (CO_2) is the most important greenhouse gas being emitted by humans.

Intergovernmental Panel on Climate Change (IPCC). International forum of experts brought together by the United Nations to undertake periodical assessments addressing how climate will change, what its impacts may be and how we can respond. It was originally formed in 1988 and published its Third Assessment Report in 2001.

internal climate variability. The "unforced" changes in climate which occur on all time and space scales.

Kyoto Protocol. International legally-binding agreement adopted at Kyoto in 1997 under the UN Framework Convention on Climate Change to reduce the emissions of **greenhouse gases**. The Protocol has not yet (April 2002) been ratified.

mitigation. Action taken to reduce the impact of human activity on the climate system, primarily through reducing net **greenhouse gas** emissions. See **adaptation**.

North Atlantic Oscillation. Changes in the difference in barometric pressure between the Azores and Iceland. These changes affect the direction and strength of flow across northwest Europe, especially in winter.

percentile. The value below which falls a specified percentage (for example 90 per cent) of a set of values. For example, the 90th percentile daily-average temperature is that which is exceeded on only one in ten days. See **quantile**.

precipitation. Water falling in some form; rain, snow, sleet and hail.

(17) Many of the definitions in the glossary are based on the IPCC (2001) standard definitions

quantile. The value below which falls a specified proportion (for example 90 per cent) of the *sum* of a set of values. For example, a year's 90th quantile daily rainfall amount is that which, if exceeded, classifies a day's rain as contributing to the heaviest 10% of the total for that year. It is an indicator of the magnitude of an event rather than the frequency. See **percentile**.

RCM. Regional Climate Model. An atmospheric model of higher resolution than the **AGCM**, it is nested within the **AGCM** to provide more detailed simulations for a particular area. HadRM3 is the RCM used for the UKCIP02 scenarios.

relative humidity. The ratio of the vapour pressure (the partial pressure exerted by the water vapour) of a sample of air to the saturation vapour pressure (the partial pressure that water vapour would exert if the air were saturated) at the same temperature. See **specific humidity**.

return period. The average time between events of a given magnitude. For example, in parts of southern England, a rainfall total of 100 mm in one day has a return period of 100 years. A 100-year return period is the equivalent of the event that has a 1 per cent probability of occurring in any given year.

scenario. A coherent, internally consistent and plausible image of a possible future state of the world; a tool to analyse how possible future changes may affect the social, economic, environmental or institutional fabric.

specific humidity. The mass of water vapour per unit mass of moist air (grams per kilogram). See **relative humidity**.

storyline. The actual description of a possible future world in the **scenario**. May be both quantitative and qualitative.

thermohaline circulation. Large-scale ocean circulation driven by density differences (caused by temperature and salinity differences) and wind stress. In the north Atlantic the circulation is known as the Gulf Stream and the North Atlantic Drift and is partly responsible for western Europe's mild climate.

time-slice. Any period of time used as a representative of time in the future. In the UKCIP02 scenarios a time-slice is 30 years, and the results for the 2020s, 2050s and 2080s are thirty-year means representing, respectively, the periods 2011 to 2040, 2041 to 2070 and 2071 to 2100.

transient climate response. The global-average temperature change at the time of CO_2 doubling (Year 70) in a model experiment in which CO_2 concentrations increase at the rate of 1 per cent per year.

Appendix 7: The Observed UK Climate Data Set

The UK climate data set is presented as a grid of 5 km by 5 km cells containing monthly, seasonal and annual statistics for 26 weather variables or their derivatives. The full list can be found in Table A.4. The period covered by these data is from 1961 to 2000, except for wind data which run from 1969 to 2000. The grids are based on the GB national grid, extended to cover Northern Ireland and the Isle of Man. Data for the Channel Islands are not currently available.

have a complete daily record with a further 50 having no more than 2 days of data missing in any month throughout the 1961 to 2000 period. In any one month approximately 550 stations are available for use and meet the set criterion of having no more than two days of data missing. A further complication is that not all stations measure all weather parameters. Table A.5 summarises the situation for all data types used to generate the 26 individual grids.

Name	Definition
Monthly Mean Air Temperature	Average of mean maximum and the mean minimum
Monthly Mean Maximum Temperature	Average of the daily highest temperature
Monthly Mean Minimum Temperature	Average of the daily lowest temperature
No. of days with Frost in month	Count of days when the minimum temperature is below 0ºC
Heating Degree Days in month	∑15.5 – daily mean temperature
Growing Degree Days in month	∑daily T-5 whenever daily mean temperature is above 5ºC
Intra-annual Extreme Temperature Range	Highest daily maximum temperature minus Lowest daily minimum temperature in the year
Annual Growing Season Length	Bounded by daily mean temperature >5ºC for >5 days and daily mean temperature <5ºC for >5 days
Summer ‘Heat Wave’ Duration	∑ days with daily maximum >3ºC above 1961-90 daily normal for >5 consecutive days (May-Oct)
Winter 'Heat Wave' Duration	As above but Nov-Apr
Summer ‘Cold Wave’ Duration	∑ days with daily minimum >3ºC below 1961-90 daily normal for >5 consecutive days (May-Oct)
Winter ‘Cold Wave’ Duration	As above, but Nov-Apr
Monthly Mean Vapour Pressure	Hourly (or 3 hourly) data averaged over each month
Monthly Mean Wind Speed	Hourly mean wind speeds averaged over the month; from 1969 only
Monthly Mean Sea Level Pressure	Hourly (or 3 hourly) data averaged over each month
Monthly Hours of Bright Sunshine	Total Hours of sunshine per month based on the Campbell-Stokes recorder
Monthly Total Precipitation	Total precipitation per month
Rain Days in month	No. of days with ≥1mm rain
Wet Days in month	No. of days with ≥10mm rain
Snow Days in month	No. of days with snow falling.
Maximum Number of Consecutive Dry Days in the Year	Dry day = rain <1 mm
Greatest 5-day Precipitation Total in the Year	Self-explanatory
Simple Daily Intensity on Raindays per Year	Total rainfall on days with ≥1 mm divided by count of days with ≥1mm of rain
Number of Days with Snow Cover	Greater than 50% of the ground covered by snow
Monthly Mean Cloud Cover	Hourly (or 3 hourly) data averaged over each month
Number of days with Ground Frost	Count of days with the grass minimum below 0ºC

Table A.4: The 26 variables included in the observed UK climate data set, together with definitions. These data files are available from the Met. Office at: www.metoffice.com/research/hadleycentre/obsdata/ukcip/index.html

The Met Office archive of UK observations has been used as the source of data for this climate data set. This archive has been built up over the years from a variety of sources of varying quality and consistency. Even the best of records suffer from periodic data loss, leaving very few stations for which a complete observational record exists. Also stations open and close on a regular basis with the turnover in the primary climate network averaging about 50 stations per year. Therefore out of a pool of over 1400 climate stations only 30

A challenge in the gridding process is to remove the effects of the constantly varying pool of stations. This could be overcome by only using the 30 stations with a complete record (even less for some parameters), but the sparseness of the network would cause the gridding to introduce even worse errors due to the spatial interpolation required. Instead, all stations believed to have a good record in any month are used, and every effort made to compensate for missing stations during the gridding process.

Parameter Type	Total sites	Sites per month
Temperature	1400	550
Rainfall (no missing days allowed)	11000	4000
Sunshine	650	300
Wind (1969-2000)	400	200
Pressure, Humidity, Cloud	400	200
Snow	1200	500

Table A.5: Number of meteorological stations contributing to the gridded climate data set.

The gridding process is accomplished in either three or four stages. Firstly, for most parameters, the monthly average or total values are turned into differences from or percentages of the 1961-1990 long period average (termed *anomalies*). This generally produces a field that is smoother than the raw observations (termed *actuals*) and therefore easier to interpolate. But the long period monthly averages need to be known and this is not the case for some of the derived parameters. Some of the derived parameters are themselves based upon departures from average, for instance heatwaves and coldwaves. Such parameters require daily long period averages. However, daily averages are notoriously noisy when viewed as an annual time series. To overcome this, a smooth curve is generated by fitting to the sines and cosines of the twelve monthly averages. This also ensures that a discontinuity does not occur between 31 December and 1 January.

The second stage is to fit a regression equation to the actual values or the anomalies, effectively producing a surface over the UK from which values can be read at any location. Different factors – such as latitude, longitude, altitude, coastal proximity and urbanisation – were used for different variables. The coastal and urban factors are derived from a land use data set produced in the late 1970s. For each grid square centre the percentage of the area within a 5 km radius that is urban or within a 2.5 km radius that is sea is determined. Therefore no attempt has been made to mitigate the effects of urbanisation on observing sites over the analysis period. It is not appropriate to use all geographic factors for all parameters, as there may not be a plausible reason for such a relationship, leading to the possibility of generating spurious correlations that only add noise to the regression surface. The fit of the regression surface to station values will not be perfect, the differences being known as regression residuals. At stations where the residuals are large they tend to be indicative of spurious values and so can be used as a quality control filter.

The third stage involves the interpolation from station values onto the 5 km grid. The regression residuals are used because they should have a comparatively small range of variability compared with the original values. Inverse distance cubed weighting is used to ensure that the station values are closely fitted. Other fitting techniques, such as splines and kriging, could be used but are so far untested.

Finally, the 5 km grid of interpolated residuals is added to the regression surface. If anomalies have been analysed the process is reverse engineered back to a field of the original parameters.

Appendix 8: The IPCC Data Distribution Centre

A Data Distribution Centre (DDC) was established by the IPCC to facilitate the timely distribution of a consistent set of scenarios of changes in climate and related environmental and socio-economic factors for use in climate impacts assessments. These new assessments were used in the review process of the IPCC, in particular the Third Assessment Report published in 2001. The initiative to establish a DDC grew out of a recommendation by the IPCC Task Group on Climate Scenarios for Impacts Assessments. The Centre is currently run by the Climatic Research Unit at the University of East Anglia in the UK and the Deutsches Klimarechenzentrum in Germany. Regional mirror sites at several locations around the world are being added.

The purpose of the DDC is to set the stage for the rapid uptake by researchers in the impacts and adaptation community of results from recent climate change experiments and to improve the consistency of the scenarios adopted in different national and international assessments. The DDC, by distributing climate scenario and related information, ensures that all researchers have the possibility of working with consistent sets of climate scenarios. The DDC provides four types of data or information. These are made available to researchers through a variety of media, including the internet, CD-ROMs and tapes. The four types of information are:

- *Observed global climate data sets*. These include a gridded terrestrial climatology of mean monthly data for 1961-1990 on a 0.5º latitude/longitude grid, together with decadal anomalies from this mean for the period 1901-1995 (shortly to be updated to 2000).

- *Socio-economic scenario information*. The socio-economic scenario data supplied are consistent with the IPCC Special Report on Emissions Scenarios (SRES).

- *Results from GCM experiments*. These monthly surface climate data have been extracted from recent global climate model simulations which include both greenhouse gas only and greenhouse gas and sulphate aerosol forcings. Consistent scenarios of global sea-level change and carbon dioxide concentrations are available.

- *Guidance material*. This document provides descriptions of the GCM experiments, discussion of scenario uncertainties, guidance on their application in impacts studies, and reporting guidelines for research results.

The DDC web site can be accessed at: **http://ipcc-ddc.cru.uea.ac.uk/**.

The DDC web site has four main functions:

- *User registration and orders for data.*

- *User support*. This provides information about the data sets available from the DDC and a list of Frequently Asked Questions (FAQs) about the use and application of scenario data.

- *Data visualisation*. Web-based software allows viewing of the various climate data sets in map and graphical form.

- *Data download*. The web site allows users to download (ASCII or binary) data files from the DDC. These data sets include global observed climate baseline data, aggregate climate change fields from the GCMs, and socio-economic scenario data.

On-line sources of UKCIP02 scenario data and related climate change information

- UKCIP02 Climate Scenario Data: www.ukcip.org.uk/scenarios/ Observed (5km), Climate change scenarios (50km) and climate scenarios (5km).

- The Climate Impacts LINK Project: www.cru.uea.ac.uk/link/ Supplying model output from the full range of Hadley Centre climate model experiments.

- Climatic Research Unit, University of East Anglia: www.cru.uea.ac.uk/ Supplying global/hemispheric temperatures and gridded climate data sets.

- The British Atmospheric Data Centre (BADC): tornado.badc.rl.ac.uk/ Supplying observed daily weather data for the UK.

- UK Marine Environmental Data Network: www.oceannet.org/ Co-ordinating available information and data for the UK marine environment.

- Solar Radiation Database for Environment (SoDa): soda.jrc.it/ Project for intregration and exploitation of international solar radiation databases.

- European Solar radiation Atlas (ESRA): www.helioclim.net/esra/radiation.html Links to information on obtaining solar radiation data for Europe.

- The Hadley Centre for Climate Prediction and Research, Met Office: www.metoffice.com/research/hadleycentre/index.html Supplying Central England Temperature, England and Wales Precipitation and air flow indices.

- The Inter-governmental Panel on Climate Change (IPCC): www.ipcc.ch/ Information about IPCC activities, assessment reports and other publications.

- The IPCC Data Distribution Centre (DDC) http://ipcc-ddc.cru.uea.ac.uk/ Supplying results from worldwide global climate model experiments and other scenario-related information.

- The IPCC Special Report on Emissions Scenarios (SRES): sres.ciesin.org/index.html Detailed information about the IPCC emissions scenarios and related non-climate scenario information.

- The Statistical DownScaling Model: co-public.lboro.ac.uk/cocwd/SDSM/IDLogin.html A public-domain weather generator.

- The LARS Weather Generator: www.iacr.bbsrc.ac.uk/mas-models/larswg.html A public-domain weather generator, designed for UK climate.

© M. Robinson

Tyndall Centre for Climate Change Research
www.tyndall.ac.uk

The Tyndall Centre is the national UK centre for trans-disciplinary research on climate change. Its purpose is to research, assess and communicate from a distinct trans-disciplinary perspective the options to mitigate, and the necessities to adapt to, climate change, and to integrate these into the global, national and local contexts of sustainable development. It is dedicated to advancing the science of integration, to seeking, evaluating and facilitating sustainable solutions to climate change and to motivate society through promoting informed and effective dialogue. The Centre was constituted in October 2000 and is the result of a unique collaboration between nine UK research institutions and three of the UK Research Councils - NERC, EPSRC and ESRC. It draws additional support from the UK Government's Department of Trade and Industry. The Centre has its Headquarters in the School of Environmental Sciences at the University of East Anglia in Norwich, but it also has regional offices at UMIST in Manchester and at the University of Southampton.

Contact:
Dr Simon Torok,
External Communications Manager,
Tyndall Centre,
School of Environmental Sciences,
UEA, Norwich NR4 7TJ, UK
tyndall@uea.ac.uk
Tel: +44 1603 593906
Fax: +44 1603 593901

Hadley Centre for Climate Prediction and Research
www. metoffice.com/research/hadleycentre/index.html

The Hadley Centre is the UK government centre for research into the science of climate change. It is a branch of the Met Office with about 100 staff, currently situated at Bracknell, but due to move to Exeter in 2003. It was opened in 1990, building on 20 years' previous research into climate. Its main roles are:

- To understand processes in the climate system and develop climate models which represent them
- To use the models to simulate change and variability in the past, and predict change in the future
- To monitor global and UK climate trends
- To attribute recent climate change to a number of possible causes, including human activities
- To advise government, industry and the media

The Hadley Centre is funded under contracts from DEFRA and the Government Meteorological Research Programme.

Contact:
Dr Geoff Jenkins,
Hadley Centre for Climate Prediction
and Research,
Met Office,
London Road,
Bracknell, RG12 2SZ, UK.
geoff.jenkins@metoffice.com
Tel: +44 1344 856653
Fax: +44 1344 854898

UK Climate Impacts Programme
www.ukcip.org.uk

The UK Climate Impacts Programme helps organisations identify how they will be affected by climate change so they can plan to adapt. The Programme was established by the Government in 1997, with the aim of providing a framework for an integrated assessment of climate change impacts. Since then it has co-ordinated stakeholder-led studies for most of the regions in England, as well as Scotland, Wales and Northern Ireland. A number of sectoral studies have also been undertaken, including research on health and nature conservation.

Contact:
Catherine Cook,
UKCIP
Union House,
12-16 St. Michael's Street,
Oxford, OX1 2DU, UK
Tel: +44 1865 432076
Fax: +44 1865 432077

ISBN 0 902170 60 0
Published by: Tyndall Centre, School of Environmental Sciences,
University of East Anglia, Norwich, UK

April 2002

Printed on Zanders Mega Matt

TCF
Printed on Recycled Paper

Design: Shorthose Russell Ltd, Norwich. Tel: 01603 785765