

UK Climate Projections science report: Climate change projections

James Murphy, David Sexton, Geoff Jenkins, Penny Boorman, Ben Booth, Kate Brown, Robin Clark, Mat Collins, Glen Harris, Lizzie Kendon, *Met Office Hadley Centre*

Annexes: Richard Betts, Simon Brown, Tim Hinton, Tom Howard, Ruth McDonald, Mark McCarthy, Richard Wood, *Met Office Hadley Centre*, Kathryn Humphrey, *Department for Environment, Food and Rural Affairs*, Ag Stephens, *British Atmospheric Data Centre*, Craig Wallace, *National Oceanography Centre*, Rachel Warren, *University of East Anglia*, Rob Wilby, *Loughborough University*

Version 3, updated December 2010

Acknowledgements

Review comments from:

Dr Richard Betts, Met Office Hadley Centre, Exeter
Dr Rachel Capon, Arup, London
Dr Vic Crisp, Chartered Institution of Building Services Engineers, London
Dr Suraje Dessai, Tyndall Centre for Climate Change Research, Norwich
Dr Bill Donovan, Environment Agency, Bristol
Dr Stephen Dye, Centre for Environment, Fisheries and Aquaculture Science, Lowestoft
Dr Clare Goodess, Climatic Research Unit, University of East Anglia, Norwich
Karl Hardy, Flood and Coastal Erosion Research Management, Defra, London
Kathryn Humphrey, Adapting to Climate Change Programme, Defra, London
Kay Jenkinson, UK Climate Impacts Programme, Oxford
Kay Johnstone, UK Climate Impacts Programme, Oxford
Prof. Phil Jones, Climatic Research Unit, University of East Anglia, Norwich
Dr Richard Jones, Met Office Hadley Centre, Exeter
Richard Lamb, UK Climate Impacts Programme, Oxford
Gerry Metcalf, UK Climate Impacts Programme, Oxford
Prof. John Mitchell, Met Office Hadley Centre, Exeter
Laurie Newton, UK Climate Impacts Programme, Oxford
Maeve O'Donoghue, Welsh Assembly Government, Cardiff
Kathryn Packer, Adapting to Climate Change Programme, Defra, London
Dr Vicky Pope, Met Office Hadley Centre, Exeter
Peter Singleton, Scottish Environment Protection Agency, Stirling
Ag Stephens, British Atmospheric Data Centre, Abingdon
Anna Steynor, UK Climate Impacts Programme, Oxford
Roger Street, UK Climate Impacts Programme, Oxford
Prof. Rowan Sutton, University of Reading
Dr Stephen Wade, HR Wallingford, Wallingford
Dr Rachel Warren, Tyndall Centre for Climate Change Research, Norwich
Dr Glen Watts, Environment Agency, Bristol
Dr Olly Watts, Royal Society for the Protection of Birds, Sandy
Dr Chris West, UK Climate Impacts Programme, Oxford
Richard Westaway, UK Climate Impacts Programme, Oxford
Prof. Rob Wilby, Loughborough University
Guy Winter, Scottish Government, Edinburgh

Second Stage International Review

Prof. Myles Allen, University of Oxford
Prof. Nigel Arnell, Walker Institute for Climate System Research, University of Reading
Dr Clare Goodess, Climatic Research Unit, UEA, Norwich
Prof. Claudia Tebaldi, Climate Central, Princeton, USA
Prof. Francis Zwiers, Climate Research Division, Environment Canada, Toronto, Canada

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

The authors would like to acknowledge the original suggestion from Professor Alan Thorpe (when Director of the Met Office Hadley Centre) for a project to quantify uncertainty using large climate model ensembles, without which the UKCP09 probabilistic projections would not have been possible.

Discussions with Prof. Jonathan Rougier, University of Bristol, have encouraged us to adopt the methodology for the UKCP09 Probabilistic Projections.

Contents

Summary	7
Purpose and design of UKCP09	7
Some examples of projected seasonal and annual changes	9
1 Introduction and overview	11
1.1 Why are climate change projections needed? Why new ones?	12
1.1.1 <i>What do we mean by probability in UKCP09?</i>	13
1.2 What information do the UKCP09 projections provide? A summary	15
1.2.1 <i>Climate change over land areas</i>	15
1.2.2 <i>Climate change over marine regions</i>	19
1.3 Uncertainty	19
1.4 Projections at a daily resolution over land	23
2 Why do we need probabilistic information? Uncertainties in climate change projections	23
2.1 Background	25
2.2 Natural variability	26
2.3 Uncertainty due to climate models	28
2.3.1 <i>Accounting for modelling uncertainty in UKCP09</i>	36
2.4 Uncertainty due to future emissions	41
2.5 Uncertainties in UKCP09 probabilistic projections and future prospects	43
2.6 References	45
3 Construction of probabilistic climate projections	47
3.1 Introduction	47
3.2 Methodology	49
3.2.1 <i>Overview</i>	49
3.2.2 <i>Process uncertainties</i>	50
3.2.3 <i>Sampling uncertainties in surface and atmospheric processes</i>	52
3.2.4 <i>Sampling uncertainties in transient climate change</i>	54
3.2.5 <i>Sampling uncertainties in additional Earth System processes</i>	58
3.2.6 <i>Combining uncertainties in different Earth System processes</i>	60
3.2.7 <i>Probabilistic projections of the equilibrium response to doubled CO₂</i>	62
3.2.8 <i>Structural model errors (discrepancy)</i>	63
3.2.9 <i>Use of climate variables to estimate discrepancy and weight projections</i>	66

continues overleaf

Contents *continued*

3.2.10	<i>Probabilistic projections of the equilibrium response to doubled carbon dioxide</i>	69
3.2.11	<i>Downscaling for UKCP09</i>	73
3.2.12	<i>Production of probabilistic projection data for UKCP09</i>	78
3.2.13	<i>Probabilistic projections for the SRES B1 and A1FI emissions scenarios</i>	81
3.3	Interpretation of UKCP09 probabilistic climate projections	81
3.4	References	86
4	Probabilistic projections of seasonal climate changes	90
4.1	Probabilistic projections as PDFs and CDFs	90
4.1.1	<i>The credibility of changes at extremes of the probability distributions</i>	92
4.1.2	<i>Consequences of having the baseline climate as 1961–1990</i>	92
4.2	Key findings	93
4.2.1	<i>National key findings</i>	93
4.2.2	<i>Regional key findings</i>	94
4.2.3	<i>Key findings for marine regions</i>	97
4.3	Maps of changes in seasonal climate	98
4.3.1	<i>Interpreting maps of probabilistic climate change</i>	98
4.3.2	<i>Projected changes to winter and summer seasonal mean temperature</i>	100
4.3.3	<i>Projections of future winter and summer seasonal mean temperature</i>	101
4.3.4	<i>Projected changes to seasonal mean temperature over marine regions</i>	102
4.3.5	<i>Projected changes to mean daily maximum temperature in summer</i>	103
4.3.6	<i>Projected changes to the warmest day of the summer</i>	103
4.3.7	<i>Projected changes to the winter and summer mean daily minimum temperature</i>	103
4.3.8	<i>Projected changes to annual-, winter- and summer-mean precipitation</i>	105
4.3.9	<i>Projected changes to the wettest day of the winter/summer by the 2080s</i>	108
4.3.10	<i>Other variables</i>	109
4.3.11	<i>Comparisons with UKCIP02</i>	109
4.4	What effect do user choices have on the probabilistic projections?	112
4.4.1	<i>How are PDFs affected by choice of emissions scenario?</i>	114
4.4.2	<i>How are PDFs affected by choice of future time period?</i>	115
4.4.3	<i>How are PDFs affected by choice of spatial averaging?</i>	115
4.4.4	<i>How are PDFs affected by choice of temporal averaging?</i>	116
4.4.5	<i>How are PDFs affected by choice of geographic location?</i>	116
4.4.6	<i>How are PDFs affected by choice of mean or extreme variables?</i>	117
4.4.7	<i>How are PDFs affected by choice of climate change or future climate?</i>	118
4.5	Probabilistic projections changing with time	119
4.6	The joint probability of the change in two variables	120
4.7	Corresponding changes in global-mean temperature	121
4.8	Variables for which probabilistic projections cannot be provided	121

Contents *continued*

5 Projections from the ensemble of regional climate models	124
5.1 Regional climate models	124
5.2 RCM experiments	126
5.3 Advantages and disadvantages of data from the RCM ensemble	126
5.4 Examples of data from the RCM ensemble	130
5.5 Some applications of RCM ensemble data	130
5.6 Reference	132
Annex 1 Emissions scenarios used in UKCP09	133
A1.1 Background	133
A1.2 Relevant work since the publication of SRES	135
A1.3 References	137
Annex 2 Sensitivity of UKCP09 projections to key assumptions	139
A2.1 Introduction	139
A2.2 Sensitivity studies	140
<i>A2.2.1 Sensitivity of results to plausible variations in the UKCP09 methodology</i>	<i>142</i>
A2.3 Comparison of UKCP09 methodology against alternative approaches	145
A2.4 Contributions to uncertainty in the UKCP09 projections	148
A2.5 Summary	153
A2.6 References	156
Annex 3 Strengths and weaknesses of climate models	157
A3.1 What are climate models?	157
A3.2 Some basic assumptions and common misconceptions in climate modelling	158
A3.3 Large-scale and small-scale processes and climate change	160
A3.4 The ability of models to represent modes of variability	164
<i>A3.4.1 The North Atlantic Oscillation</i>	<i>164</i>
<i>A3.4.2 Storm tracks and blocking</i>	<i>165</i>
A3.5 The effect of mean biases in models	168
A3.6 Discussion	169
A3.7 References	170
Annex 4 Probabilistic projection data	171
A4.1 Cumulative distribution functions	171
A4.2 Sampled data	171
Annex 5 Changes to the Atlantic Ocean circulation (Gulf Stream)	175
A5.1 How does the Atlantic Ocean circulation influence UK climate?	175
A5.2 Is the Atlantic Meridional Overturning Circulation changing?	176
A5.3 Projections of future changes in the Atlantic circulation	178
A5.4 References	180

continues overleaf

Contents *continued*

Annex 6 Future changes in storms and anticyclones affecting the UK	181
A6.1 Introduction	181
A6.2 Future changes in mid-latitude depressions	182
A6.3 Future changes in blocking	184
A6.4 Summary	185
A6.5 Reference	186
Annex 7 Urban heat island effects	187
A7.1 Causes of the Urban Heat Island and observations	187
A7.2 Future changes in the Urban Heat Island	188
A7.3 References	190

Summary

The UK Climate Projections (UKCP09) provide projections of climate change for the UK, giving greater spatial and temporal detail, and more information on uncertainty, than previous UK climate scenarios.

This report is designed for those who wish to find out more about the purpose and design of the UKCP09 methodology for producing the probabilistic projections of climate change, and is drafted to suit a range of levels of expertise. It shows some examples of projections; the full set of results is available through the User Interface and the pre-prepared maps and graphs, with key findings presented in the Briefing Report.

Purpose and design of UKCP09

- Over land, UKCP09 gives projections of changes for a number of climate variables, averaged over seven overlapping 30-yr time periods, at 25 km resolution and for administrative regions and river basins. Similar projections are given for a smaller number of variables averaged over marine regions around the UK (Chapter 1).
- UKCP09 is the first set of UKCIP projections to attach probabilities to different levels of future climate change. The probabilities given in UKCP09 represent the relative degree to which each climate outcome is supported by the evidence currently available, taking into account our understanding of climate science and observations, and using expert judgement (Chapter 1).
- The Met Office Hadley Centre has designed a methodology to provide probabilistic projections for UKCP09, based on ensembles of climate model projections consisting of multiple variants of the Met Office climate model, as well as climate models from other centres. These ensembles sample major known uncertainties in relevant climate system processes (Chapters 2 and 3).

- UKCP09 gives projections for each of three of the IPCC's Special Report on Emissions Scenarios (SRES) scenarios (A1FI (called High in UKCP09), A1B (Medium) and B1 (Low)) to show how different emissions pathways affect future climate (Chapter 2 and Annex 1). Each of the emissions scenarios suggests a different pathway of economic and social change over the course of the 21st Century; it is not possible to assign probabilities to each scenario. They do not include planned mitigation measures directly.
- For a given emissions scenario, the UKCP09 probabilistic projections account for uncertainties arising from the representation of climate processes, and the effects of natural internal variability of the climate system (Chapter 2).
- Changes to external factors such as solar activity and volcanic eruptions cannot be predicted, and are not considered (Chapter 2).
- UKCP09 projections explicitly include the climate carbon cycle feedback for the first time, and uncertainties in the feedback from the land carbon cycle. They also include the direct and first indirect effects of sulphate aerosol and uncertainties in these. Some feedbacks, such as those from the methane cycle, are not well enough understood to be included (Chapter 2).
- The UKCP09 methodology uses the Met Office regional climate model (RCM) to downscale global climate projections to a 25 km scale; uncertainties in this downscaling are also included in the probabilistic projections (Chapter 3).
- Continuous daily time series from 1950 to 2099 for 11 variants of the Met Office RCM are available via a separate project called LINK. These time series are spatially coherent between grid squares and are available over land and sea. However, being based only on Met Office models, they do not take as much uncertainty into account (Chapter 5)
- It has not been possible to produce probabilistic projections of changes in snowfall rate, and users are recommended to take these from the 11-member RCM ensemble (Chapter 4)
- The current observed strength of the Urban Heat Island effect is included in the projections of future climate, but possible changes in the strength of the Urban Heat Island in the future cannot yet be included (Annex 7).
- It is unlikely that an abrupt change in the Atlantic Ocean Circulation will occur this century. The effects of a gradual weakening of the circulation over time are included in the UKCP09 climate projections (Annex 5).
- Models will never be able to exactly reproduce the real climate system; nevertheless there is enough similarity between current climate models and the real world to give us confidence that they provide plausible projections of future changes in climate (Annex 3).
- There is a cascade of confidence in climate projections, with moderate confidence in those at continental scale; those at 25 km resolution are indicative to the extent that they reflect large-scale changes modified by local conditions such as mountains and coasts. The level of confidence is different for different variables.

- Errors in global climate model projections cannot be compensated by statistical procedures no matter how complex, and will be reflected in uncertainties at all scales.

Some examples of projected seasonal and annual changes

We summarise in the box below some changes by the 2080s with Medium emissions, but stress that projections can be very different for other time periods and other emissions scenarios. Users should look at the time period appropriate for their decisions, and examine projections for all three emissions scenarios, to gain a full appreciation of changes to which they might have to adapt.

Summer, winter and annual mean changes by the 2080s (relative to a 1961–1990 baseline) under the Medium emissions scenario. Central estimates of change (those at the 50% probability level) followed, in brackets, by changes which are very likely to be exceeded, and very likely not to be exceeded (10 and 90% probability levels, respectively).

- All areas of the UK warm, more so in summer than in winter. Changes in summer **mean temperatures** are greatest in parts of southern England (up to 4.2°C (2.2 to 6.8°C)) and least in the Scottish islands (just over 2.5°C (1.2 to 4.1°C)).
- **Mean daily maximum temperatures** increase everywhere. Increases in the summer average are up to 5.4°C (2.2 to 9.5°C) in parts of southern England and 2.8°C (1 to 5°C) in parts of northern Britain. Increases in winter are 1.5°C (0.7 to 2.7°C) to 2.5°C (1.3 to 4.4°C) across the country.
- Changes in the **warmest day of summer** range from +2.4°C (–2.4 to +6.8°C) to +4.8°C (+0.2 to +12.3°C), depending on location, but with no simple geographical pattern.
- **Mean daily minimum temperature** increases on average in winter by about 2.1°C (0.6 to 3.7°C) to 3.5°C (1.5 to 5.9°C) depending on location. In summer it increases by 2.7°C (1.3 to 4.5°C) to 4.1°C (2.0 to 7.1°C), with the biggest increases in southern Britain and the smallest in northern Scotland.
- Central estimates of **annual precipitation** amounts show very little change everywhere at the 50% probability level. Changes range from –16% in some places at the 10% probability level, to +14% in some places at the 90% probability level, with no simple pattern.
- The biggest changes in **precipitation in winter**, increases up to +33% (+9 to +70%), are seen along the western side of the UK. Decreases of a few percent (–11 to +7%) are seen over parts of the Scottish highlands.
- The biggest changes in **precipitation in summer**, down to about –40% (–65 to –6%), are seen in parts of the far south of England. Changes close to zero (–8 to +10%) are seen over parts of northern Scotland.

- Changes in the **wettest day of the winter** range from zero (–12 to +13%) in parts of Scotland to +25% (+7 to +56%) in parts of England.
- Changes in the **wettest day of the summer** range from –12% (–38 to +9%) in parts of southern England to +12% (–1 to +51%) in parts of Scotland.
- **Relative humidity** decreases by around –9% (–20 to 0%) in summer in parts of southern England — by less elsewhere. In winter changes are a few percent or less everywhere.
- **Summer-mean cloud amount** decreases, by up to –18% (–33 to –2%) in parts of southern England (giving up to an extra +20 Wm⁻² (–1% to +45 Wm⁻²) of downward shortwave radiation) but increase by up to +5% (zero to +11%) in parts of northern Scotland. Changes in cloud amount are small (–10 to +10%) in winter.

- Projected changes in **storms** are very different in different climate models. Future changes in anticyclonic weather are equally unclear (Annex 6).
- We have been unable to provide probabilistic projections of changes in **snow**. The Met Office Hadley Centre regional climate model projects changes in winter mean snowfall of typically –65% to –80% over mountain areas and –80% to –95% elsewhere.
- We make no assessment of how the **Urban Heat Island** effect may change (Annex 7).
- It is very unlikely that an abrupt change to the Atlantic Ocean Circulation (**Gulf Stream**) will occur this century (Annex 5).
- UKCP09 provides a state-of-the-art basis for assessing the risk of different outcomes consistent with current climate modelling capability and understanding. As our understanding, and our modelling and statistical capabilities, improve in future, the projections are very likely to change (Chapter 3 and Annex 2).
- UKCP09 projections are appropriate for decisions on adapting to long-term climate change which need to be taken on the basis of current knowledge (Chapter 2).