



University of  
**Reading**

Developing H++ climate  
change scenarios for heat  
waves, droughts, floods,  
windstorms and cold  
snaps

Adaptation Sub-Committee

October 2015

Authors:

Steven Wade, Michael Sanderson, Nicola Golding, Jason Lowe and Richard Betts, Met Office

Nick Reynard, Alison Kay, Lisa Stewart and Christel Prudhomme, Centre for Ecology and Hydrology (CEH)

Len Shaffrey, Ben Lloyd-Hughes and Ben Harvey, University of Reading

Internal reviewers:

Simon Brown (Met Office); Helen Hanlon (Met Office)

This report has been produced by the Met Office, University of Reading and CEH for the Adaptation Sub-Committee and to support the second Climate Change Risk Assessment (CCRA).

Acknowledgements

A number of colleagues have provided valuable inputs to the early and final drafts including Sarah Johnson (Met Office), Lizzie Kendon (Met Office), Julia Slingo (Met Office), Kathryn Humphrey (ASC) and Manuela di Mauro (ASC). Prof Brian Hoskins (Imperial College London) and Peter von Lany (Ch2M Hill), provided very useful comments as peer reviewers at the draft stage.

In addition, members of the Project Steering Group have provided useful inputs throughout the project: Amanda Charles (GO-Science), Claudette Thompson (Cabinet Office), Edward Foale (Cabinet Office), David Ramsbottom (HR Wallingford), Tracey Dunford (Natural Resources Wales), Zhong Zhang (Natural Resources Wales), Paul Dunhill (Welsh Government), Melanie Harrowsmith (Met Office), Helen Balmforth (Health and Safety Laboratory), Ken Wright (DECC), Mike Thompson (Environment Agency), Zebedee Nii-Naate (Defra), Patrick Cowdy (Welsh Government), Ragne Low (Edinburgh University), Helen Reeves (BGS), Simon Sharpe (FCO), Tim Reeder (Environment Agency), Glenn Watts (Environment Agency), Rosalind West (Defra), Kathryn Humphrey (CCC), Manuela DiMauro (CCC), Daniel Johns (CCC) and Steve Smith (CCC).

## Contents

<b>Summary</b> .....	<b>iii</b>
Guidance on the use of H++ scenarios .....	iv
Summary of H++ scenarios .....	v
<b>Chapter 1 Introduction</b> .....	<b>1</b>
1.1 Project background.....	1
1.2 What is the H++ concept?.....	1
1.3 Guidance on using H++ .....	3
1.4 Approach .....	5
<b>Chapter 2 Heat waves</b> .....	<b>8</b>
2.1 Summary of the High++ Hot Day and Heat Wave Scenarios .....	8
2.2 Historical data.....	9
2.3 UKCP09.....	14
2.5 Physical limits .....	14
2.4 Other evidence .....	15
2.6 H++ scenarios.....	16
<b>Chapter 3 Low rainfall</b> .....	<b>21</b>
3.1 Summary of the High ++ low rainfall scenarios .....	21
3.2 Historical data and methods.....	22
3.3 UKCP09.....	31
3.4 Evidence from CMIP5 climate models .....	33
3.5 Physical limits .....	38
3.6 Other evidence .....	39
3.7 Summary of H++ scenarios.....	40
<b>Chapter 4 Low flows</b> .....	<b>41</b>
4.1 Summary of the H++ low flow scenarios .....	41
4.2 Historical data and methods.....	42
4.3 UKCP09.....	50
4.4 Physical limits .....	50
4.5. Other evidence .....	50
4.6 H++ scenarios.....	52
<b>Chapter 5 High rainfall</b> .....	<b>54</b>
5.1 Summary of the High ++ high rainfall scenarios .....	54
5.2 Historical observations .....	55

5.3 UKCP09.....	63
5.4 Evidence from CMIP5 and other climate models.....	67
5.5 Physical limits .....	70
5.6 Other evidence .....	71
5.7 H++ scenarios.....	72
<b>Chapter 6 High flows.....</b>	<b>75</b>
6.1 Summary of the High ++ ‘high flow’ scenarios.....	75
6.2 Background .....	75
6.3 Approach .....	76
6.4 Physical limits .....	78
6.5 Review of other evidence.....	78
6.6. H++ scenarios.....	82
<b>Chapter 7 Windstorms .....</b>	<b>85</b>
7.1 Summary of the H++ windstorm scenario .....	85
7.2 Historical data.....	85
7.3 UKCP09.....	89
7.4 Evidence from CMIP5 models.....	89
7.5 Physical limits .....	95
7.6 Summary on Windstorms.....	95
<b>Chapter 8 Cold snaps .....</b>	<b>97</b>
8.1 Summary of L-- cold snap and cold winter scenarios .....	97
8.2 Historical data.....	98
8.3 UKCP09.....	106
8.4 Physical limits .....	107
8.5 Other evidence .....	110
8.6 L-- cold scenarios .....	110
<b>Chapter 9 Other hazards, wildfires and combined events .....</b>	<b>114</b>
9.1 Other hazards.....	114
9.2 Systemic risks.....	114
9.3 Wildfires.....	115
<b>Chapter 10 References .....</b>	<b>124</b>
<b>Annex 1 Caveats and guidance.....</b>	<b>140</b>
<b>Annex 2 Data Sources .....</b>	<b>142</b>

## Summary

This report describes the results of a project to investigate the development of plausible high-end climate change scenarios for potential use in the 2016 UK Climate Change Risk Assessment (CCRA) Evidence Report. It covers the following climate hazards: heat waves, cold snaps, low and high rainfall, droughts, floods and windstorms. The scope of the project does not extend into defining the consequences of these hazards such as mortality, property damage or impacts on the natural environment.

The scenarios created for this report are referred to as H++ scenarios, and are typically more extreme climate change scenarios on the margins or outside of the 10<sup>th</sup> to 90<sup>th</sup> percentile range presented in the UKCP09 projections (Murphy et al., 2009). For each hazard considered, H++ information is presented alongside selected indicators from UKCP09 or a range of possible changes from selected global models from the Climate Model Inter-comparison Project (CMIP5) archive (Table S1 and Sections 2 to 8).

The 2016 CCRA Evidence Report is being delivered to the UK Government by the Adaptation Sub Committee of the Committee on Climate Change. In 2012, the previous CCRA Evidence Report (Wade et al., 2012) described the potential impacts of climate change based largely on the UKCP09 projections. Although it considered High emissions scenarios<sup>1</sup>, it did not include H++ scenarios. In some sections and in the overall summary of risks the report focused only on the Medium emissions scenario<sup>2</sup>.

In the context of the second CCRA, H++ scenarios can help to more fully explore the potential consequences of climate change and flexibility of current and future adaptation plans. This consideration of low probability, high impact risks is a fundamental component of good risk management, and this applies as much to climate change as it does to other types of risks (King et al., 2015)<sup>3</sup>. These kinds of scenarios can be used for sensitivity testing different adaptation options against an extreme level of risk, which

---

<sup>1</sup> The CCRA considered Low (SRES B1), Medium (SRES A1B) and High (SRES A1FI) Emissions and the 10 % to 90 % probability levels to define upper and lower limits of possible changes as well as range of population scenarios.

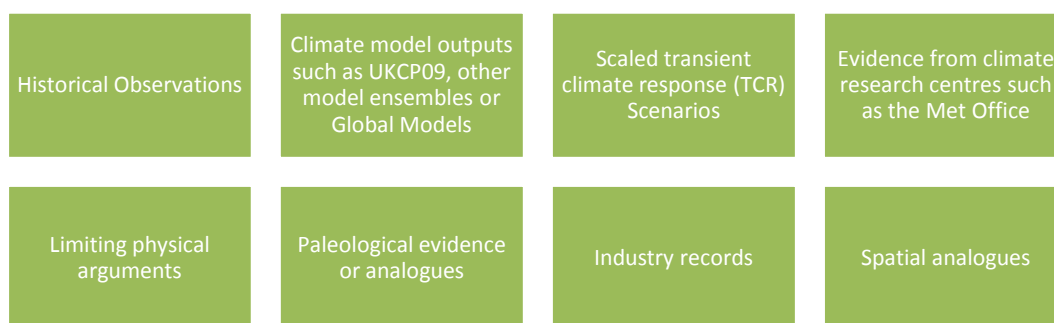
<sup>2</sup> The key summary 'onset plots' of threats and opportunities used the Medium emissions scenario, whereas the more detailed 'scorecards' considered the full range.

<sup>3</sup> This report prepared jointly by experts representing the UK, US, China and India recommends that the general principles of risk assessment should be applied to climate change risk assessments. These include, among other things, "finding out more about the worse-case scenarios in relation to long-term changes as well as short-term events, and assessing the full range of probabilities, bearing in mind that a low-probability event may correspond to a very high risk, if the impact is catastrophic".

is useful for long term climate change adaptation planning<sup>4</sup>. These more extreme scenarios cannot be ruled out based on current understanding and may occur at some point in the future. They are often not tied to a specific time frame (e.g. 2080s), or a given level of global temperature rise from a defined baseline (e.g. 6°C).

The H++ scenarios developed in this report are based on information from different evidence sources. Some were based on simply looking further into the tails of the uncertainty distributions of UKCP09 than was the case in CCRA1, but many also include evidence from historical observations, global and regional climate models, and/or consideration of limiting physical arguments. They all include some expert opinion, if only on the choice of evidence strands to include.

#### *Evidence sources considered for the development of H++ scenarios*



The best example of the use of H++ scenarios for adaptation planning to date is the Thames Estuary 2100 project<sup>5</sup>. It used a H++ sea level rise and storm surge scenario to help policy makers to think in more detail about flexible adaptation strategies and to support engineers to implement plans that will help protect London from any plausible increase in coastal flood risk up to 2100 (Ranger, Reeder and Lowe, 2013). This project is the first step in a feasibility study to consider extending the idea of the H++ scenario from the original work done for sea level rise and storm surge to other types of climate hazards.

### ***Guidance on the use of H++ scenarios***

Including information on plausible but extreme risks is an important component of robust risk management practice (King et al., 2015). We advocate using H++ scenarios in climate change risk assessments to help to provide a high impact, low likelihood event to

<sup>4</sup> Typically the upper end of a H++ scenario has a low probability but it is difficult and often impossible to reliably quantify this probability.

<sup>5</sup> This is written up in the UKCP09 Marine Projections and available on the UKCP09 web site <http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=87906&filetype=pdf>

compare against more likely outcomes. In making their assessment, decision makers need to consider the full range of possibilities, and then consider their own specific appetite for risk in making a decision on what actions to take. This means that H++ scenarios should not be used in isolation. Instead they should be used alongside estimates of the more likely range of future outcomes, for instance from the likely range or 10<sup>th</sup> to 90<sup>th</sup> percentile range of UKCP09 or CMIP5 models as well as information on impacts, adaptation and vulnerability.

H++ scenarios can be useful scenarios for identifying a wide range of adaptation options or adaptation pathways and discovery of the 'limits to adaptation'. They may help to identify specific types of adaptation, for example flexible plans that can be adjusted if rates of warming are greater or less than anticipated or used to highlight the importance of monitoring to understand trends or rates of change. They could be useful for screening risks or to set the boundaries for more detailed sensitivity analysis, impacts assessment or risk assessment studies. Further work is needed to explore how H++ might be used alongside a range of existing decision making approaches.

### ***Summary of H++ scenarios***

The following table summarises the H++ scenarios for each hazard and compares it with selected indicators covering a more likely range of possible outcomes. Some of scenarios relate to 30 year average conditions, whereas others relate to single years or events (long droughts). The type of scenario is indicated in Table S1 and explained in the relevant chapter. Following feedback we also use the term L-- specifically for the 'cold snap' scenario to emphasise that it is at the opposite end of the scale to the extreme warm summer temperatures in H++ and linked to Low emissions. The methodologies and conceptual framing for H++ and L-- are similar.

Some of these changes, such as summer heat waves, are much more extreme than is currently experienced and at the margins or beyond the 2080s UKCP09 High Emissions projections. Other scenarios, such as long droughts, have magnitudes that are more in line with current experience. The choice of H++ scenarios reflects the best evidence available and limitations of current climate models; it is possible that ongoing projects, such as the current NERC Drought programme, identify more extreme plausible scenarios and these should not be ruled out based on this assessment.

**Table S1: A summary of the H++ scenarios presented in this report and comparisons to selected indicators from UKCP09, selected CMIP5 models or the Climate Change Risk Assessment 2012. (Event based or annual average scenarios are marked with the symbol:\*. All other scenarios relate to 30 year means).**

Hazard	Scenario	Scenario description	Main basis
Heat waves	*H++	<ul style="list-style-type: none"> <li>* Annual average summer maximum temperatures exceeding 30°C over most of the UK and 34°C over much of central and southern England.</li> <li>* Hottest days would exceed 40°C in some locations, with 48°C being reached in extreme cases.</li> </ul>	Historical data, particularly anomalies related to the hot summers of 1976 and 2003; UKCP09 High emissions scenario, 90% probability level. <i>Explicit consideration of the Urban Heat Island effect was excluded.</i>
	UKCP09 High Emissions	Average summer maximum temperatures in most of England and Wales are around 14 to 22 °C (1961-1990). Under the UKCP09 2080s High emissions scenario, at the 90% probability level and regional scale, summer 30-year mean maximum temperatures are projected to be 8-9°C warmer than 1961-1990. (22 to 31 °C in most of England and Wales), but the hottest day could be 10-12°C warmer (24 to 34 °C in most of England and Wales).	UKCP09 Trends Report Figure 2.12 gridded data.  UKCP09 projections (This report Section 3.3) administrative regions <a href="http://ukclimateprojections.metoffice.gov.uk/23673?emission=high">http://ukclimateprojections.metoffice.gov.uk/23673?emission=high</a>
Low rainfall	*H++	<ul style="list-style-type: none"> <li>* A 6 month duration summer drought with rainfall deficits of up to 60% below the long term average (1900-1999).</li> <li>* Longer dry periods spanning several years with rainfall deficits of up to 20% below the long term average (1900-1999) across all of England and Wales, similar to the most severe and extensive long droughts in the historical record.</li> </ul>	Historical data, particularly the UK regional precipitation series (HadUKP); selected Coupled Model Inter-comparison Project (CMIP5) climate models; calculation of rainfall deficits over a range of time periods from 6 months to 5 years. <i>See note below on interpretation of these deficits.</i>
	CMIP5 range	* The CMIP5 baseline indicates maximum 6 month summer rainfall deficits across England and Wales of 50% below normal. CMIP5 future projections indicate a wide spread in possible 6 month summer drought severities. These may increase up to a maximum reduction of 60% below normal, or decrease to a maximum reduction of 30% below normal. No change in winter or longer duration droughts. UKCP09 does not provide drought indices.	England and Wales Precipitation (EWP). See Figure 4.4. Selected CMIP5 models. See Section 4 and Figure 4.10. <i>The baseline is 1900-1999 rather than 1961-90. These scenarios cannot be compared directly to deviations from a 1961-1990 baseline or data for smaller areas or maps with gridded data. A large average deficit across England and Wales indicates the potential for much larger local deficits.</i>
Low river flows	*H++	<ul style="list-style-type: none"> <li>* A 40-70 % reduction in 'low flows' (Q95) in England and Wales in a single summer.</li> <li>* For multi-season droughts, including 2 summers, a 20 to 60 % reduction in low flows in England and Wales.</li> </ul>	Historical data; selected Coupled Model Inter-comparison Project 5 (CMIP5) climate models used for low rainfall; use of case studies and sensitivity analysis to estimate impacts of rainfall deficits on flows. <i>The baseline is 1900-1999 rather than 1961-90.</i>
	CCRA1/ UKCP09 High Emissions	In Anglian Region for 2080s High emissions scenario, changes in annual Q95 from -38% to -70% with less severe reductions elsewhere, e.g. -13% to 33% in Orkney and Shetland.	Based on the results of water company studies (using a 1961-1990 baseline). <i>The H++ scenarios cannot be compared directly to results from smaller areas or different baselines.</i>
High	H++	A 70%-100% increase in winter rainfall	Historical data; UKCP09 High



Hazard	Scenario	Scenario description	Main basis
rainfall		(Dec to Feb) from a 1961-1990 baseline. An up to five-fold increase in frequency and 60% to 80% increase in heavy daily and sub-daily rainfall depths, for both summer and winter events (all year round).	emissions; high resolution climate modelling; physical processes i.e. the Clausius-Clapeyron relationship between temperature and rainfall.
	UKCP09 High Emissions	A 6% to 58% increase in winter rainfall (Dec, Jan, Feb) for London (1961-1990 baseline) with greater increases elsewhere. <i>Note that UKCP09 did not indicate increases in heavy summer rainfall.</i>	UKCP09 10% to 90% probably levels. See UKCP09 web site: <a href="http://ukclimateprojections.metoffice.gov.uk/23674?emission=high">http://ukclimateprojections.metoffice.gov.uk/23674?emission=high</a>
High river flows	H++	A 60% to 120% increase in peak flows at the 'lower end' of the H++ scenarios for some regions in England and Wales. The upper limit for any region is a 290% increase in peak flows (1961-1990 baseline). <i>The scenarios are based on the average response of "Enhanced-high" catchments, which are particularly sensitive to increases in rainfall.</i>	Historical data; Flood Estimation Handbook; UKCP09 High emissions; based on detailed hydrological modelling completed for the Environment Agency. Scenarios are presented for all major UK river basins.
	UKCP09	A 5% to 70% increase in peak flows in the River Thames basin (1961-1990 baseline). (The typical 'change factor' used in flood risk studies was +20%, see Section 7.2)	Analysis using UKCP09 sampled data. Low Emissions 10% probability level to High Emissions 90% probability level (Kay, <i>pers. comm.</i> )
Wind storms	H++	A 50-80% increase in the number of days per year with strong winds over the UK (1975-2005 baseline). <i>A strong wind day is defined as one where the daily mean wind speed at 850 hPa, averaged over the UK (8W-2E, 50N-60N), is greater than the 99th percentile of the historical simulations.</i>	Historical data, selected Coupled Model Inter-comparison Project 5 (CMIP5) climate models; UKCP09. <i>The caveat is that CMIP5 climate model simulations contain biases in the position of North Atlantic storm track and systematically under-represent the number of intense cyclones.</i>
	CMIP5	A change in number of days per year with strong winds over the UK between -20% to +40%.	Analysis using a sub-set of CMIP5 models and estimating 10% and 90% probability levels for RCP4.5 emissions. Baseline is 1975-2005.
Cold snaps	*L--	* In the 2020s, UK average winter temperatures (December, January and February) of 0.3°C and for the 2080s, UK average winter temperatures would be around -4°C. * In the 2020s, UK average temperatures on the coldest day would be -7°C in some locations. UK average temperature of the coldest day would be around -11°C.	Historical data, particularly the cold winter of 1962/63; UKCP09 Low emissions scenario 10% probability level; a slowdown or collapse of the Atlantic Meridional Overturning Circulation by 2080s and reductions in solar output. <i>Short-term cooling due to volcanic activity was excluded.</i> (Section 8).
	UKCP09 Low Emissions	Annual average winter temperatures for most of England and Wales are around +2 to +4 °C (1961-1990). Under the Low emissions scenario, at the 10 % probability level and regional scale, 30-year average winter (Dec-Jan-Feb) warming is 0.2 to 0.5 °C in the 2020s and 1.0 to 1.4°C in 2080s above 1961-90.	UKCP09 Trends Report Figure 2.3 gridded data  UKCP09 projections (This report Section 2.3) administrative regions. <a href="http://ukclimateprojections.metoffice.gov.uk/23672?emission=low">http://ukclimateprojections.metoffice.gov.uk/23672?emission=low</a>

# Chapter 1 Introduction

This report describes the development of H++ scenarios for use in the UK Climate Change Risk Assessment Evidence Report, which is being delivered by the Adaptation Sub Committee. It covers heat waves, cold snaps, low and high rainfall, droughts, floods and windstorms.

This chapter provides some background to the project and outlines the concept and use of H++ scenarios. Subsequent chapters present the analysis and description of each H++ scenario for the climate hazards considered. The evidence used is based on historical observations, climate model outputs, limiting physical factors that constrain future changes and, in some cases, key thresholds that are important for impacts and adaptation.

## ***1.1 Project background***

Prior to this project, two specific studies have advanced the idea of H++ scenarios. Firstly, a H++ scenario for sea level rise and tidal surge was included as an output in the 2009 UK Climate Projections and then used for the Thames Estuary (TE2100) project. Secondly, regional H++ peak flow scenarios were developed by the Environment Agency and included in advice for flood risk managers<sup>6</sup>.

The first Climate Change Risk Assessment (CCRA) published in 2012, made reference to the H++ scenarios for sea level rise and tidal surge but did not use this in its assessment of coastal flooding, or extend the idea of an H++ scenario to other extreme events such as river and surface water flooding, drought, heat waves and cold snaps.

## ***1.2 What is the H++ concept?***

A H++ scenario can be envisaged as a 'high end' range of a change in the frequency, intensity or magnitude of a particular climate metric or hazard. In this project it is typically beyond both the likely range and 10<sup>th</sup> to 90<sup>th</sup> percentile range of climate futures described by the UKCP09 approach. The H++ scenario has an evidential basis that

---

<sup>6</sup> Environment Agency. Advice for Flood and Coastal Erosion Risk Management Authorities. September 2011. See <https://www.gov.uk/government/publications/adapting-to-climate-change-for-risk-management-authorities>

cannot be ruled out based on current understanding *and that may occur at some point in the future, and may or may not be tied to a specific time frame (e.g. 2020s, 2050s or 2080s)* (Table 1.1). With the exception of cold snaps, the high end scenarios are associated with the High Emission scenarios, which typically do not consider climate mitigation policy and have emissions growing into the future. Such scenarios typically do not have precise probabilities associated with them but are at the extreme end of the range and are assumed to be of very low probability. The difficulty in assigning a probability is partly due to gaps in understanding how the climate system works and also due to uncertainty in which emissions future will be followed. The H++ scenario can be considered to consist of both the numerical information on future change, and the narrative information on why certain strands of evidence have been chosen and the confidence in that evidence. Expert judgement is a key part of the H++ scenario development. The existence of H++ has encouraged policy makers to think in more detail about flexible adaptation strategies and limits to adaptation (Ranger, Reeder and Lowe, 2013). In particular, in the context of the second CCRA consideration of H++ scenarios can help to fully explore the consequences of extreme events outside of the ranges considered in the first assessment (Wade et al., 2012). Following feedback we also use the term L-- to describe the cold snap scenario, in order to emphasise that it is at the opposite end of the scale to the extreme warm summer temperatures in H++. The methodologies and conceptual framework for H++ and L-- are similar and they are often both referred to as H++ type events.

There will always be uncertainty associated with projections of future climate variability and change. Techniques (such as the ASK method<sup>7</sup> or UKCP09<sup>8</sup> approach) can be used to estimate some of the uncertainty by comparing model outputs against observations, and by comparing the outputs of different models against each other. This uncertainty can then be described by means of a formal probability distribution, which allows risk based decision making to be considered.

The starting point for considering H++ scenarios is often to look further into the tails of the distributions from available climate model projections, such as looking beyond the 90<sup>th</sup> percentile in UKCP09. However, there are reasons to believe that some models may not be reliable in these more extreme regimes, for instance because of limitations in the

---

<sup>7</sup> The likelihoods of future changes are estimated by scaling the response to historical climate forcings as simulated by a model and using the scaling factors to adjust the future predictions by the same model. The basic assumption is that if a climate model under/overestimates the response to past climate forcings as compared with observed climate changes, then it will also under/overestimate the response to future forcings provided the forcings remain similar. For example see Allen et al (2000)

<sup>8</sup> Further background on UKCP09 is available from: <http://ukclimateprojections.metoffice.gov.uk/21678>

range over which components of the climate models have been designed to operate or because of known or unknown missing processes. While the models provide useful information the H++ and L-- approach also considers other strands of evidence, such as palaeo results, to give a range of high-end or low-end estimates. The number and choice of different evidence strands used will be dictated by data availability and the expert judgement of the scientists constructing the scenario. Where available information on the confidence of different evidence streams is available it may also be used as part of the process.

What H++ is	What H++ is not
<ul style="list-style-type: none"> <li>• A range of values in the tail of the uncertainty distribution</li> </ul>	<ul style="list-style-type: none"> <li>• A projection of the likely future outcome</li> </ul>
<ul style="list-style-type: none"> <li>• A range suitable for sensitivity testing and investigation of no-regrets options</li> </ul>	<ul style="list-style-type: none"> <li>• A single value</li> </ul>
<ul style="list-style-type: none"> <li>• A process for combining information from different sources (not from just a single model framework)</li> </ul>	<ul style="list-style-type: none"> <li>• The maximum value possible or worst case scenario</li> </ul>
<ul style="list-style-type: none"> <li>• A tool to encourage planners and practitioners to think about their risk appetite and where crossing a specific threshold has a large impact</li> </ul>	<ul style="list-style-type: none"> <li>• Typically although H++ is known to be in the tail of the uncertainty distribution it is usually not possible to specify a precise probability for components of H++</li> </ul>

**Table 1.1: Explaining H++ scenarios**

### **1.3 Guidance on using H++**

Including information on extreme risks is an important component of robust risk management practice. Very often, climate change risk assessments in the past in the UK (including CCRA1) have focussed on a central estimate of potential future change, and ignore the tails of the uncertainty distribution. Consequently, this means that low likelihood, high impact events are not considered in decision making related to adapting to climate change. In comparison, other assessments such as the Cabinet Office’s National Risk Assessment deliberately focus on a low likelihood, high impact event, specifically “*the maximum scale, duration and impact, that could reasonably be expected to occur*”, but do not consider the longer time periods of importance to CCRA2.<sup>9</sup>

<sup>9</sup> <https://www.gov.uk/risk-assessment-how-the-risk-of-emergencies-in-the-uk-is-assessed>

During the Thames Estuary 2100 (TE2100) project the H++ scenario range was used alongside UKCP09 scenarios. In this case “H+” and “H++” scenarios were developed and used to explore and select the best options for long term flood risk management. The final strategy was flexible; a selected programme of work was designed to protect London against floods risks under central climate change estimates to beyond 2100 (to cover the full design life of structures) but these options can be adapted to protect London from the H++ scenario (Ramsbottom, *pers. comm.*).

To bring climate change risk management more in line with other types of risk management (King et al, 2015), H++ type scenarios should therefore be used in climate change risk assessments to help to provide a high impact, low likelihood event to compare against more likely outcomes. In making their assessment, decision makers need to consider the full range of risk, and then consider their own specific appetite for risk in making a decision on what actions to take to manage the risk. This means that H++ scenarios should not be used in isolation. Instead they should be used alongside estimates of the more likely range of future outcomes, for instance from the likely range or 10<sup>th</sup> to 90<sup>th</sup> percentile range of UKCP09 or CMIP5 models as well as information on impacts, adaptation and vulnerability.

The specific benefits of H++ scenarios will depend on the adaptation planning methods in different sectors, however, in general:

- They can be useful scenarios for exploring long term climate change, identifying a wide range of adaptation options or adaptation pathways and discovery of the ‘limits to adaptation’.
- They may help to identify specific types of adaptation, for example flexible plans that can be adjusted if rates of warming are greater or less than anticipated or used to highlight the importance of monitoring to understand trends or rates of change.
- They could be useful for screening risks or to set the boundaries for more detailed sensitivity analysis, impacts assessment or risk assessment studies.

An important issue for users of H++ is to consider what early warning could be put in place to detect if the real world climate is deviating from the likely projected range and heading towards the H++ or L-- values. In some cases the change may result from abrupt events and so the amount of early warning may be limited but still potentially

useful. In many cases the onset might be much slower. For some H++ cases existing observing systems, for instance for temperature or sea level, might be utilised.

The H++ type scenarios outlined in this report only consider changes in climate hazards; i.e. the frequency, intensity or magnitude of a weather-related event. It has not been possible with the resources available to extend these scenarios into describing the consequences of such events such as the impact on mortality, property damage or impacts on the natural environment. Further work to consider these consequences would be useful to give a fuller picture of the impact of such scenarios. In particular, some consideration of consequences is needed by the authors of the CCRA2, to give a sense of how they compare to more likely outcomes. Some of this work has been carried out in two of the other research projects funded to input into CCRA2 that are available alongside this report, on projections of flood risk, and projections of future water availability.

Finally we note that a key part of future planning is communication, both of the threats and opportunities of climate variability and change and of the decisions that are made when developing adaptation plans. We strongly recommend where possible that the H++ and L-- scenarios are communicated alongside the likely range and following a clear discussion of the concepts of low probability high impact events. The purpose of including these scenarios should be made clear to all involved stakeholders. Limitations and caveats related to the use of H++ concepts are discussed in Annex 1, which also includes further draft guidance on their use in the CCRA and elsewhere.

## **1.4 Approach**

In this feasibility study of developing H++ type scenarios we first decided on a structured approach for including a range of different types of evidence. This was based on experience from developing the earlier sea level H++ scenarios and expert judgement of the science leads in the project. The strands of evidence considered are summarised in the diagram below (Figure 1.1). Expert judgement forms a key ingredient in both selecting the evidence sources and ensuring data sources are used sensibly, and providing a means of combining evidence or dealing with conflicting evidence. If a confidence level can be assigned to the evidence strands this can form part of the H++ type scenario. The scale of confidence ratings is guided by that of the IPCC (Mastrandea et al, 2010), where very high confidence corresponds to their being both

robust evidence and agreement between sources and very low confidence means there is either limited evidence or poor agreement between evidence.

Historical Observations	<ul style="list-style-type: none"> <li>This aims to identify the 'biggest known events' in the historical record (magnitude, location, extent, duration). It also forms a key communications tool for H++ type scenarios and provides a sanity check on all other evidence sources.</li> </ul>
UKCP09, other model ensembles or Global Models	<ul style="list-style-type: none"> <li>UK Climate Projections (UKCP09) distribution tails - while most focus has been on the full distribution here we recommend looking in the tails of the probability distribution and local outliers of the regional climate model (RCM) simulations. If using the sample data product the largest number of samples should be used.</li> <li>Other Global Models, especially the Coupled Model Intercomparison Project (CMIP5) range up to 2100 - these are structurally different to the Met Office HadCM3 model used in UKCP09 and so may perform differently. However, the ensemble has not been set up to sample uncertainty so should be used with caution. This also includes experiments designed to test particular physical mechanisms, such as a collapse of the AMOC.</li> </ul>
Scaled TCR Scenarios	<ul style="list-style-type: none"> <li>This involves translation of CMIP5 extended Representative Concentration Pathway (RCP) experiments as an analogue for higher Transient Climate Response (TCR) or greater radiative forcing. Upper limits for TCR will be taken from multiple evidence strands in the IPCC 5th assessment.</li> </ul>
Evidence from Met Office & other climate research centres	<ul style="list-style-type: none"> <li>These often involve single simulations of high resolution climate or impact models or creation of new datasets, for example Kendon et al 2014.</li> </ul>
Limiting physical arguments	<ul style="list-style-type: none"> <li>There may be limiting physical arguments which bound the extent of potential future outcomes. Consideration of these will also serve to provide a sanity check on the rest of the analysis.</li> </ul>
Paleo evidence or analogues	<ul style="list-style-type: none"> <li>We will include evidence from studies of tree rings, lake sediments and evidence of coastal or river erosion where these are relevant.</li> </ul>
Industry records	<ul style="list-style-type: none"> <li>Some industries such as energy, transport and water may hold valuable independent records relevant to this analysis. Access to these will be sought where relevant.</li> </ul>
Spatial analogues	<ul style="list-style-type: none"> <li>For some analyses, consideration of spatial analogues may be useful to provide context. However, issues of consistency will need to be taken into account, e.g. analogues based on temperature alone may select weather regimes with very different conditions to the UK under current and future conditions.</li> </ul>

**Figure 1.1: Structured approach - consideration of data sources**

Each Hazard was then assigned to a lead scientist who was asked to apply the H++ methodology as they understood it, and as time allowed. For each hazard the leads were each asked to consider:

- The most appropriate source(s) of data for scenario generation, e.g. UKCP09 or CMIP5 models

- Existing research, particularly impacts modelling and links with other projects funded by the ASC to inform the CCRA (on water resources, floods and ecological impacts) to ensure consistency in the approaches used
- Information on relevant thresholds that are important for impacts assessment (where possible)

Each source of evidence has been reviewed and evaluated in terms of its contribution to the development of the H++ scenario. Where climate models are the primary source of information, an assessment was made of their level of skill and where appropriate caveats are highlighted at the beginning of each section.



## Chapter 2 Heat waves

### **2.1 Summary of the High++ Hot Day and Heat Wave Scenarios**

The H++ hot day and heat wave scenarios span a range of time scales (1 day to a season) and encompass the entire UK. The time scales of the H++ scenarios are relevant for a variety of purposes. Mortality is elevated during heat waves, especially among the elderly (Hajat et al., 2014). Infrastructure can be affected by hot temperatures – for example, buckling of railway tracks (Dobney et al., 2009). Periods of very high temperatures are also often accompanied by little or no rainfall, leading to drought conditions and placing even greater demand on the water supply system (Chapter 5).

Future summers, heat waves and hot temperatures in the UK are likely to be hotter and last longer than present day events. Under the UKCP09 2080s High Emissions scenario at the 90% probability level and regional scale, 30-year average UK regional summer temperatures are 6.0°C to 8.1°C warmer than the 1961-1990 baseline<sup>10</sup>. These changes were considered along with data from the 1976 and 2003 hot summers/heat waves to derive H++ scenarios for hot summers, heat waves and hottest days of the summer.

**Under these H++ scenarios average summer maximum temperatures would exceed 30°C over most of the UK, and would exceed 34°C over much of central and southern England. Temperatures of the hottest days would exceed 40°C, with 48°C being reached in London.**

The H++ scenarios were developed using historical extreme heat waves and days with record high temperatures, and modelled changes in summer temperatures from the UKCP09 projections. The H++ methodology involved calculating summer average baseline temperatures for the UK using observed daily maximum temperatures for the period 1961-1990. Anomalies for the hottest days, hottest heat wave and hottest summer relative to that baseline period were also calculated<sup>11</sup>.

---

<sup>10</sup> <http://ukclimateprojections.metoffice.gov.uk/23673?emission=high>

<sup>11</sup> This approach was adopted following peer review and is simpler than the work previously presented in the first draft report, which was based on analysis of the Met Office Hadley Centre Regional Climate Model and included information on the extension of heat wave durations.

As for the cold H++ scenarios, this approach is subject to a number of caveats. First, it assumes that the anomalies of the 1976 summer and 2003 heat wave average and hottest days from a long term mean can be added to future summer mean temperatures. Secondly, the calculation does not explicitly consider the urban heat island (UHI) effect, assuming that this is captured in the anomalies of these two events<sup>12</sup>. Thirdly, in the presentation of gridded data (Figure 2.2) it adopts the spatial patterns of anomalies observed in previous events when future heat waves could be centred differently and have larger (or smaller) spatial extents. Finally, all changes were calculated at the scale of the climate model (25 km) and temperatures at some individual locations are likely to be hotter still<sup>13</sup>.

The assumptions adopted here have been accepted in other peer reviewed studies (e.g. Schoetter et al., 2014) and the results are also consistent with other studies over Europe (Russo et al., 2014) and the UK (Brown et al., 2014), albeit producing slightly higher maximum temperatures. There will be dynamical and thermodynamic limits on how high temperatures in the UK could become in the future, but is not known what those limits are. The temperatures of very hot summers are controlled by several different factors, of which the most important are the synoptic patterns. For example, during August 2003, very hot air was transported from continental Europe to the UK which led to the record temperatures. Droughts exacerbate the temperatures, since there will be little or no cooling of the land via evaporation of water from the soils. These physical limits are discussed in more detail in section 2.5.

## **2.2 Historical data**

There are several different data sources which can be studied to examine how periods of warm weather have changed in the past and provide guidance on suitable H++ scenarios. Northern hemisphere annual average temperatures have been estimated using a wide range of proxy data, such as tree ring widths, composition of lake sediments and pollen samples. Some of these proxy records cover the past 2000 years. The Central England Temperature record (CET; Parker et al., 1992) dates back to 1659, and is the longest instrumental series of this kind in the world. Monthly mean temperatures are available over the entire series. Gridded temperatures based on weather station records are available from 1910 (Perry and Hollis, 2005). Briefly, data

---

<sup>12</sup> Refer to Annex 7 of the UKCP09 climate projections report <http://ukclimateprojections.metoffice.gov.uk/22530>

<sup>13</sup> A comparison of the gridded temperatures at the 5 km and 25 km spatial scales showed that the 5 km data can be up to 3-4°C hotter than the 25 km data.

from the UK weather and climate station network were gridded by regression and interpolation to a 5 km × 5 km grid, taking into account factors such as latitude, longitude, coastal proximity and local topography (Perry and Hollis, 2005; Perry et al., 2009). These data have been aggregated to the 25 km × 25 km grid used by the UKCP09 climate projections. Monthly data are available from 1910, and daily data from 1960.

#### *Historical northern hemisphere mean temperatures*

Annual average temperatures for all or part of the northern hemisphere for the last 2000 years have been reconstructed using a wide range of proxy data (Masson-Delmotte et al., 2013). These reconstructions show that annual temperatures were anomalously warm between about 950 and 1250, a period referred to as the Medieval Climate Anomaly (or Medieval Warm Period). They also indicate that any 30 or 50 year average temperature was very likely cooler during the past 800 years than the 1983-2012 or 1963-2012 instrumental temperatures (Masson-Delmotte et al., 2013). Some reconstructions for the first millennium suggest that some 30 or 50 year periods may have been as warm as 1963-2012. Confidence in this finding is low as there are fewer proxy records and less independence among the reconstructions (Masson-Delmotte et al., 2013).

The record-breaking summer of August 2003 in Europe is the hottest for Europe in the instrumental record (which begins in 1850<sup>14</sup>). Record temperatures from this heat wave have not been reached or exceeded since in many countries. This heat wave claimed many lives, mostly among the elderly. However, an analysis of a new source of proxy data (grape harvest dates between 1444 and 2011) in Switzerland suggests that the late spring and early summer (April to July) of 1540 may have been even hotter than 2003 (Wetter and Pfister, 2013). An exceptionally long drought occurred during 1540 which contributed to the unusually high temperatures (Wetter et al., 2014). Temperature anomalies for 1540 were estimated to be between 4.7°C and 6.8°C hotter during April-July than the 1901-2000 mean temperature for April-July in the Alpine region. The same late spring-early summer period in 2003 was only 2.86°C hotter. Other historical reports show that temperatures were still anomalously warm in Switzerland (“like April”) in winter

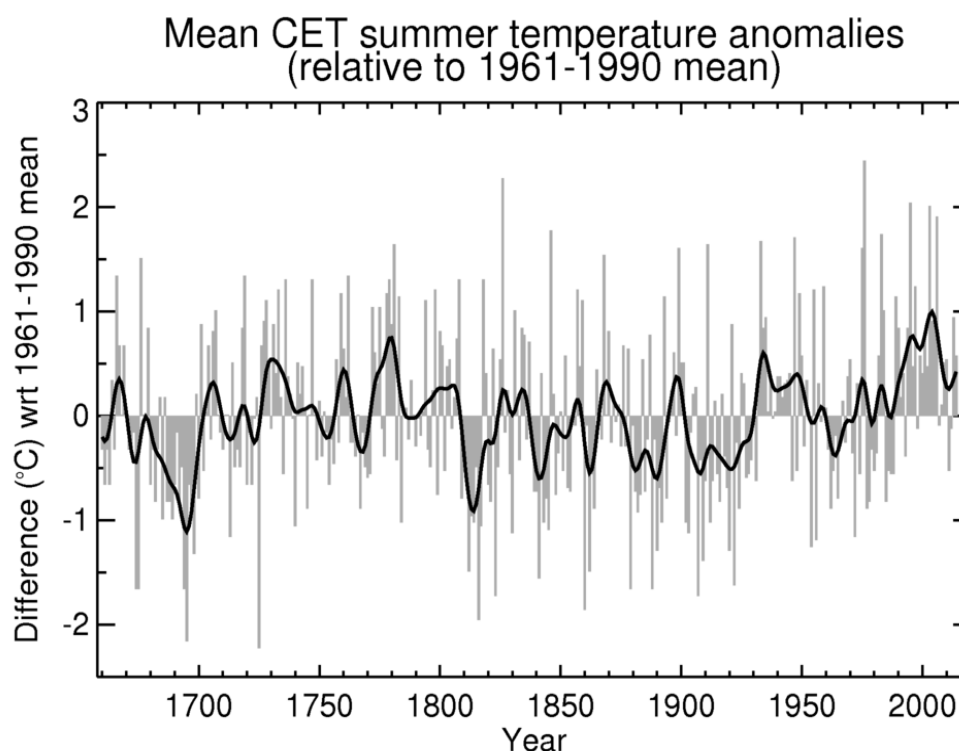
---

<sup>14</sup> Measurements of temperature are available at a small number of locations before 1850 in Europe. For example, temperatures at four European stations are available from 1721 (Jones and Moberg, 2003), but none of these stations indicate temperatures between 1721 and 1850 were as warm as those in 2003. The number of sites prior to 1850 is probably too small to estimate Europe-wide temperatures.

1540/1541, and no frost or snow covered the ground (Wetter and Pfister, 2013). Kington (2010) states that Britain was affected by a severe drought between 1538 and 1541, with the Thames so low that salt water flowed as far upstream as London Bridge. He also suggests that the summer of 1540 was probably one of the warmest on record. The study of Wetter and Pfister (2013) suggests a heat wave much hotter than that of 2003 is possible in a single country even without any effects of anthropogenic warming.

### *Warm Summers in the Central England Temperature Record*

Summer (June, July and August) mean temperature anomalies (relative to the 1961-1990 average) between 1660 and 2014 from the CET are shown in Figure 2.1. Summer temperatures at the beginning of the series (up to about 1700) were generally colder than average, as this period is at the end of the Little Ice Age. Summers between 1700 and 1810 tended to be warmer than average, followed by a second period of cooler summers (1810 to 1930).



**Figure 2.1. Summer mean temperature anomalies for the years 1660-2014 relative to the 1961-1990 annual mean. The grey bars show individual anomalies for each year. The black line is a smoothed version created with a 21-term binomial filter (Parker, 2009).**

As always, there are exceptions; the summer of 1826 is the second warmest in the CET, only the summer of 1976 is warmer. Other notable warm summers are 1995, 2003 and 2006. There has been an unusually long run of warm summers since 1990. A positive trend of  $0.075 \pm 0.050^{\circ}\text{C}$  per decade in summer mean temperatures exists between

1900 and 2014. An analysis by eye of the summer temperature anomalies shown in Figure 2.1 suggests that the coldest summers have warmed by about 1°C since 1950. Temperatures of the warmest summer anomalies have also increased, from about 1.3°C during the 18<sup>th</sup> century to around 1.7°C in the late 20<sup>th</sup> and 1.9°C in the early 21<sup>st</sup> century.

### *UK hot temperature records*

The hottest days and nights in the UK have been identified from weather stations by the NCIC, and the hottest days and nights for each part of the UK are shown in Table 2.1. Many of the record hot temperatures occurred during the heat waves of 1976, 1990 and 2003. Interestingly, none of these records occurred during the hot summer of 2006, when temperatures in excess of 36°C were recorded near London. Very warm temperatures were recorded on the 1<sup>st</sup> July 2015 at many stations across the UK, but they did not exceed the absolute records in Table 2.1

**Table 2.1. UK record hot temperatures from weather stations, which date back to the 1850s**

<b>UK Region</b>	<b>Hottest Daily Maximum / °C</b>	<b>Date</b>	<b>Hottest Daily Minimum / °C</b>	<b>Date</b>
<b>Scotland</b>	32.9	09.08.2003	20.5	02.08.1995
<b>England</b>	38.5	10.08.2003	23.9	03.08.1990
<b>Northern Ireland</b>	30.8	30.06.1976 12.07.1983	20.6	31.07.1868
<b>Wales</b>	35.2	02.08.1990	22.2	29.07.1948

### *Historical changes in hot days and heat waves*

Della-Marta et al. (2007) analysed a data set of 54 high-quality homogenized daily maximum temperature series from western Europe for the period 1880-2005. A hot day was defined as any day whose maximum temperature exceeded the 95<sup>th</sup> percentile of summer (June, July and August) daily maximum temperatures for the period 1906-1990. A heat wave was the longest number of consecutive hot days in any given year. Della-Marta et al. (2007) concluded that over the period 1880 to 2005 the length of summer heat waves over western Europe had doubled and the frequency of hot days had almost tripled. Heat waves had also become  $1.6 \pm 0.4^\circ\text{C}$  hotter over this period.

The Intergovernmental Panel on Climate Change (IPCC) Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) concluded that there was medium confidence that the length and/or number of

heat waves had increased globally since the middle of the 20th century and that it was very likely that the length, frequency, and/or intensity of these events would increase over most land areas by the end of the 21st century (Seneviratne et al., 2012). These conclusions were reiterated and strengthened by the IPCC Fifth Assessment Report (AR5; Hartmann et al., 2015).

Heat waves in the UK were identified and analysed using 5 km gridded daily maximum temperatures for the period 1960 – 2013 (Perry and Hollis, 2005; Perry et al., 2009). A simple heat wave definition was used, where a threshold temperature of 30°C had to be exceeded on 3 or more consecutive days (Perkins and Alexander, 2013). This threshold is arbitrary but a day when maximum temperatures reached or exceeded 30°C would be considered to be a very hot day (Schoetter et al., 2014). This threshold was exceeded in all of the major heat waves of the twentieth and early twenty-first century (Burt, 2004). The most extreme heat wave was then identified using a variety of definitions: (a) highest temperatures reached, (b) longest consecutive period with daily maximum temperatures at or above 30°C, and (c) largest area of the UK where 3 or more consecutive days reached or exceeded 30°C.

Heat waves in the UK vary considerably in their characteristics. The most extreme heat wave identified depends on the definition used. The highest temperatures occurred in 2003, where 38.1°C is present in the gridded data (note that the highest actual temperature measured during 2003 was 38.5°C at Faversham in Kent on 10<sup>th</sup> August). The longest heat wave occurred in 1976, where sixteen consecutive days were at or above 30°C at 12 locations around the UK. The total number of days where 30°C was reached or exceeded in one or more locations was twenty in both 1976 and 1990. The largest total land area in the UK where 3 or more consecutive days were above 30°C at some point during the summer months was 81,000 km<sup>2</sup> during 1976, closely followed by 73,000 km<sup>2</sup> in 1995. For comparison, the areas in 2003 and 2006 were 32,400 and 68,000 km<sup>2</sup> respectively.

These results illustrate that characteristics of historical heat waves can be very different. For example, record high temperatures were recorded during the 2003 heat wave, but the longest heat wave, greatest spatial extent of a heat wave and hottest summer all occurred in 1976. These results are dependent on the threshold used to define a heat wave. The use of a lower or higher threshold would change the lengths and numbers of heat waves identified. However, the broad findings above are unlikely to change drastically.

## **2.3 UKCP09**

In the UKCP09 projections all areas of the UK warm, more so in summer than in winter (Murphy et al., 2009). For the Medium emissions scenario changes in 30-year summer mean temperatures for the 2050s are greatest in parts of southern England (up to 4.2°C (2.2 to 6.8°C))<sup>15</sup> and least in the Scottish islands (just over 2.5°C (1.2 to 4.1°C))<sup>16</sup>.

Under the UKCP09 2080s High emissions scenario, at the 90% probability level and regional scale, UK regional 30-year mean summer temperatures are 6.0°C to 8.1°C warmer than the 1961-1990 baseline<sup>17</sup>. Gridded data for this specific scenario are included in the calculation of H++ scenarios in Section 2.5.

30-year average 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 (Murphy et al., 2009). Modelled changes in the 30-year average warmest day of summer from the UKCP09 projections (using the 90% probability data) are larger than changes in summer mean maximum temperatures. For example, around London summer average 30-year mean maximum temperatures are projected to be 8-9°C warmer, but the hottest day could be 10-12°C warmer. These results suggest that the highest temperatures will warm at a faster rate than mean temperatures during the summer months (see physical limits section).

UKCP09 did not consider potential future changes in the Urban Heat Island (UHI) effect, although this is discussed in Annex 7 of the climate projections report (Murphy et al., 2009).

## **2.5 Physical limits**

Miralles et al. (2014) investigated the physical processes underlying recent extreme heat waves using satellite and balloon measurements of land and atmospheric conditions from the summers of 2003 in France and 2010 in Russia. They found that these extreme heat waves could only occur with very dry soils, advection of heat and the presence of a

---

<sup>15</sup> 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).

<sup>16</sup> Based on the summary report <http://ukclimateprojections.metoffice.gov.uk/22530>

<sup>17</sup> The range represents different rates in different UKCP09 administrative regions <http://ukclimateprojections.metoffice.gov.uk/23673?emission=high>

high pressure system nearby; similar conclusions were reached by Quesada et al. (2012). During daytime, heat was supplied by large-scale horizontal advection, warming of an increasingly dry land surface and enhanced entrainment of warm air into the atmospheric boundary layer. Overnight, the heat generated during the day was preserved in an anomalous kilometres-deep atmospheric layer located several hundred metres above the surface. This layer then re-entered the atmospheric boundary layer during the next diurnal cycle. These processes resulted in a progressive accumulation of heat over several days, which enhanced soil desiccation and led to further escalation in air temperatures. Miralles et al. (2014) suggested that the very hot temperatures observed during extreme heat waves can be explained by the combined multi-day memory of the land surface and the atmospheric boundary layer. Miralles et al. (2014) noted that the length and severity of heat waves is ultimately determined by the synoptic conditions. Rainfall deficits leading to dry soils are not a necessary requirement, and soil desiccation may not play a role in determining the duration of the heat wave.

## **2.4 Other evidence**

Several recent papers have considered the impacts of climate change on heat waves. Russo et al. (2014) developed a new heat wave metric, which accounts for both magnitude and duration of heat waves. Using this metric, they studied extreme heat waves which occurred worldwide between 1980 and 2012, and projected changes in spatial extents and severity of heat waves under a range of emissions scenarios. However, this new metric does not seem to have identified the severe heat wave which occurred in Australia between 25th January and the 9th February 2009 (Australian Government, 2009).

Russo et al. (2014) noted that the CMIP5 models do not reproduce heat waves as severe as that of August 2003 during the historical period. Heat waves similar to August 2003 were projected to become the norm in Europe after 2070 under the high emissions scenario (RCP8.5). Very extreme heat waves (worse than 2003) were only projected under the RCP8.5 scenario during the period 2068-2100, and occurred 1-2 times per year. Stott et al. (2004) used a different climate model (HadCM3) and greenhouse gas emission scenario (SRES A2) and projected that summers like 2003 could be normal as early as 2040, and would even be considered cool by 2060.

Brown et al. (2014) used extreme value analysis together with emulated climate model data to estimate the future 1 in 50 year summer daily maximum temperature for London.



This estimate was made for 1961-1990 and a 20 year period centred on 2050 using the A1B emissions scenario. The 1 in 50 year temperature for 1961-1990 was 35.7°C, and for 2040-2060 was estimated to lie between 35.9°C and 42.1°C (10<sup>th</sup> – 90<sup>th</sup> percentiles). The estimated maximum temperatures for H++ scenarios for London on the two hottest days in Figure 2.2 (lower panels) are 46.1°C and 48.1°C, which are higher than the estimates of Brown et al. (2014). However, Brown et al. (2014) used the medium emissions scenario (A1B). If a high emissions scenario had been used (e.g., A1FI, A2, RCP8.5), and the estimate was made for the end of the 21<sup>st</sup> century instead of 2050, the estimated 1 in 50 year temperatures would be higher.

## **2.6 H++ scenarios**

The summer of 1976 is the hottest in the UK instrumental record, and also contains the heat wave which lasted the longest (16 days) and had the greatest spatial extent. The 2003 heat wave is the hottest (so far) to occur in the UK. During the period 3<sup>rd</sup> - 12<sup>th</sup> August temperatures exceeded 30°C over some or most of the UK (Burt, 2004). The hottest two days were the 9<sup>th</sup> and 10<sup>th</sup> of August. On the 9<sup>th</sup> August temperatures exceeded 30°C over almost all of the UK, and temperatures in south-east England reached around 37°C in many locations. On the 10<sup>th</sup> August 2003, a slow moving cold front was bringing cooler conditions to most of the UK, but the highest temperatures of the heat wave (exceeding 38°C) were recorded in south-east England on this day. The 12<sup>th</sup> August was the last day when temperatures were at or above 30°C over south-east England. By the 15<sup>th</sup> August temperatures had returned to near normal (Burt, 2004).

The daily maximum temperature anomalies for the 9<sup>th</sup> and 10<sup>th</sup> August 2003 (the two hottest days of the heat wave) were compared with the projected changes in the 30-year average hottest day of summer from the UKCP09 projections at the 90<sup>th</sup> probability level (Murphy et al., 2009). Although the spatial distributions of the temperatures differed, the magnitudes were very similar. This result suggests that the hottest days of the August 2003 heat wave could be indicative of the typical hottest day of summer at the end of the 21<sup>st</sup> century (i.e. the 30 year average).

The data in Table 2.2 were used to construct a H++ summer, a H++ heat wave and two H++ hottest days. Maps illustrating the four H++ scenarios are shown in Figure 2.2. First, a new baseline was created, which is the sum of the 1961-1990 average and the UKCP09 30-year average change in summer mean maximum temperature (90<sup>th</sup>

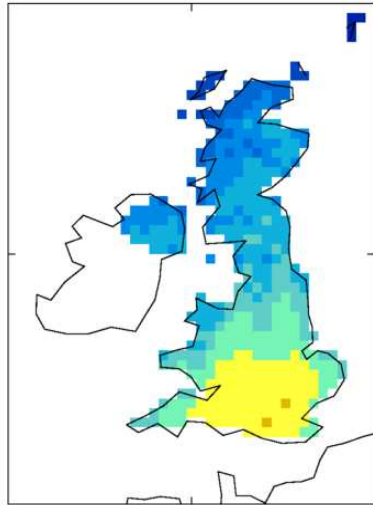
probability level). The H++ summer is the sum of the new baseline and the summer 1976 mean anomalies. The August 2003 heat wave anomalies were then added to the new baseline summer temperatures to create the H++ heat wave. Finally, temperature anomalies associated with the two record hottest days (9th and 10th August 2003) were added to the new baseline to create two possible H++ hottest summer days. These scenarios are therefore event based and describe hot conditions over specific time periods.

The maps shown in Figure 2.2 show that average temperatures in the H++ summer and heat wave are very similar. A H++ summer could be considered to be a continuous heat wave, and so would last around 90 days.

**Table 2.2 Data used to create the H++ scenarios for summer, a heat wave and hottest days.**

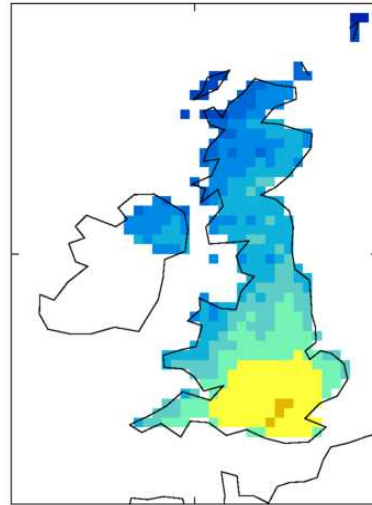
<b>Variable</b>	<b>Description</b>	<b>Type</b>
<b>Baseline</b>	1961-1990 summer mean of daily maximum temperatures	Gridded
<b>Change in summer mean maximum temperature</b>	UKCP09 2080s (2070-2099), high emissions scenario, 90% probability level	Gridded
<b>Hottest summer average temperature anomalies</b>	Summer 1976	Gridded
<b>August 2003 heat wave mean anomaly</b>	Average maximum temperature anomaly for the period 3 <sup>rd</sup> -12 <sup>th</sup> August 2003	Gridded
<b>August 9<sup>th</sup> 2003 anomaly</b>	Daily maximum temperature anomaly for the 9 <sup>th</sup> August 2003	Gridded
<b>August 10<sup>th</sup> 2003 anomaly</b>	Daily maximum temperature anomaly for the 10 <sup>th</sup> August 2003	Gridded

H++ Summer (mean Tmax)



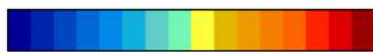
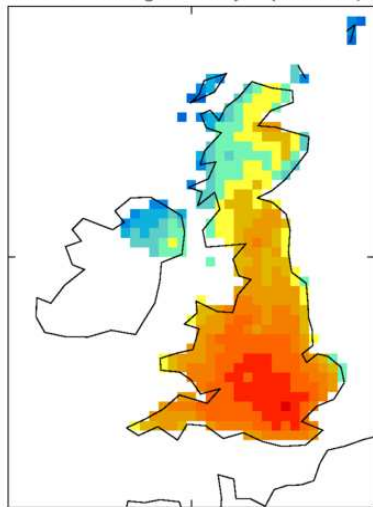
22 26 30 34 38 42 46

H++ heat wave (mean Tmax)



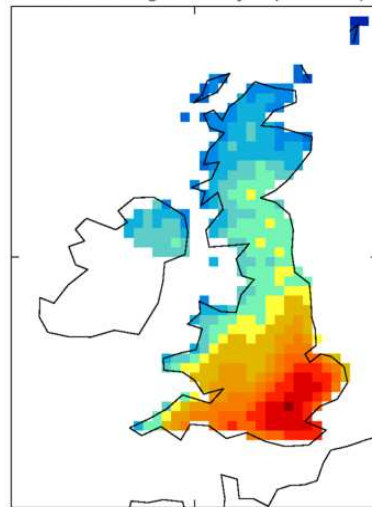
22 26 30 34 38 42 46

H++ single day (Tmax)



22 26 30 34 38 42 46

H++ single day (Tmax)



22 26 30 34 38 42 46

**Figure 2.2 H++ scenarios for summer, a heat wave, and two possible hottest days. All temperatures are in °C.**

The approach used here assumes that the anomalies of the 1976 summer and 2003 heat wave average and hottest days from a long term mean can be added to future 30-year average summer mean temperatures. Schoetter et al. (2014) studied changes in

heat waves in the CMIP5 ensemble. They found that a shift in the temperature distribution towards higher temperatures was more important for the increase in heat wave severity than any changes in the width of the distribution. This result suggests that adding observed anomalies to changes in average summer temperatures is reasonable. There will be dynamical and thermodynamic limits on how high temperatures in the UK could become in the future, but it is not known what those limits are.

All changes shown in Figure 2.2 were calculated at the scale of the climate model (25 km) and are based on projections of a 30-year average change rather than changes for single years, which would be higher in some cases. Temperatures at individual locations are therefore likely to be hotter still. A comparison of the gridded temperatures at the 5 km and 25 km spatial scales showed that the 5 km data can be up to 3-4°C hotter than the 25 km data. Finally the calculation does not consider potential future changes in the urban heat island effect, which raises temperatures by 1 to 2 °C even under current conditions<sup>18</sup>.

**Under the H++ scenarios average summer (JJA) maximum temperatures would exceed 30°C over most of the UK, and would exceed 34°C over much of central and southern England. Temperatures of the hottest days would exceed 40°C, with 48°C being reached in London.**

The anomalies for the hottest days (from observations) were compared with projected changes in the hottest day of summer from the UKCP09 projections. The magnitudes of the observed and modelled anomalies were very similar. The observed anomalies could be considered as representative of future very hot days. Projected changes in mean summer maximum temperatures from the UKCP09 projections were added to the baseline along with the anomalies for the hottest days and heat wave to create the H++ scenarios. The reported temperatures are the highest that can be estimated from the models and observations.

A summary of the data sources used to estimate the H++ scenarios is given below.

- Palaeo. Reconstructed northern hemisphere annual average temperatures for 30 and 50 year periods over the past 2000 years suggest present-day temperatures have not been reached or exceeded in the past 800 years. However, one recent

---

<sup>18</sup> Refer to Annex 7 of the UKCP09 climate projections report <http://ukclimateprojections.metoffice.gov.uk/22530>

reconstruction suggested the late spring and early summer of 1540 in central Europe was much hotter than 2003. It is not clear whether the UK also experienced extreme hot temperatures during the same period.

- Historic. The CET shows that 1976 was the hottest summer overall, although individual months were hotter in other years. The CET also shows that temperatures of the coldest and warmest summers have become higher, and there has been a series of warm summers since 1990.
- UKCP09. These climate projections all suggest that summers will be hotter in the future. Modelled increases in the temperature of the hottest day of summer are larger than changes in summer mean temperatures.
- CMIP5. Analyses of European temperature changes all suggest that summers in the future will be hotter and heat waves will be more severe. The CMIP5 models do not simulate heat waves as severe as 2003, and so may underestimate future heat wave severity. Very few of the published studies of future heat waves specifically consider the UK.

## Chapter 3 Low rainfall

### 3.1 Summary of the High ++ low rainfall scenarios

The High ++ low rainfall scenarios span a range of time scales (6 to 60 months) and three major UK regions (England & Wales, Scotland, and Northern Ireland).

Future summer meteorological droughts in England and Wales could be more or less severe. Severe short drought (6 months) and long multi-season drought (of three years or more) are of particular interest to users in specific sectors, for example:

- a) Agriculture – short period droughts (6 months in either winter or summer) with little/no rainfall. These may also be associated with extremes in temperature (hot summer, cold winter).
- b) Water supply systems - long period droughts (multi-season, 3 years or more) as these can have a significant impacts on public water resources systems designed to cope with shorter drought periods.

The H++ scenarios were developed using a credible set of climate models selected from the UKCP09 and CMIP5 archives.

The H++ methodology for low rainfall involved computing changes in the probability of precipitation deficits of a given magnitude over a range of accounting periods. The reported changes in probability are the largest (in terms of a move toward drier conditions) that can be estimated from the models (7 member subset from CMIP5 archive) under the most pessimistic emissions pathway (RCP8.5).

Drought can be initiated either by a reduction in delivery (e.g. fewer cyclones) and/or the suppression of precipitation (more anticyclones). Competing physical factors influence periods of low rainfall in the UK and one important caveat is that climate models do not simulate all these features effectively. However a consideration of these competing influences indicates changes that are broadly consistent with the empirical findings from the climate models analysed.

A characteristic of UK drought is low frequency variability (see Figure 3.1). This means that the relatively short UKCP09 reference period (1961-1990) is inadequate for a

reliable assessment of baseline drought probabilities and thus UKCP09 is not considered to be appropriate for the analysis of low rainfall. For this reason this chapter places greatest emphasis on the use of historical data and CMIP5 model outputs.

**The H++ low rainfall scenario is for a significant increase in 6 month duration summer drought with deficits up to 60%. Climate models suggest no significant change in winter droughts; however, the possibility remains of some longer dry periods across the whole of England and Wales with rainfall deficits of up to 20% lasting 3 to 5 years similar to the most severe long droughts on record.**

Where direct observations are available this study uses the full instrumental record. The reference period for climate models is 1900-1999 and the future is 2070-2099. The data sources used are described in Annex 2.

#### Box 3.1 Low rainfall scenarios and drought risks

Droughts have severe impacts on societies, economies, agriculture and ecosystems. The multi-annual 1975-76 UK drought had a devastating effect on the UK economy causing an estimated £3,500M loss to agriculture, £700M of subsidence damage to buildings and a £400M cost to the water industry (figures adjusted for inflation, (Rodda and Marsh 2011)).

Low rainfall is closely related to the concept of drought and shares many of the difficulties which complicate a precise definition of the peril (Lloyd-Hughes 2014). The primary difficulties are the choice of starting point and accounting period over which precipitation deficits are accrued. The approach of this study is to consider accumulated precipitation totals computed at the end of the winter (April) and summer (October) half years for a wide range of accounting periods: 6, 12, 24, 30, 36, 42, 48, 54, and 60 months. This provides the necessary granularity to inform on the credible impacts of climate change on two distinct drought scenarios of interest (see above).

### **3.2 Historical data and methods**

For this scenario the observational data is used mainly for context setting and filtering models based on historical performance.

### *HadUKP - UK regional precipitation series*

HadUKP (Alexander and Jones 2000) is a series of datasets of UK regional precipitation, which incorporates the long-running England & Wales Precipitation (EWP) series beginning in 1766, the longest instrumental series of this kind in the world. The map (Figure 3.1) shows the regions that are available.



**Figure 3.1 HadUKP precipitation regions.**

HadUKP incorporates a selection of long-running rainfall stations to provide the best available long term average precipitation across a large area (Alexander and Jones, 2001)<sup>19</sup>. The monthly EWP series goes back to 1766, whereas the monthly series for the sub-regions of England and Wales begin in 1873. The monthly series for Scotland (and sub-regions) and Northern Ireland begin in 1931.

#### *Methodology*

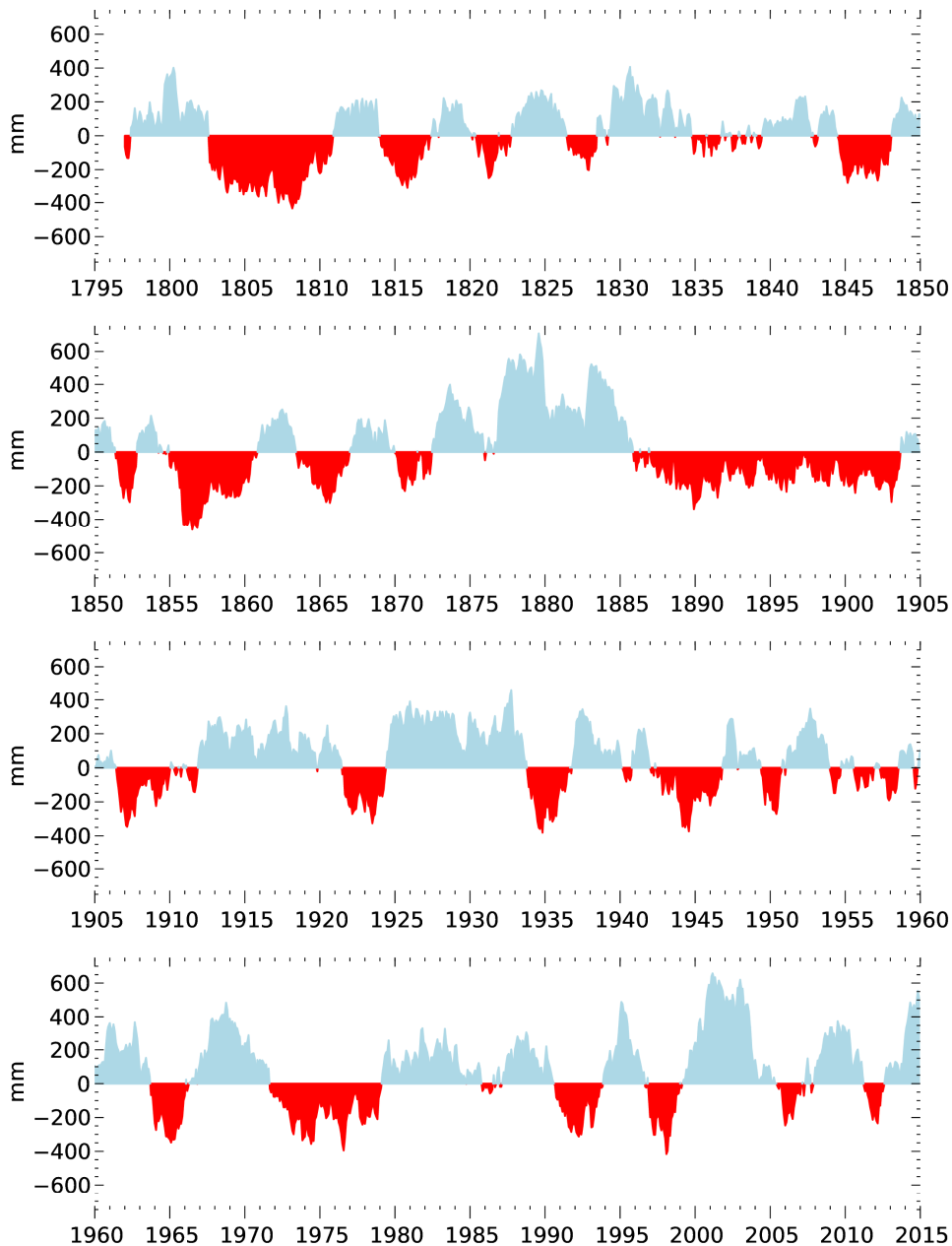
Accumulated precipitation totals have been computed, as measured at the end of the winter (April) and summer (October) half years, for the set accounting periods: 6, 12, 24, 30, 36, 42, 48, 54, and 60 months for each of the HadUKP (Alexander and Jones 2000) regional time series and for equivalent regional time series extracted from the CMIP5 models. The accumulated totals have been converted into time series of anomalies by subtraction of the long term running mean total for relevant accounting period and time

<sup>19</sup>The data and a description of how it was created are available on the Met Office web site <http://www.metoffice.gov.uk/hadobs/hadukp/>



of year. Anomalies for model projections of the future 2070-2099 are relative to a reference period defined as 1900-1999. An example time series of 36-month accumulations for the EWP region is shown in Figure 3.2.

### EWP anomalies (36 month accumulation)



**Figure 3.2** Time series of 36 month precipitation anomalies for EWP (England and Wales Precipitation). The anomalies are departures of precipitation relative to long term averages for that time of year. Red (blue) shading indicates periods of time when conditions were drier (wetter) than average.

### *Selection of credible models*

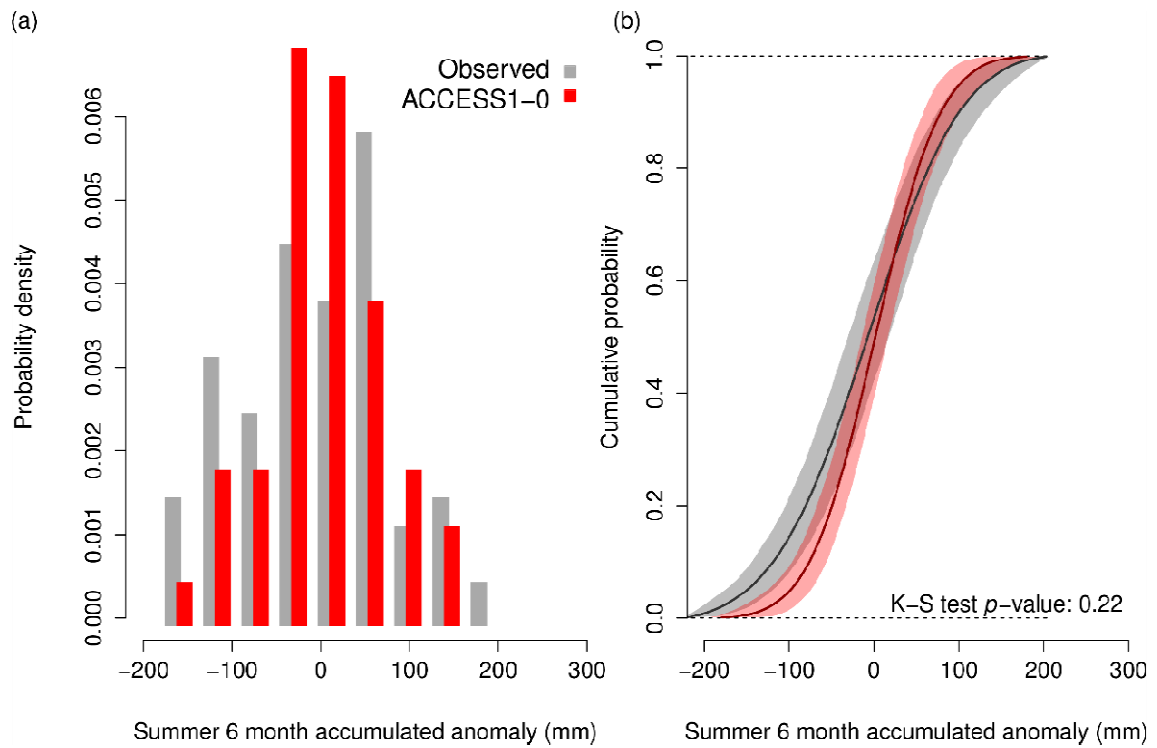
The fidelity of the dynamics emerging from the CMIP5 models has been analysed in detail by McSweeney et al. (2014). Accepting only those models identified as ‘satisfactory’ for all indicators across Europe and eliminating those with ‘significant biases’ elsewhere resulted in a candidate pool of 11 models. Since climate models do not attempt to reproduce the time sequencing of events in recent climate (they are uninitialized) models are evaluated using probability distributions. Synthetic 6-month accumulated precipitation anomalies from the candidate models were compared with observations for each of the HadUKP regions for the summer and winter half years for all years 1900-1999. A model was deemed to be ‘credible’ if the empirical cumulative distributions of the modelled data were consistent with the observations at the 10% significance level as measured by the Kolmogorov–Smirnov (K-S) test. A total of 7 models were found to produce realistic looking droughts over the EWP region. These are listed in table 3.1 with p-values for the Kolmogorov–Smirnov (K-S) test, where P values higher 0.1 (10%) indicate a good fit between the observed and modelled data. If the model and observations are sampled from identical distributions then the p-value gives the probability of the K-S statistic being as large or larger than calculated. An example visual comparison of modelled versus observed accumulated distributions is shown in Figure 3.3 for the ACCESS1-0 model for the summer half year. Thus we conclude there is some limited skill in the model at presenting EWP values.

**Table 3.1 Model performance as measured by the distributional adequacy of 6-month precipitation anomalies for the EWP region 1900-1999.**

<b>Model</b>	<b>K-S <i>p</i>-value Summer</b>	<b>K-S <i>p</i>-value Winter</b>
<b>ACCESS1-0</b>	0.22	0.32
<b>CMCC-CM</b>	0.22	0.22
<b>CNRM-CM5</b>	0.10	0.22
<b>GFDL-CM3</b>	0.15	0.22
<b>GFDL-ESM2M</b>	0.32	0.10
<b>HadGEM2-ES</b>	0.15	0.15
<b>MPI-ESM-MR</b>	0.22	0.10

It is notable that no credible models could be identified for the HadUKP regions beyond the EWP region (and even here models are only just credible, see for example the lower tails of Figure 3.3 where the distributions only just overlap at the 95% level of confidence). The relatively small geographical extents of these regions increases the relative importance of local scale effects on the variability of the precipitation totals to an extent that cannot be matched by the spatio-temporal resolution of the current generation of climate models. In contrast, the characteristics of simulated droughts at the

European scale are found to be in excellent agreement with observations (Lloyd-Hughes et al. 2013).



**Figure 3.3 Comparison of distributions (a) histogram and (b) maximum entropy estimates of the cumulative distribution function of modelled (red) and observed (grey) accumulated precipitation anomalies for EWP in summer 1900-1999. The shading on the cumulative curves represents the 95% confidence interval.**

### *Historical droughts*

Drought is quasi-regular feature of the UK climate and a significant event is to be expected every 5 to 10 years (as can be inferred from Figure 3.1; a detailed analysis of probability is provided below). The Centre for Ecology & Hydrology (CEH) have published reports on the most notable recent events including 1976 (Rodda and Marsh 2011), 1984 (Marsh and Lees 1985), 1988-1992 (Marsh et al. 1994), 2003 (Marsh 2004), and 2010-2012 (Marsh et al. 2013). A discussion of major drought events for England and Wales since 1800 is provided by Marsh, Cole, and Wilby (2007a). Of particular note, are the changes in variance (heteroskedasticity) seen in Figure 3.1 and similar plots of drought intensity. Such variability gave rise to the ‘Long Drought’ of the nineteenth century which would represent a considerable challenge to the water industry across England and Wales (Watts et al. 2012).

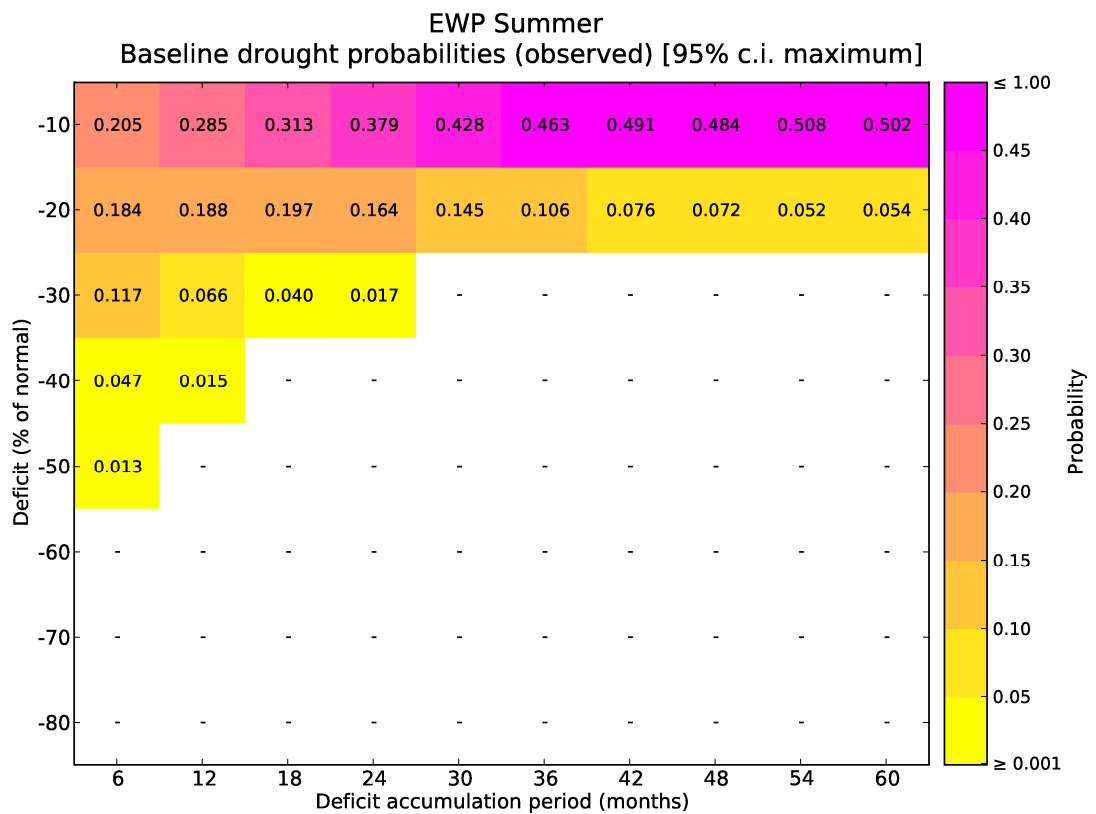
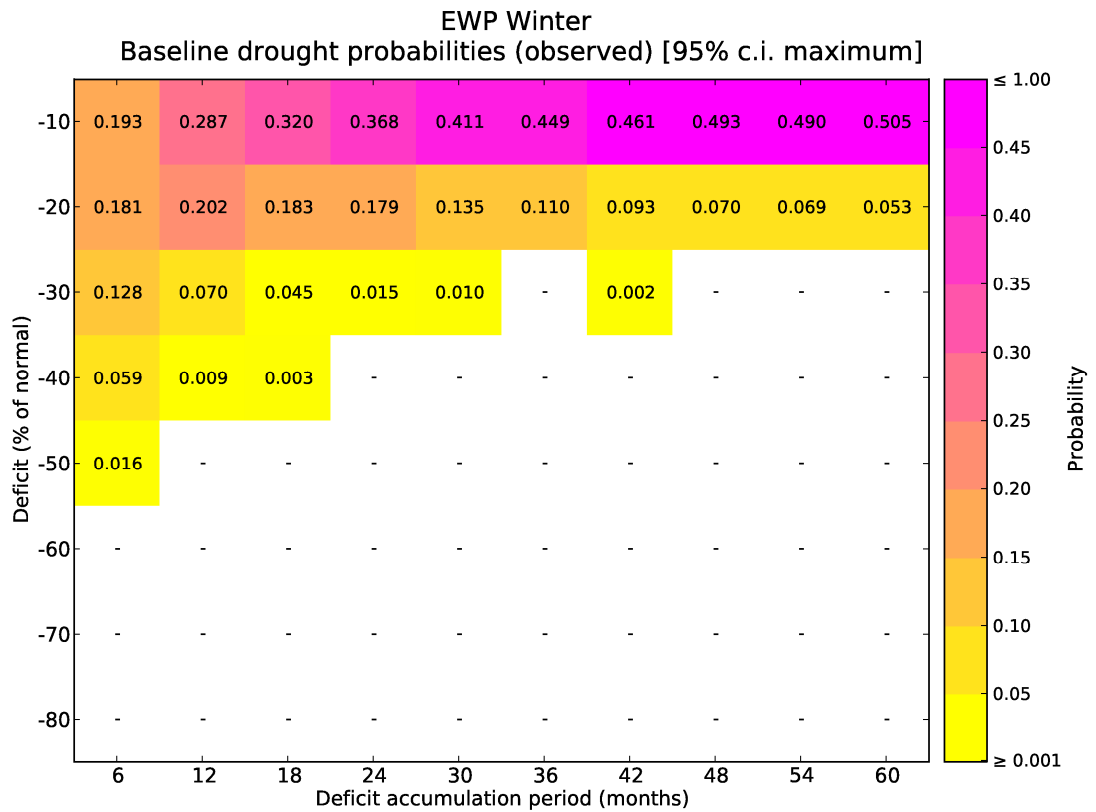
UK droughts are typically associated with large scale blocking high pressure systems and rarely exist in isolation; a characterisation of recent historical droughts on a European scale, using indicators of both rainfall and river flows is provided by Hannaford et al. (2011).

#### *Historical probabilities (baseline risk)*

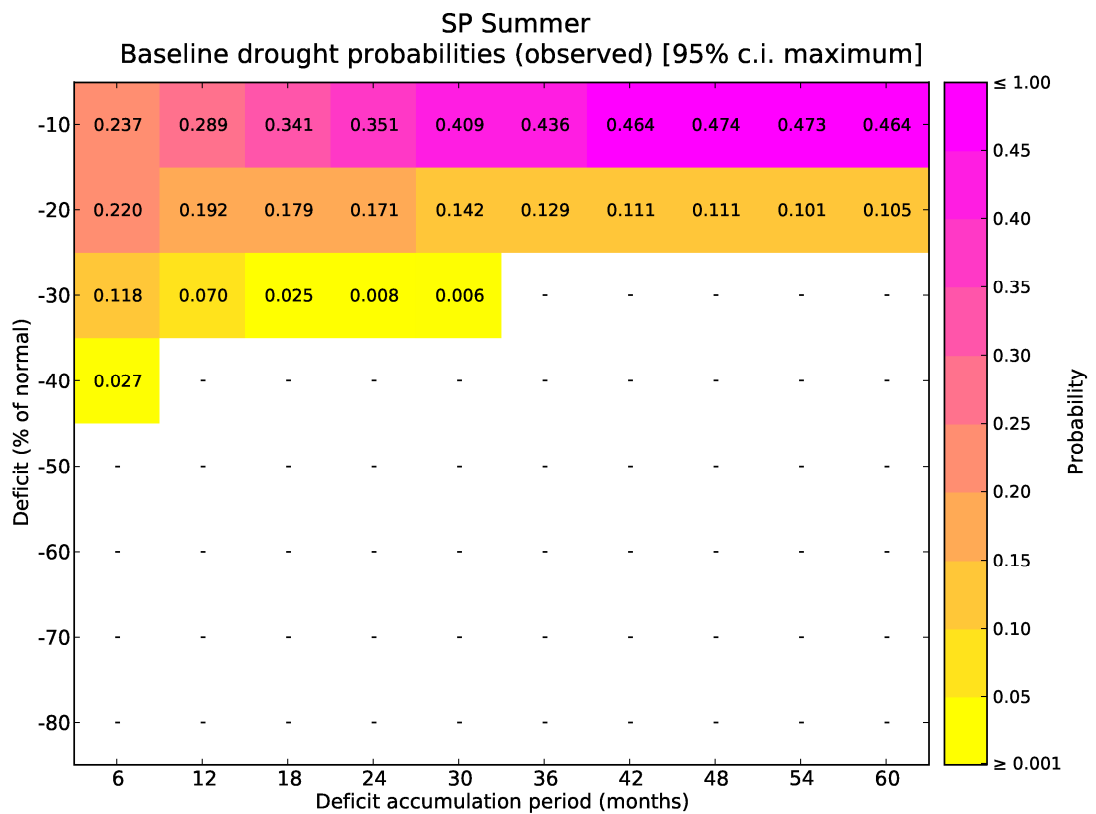
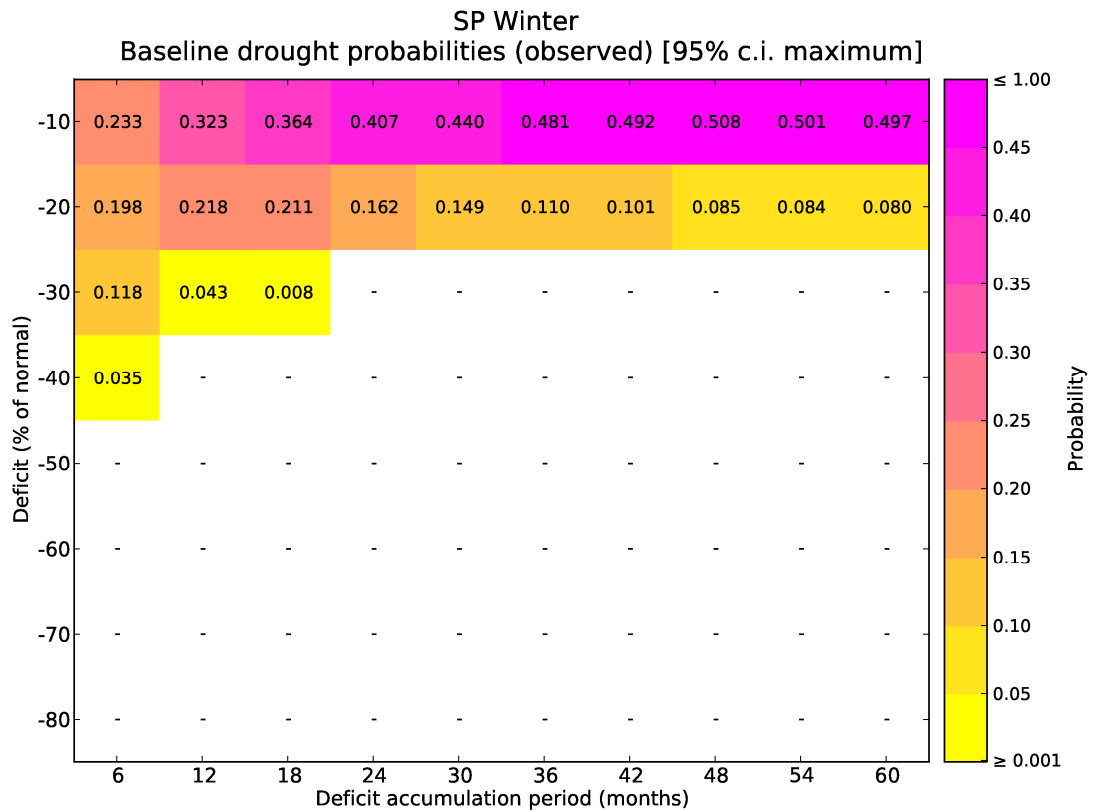
The UK has some of the longest precipitation records in the world in the form of the HadUKP time series (Alexander and Jones 2000). These provide an excellent basis for the assessment of baseline probabilities for precipitation deficits. Upper estimates of these are presented in Figures 3.4, 3.5 and 3.6 for the England and Wales Precipitation (EWP), Scotland Precipitation (SP) and Northern Ireland Precipitation (NIP) regions respectively. These figures show probabilities in the format of a pair of matrices (one for each half year; winter (April) and summer (October))<sup>20</sup>. The columns correspond to the time period over which the precipitation anomaly is measured (e.g. 6 month total, 12 month, etc.). The rows correspond to the severity of the deficit expressed as a percent of the total which can be expected at this time of year for the given accumulation period under the current climate (as estimated from observations of the recent climate; 1900-1999 for EWP; 1931-1999 for SP and NIP). Therefore the H++ values for low rainfall can be taken directly from these figures and the differences between the observed period and the future can also be assessed. For example, the most severe EWP summer rainfall deficit over 6 months based on observed data was 50% (Figure 3.4, lower pane) and the H++ EWP summer rainfall deficit over the same period is 60% (Figure 3.10, lower pane). The choice of accumulation period and deficit measure facilitates the direct comparison with the Low Flows section of this report (Section 4).

---

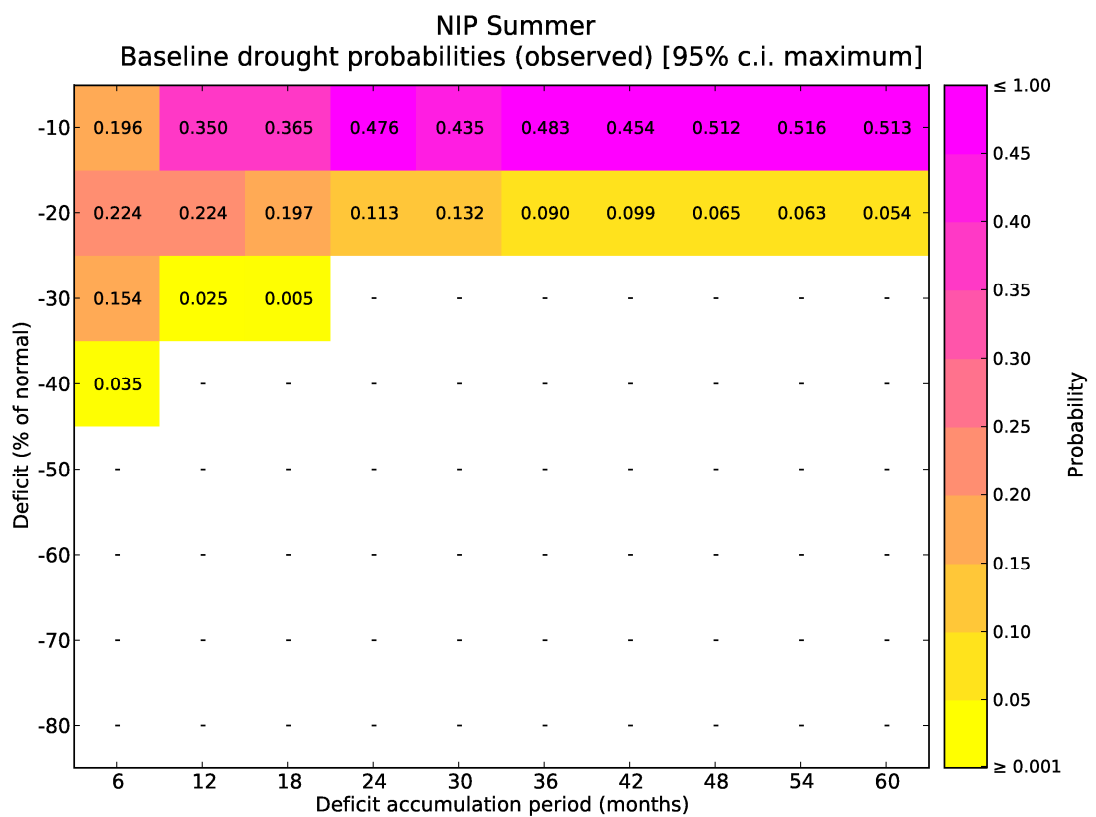
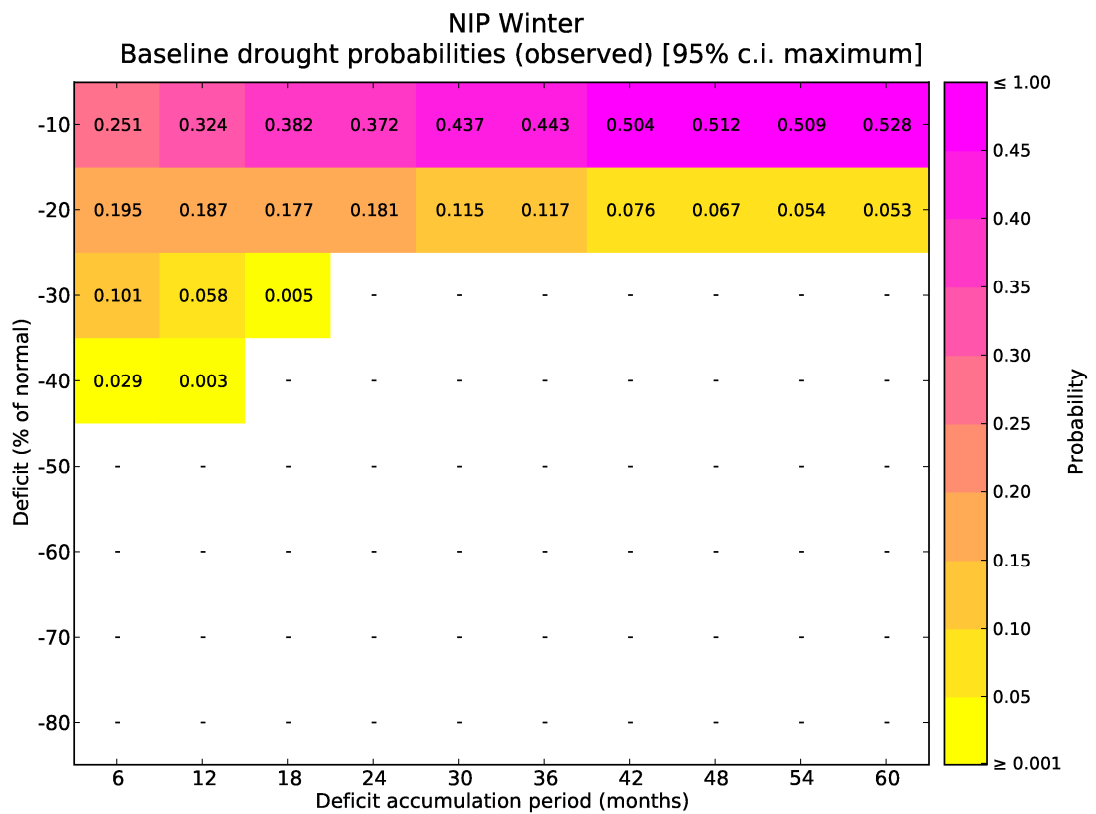
<sup>20</sup> The quoted probabilities represent the upper bound of a 95% confidence interval (c.i.) of probabilities derived from the data. The probabilities themselves were estimated by repeatedly fitting a maximum entropy distribution to each of 1000 bootstrap resamples taken from the data. Maximum entropy (MaxEnt) is a non-parametric method for statistical inference about the probability density function of a given sample of data which estimates the least biased distribution among all others that satisfy the constraining moments from the sample. A detailed description of MaxEnt procedure is provided by (Petrov, Soares, and Gotovac 2013).



**Figure 3.4** Upper estimates of drought probability for the England and Wales precipitation region (EWP). The quoted probabilities represent the upper bound of a 95% confidence interval (c.i.) of probabilities derived from the data 1900-1999.



**Figure 3.5 Upper estimates of drought probability for the Scottish precipitation region (SP). The quoted probabilities represent the upper bound of a 95% confidence interval (c.i.) of probabilities derived from the data 1931-1999.**

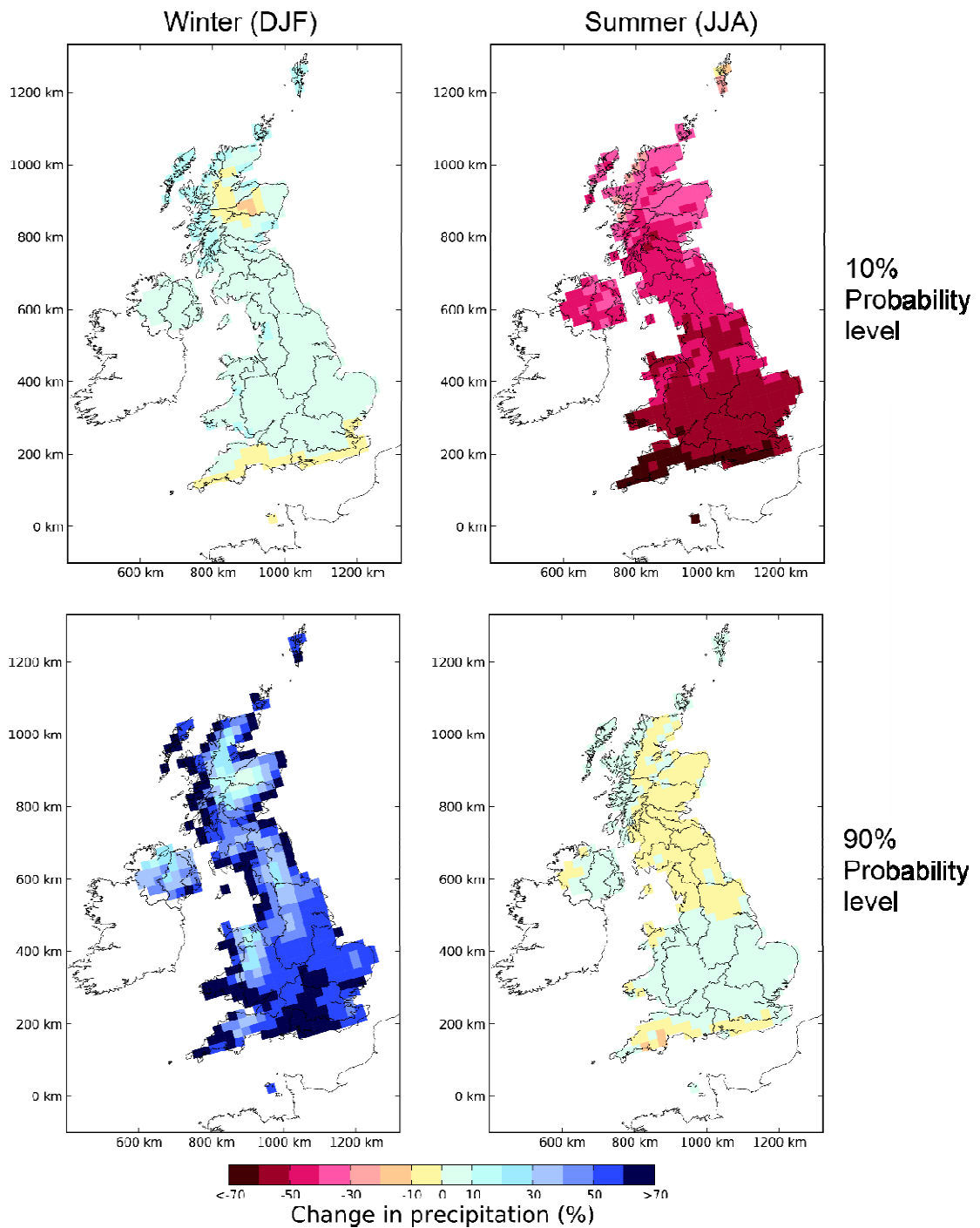


**Figure 3.6** Upper estimates of drought probability for the Northern Ireland precipitation region (NIP). The quoted probabilities represent the upper bound of a 95% confidence interval (c.i.) of probabilities derived from the data 1931-1999.

### **3.3 UKCP09**

Whilst UKCP09 is not suitable for the analysis of low precipitation accumulated over extended time periods (multi-year droughts) it does provide some information on changes at the seasonal timescale. Figure 3.7 shows projected changes in winter (left) and summer (right) precipitation totals expected by 2070-2099 under the UKCP09 high emissions scenario. The upper panels represent changes at the 10% probability (i.e. driest) level of the probabilistic range. The lower panels represent changes at the 90% probability (i.e. wettest) level. The overall pattern is a move toward wetter winters and drier summers. The range of the projected changes varies considerably across the probability ranges from almost no change through to shifts of greater than 70% of the 30-year average value. Geographically there is some indication that the largest reductions in summer precipitation are biased toward central and southern regions. However, these shortfalls may be compensated for through the enhanced winter rainfall projected for the same regions.



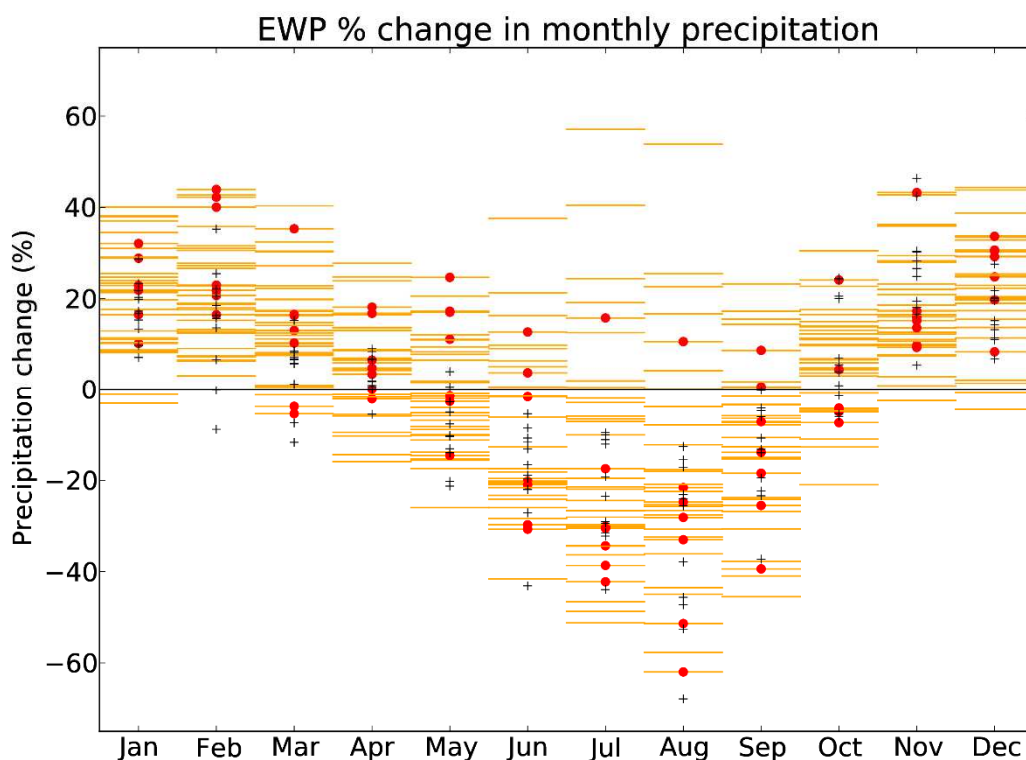


**Figure 3.2** Projected changes in winter (left) and summer (right) precipitation totals expected by 2070-2099 under the UKCP09 high emissions scenario. The upper panels represent changes at the 10% probability (i.e. driest) level of the probabilistic range. The lower panels represent changes at the 90% probability (i.e. wettest) level.

### 3.4 Evidence from CMIP5 climate models

CMIP5 (Taylor, Stouffer, and Meehl 2012) represents the current state-of-the-art in GCMs and earth system models (ESMs) that have been submitted to the World Climate Research Programme. A subset of 35 models was used in this study (based on availability at the time of writing).

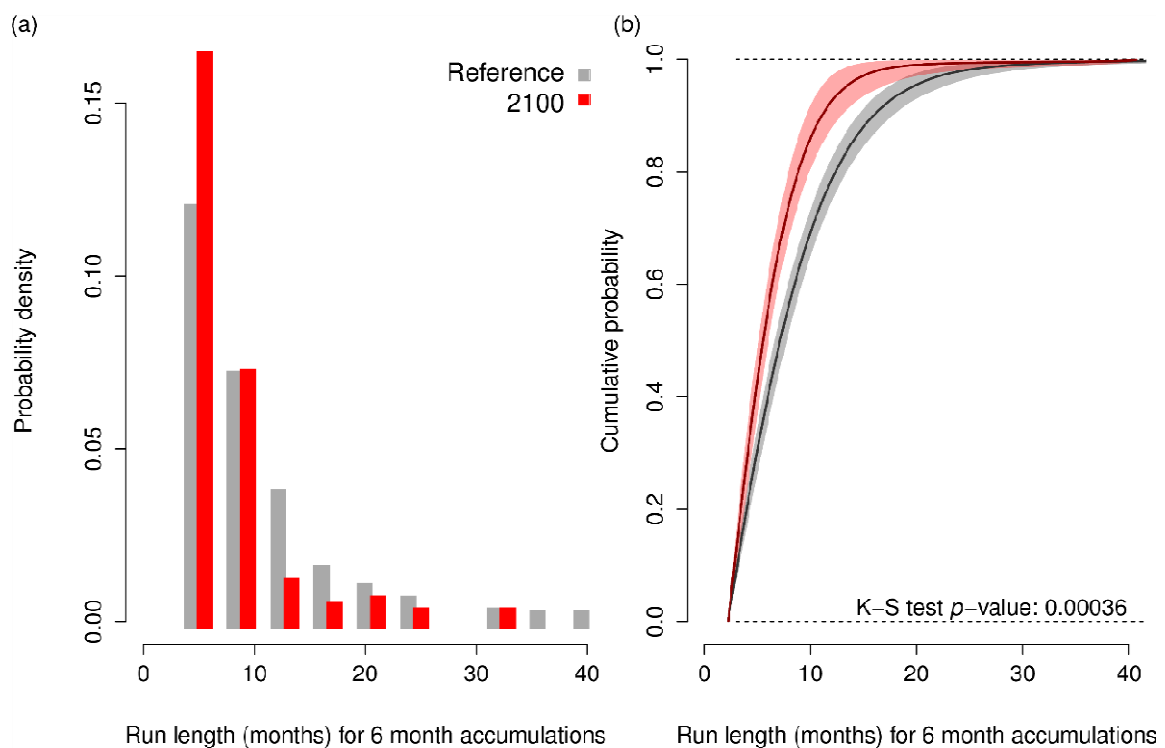
The magnitudes of projected changes in precipitation are shown in Figure 2.8 for the 35 CMIP5 models (orange lines) the 11-member Met Office regional climate model (black crosses) and the seven credible<sup>21</sup> CMIP5 models identified above (red circles). The values vary dramatically from model to model and from summer to winter. Whilst the pattern is noisy, the majority of the models projects a move toward wetter winters and drier summers, a result that is consistent with the projections of UKCP09 (Jenkins et al. 2009) and UKCIP02 (Hulme et al. 2002). It is notable that degree of spread is largely similar irrespective of the model subset.



**Figure 3.8 Projected changes (% difference from the 1900-1999 baseline) in expected monthly precipitation totals for 2070-2099 by month for each of the 35 CMIP5 models (orange lines), 11 UKCP09 regional models (black crosses) and the seven credible models (red dots).**

<sup>21</sup> Credible models based on the K-S test described earlier in the section (Table 3.1)

Since credible models (albeit only marginally credible) of low precipitation exist for the EWP region for the reference period (1900-1999) it is reasonable to examine their projections for the future (2070-2099) under the H++ scenario. The mixed pattern of changes in the average monthly precipitation totals lead to a mixed pattern of changes in the precipitation anomalies accumulated over longer time scales. In general, wetter winters tend to ameliorate the effects of summer droughts and serve to break up the longest sequences of below normal rainfall. Thus, the risk of multi-annual droughts might be thought to decrease. However, the risk of a dry winter in a particular year or series of years, whilst reduced, still remains, and when a particular occurrence is coupled with a dry summer, a severe long-period drought can still emerge. Such a mixture of effects can be seen in Figure 3.9 which compares the distribution of dry run lengths (consecutive negative precipitation anomalies for 6-monthly accumulations) between the reference period and the projected future. The shape of the distribution shifts to favour the probability of short period droughts whilst the risk of long period events remains.



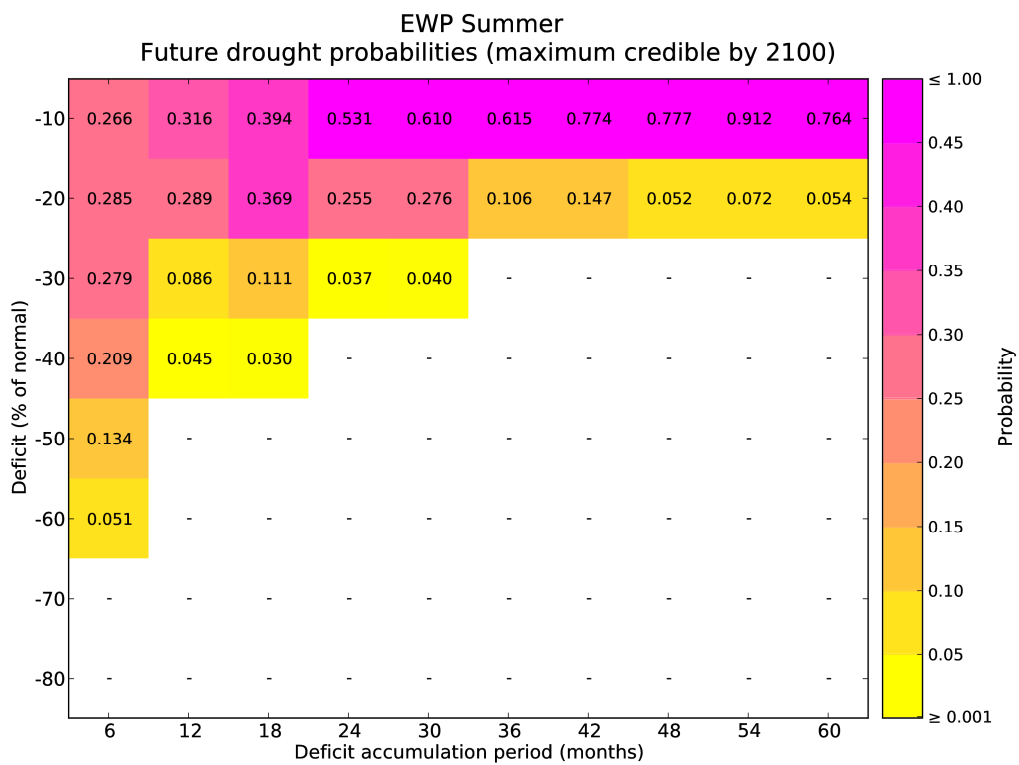
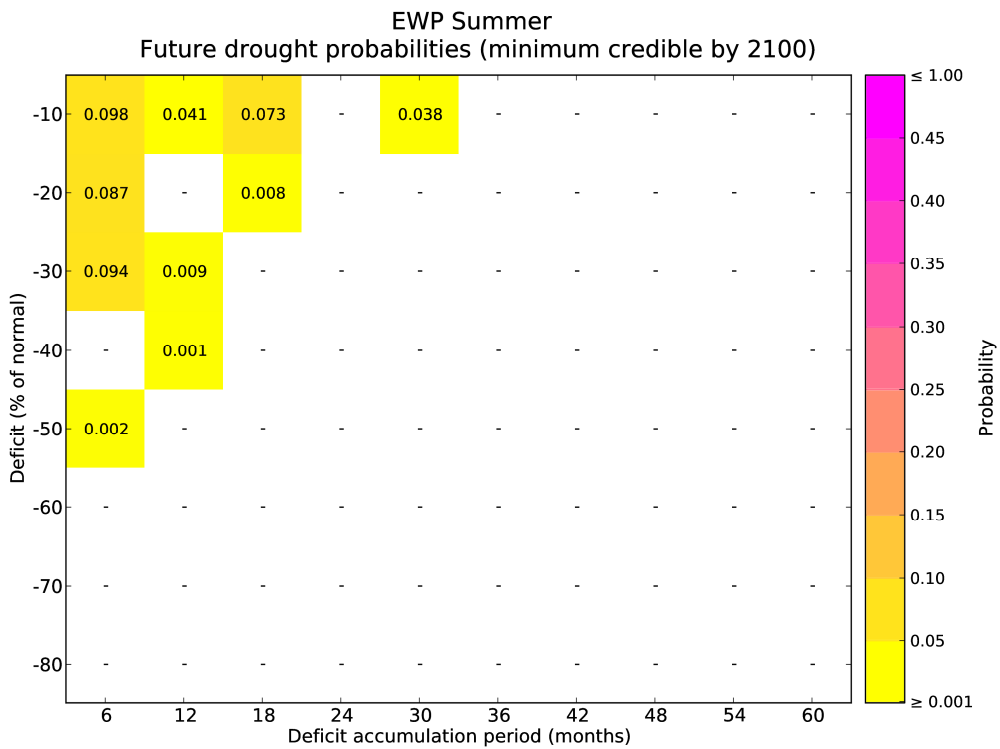
**Figure 3.9 Comparison of distributions of dry run lengths (consecutive negative precipitation anomalies for 6-monthly accumulations) between the reference period and the projected future (by 2100). The grey bars in panel (a) show the histogram of run lengths (drought durations) under the present climate. The red bars are model estimates for the climate in 2100. Panel (b) shows the same data as cumulative distributions with a 95% confidence interval (shaded).**

A similar pattern is seen in the changes in probability of low rainfall over short and long durations for England and Wales between the baseline and future periods; that is with the largest changes for 6 month durations, while the possibility of longer drought remains. These are presented for summer and winter droughts in Figures 3.10 and 3.11 respectively. The figures indicate credible ranges on the probabilities expected by 2100. The changes in probability are computed on a cell by cell basis. Minimal (optimistic) estimates are computed by applying the minimum shift (in terms of a move toward drier conditions) from the 7 credible models to the lower bound of the 95% confidence interval of the present day probabilities (estimated from the full observed EWP time series). Likewise, maximal (pessimistic) estimates are computed by applying the maximum shift from the 7 models to the upper bound of 95% confidence interval of the present day probabilities (i.e. by shifting the probabilities shown in Figure 3.3). Comparison of the baseline figures to the minimal and maximal future figures provides information on the possible changes in future periods of low rainfall. For example for England and Wales 6 month summer rainfall there was 1.3% chance of a 50% rainfall deficit for the baseline period (Figure 3.4 lower pane), which changes to a 0.2% to 13.4% chance of a 50% rainfall deficit in future periods (Figure 3.10). For England and Wales winter rainfall there is a 1% chance of 30% rainfall deficit over 30 months for the baseline period (Figure 3.4, upper pane), which becomes less likely changing to a zero to 1% chance in future (Figure 3.11).

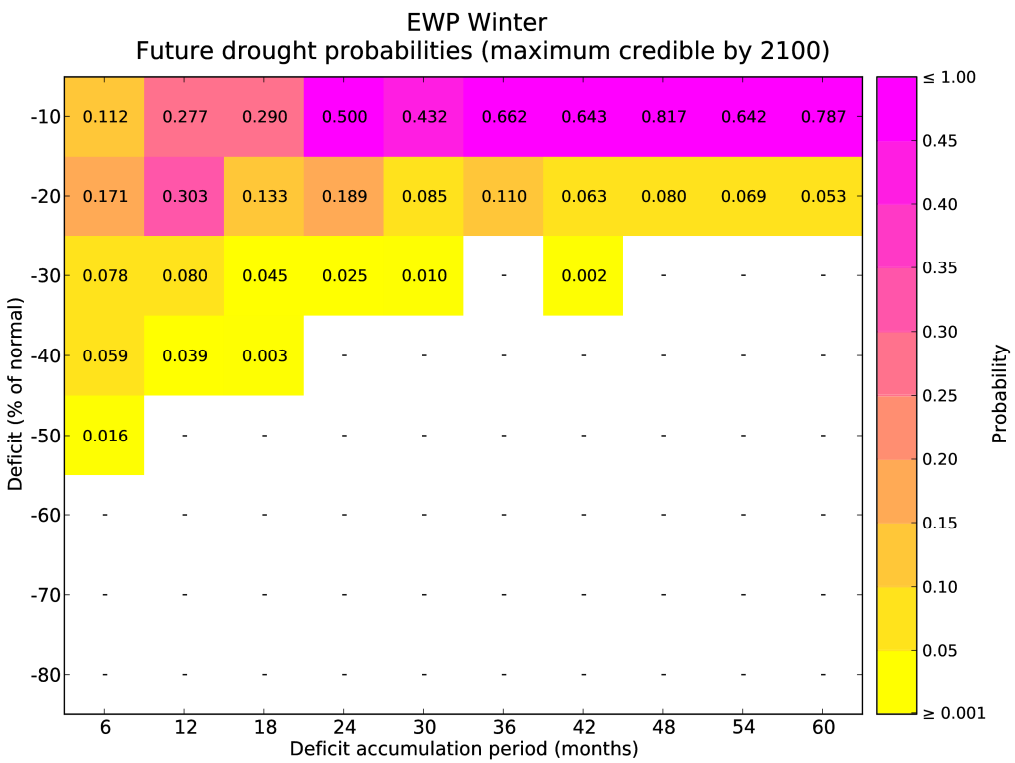
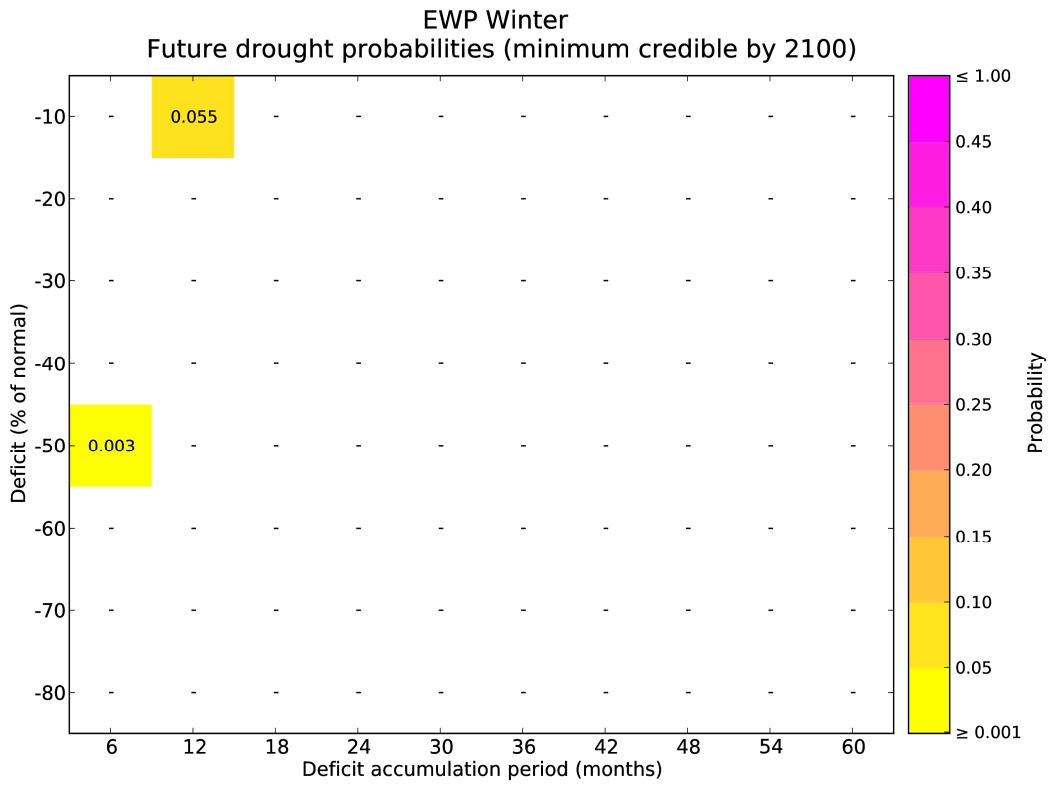
In the context of developing H++ scenarios for short and longer droughts, these results suggest:

- Future summer meteorological droughts in England and Wales could be more or less severe; **the largest changes suggest the possibility of significant increases in the probabilities of severe 6 month duration summer droughts. The chance of encountering deficits of up to 60% of the expected precipitation (under the current climate) increases from 0% to 5%.**
- No significant change in winter droughts; however, the possibility remains of some longer dry periods lasting several years **similar to the most severe long droughts on record.**

The current generation of global climate models are not capable of synthesising realistic droughts for regions as small as Scotland and Northern Ireland and little can be inferred about the change in risk over these regions.



**Figure 3.10 Upper (top panel) and lower (bottom panel) estimates of summer drought probability for the England and Wales precipitation region (EWP) credible by 2100.**



**Figure 3.11 Upper (top panel) and lower (bottom panel) estimates of winter drought probability for the England and Wales precipitation region (EWP) credible by 2100.**

### **3.5 Physical limits**

Thermodynamic arguments favour moister air in a warmer world and increased rainfall intensities (Allan 2011) (Section 5) however for this to be realised the moisture must be delivered and precipitated out. In general for the UK, large scale low pressure (cyclonic) systems deliver new water into the hydrological system which is in turn recycled through local convection. Drought can be initiated either by a reduction in delivery (fewer cyclones) and/or the suppression of precipitation (more anticyclones). Mid latitude cyclones and anticyclones are an inherent feature of our climate system resulting from the rotation of the Earth and its orientation to the sun (Carlson 1991). The path of cyclones across the north Atlantic and hence their incidence over the UK is biased toward a particular path and results in the emergence of what is known as the north Atlantic storm track. Analysis suggests that the position of the storm track is dependent on ocean-atmosphere coupling (Woollings et al. 2012). The dynamics which control the position of the storm track are complicated and poorly understood (Woollings 2010). However, under anthropogenic greenhouse-gas forcing, there is some evidence for the strengthening and eastward extension of the storm track towards Europe which may favour enhanced precipitation (Woollings et al. 2012) and an increased number of cyclones in winter incident upon central Europe (Zappa et al. 2013) (Section 4). This enhancement is counter balanced by the tendency of more warmer conditions to favour the development of larger scale anticyclonic systems (~2% larger for a warming of 4°C) (James 1951, Holton 2004). There is also evidence that high temperatures, a common feature of anticyclones in summer, can dry the soil which in turn reduces the amount of latent cooling and can thus drive temperatures even higher and soil moisture lower (Fischer et al. 2007). This in turn reduces the moisture available for local recycling. Physical considerations thus reveal competing influences which are consistent with the empirical findings from the climate models analysed.

#### *Spatial coherency*

A detailed analysis of the spatial coherency of UK droughts is provided by Rahiz and New (2012). They report a complex picture dependent on drought severity, duration and timing. This is consistent with previous analysis by the UK Environment Agency at the European scale (Hannaford et al. 2009). In general, drought over the UK is associated with blocked atmospheric flow across the North Atlantic Ocean and/or Eurasian land mass. The associated high pressure (anticyclonic) features that tend to suppress rainfall have a typical area that is several times that of the UK. Thus, whilst not all UK droughts

are spatially coherent, since the high pressure centre may not be located directly over the UK, the underlying physics suggest that spatial coherency is always a possibility. Thus, in this section we have used the physical limits concept as a sense check of the results and to provide some explanation of the model behaviour.

### **3.6 Other evidence**

#### *Palaeo analogue / evidence*

Analysis of European tree-ring data from the last 2500 years (Buntgen et al. 2011) suggest that earlier hydro-climatic changes have at times exceeded recent variations. Particularly alarming is the 200 year long period of reduced precipitation around 500 AD. During this period precipitation was reduced by 15% to 50% of the long-term average (range defined by  $\pm 1$  standard deviation) for a continuous period of 50 years. This period of time coincided with the demise of the Western Roman Empire and the turmoil of the Migration Period (*ibid*). The severity of this low rainfall period (15%-50% deficits) is similar to what is proposed for a H++ low rainfall (10%-60% over specific time periods) but clearly its longer duration is significant and is a scenario that has not been considered as part of H++. The lack of specific paleo data for the UK precludes any further analysis here but suggests an area for further research.

#### *Industry data*

The water industry use information on meteorological droughts for the design of water infrastructure, supply-demand planning and drought planning. In general the industry uses long term records (1920-present day) to understand drought risks and several companies have also considered more severe long duration droughts from the late 19<sup>th</sup> century. For strategic planning climate change scenarios are used to perturb the historical data making historical droughts in summer more severe but not changing the duration or spatial extent of droughts. For drought planning companies consider the drought situation and plan ahead using historical analogues – “what if the drought develops like 1976”, or simple percentage deficits of rainfall, for example a 20% reduction in rainfall over 12 months. The biggest concerns for UK water companies are related to long multi-season droughts with durations of 18 months to 3 or more years. The water resources impacts of H++ have been considered in a separate ASC project (HR Wallingford, 2015).



### 3.7 Summary of H++ scenarios

Future summer meteorological droughts in England and Wales could be more or less severe. Under H++ the largest changes suggest the possibility of significant increases in the probabilities of severe 6 month duration summer droughts. The chance of encountering deficits of up to 60% of the expected precipitation (under the current climate) increases from 0% to 5%.

Climate models suggest no significant change in winter droughts; however, the possibility remains of some longer dry periods lasting several years similar to the most severe long droughts on record. Table 3.2 provides a summary of the risk of low rainfall estimated from present day observations, UKCP09, CMIP5 and physical reasoning.

**Table 3.2 Summary of H++ risk assessment for rainfall deficits**

	Summer	Winter	Multi-year	Spatial coherence
Historic	Maximum deficit 50% of normal is credible	Maximum deficit 50% of normal is credible	<b>Credible 5 year drought with maximum deficit of 20% below normal</b>	UK wide droughts are possible
UKCP09	Increased probability	No change	No change	UK wide droughts remain possible. Some indication that the largest reductions in summer rainfall are biased toward central and southern regions
CMIP5**	<b>Maximum deficit of 60% below normal becomes credible (probability increases from 0 to 5%)</b>	No change	No change	<b>UK wide droughts</b> remain possible
Palaeo	N/a	N/a	Multi-decadal droughts are possible	Large scale droughts are possible
Physics	Increased probability***	Decreased probability***	No change	UK wide droughts could become more likely

\* The current generation of climate models are not capable of synthesising realistic droughts for regions as small as Scotland and Northern Ireland and less credibility is assigned to the change in risk over these regions.

\*\* The results quoted for CMIP5 are considered to be more credible than those for UKCP09 because of the longer baseline and stringent model selection criteria.

\*\*\* These entries are highly uncertain because the dynamics which control the position of the storm track are complicated and poorly understood (Woollings 2010).

## Chapter 4 Low flows

### 4.1 Summary of the H++ low flow scenarios

H++ low flow scenarios are defined as changes in Q95 (flow exceeded 95% of the time) associated with rainfall deficits based on CMIP5 outputs from England and Wales for 2080s as described in Chapter 3. Thus, this H++ can be seen as an extension of the rainfall scenarios. The low rainfall scenarios indicated a significant increase in the frequency of 6 month duration summer droughts as well as a potential increase in magnitude from a 50% to 60% deficit over this period. However there was little change in winter as increases in winter rainfall typically returned deficits to normal. Consequently, the most significant H++ low flow scenarios are for the summer period. There are three H++ low flow scenarios for single season (6 months), multi-season (2-3 seasons) and long droughts (2 years or more).

**The H++ scenario for summer low flows is a reduction in the Q95 by between 40 and 70 percent in England and Wales and 30 and 60 percent for Scotland and Northern Ireland. The H++ scenario for multi-season (2-3 seasons) droughts with consecutive summers is a 20 to 60 percent reduction in flows in England and Wales and 20 to 50 percent reduction in Scotland and Northern Ireland. For longer droughts (2 years or more) the H++ scenario is for up to 50 percent and 45 percent reductions in flow for England and Wales and Scotland and Northern Ireland respectively<sup>22</sup>.**

The H++ scenarios were developed by combining the work on low rainfall (Chapter 4) with catchment case studies that make use of set of response surfaces linking changes in precipitation to flow that were developed as part of another Environment Agency project (Ledbetter, Anderton, & Prudhomme, 2015).

The assessment is subject to a number of important caveats, particularly that the H++ results are defined from national rainfall scenarios and it is possible that more severe events could occur at local scale. In addition, rivers in the UK are regulated and influenced by abstractions and discharges, which are managed during drought situations to maintain water resources and protect the environment. This assessment has not considered these effects or new infrastructure that may be

---

<sup>22</sup> H++ low flow scenarios are given for three durations as impact and management options are likely to differ as drought prolongs: single season; multiple seasons (2-3); and multiple years. To capture uncertainty in projections upper and lower estimates are given.

developed as part of water companies long term plans<sup>23</sup>. A separate research project available alongside this report (Project B – projections of future water availability) has considered the impacts of climate change on UK water resources.

## **4.2 Historical data and methods**

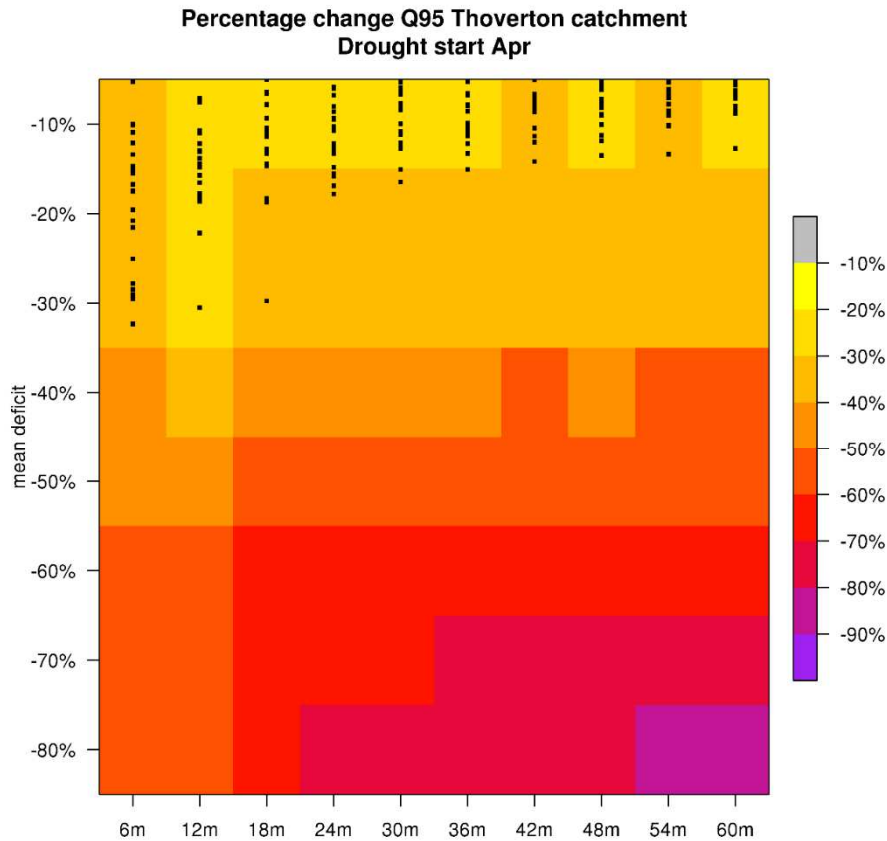
### *Background*

Compared with floods, very little research has been conducted to develop methods and investigate the impact of climate change on droughts and low flows. The main tools available to link H++ scenarios of low rainfall with low flows and subsequently water resources deficits (Project B) are response surfaces generated in an EA research project on investigating the resilience of water supply systems to extreme droughts (SC0120048). These response surfaces present a low flow/drought index based on an ensemble of daily time series river flow simulations in response to synthetic drought scenarios for a number of river basins. An illustrative example of a response surface is shown in Figure 4.1. The key features of the analysis are as follows:

- The response surfaces represent the local sensitivity of river flow to meteorological droughts, defined by their average rainfall deficit (y-axis) and duration of rainfall deficit (x-axis). The colour associated with each combination (duration, deficit) represents the change in the low flow indicator.
- Consistently with current UK practice to quantify low flows (Environment Agency, 2013a, 2013b; Lang Delus et al., 2014), the low flow indicator used is the percentage change in Q95 (calculated over the duration of the drought).
- Drought characteristics of the H++ low rainfall scenarios are quantified as rainfall deficit (departure from the long term average LTA, as % of baseline) and duration (in months). For each duration, the rainfall deficit probabilities in Chapter 4 were used to estimate a 10% and 1% probability of rainfall deficits in the 2080s.
- Then these rainfall deficits were used in combination with local drought response surfaces (for each river basin) to estimate local impacts of H++ low rainfall on low flows at the 10% and 1% probability levels.

---

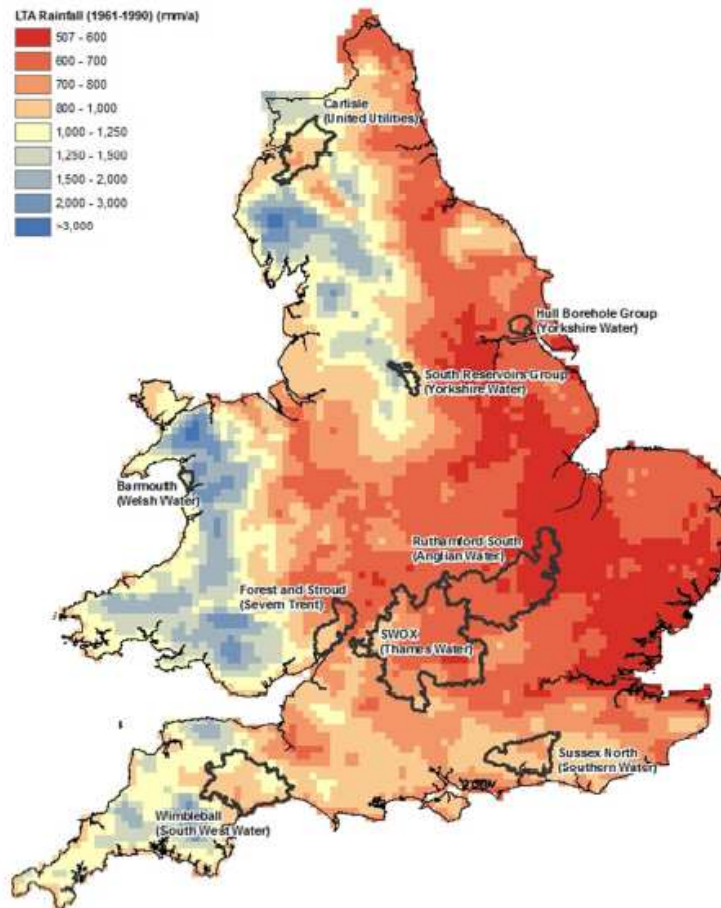
<sup>23</sup> Current water resources planning guidelines consider climate change with a focus on the use of UKCP09 Medium Emissions gridded or catchment average data.



**Figure 4.1: An illustrative example of a response surface from EA research project SC0120048. The y axis describes rainfall deficits, x-axis the duration in months and the colours describe impacts on the Q95 flow indicator. The black dots represent historical events.**

#### *Data and baseline modelling*

Analysis was based on the limited modelling undertaken in the project SC0120048 of six river basins selected according to their location and model performance. The case studies refer to the name of the four water supply systems considered in the original project SC0120048 where the river basins are located. They show a gradient of mean annual rainfall between 624 mm (Ruthamford) to 1980 mm (Barmouth). Due to the budget and time constraints to develop the H++ low flow scenarios, no further modelling could be done and the six river basin results are assumed to be representative of the range of possible hydrological response to meteorological droughts in England and Wales. It can be seen from Figure 4.2 that these basins cover a reasonable range of annual average rainfall conditions but there are more basins in central and southern areas.



**Figure 4.2. Location of case studies considered in project SC0120008. Background shading according to the long term average LTA Rainfall (1961-1990). Source Ledbetter, pers. communication.**

Case Study	River basin	NRFA Gauge	Long term average Rainfall (mm)
Barmouth	Llyn Bodlyn	N/A	1980
Carlisle	Eden	Eden at Sheepmount – 76007	1212 (Based on the nearby Gelt basin)
	Gelt	N/A	1212
Ruthamford South	Offord	Ouse at Offord – 33026	624
Wembleball	Haddeo	Haddeo at Hartford* – 45010	1308
	Thorverton	Exe at Thorverton - 45001	1284

**Table 4.1. Case study used for low flow/ droughts analysis. \*River flow discharge was scaled to reflect reservoir inflow prior to modelling**

For the development of the local ‘drought response surfaces’, catchment average daily rainfall data was calculated from the CEH-GEAR 1-km gridded daily areal rainfall dataset for the period 1961-2012 (Keller et al., 2015; Tanguy, Dixon, Prosdociimi, Morris, & Keller, 2014). Catchment average monthly potential evapotranspiration PET was derived from the Met Office Rainfall and Evaporation Calculation System MORECS (Thompson,

Barrie, & Ayles, 1982), and monthly PET distributed evenly throughout the months for the period 1961-2010. Daily gauged river flow time series were obtained from the National River Flow Archive when available and from relevant water companies otherwise. Catchment hydrological models were created and calibrated using HR Wallingford's water resources modelling framework using a PDM (Moore, 2007) type model.

### *Populating drought response surfaces*

The impacts (change in Q95) represented in the drought response surfaces were created using hydrological modelling. Rainfall drought scenarios were defined as a matrix of drought duration (ranging from 6 months to 5 years in 6-month increments) and drought severity (average rainfall deficit of -10% to -90% of LTA). For each drought scenario, synthetic rainfall and PET sequences were created by resampling local historical rainfall and PET daily sequences with monthly rainfall total matching the drought scenario characteristics. The drought sequences, along with preceding and recovery phases of LTA rainfall, were input in the hydrological models and daily river flow sequences generated. Response surfaces were then derived by calculating the low flow index associated with each drought sequence scenario. Details of the methodology can be found in (Ledbetter, Anderton, & Prudhomme, 2015).

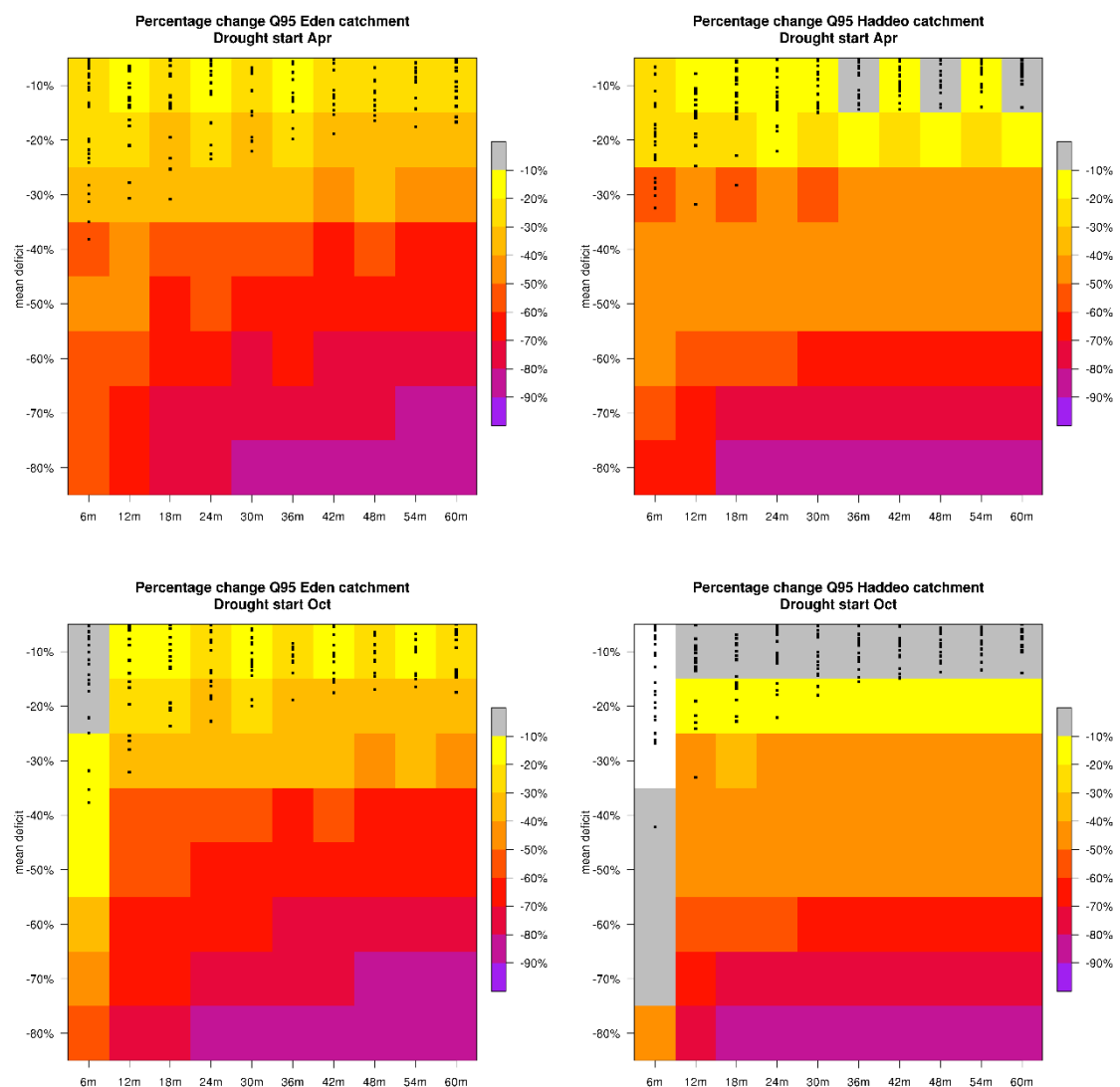
### *Method*

The H++ risk assessment for national rainfall deficits (Table 3.2) was applied to the local response surfaces to estimate H++ low flow scenarios based on the same CMIP5 models. This approach is very similar to the use of response functions in the CCRA 2012 Water Sector report, albeit more complex as it is considering multiple drought magnitudes and durations simultaneously. The big assumption in this approach is that the national rainfall deficits for England and Wales translate to the same percent deficits locally. In practice, there will be some variation and local deviations will tend to be much greater in the 'epicentre' of a meteorological drought and much less in distant surrounding areas.

For each river basin, the drought characteristics of the summer and winter 10% and 1% probability levels of the H++ low rainfall scenarios (2080s time horizon) were identified and the associated values in the response surface extracted for each duration. The lower (upper) end of the H++ range are then defined as the corresponding minimum

(maximum) absolute change for the 10% (1%) probability level out of the six river basin responses for each duration.

Five H++ low flow scenarios are considered: single season (6 month) summer and winter droughts, corresponding to short intense events; multiple season droughts starting in summer and winter (e.g. with two consecutive dry winters/summers); and long, multi-year droughts (from 24 to 60 month duration). As no local response surface was available outside England and Wales, the H++ low rainfall scenarios of both Scotland and Northern were used along with local responses in England and Wales and combined to provide the Scotland and Northern Ireland H++ low flow scenarios.



**Figure 4.3 Examples of response surface of Q95 anomaly (over drought duration; %) compared to baseline Q95 (annual) for April (top) and October (bottom) drought start**

### *Historical observations*

Ways of characterising historic episodes of low flows and hydrological droughts in the UK are currently investigated in several NERC-funded projects specifically 'DRIVER' (G8MUREFU3FP-2200-108) and Historic drought (NE/L01016X/1), but projects are still underway and have not yet reported characteristics of the most severe events recorded the UK. For example, an inventory of historic droughts for the UK is expected to be published by the Historic drought project around March 2018.

In a recent review of climate-driven changes in UK river flows, (Hannaford, 2015) noted a general lack of evidence for trends in UK low flows (especially in the 1960s to early 2000s period), despite some recent high-profile drought events with significant societal impacts such as 2004 to 2006 and 2010 to early 2012. Instead, historic droughts have clustered with drought-rich (including multi-year episodes) and drought-poor periods, but there is a general lack of understanding of the causes of this variability (ibid).

The most comprehensive source of information on major historical UK droughts can be found in (Marsh, Cole, & Wilby, 2007), summarised in Table 2. It shows that droughts have manifested themselves over a range of durations. This feature can be seen in the runoff deficit time series associated with reconstructed monthly river flows produced by (Jones & Lister, 1998) shown in Figure 4.4, with both short intense events (e.g. Wharfe in mid 1930s) and long and relative widespread events (e.g. early 1900 in many of the catchments) identifiable. This range of spatio-temporal patterns was also highlighted by (Parry, Lloyd-Hughes, Hannaford, Prudhomme, & Keef, 2011) who examined the spatio-temporal footprints of five major European droughts over the period 1961-2005. This suggests that H++ low flow scenarios should be defined over a range of durations.



Year	Duration	Comments
1854–1860	Long drought	<b>Major long duration drought.</b> Sequence of dry winters in both the lowlands (seven in succession at Oxford) and northern England. Major and sustained groundwater impact.
1887/88	Late winter 1887 to summer 1888	<b>Major drought.</b> High-ranking rainfall deficiencies across a range of timeframes. Very widespread (across most of British Isles). Extremely dry 5-month sequence in 1887. Primarily a surface water drought – severe in western Britain (including northwest).
1890–1909	Long drought	<b>Major drought – long duration</b> (with some very wet interludes, 1903 especially). Initiated by a sequence of notably dry winters. Latter half of the period features a cluster of dry winters. Major and sustained groundwater impact, with significant water supply problems. Most severe phases: 1893, 1899, 1902, 1905. Merits separate investigation.
1921–22	Autumn 1920 to early 1922	<b>Major drought.</b> Second lowest 6-month and third lowest 12-month rainfall totals for England and Wales. Very severe across much of England and Wales (including Anglia and southeast; parts of Kent reported <50% rainfall for the year); episodic in northwest England.
1933/34	Autumn 1932 to autumn 1934	<b>Major drought.</b> Intense across southern Britain. Severe surface water impacts in 1933 followed by severe groundwater impacts in 1934, when southern England heavily stressed (less severe in the more northerly, less responsive, chalk outcrops).
1959	Feb to Nov	<b>Major drought.</b> Intense 3-season drought – most severe in eastern, central and northeastern England. Significant spatial variation in intensity. Modest groundwater impact.
1976	May 1975 to Aug 1976	<b>Major drought.</b> Lowest 16-month rainfall in E&W series (from 1766). Extreme in summer 1976. Benchmark drought across much of England and Wales – particularly the lowlands; lowest flows on record for the majority of British rivers. Severe impact on surface water and groundwater resources
1990–92	Spring 1990 to summer 1992	<b>Major drought.</b> Widespread and protracted rainfall deficiencies – reflected in exceptionally low groundwater levels (in summer 1992, overall groundwater resources for England and Wales probably at their lowest for at least 90 years). Intense phase in the summer of 1990 in southern and eastern England. Exceptionally low winter flows in 1991/1992.
1995–97	Spring 1995 to summer 1997	<b>Major drought.</b> Third lowest 18-month rainfall total for England and Wales (1800–2002). Long-duration drought with intense episodes (affecting eastern Britain in hot summer of 1995). Initial surface water stress, then very depressed groundwater levels and much diminished lowland stream network.

**Table 4.2 Major droughts in England and Wales, 1800–2007 (from (Hannaford, 2015) and (Marsh et al., 2007)).**

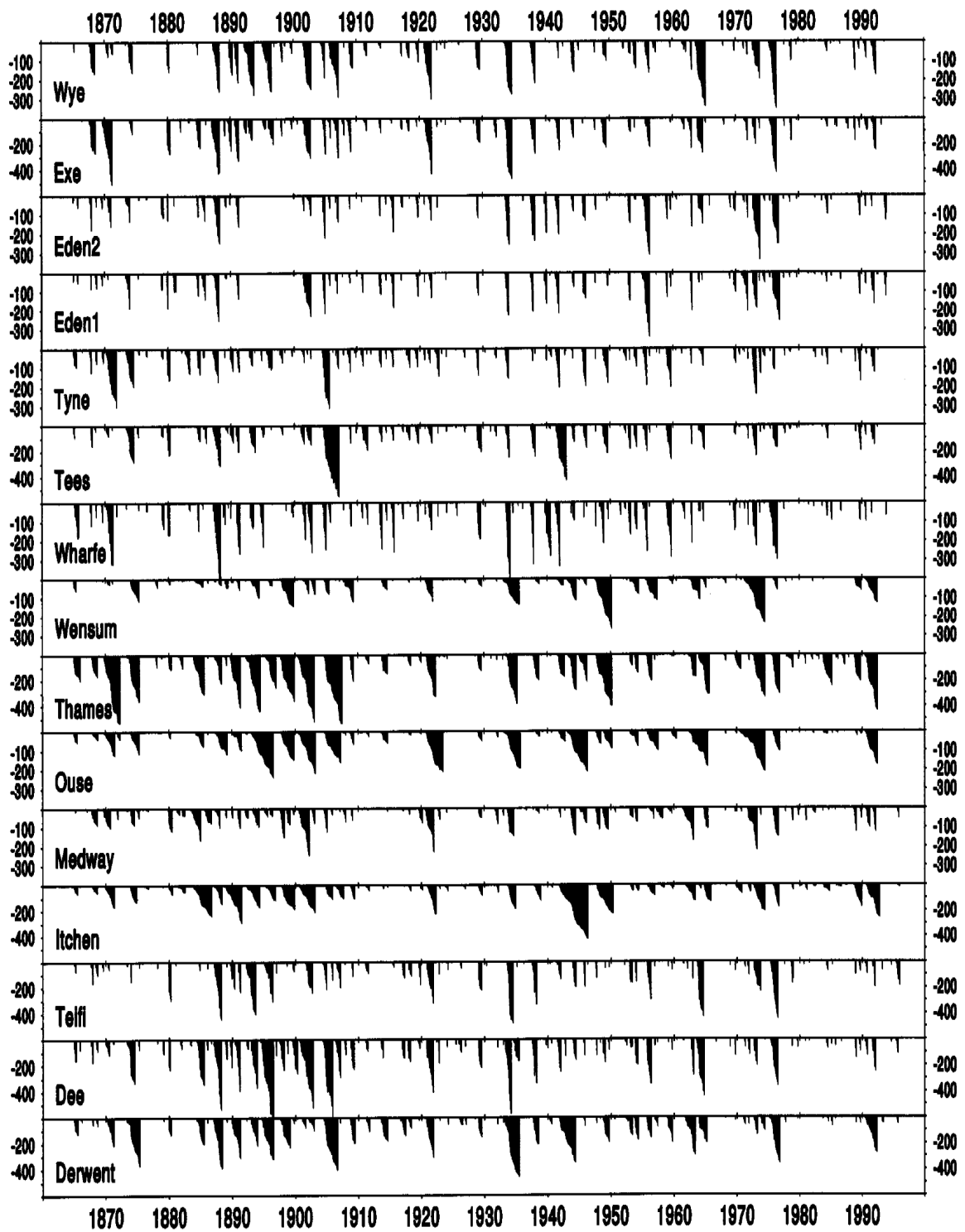


Figure 4.4 Runoff deficit index (mm) for 15 catchments based on reconstructed monthly river flow. Note difference in scale between some catchments. From (Jones & Lister, 1998)

### **4.3 UKCP09**

UKCP09 does not include projections of future river flow, although all UK water companies have made use of the projections to estimate the impacts on water resources systems. In 2012, the CCRA used UKCP09 and the results of water company studies in 2009, to estimate potential impacts on low flows at a regional scale. For example in Anglian Region for the 2050s Medium emissions scenario, it estimated changes in Q95 between -14 and -50% and for the 2080s High emissions scenario, changes from -38% to -70% (Wade et al., 2012). A more comprehensive approach adopted for CCRA2 suggests marginally smaller reductions in low flows (Section 4.5).

### **4.4 Physical limits**

Physical limits have not been considered in detail as part of the H++ low flow assessment. However, it is important to recognise that changes in low flows are very sensitive to both catchment characteristics and artificial influences. Groundwater dominated streams are a special case with some headwater streams drying out naturally under drought conditions, whereas others are impacted by groundwater abstraction. Many rivers are sustained by groundwater, even in very dry summers and a significant reduction in groundwater levels would be required to reduce flows. Other rivers are maintained by discharges (effluent and storm water discharges). Detailed catchment studies are required to understand the potential impacts of H++ low rainfall scenarios on specific catchments.

### **4.5. Other evidence**

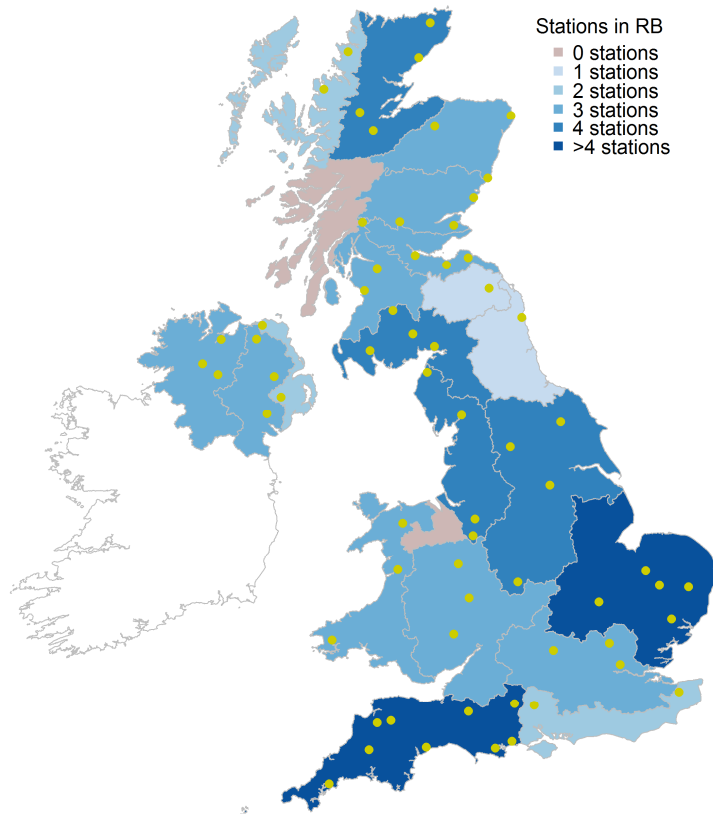
To complement the limited number of case studies where the H++ low rainfall scenarios could be applied, the modelling results of the CCRA2-B project (HR Wallingford, 2015) were considered and summarised in Table 4.3. Modelling was undertaken for all Future Flows catchments (Prudhomme et al., 2013) with available PDM model (Moore, 2007; Christel Prudhomme et al., 2012). Future climate time series input in PDM (rainfall and PET) were generated using the change factor method (Hay, Wilby, & Leavesley, 2000) based on gridded UKCP09 probabilistic change factors under the High emission scenarios for the 2080s time slice (Murphy et al., 2009). For each 10,000 resulting river flow time series, Q95 (annual) was calculated and compared with that derived from simulations driven by observed climate time series. Regional changes were then derived as an average of catchment changes (weighted by basin area) and the lowest 10% probability level was estimated. UKCP09 upper end (lower end) scenarios for

England, Wales and Scotland correspond to their maximum (minimum) absolute 10% probability level of change found in the region. Note the different number of catchments/ information used to derive regional and national estimates.

By construction the UKCP09 climate scenarios do not include any information on change probability in drought duration or intensity of extreme events but instead give an estimate of how the whole flow regime might shift. While some regional variations are seen, there is a noticeable homogeneity in the UKCP09 upper end changes of a decrease of -50% in Q95.

England		Wales		Scotland	
UKCP09 upper end	-45	UKCP09 upper end	-50	UKCP09 upper end	-45
UKCP09 lower end	-30	UKCP09 lower end	-50	UKCP09 lower end	-10
<b>Anglian</b>	-40	Dee	-50	Argyll	-45
<b>Humber</b>	-30	Severn	-50	Clyde	-45
<b>Northumbria</b>	-30	Western Wales	-50	Forth	-30
<b>Northwest England</b>	-45			Northeast Scotland	-15
<b>southeast England</b>	-35			north Highland	-25
<b>southeast England</b>	-45			Solway	-45
<b>Thames</b>	-30			Tay	-30
				Tweed	-40
				west highland	-10

**Table 4.3 UKCP09 low flow scenarios for the 2080s expressed as changes in annual Q95 based on 10% probability level of changes in simulated river flows driven by the 10,000 probabilistic UKCP09 change factor applied to baseline climate as described in (Christel Prudhomme et al., 2012). [Note that all values are rounded to the nearest 5%.]**



**Figure 5.5 Location of FFH stations within each River Basin region in the UK. The river basin regions are coloured according to the number of stations found in each region.**

### **4.6 H++ scenarios**

Based on the analysis described in Section 3.1, several H++ low flow scenarios were developed and are summarised in Table 4.4.

**The H++ scenario for summer low flows is a reduction in the Q95 by between 40 and 70 percent in England and Wales and 30 and 60 percent for Scotland and Northern Ireland by the 2080s. The H++ scenario for multi-season droughts with consecutive summers is a 20 to 60 percent reduction in flows in England and Wales and 20 to 50 percent reduction in Scotland and Northern Ireland. For longer droughts the H++ scenario is for up to 50 percent and 45 percent reductions in flow for England and Wales and Scotland and Northern Ireland respectively<sup>24</sup>.**

Single season summer droughts are the most severe of the H++ low flow scenarios as the naturally occurring low flows (defined by the Q95 statistic) are further reduced by

<sup>24</sup> H++ low flow scenarios are given for three durations as impact and management options are likely to differ as drought prolongs: single season; multiple seasons (2-3); and multiple years. To capture uncertainty in projections upper and lower estimates are given.

40% to 70%. This is a very similar range as presented for Anglian Region for 2080s High emissions in the CCRA 2012 but here it applies to the whole of England and Wales not just the driest UKCP09 region in England.

Winter droughts are still possible with Q95 deficits of 0 to 40%. When droughts prolong to 2 or 3 seasons the impact of the seasonality reduces, while their probability is reduced due to the projected wetter winters. Multi-year droughts events may still occur in the future and these could be associated with a reduction in low flows of 0- 50% (Q95) over up to 5-year period.

	Summer	Winter	2-3 season (1 or 2 consecutive summers)	2-3 season (1 or 2 consecutive winters)	Long (>= 2 years)
	<i>Increased probability</i>	<i>No change/ decrease</i>	<i>Increased probability</i>	<i>No change</i>	<i>No change</i>
<b>England and Wales</b>					
<b>H++ upper end</b>	-70	-40	-60	-60	-50
<b>H++ lower end</b>	-40	0	-20	-10	0
<b>Scotland and Northern Ireland</b>					
<b>H++ upper end</b>	-60	-25	-50	-45	-45
<b>H++ lower end</b>	-30	0	-20	-10	-5

**Table 4.4 H++ low flow scenarios for England and Wales for the 2080s time horizon, expressed as percentage changes in Q95. [Note that all values are rounded to the nearest 5%.] Probability of occurrence based on evidence given in Section 3.**

#### *Caveats*

The methodology used to define the H++ low flow scenarios is attached with a number of assumptions that must be considered when using the scenarios. They are summarised below:

- The H++ low rainfall scenarios on which the method is based are national-scale projections; locally it is likely that more extreme low rainfall (and by extension, low flow) scenarios could occur;
- The H++ low flow scenarios are based on response surfaces of six river basins from four case studies. It is possible more extreme response could be found if a wider range of test catchments were considered;
- No simulation was available outside England and Wales so the response surfaces obtained for the case study catchments were used as proxy for Scotland and Northern Ireland. Further work needs to be done to refine the H++ scenarios outside England and Wales.

## Chapter 5 High rainfall

### 5.1 Summary of the High ++ high rainfall scenarios

There are two scenarios for high rainfall, the first is for increases in average winter rainfall (Dec-Jan-Feb), which is important for fluvial and groundwater flood risk, as demonstrated by the flooding in winter 2013/14 that affected large areas of England and Wales, including the Somerset Levels. The second is for heavy daily and sub-daily rainfall in winter or summer, which is important for river flooding, flash flooding and urban drainage, such as the rainfall events in Cumbria in 2009 and Boscastle in 2004 that caused severe flooding. Both scenarios relate to 30 year average conditions.

**The H++ scenario for average winter rainfall is an increase of 70% to 100% on the 1961-1990 baseline by the 2080s, which overlaps but is marginally higher than the UKCP09 2080s High emissions scenarios. The H++ for heavy daily and sub-daily rainfall for the same period is a 60% to 80% increase in rainfall depth for summer or winter events based on a consideration of new high resolution modelling and physical processes. This is within the UKCP09 distribution tails for the 2080s High emissions “wettest day of the winter” variable but higher than uplifts previously considered for summer.**

For winter rainfall the final High ++ scenario is based primarily on UKCP09, CMIP5 modelling results and expert opinion<sup>25</sup> and is presented as a range of percentage uplifts on average winter rainfall. For daily and sub-daily rainfall the results are based on high resolution modelling and expert opinion which considers the physical limits to rainfall depths and is presented as a percentage increase in rainfall event depths and a range of increases in frequency of heavy rainfall events<sup>26</sup>.

Information on H++ scenarios is already included in the Environment Agency FCERM guidance on “*Adapting to Climate Change*”, which will be updated again in 2015 (EA, 2015). This explains how H++ scenarios can be used in flood risk management. In addition, the same high resolution modelling results have been considered in new

---

<sup>25</sup> Expert opinion has been used to weigh up the evidence and decide on the final H++ ranges presented at the end of the section. This is based on opinion of the authors rather than a formal expert elicitation exercise.

research for urban drainage design as part of the UKWIR report “Rainfall Intensity for Sewer Design” (UKWIR, 2015).

## 5.2 Historical observations

### *High winter rainfall*

Considering the UK as a whole and based on data from 1910, four of the five wettest calendar years have been since 1999 (2000, 2012, 1954, 2014, 2008) and the wettest winters (Dec-Jan-Feb) were 2013/14, 1994/95, 1989/90, 1914/15, 2006/07<sup>27</sup>.

The winter of 2013/14 was an exceptional period of winter rainfall affecting a large area of the UK (Figure 5.1). The clustering and persistence of the storms was highly unusual, making December and January exceptionally wet months with a total rainfall of 372 mm over the two months for the south east and central southern England. The monthly totals were greater than 175% and 200% of 1981-2010 average rainfalls, for December and January (Figure 5.1). It was the wettest any 2-month period in the series from 1910. If a large area of England and Wales is considered this is likely to have been the wettest winter in at least 248 years (Met Office and CEH, 2014). Huntingford *et al* (2014) described the driving meteorological factors that influenced the 2013/14 flooding (see Chapter 7).

Figure 5.2 shows a time series of winter precipitation for the south east and south west of England (lines) and deviations from the 1961-1990 average winter precipitation (bars); the winter 2013/14 was the wettest in both regions but there were also notably wet winters in 1929/30 and 1936/37.

### *Trends in winter rainfall*

Any analysis of rainfall trends is hampered by limitations of observing systems, the high natural variability of rainfall and sensitivity to start and end dates. According to the UKCP09 trends report observed increases in winter rainfall (Dec-Feb) from 1961 have been greatest in Scotland and Wales (Jenkins *et al.*, 2008). There is some evidence for an increasing trend in the amounts of precipitation over northern Europe between 1900 and 2005 and increases in heavy rainfall over the UK (Osborn *et al.*, 2000). Kendon (2014) took a novel approach and explored trends in record breaking weather using data from the National Climate Information Centre (NCIC), which highlighted a period of

---

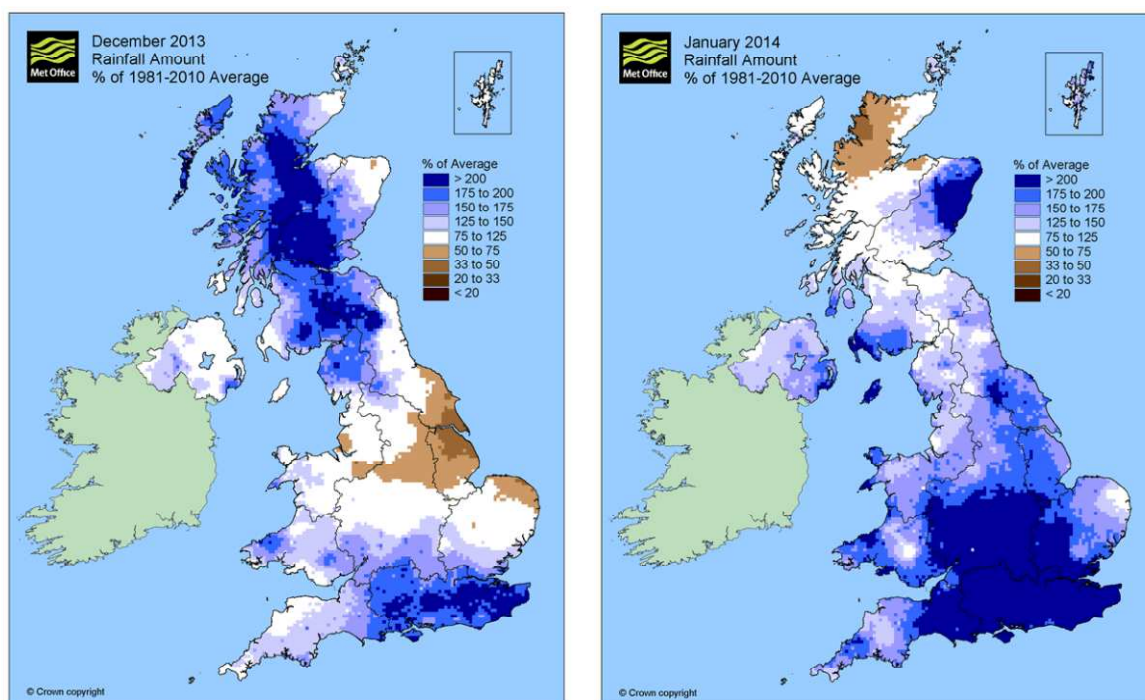
<sup>27</sup> UK Rainfall areal series starting from 1910. Allowances have been made for topographic, coastal and urban effects where relationships are found to exist. Data are provisional from September 2014 & Autumn 2014. Last updated 02/03/2015



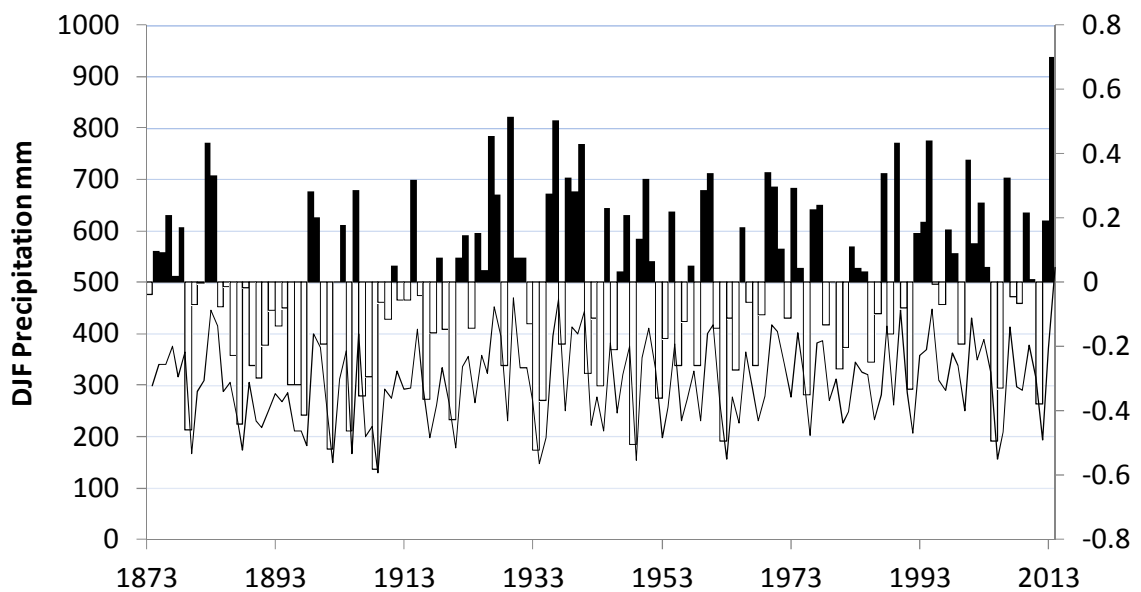
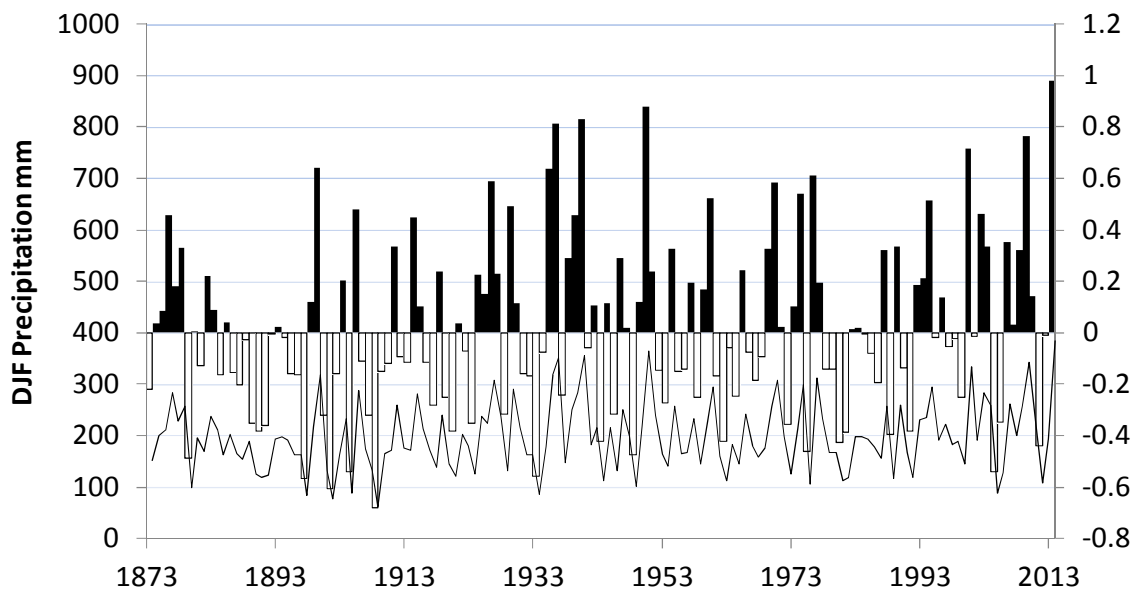
record breaking heavy rainfall in the second decade of the 20<sup>th</sup> century (1910s) and a large number of notable events since 2000.

#### *Attribution to climate change*

Several authors have linked periods of heavy rainfall to climate change. For example, Pall et al. suggested that climate change had already increased the chance of the rainfall that caused the 2000 floods more than two-fold (Pall et al., 2011). A more comprehensive hydrological analysis using similar climate change model data confirmed that the risk of flooding in autumn (September to November) is likely to have increased due to climate change, but suggested a lower increase in the frequency of events (Kay et al., 2011). Similar research on the winter 2013/14 flooding is in progress and will shortly be published. However, this type of attribution activity is still an active area of scientific research and whilst the results are consistent with our understanding of basic atmospheric thermodynamics there is still significant uncertainty in the size of these effects. Furthermore, we should not assume that all recent extreme rainfall events can be attributed to human drivers.



**Figure 5.1. Rainfall for December 2013 and January 2014 from the observational network, showing the distribution of rainfall anomalies as a % of the long-term average from 1981-2010.**



**Figure 5.2. South East of England (top) and South West and South Wales precipitation (bottom) for December, January and February (line) and deviation from the 1961-1990 average (bars) from the Met Office regional precipitation time series**  
 Source: <http://www.metoffice.gov.uk/hadobs/hadukp/>

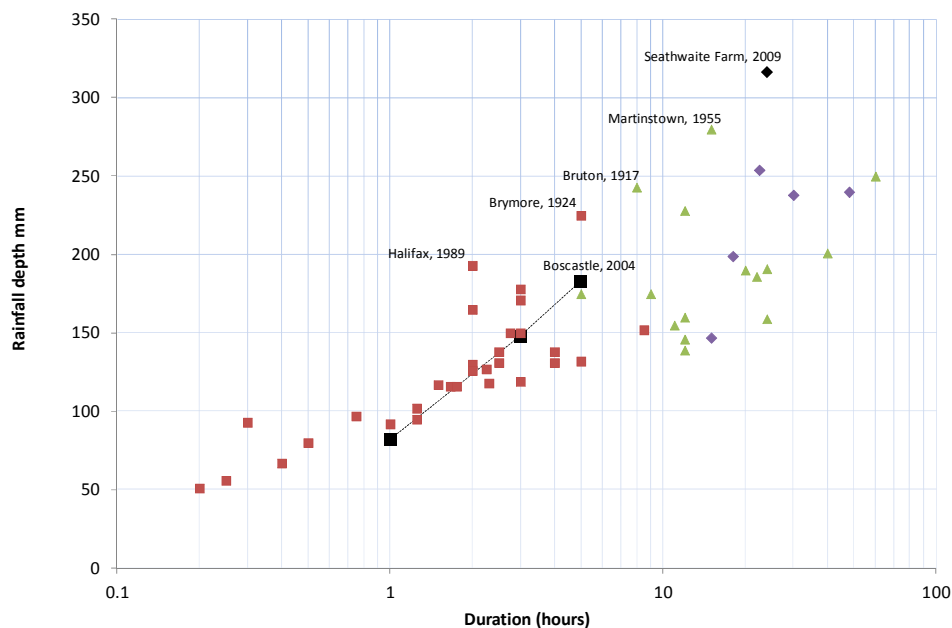
*Rainfall events*

Hand et al (2004) investigated extreme rainfall events in the United Kingdom from 1900 to 2000 with durations of up to 60 hours. They found suitable conditions for extreme rainfall in different meteorological situations related to orographic, frontal and convective systems. Convective conditions caused the heaviest rainfall at short durations and

orographic and frontal conditions caused heavier rainfall at durations greater than five hours (Figure 5.3). Particularly notable events have occurred in the summer (June, July or August) for example :

- Castleton (Yorkshire) with 250 mm in 60 hours (frontal)
- Lynmouth in 1952 with 228 mm in 12 hours, which caused devastating floods
- Martinstown (Dorset) in 1955 with 280 mm in 15 hours (both classified as frontal with a significant convective component)
- Hindolvesten (Norfolk) in 1959 with 93 mm in around 20 minutes (convective).

More recently heavy rainfall events that caused severe flooding have occurred at Boscastle in Cornwall (2004) and in Cumbria (2009). The Boscastle floods, 16th August 2004, were caused by a sequence of convective storms that channelled along the North Cornish coast. One station at Lesnewth indicated accumulations of 82mm, 148mm and 183mm over 1, 3 and 5 hours and a peak instantaneous rain rate of nearly 300 mm hr<sup>-1</sup> (Fenn et al., 2005). Otterham, near Boscastle, recorded 200 mm in 5 hours (Stewart et al., 2013). The Cumbria floods in 2009 were triggered by an exceptional longer duration rainstorm with 316.4 mm recorded at Seathwaite Farm, Borrowdale (Stewart et al., 2012). This is a UK record for rainfall over any 24 hour period and was an exceptional event with an annual probability of approximately 0.1% or 1 in 1000 years.



**Figure 5.3. Plot of point rainfall amount (mm) versus duration (h) (on a logarithmic scale) for different event categories, square – convective, triangle – frontal and diamond – orographic (adapted from Hand, 2004).**

### *Trends*

Jones et al. (2013) reported increases in spring and autumn extreme rainfall events in the UK, with longer duration winter events increasing in intensity and becoming more frequent. They also indicate more frequent heavy rainfall events in Scotland and Southwest England. Overall these findings are consistent with the changes projected in UKCP09, based on indicators such as “the wettest day of the winter” and outputs of the UKCP09 weather generator. Over the same period they found that short-duration summer rainfall events had declined in intensity

### *Attribution*

There has been less work on attribution of daily and sub-daily rainfall, primarily due to the inadequate spatial resolution and low skill of climate models at reproducing heavy rainfall events in summer months. In response to the July 2007 floods, Otto et al. (2014) concluded that 5-day rainfall events in July were likely to be heavier and more frequent in comparison to the 1960s.

### *Estimation of design rainfall*

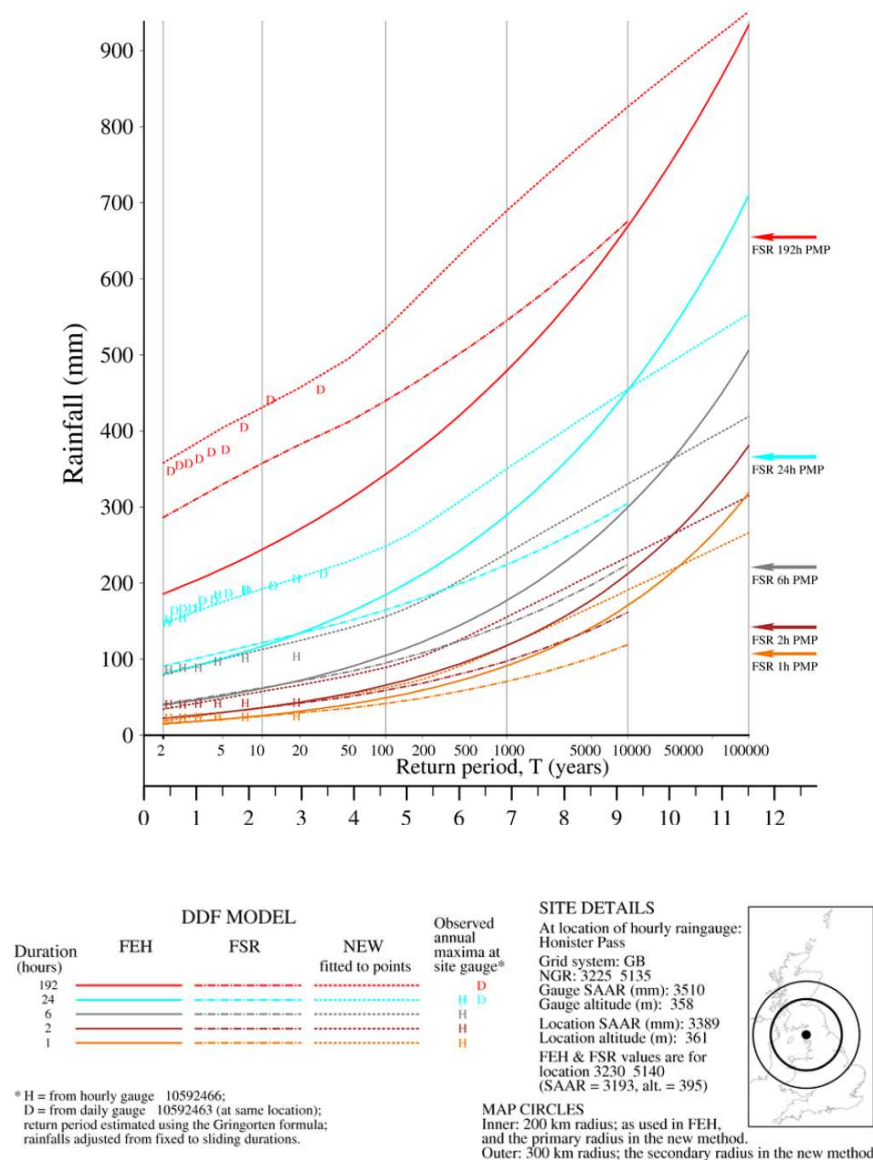
Flood risk, drainage and reservoir engineers use estimates of rainfall depths for the design of flood risk management schemes, urban drainage systems and reservoir spillways. Design estimates are normally based on an agreed national method using either observed data from a single site or, more appropriately, a larger number of sites as in the Flood Studies Report (FSR) or Flood Estimation Handbook (FEH).

A new statistical model of point rainfall depth-duration-frequency (DDF) (FEH13) is under development at CEH and replaces the previous model (FEH99). The supporting research considered historical extremes, Probable Maximum Precipitation (PMP) and different statistical models for estimation of low probability or long return period rainfall events (Stewart et al., 2013). The heaviest events<sup>28</sup> generated in England by the new DDF model are of the order of 500 mm in 24 hours (e.g. Honister Pass, Cumbria, SAAR 3193 mm yr<sup>-1</sup>, Fig. 9-20 in Stewart et al 2013) and of the order of 220 mm in London (Kew, SAAR 605 mm yr<sup>-1</sup>, Fig. 9-26 in Stewart et al 2013). For the locations and events included in Figure 4.3, many of the largest observed events, such as Martinstown in 1955 and Halifax in 1989, are close to or even greater than estimates of PMP.

---

<sup>28</sup> These are estimated to have a return period of 1 in 100,000 years

In general terms both rainfall models (FEH13 and FEH99) produce similar design rainfall depths up to return periods of around 1 in 50 years (probability 2%). The new rainfall model (FEH13) generally produces lower rainfall depths for lower probability events as illustrated in Figures 5.4 to 5.7. The differences between the rainfall models can be large, which highlights the sensitivity of these estimates to different periods of rainfall data as well as methods of analysis. Comparison of these statistical models to historic events (Figures 5.5 to 5.7) indicates that more extreme events are always possible and also that theoretical Probable Maximum Precipitation (PMP) estimates can be exceeded.

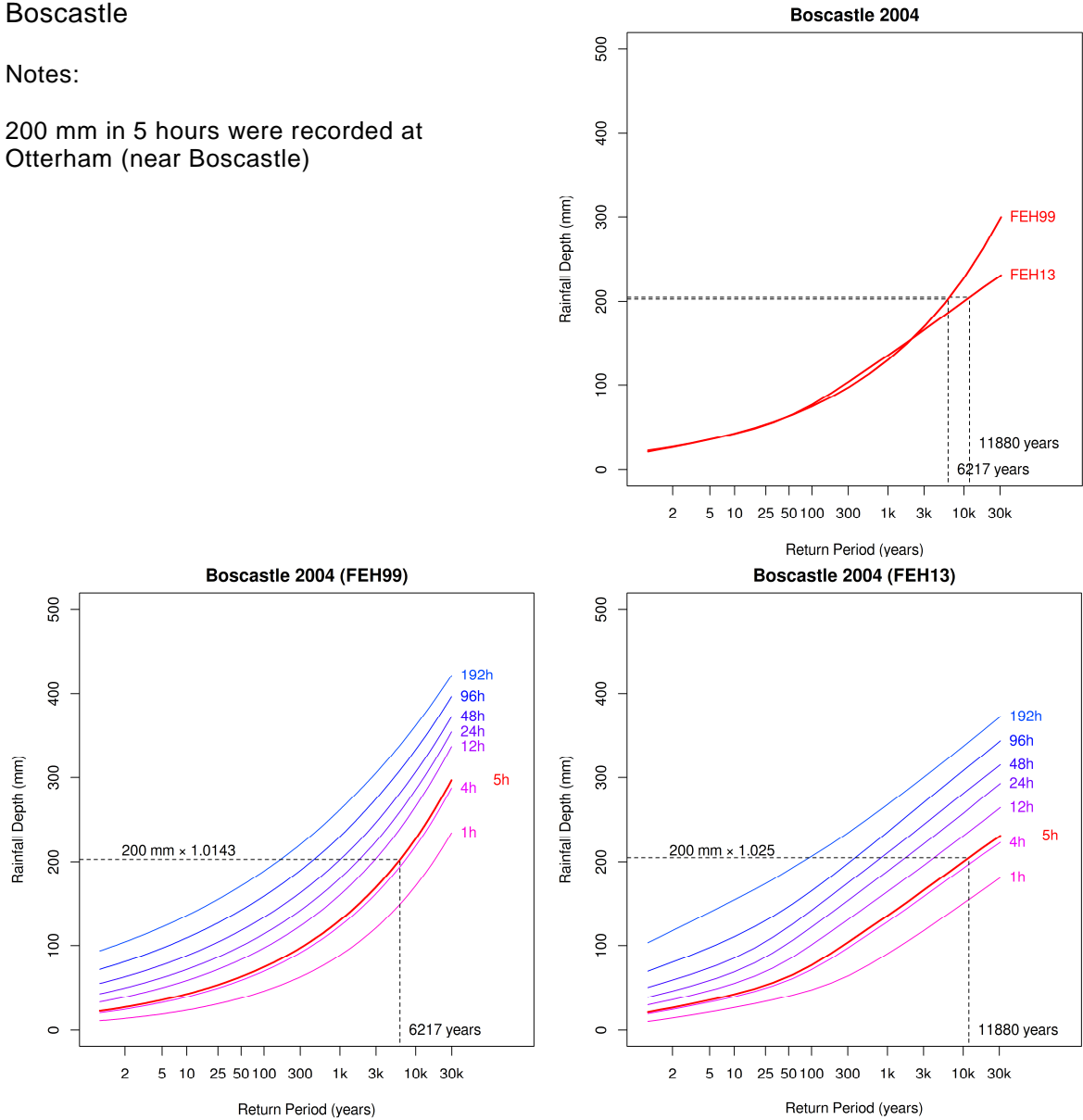


**Figure 5.4. Examples of models of extreme precipitation fitted to Honister Pass, Cumbria with 24 hour precipitation shown in blue and previous Flood Studies Report (FSR) Probable Maximum Precipitations as arrows (SAAR 3193 mm yr-1, Fig. 9-20 in Stewart et al 2013). The lower x-axis shows the reduced variate.**

## Boscastle

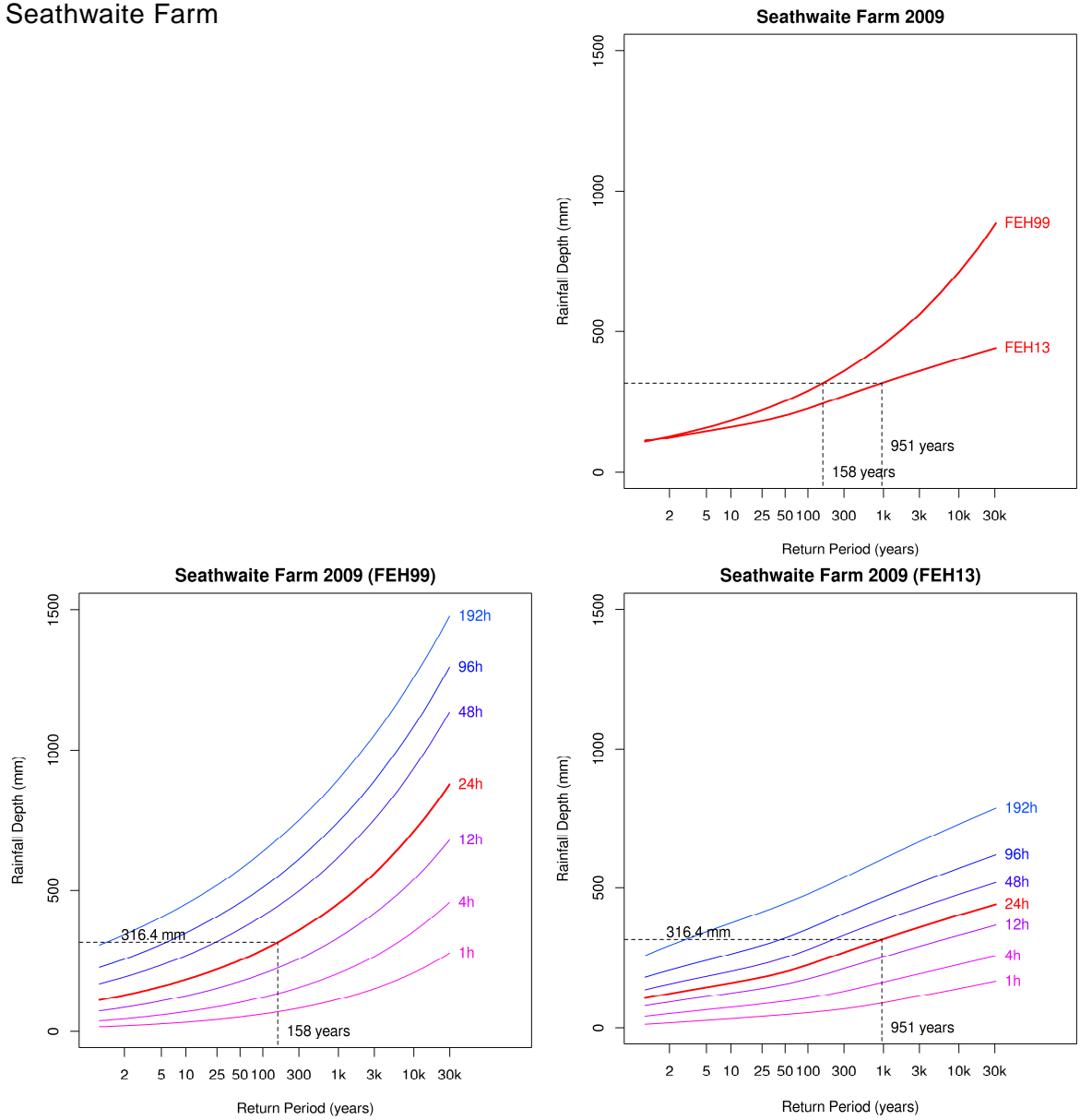
Notes:

200 mm in 5 hours were recorded at Otterham (near Boscastle)

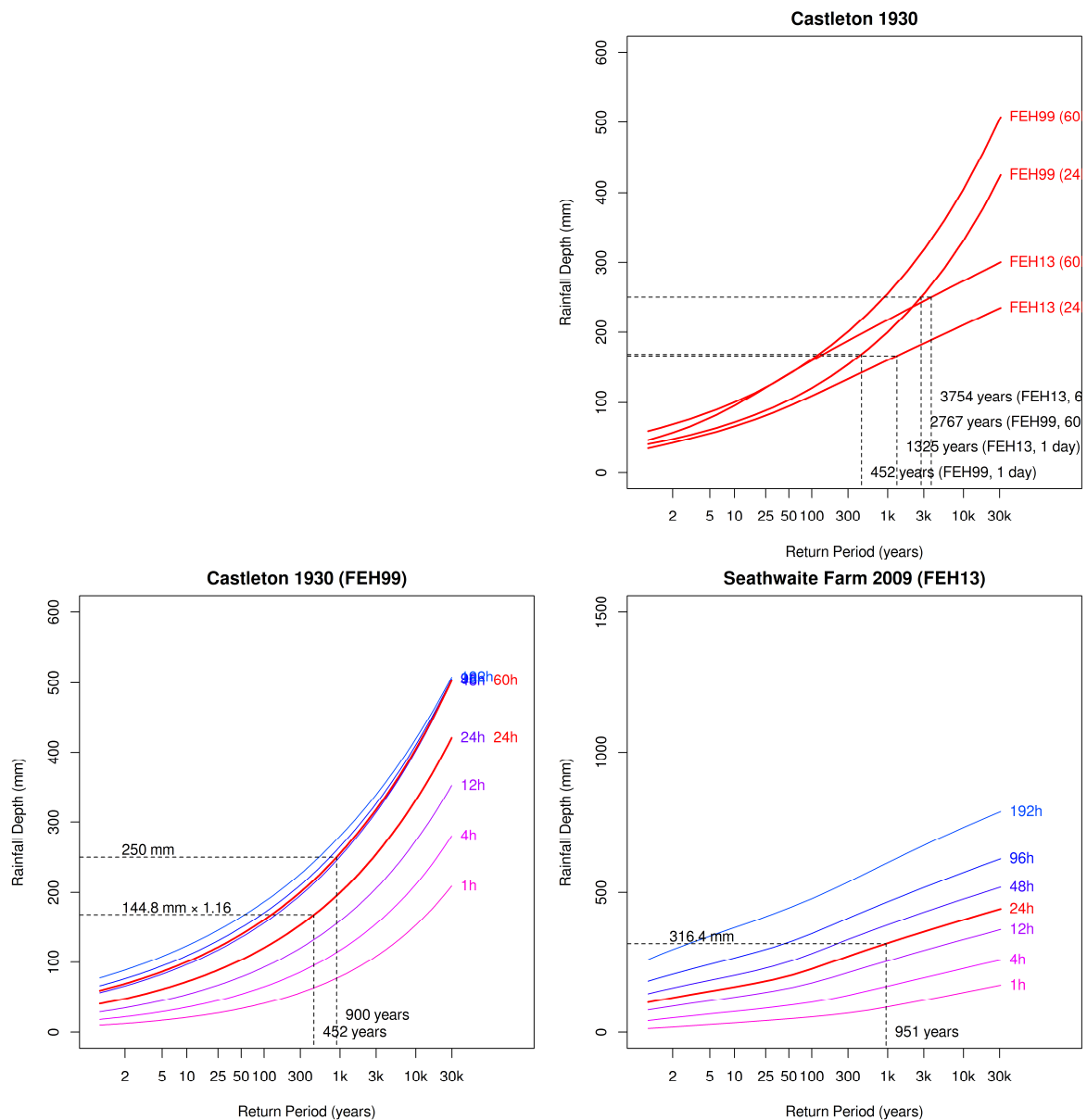


**Figure 5.5 Estimate of extreme rainfall at Boscastle according to the FEH99 and FEH13 rainfall models.**

# Seathwaite Farm



**Figure 5.6. Estimate of extreme rainfall at Seathwaite Farm in Cumbria according to the FEH99 and FEH13 rainfall models.**



**Figure 5.7. Estimate of extreme rainfall at Seathwaite Farm in Cumbria according to the FEH99 and FEH13 rainfall models.**

### 5.3 UKCP09

#### Winter rainfall

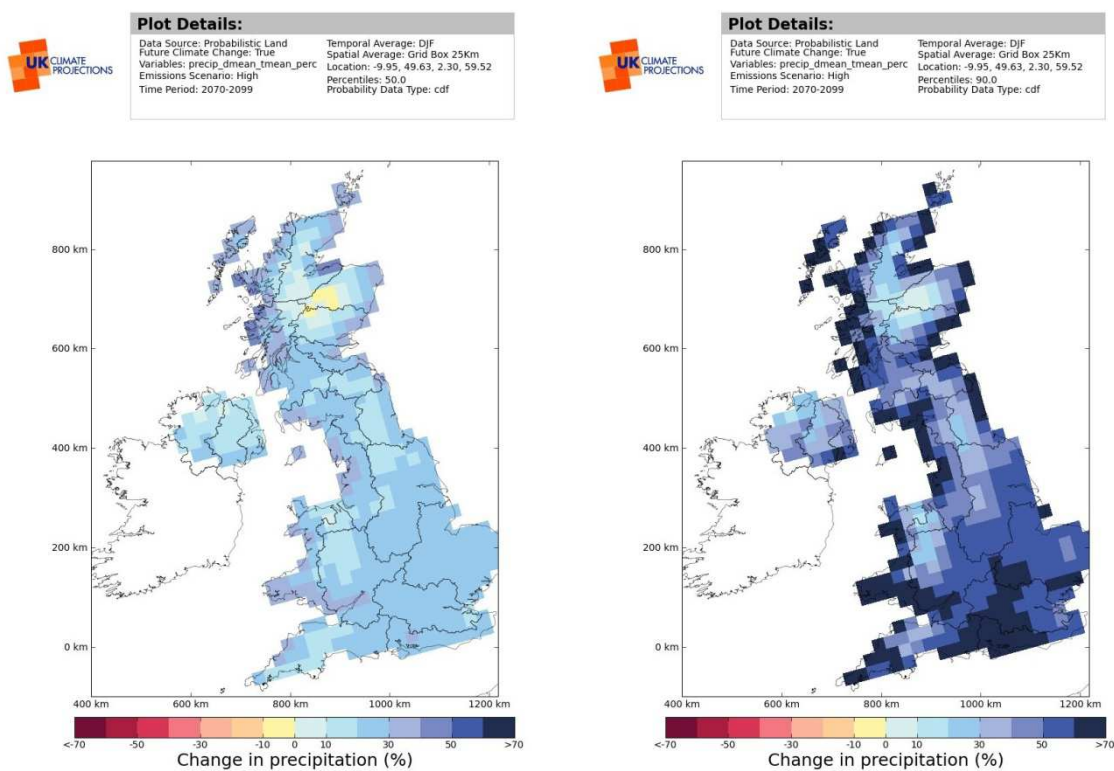
The UKCP09 projections provide information on future changes in the average annual rainfall, seasonal rainfall and “wettest day of the year/season” (Murphy et al., 2009).

Figure 5.8 provides maps of projected changes in 30-year average winter precipitation and wettest day of the year<sup>29</sup> (winter) for the High Emissions 2080s and the 50<sup>th</sup> and 90<sup>th</sup>

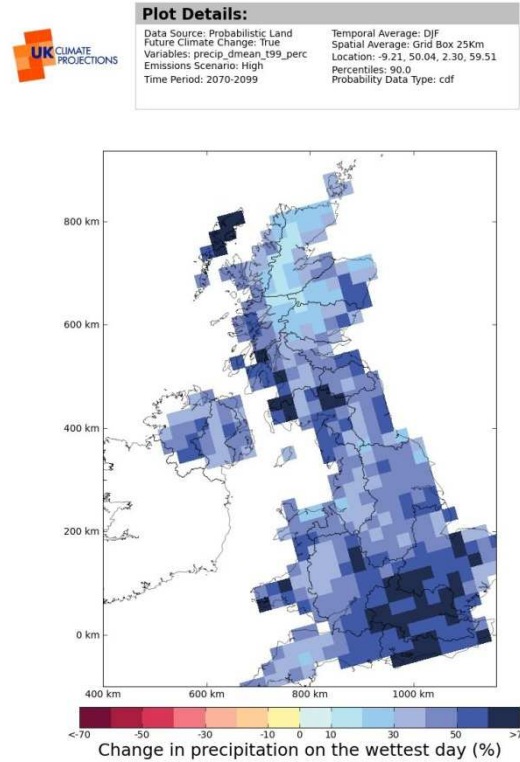
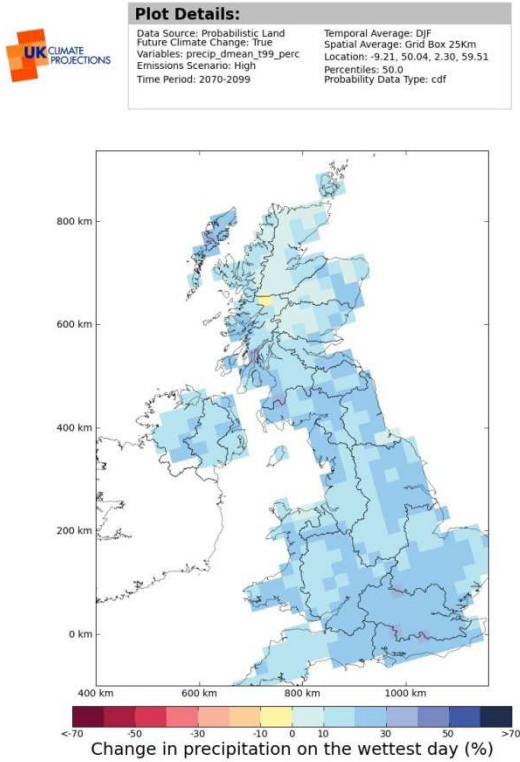
<sup>29</sup> This is calculated as the 99<sup>th</sup> percentile, so for the annual figure it may be exceeded 3 or 4 days a year but at a seasonal scale it is equivalent to wettest day and measures such as the mean of annual maxima or  $R_{med}$ .



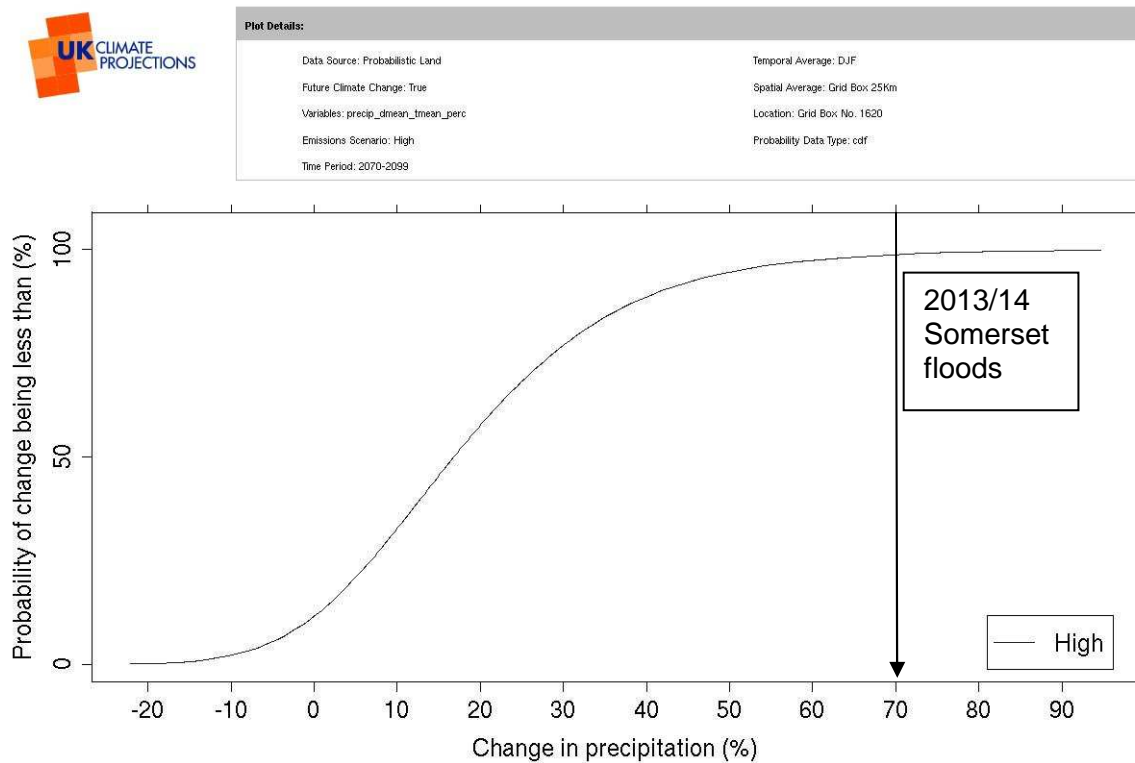
percentiles of the UKCP09 sampled data. Both indicate the possibility of changes of around 70 percent (or greater); within individual grid squares projected changes in the wettest day of the winter and average winter precipitation reach 80 and 90 percent respectively (Figures 4.9 and 4.10). The projections provide robust estimates of future changes in winter rainfall (mostly frontal in nature) but are less appropriate for considering heavy summer rainfall (see the following section). Changes of 70-90% are very unlikely under the High Emissions scenario but the tails of the distribution indicate that a winter precipitation like 2013/14 could be an average winter by the 2080s.



**Figure 5.8. Change in precipitation in winter (DJF) for the 2080s High Emissions scenario and 50<sup>th</sup> and 90<sup>th</sup> percentiles**

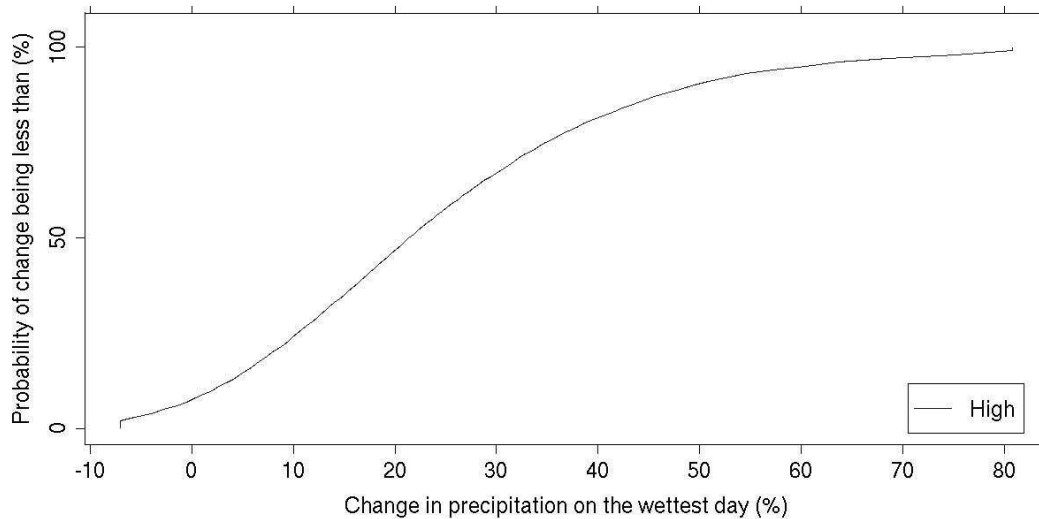


**Figure 5.9. Change in precipitation on the “wettest day” of the winter (DJF) for the 2080s High Emissions scenario and 50<sup>th</sup> and 90<sup>th</sup> percentiles**



**Figure 5.10. Change in 30 year average winter precipitation on the Somerset Levels in winter (DJF) for the 2080s High Emissions scenario shown with the single year of 2013/14 for illustration purposes**

Plot Details:	
Data Source: Probabilistic Land	Temporal Average: DJF
Future Climate Change: True	Spatial Average: Grid Box: 25km
Variables: precip_dmean_199_perc	Location: Grid Box: No. 1653
Emissions Scenario: High	Probability Data Type: cdf
Time Period: 2070-2099	



**Figure 5.11. Change in average precipitation on the North Cornwall coast on the “wettest day” of the winter (DJF) for the 2080s High Emissions scenario**

### Daily rainfall

The UKCP09 weather generator (Jones et al., 2009), which has been widely used to estimate uplifts in daily rainfall, produced increases in median annual maximum daily rainfall ( $R_{med}$ ) of around 12 to 23 percent for the Medium Emissions scenario (P50) and these were used in the CCRA (Wade et al., 2012)<sup>30</sup>. The weather generator was updated in 2011<sup>31</sup>. All locations exhibited a wider uncertainty range both in the baseline and the future with increases in the 90<sup>th</sup> percentile values and decreases in the 10th percentile values in the future projections compared to the original version. (The uplifts were similar in percentage terms). Using a very different approach based on non-stationary Extreme Value Analysis, data from Regional Climate Models and a 2050s Medium emissions scenario (A1B), Brown et al estimated changes in extreme summer daily rainfall between -16% and +24% and an increase in 5 day autumn rainfall of between 1% and 24% compared to a 1961-1990 baseline (Brown et al., 2014).

<sup>30</sup> The largest uplift reported was 38% (2080s Medium Emissions p90/Control p90)

<sup>31</sup> <http://ukclimateprojections.metoffice.gov.uk/22585>

## 5.4 Evidence from CMIP5 and other climate models

A recent Met Office review compared the outputs of CMIP5 models to UKCP09. The ranges of future change in average climatological conditions across CMIP5 models were generally found to be consistent with the probabilistic projections from UKCP09. However, the study did find some significant differences for projections of UK summer rainfall. While UKCP09 and CMIP5 agree that average summer rainfall is more likely to reduce rather than increase in the future, CMIP5 suggests smaller reductions than UKCP09 and a somewhat larger chance that UK summer rainfall could remain similar or become wetter than it is today (Sexton et al., 2013).

The CMIP5 models indicate an increase in heavy rainfall globally, with the greatest changes in the tropics. Lau et al. (2013), from analyses of projections of 14 CMIP5 models, found a robust canonical global response in rainfall characteristics to a warming climate. Under a scenario of 1% increase per year of CO<sub>2</sub> emission, the model ensemble projects globally more heavy precipitation<sup>32</sup> ( $+7 \pm 2.4\% \text{ K}^{-1}$ ), less moderate precipitation ( $2.5 \pm 0.6\% \text{ K}^{-1}$ ), more light precipitation ( $+1.8 \pm 1.3\% \text{ K}^{-1}$ ), and increased length of dry (no-rain) periods ( $+4.7 \pm 2.1\% \text{ K}^{-1}$ ). The sensitivity of rainfall to temperature varies geographically as well over land and oceans, for example Lui et al, (2012) indicated a scaling of 2-4 percent increase in precipitation per degC over land and of the order of 4-15 percent per degC in the tropics.

Lavers et al., (2013) showed that 'Atmospheric Rivers' (ARs), which can be linked to winter flooding in the UK, are likely to approximately double in frequency by the end of the century. ARs are key synoptic features which deliver the majority of poleward water vapour transport that are associated with episodes of heavy and prolonged rainfall. The analysis was based on five global climate models (GCMs) in the fifth Climate Model Intercomparison Project (CMIP5). It suggests that the projected change in ARs is predominantly a thermodynamic response to warming resulting from anthropogenic radiative forcing.

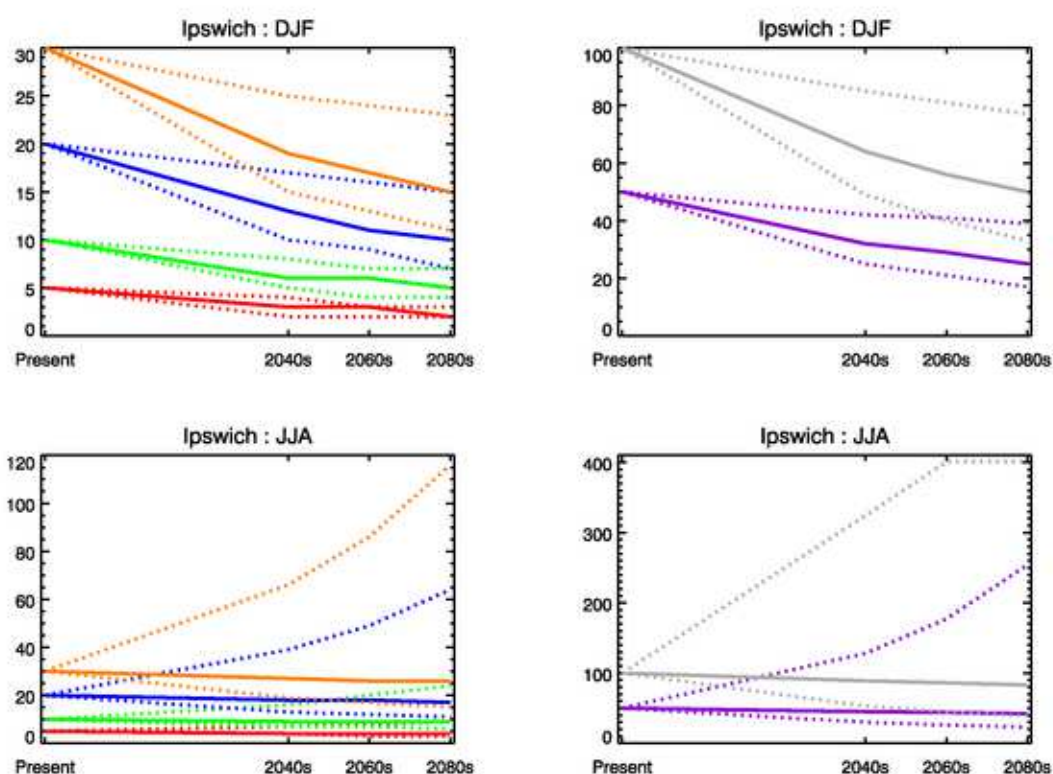
### *HadRCM*

As part of a review for the water regulator Ofwat, Sanderson (2010) estimated the magnitudes of daily rainfall events in 40 cities for events with return periods of 1 in 5, 10, 20, 30, 50 and 100 years from observed and Hadley Centre regional climate model data

---

<sup>32</sup> Defined as events above the 98.5<sup>th</sup> percentile

for the 2040s, 2060s and 2080s. The RCM was based on a Medium Emissions scenario and does not span the full uncertainty range in UKCP09. All winter rainfall events are projected to become more frequent. During winter, the biggest increases in frequency of 5 and 10 year events were projected to occur over Essex, Sussex and Kent. For the 20, 30, 50 and 100 year events, the biggest increases occur over Suffolk with a two- to three-fold increase in heavy rainfall events by the end of the century (Figure 4.12). Changes in summer rainfall were more uncertain and summer rainfall events could become much less frequent or more frequent according to this assessment.



**Figure 5.12. Change in return period for rainfall events with present-day return periods of 1 in 5 years (red), 1 in 10 years (green), 1 in 20 years (blue), 1 in 30 years (orange) [left-hand panels] and 1 in 50 years (purple) and 1 in 100 years (grey) [right-hand panels].**

*Notes: The return periods are shown on the y-axis. The central estimate (50th percentile) is indicated by a solid line, and the 10th and 90th percentiles, calculated using the full range of probabilistic projections from UKCP09, illustrate the possible range of return periods and are shown by dotted lines. The present-day return periods are positioned at 1980 on the x-axis (marked as 'Present'). Changes for winter (DJF, top row) and summer (JJA, bottom row) have been calculated separately. Note that the scale of the y-axis is different for each panel.*

### *The CONVEX project*

As part of the recently completed CONVEX project (**CON**Veptive **EX**trems), the Met Office carried out the first climate change simulations at a very high resolution of 1.5km. This allowed convection to be modelled explicitly, providing an improved assessment of

the impacts of climate change on heavy rainfall events in summer (Kendon et al., 2014). The model was based on a high emissions scenario (RCP 8.5) and compared heavy sub-daily rainfall for a thirteen year period at the end of the century to a baseline period of the same length. It was the first assessment to use such a high resolution model and provides key evidence about possible changes in summer rainfall. However, it only provides a single run, and therefore does not quantify the uncertainties around estimates of the changing frequency of events. Multiple model runs at these high resolutions are required to assess these uncertainties and to infer an “upper end/range” of potential increases in the frequency of heavy summer precipitation. There is currently effort underway as part of the ERC-funded INTENSE project to link up results from kilometre-scale models run at different climate research centres, to examine the extent to which the CONVEX results are robust across different regions and models. In addition, for UKCPnext there are plans to carry out high resolution regional downscaling which could include an ensemble of runs at kilometre-scales across the UK.

The CONVEX results suggest that extreme summer rainfall may become more frequent in the UK. Although summers are expected to become drier overall by 2100, intense rainfall indicative of serious flash flooding could become several times more frequent. For example, the 1.5km model suggests intense rainfall associated with flash flooding (more than 30mm in an hour) could become almost five times more frequent by 2100 compared to a recent baseline of 1996 to 2009 (Kendon et al, 2014). This is just one possible plausible realisation. However, it should be noted that an increase in heavy summer rainfall is consistent with the theory of an intensification of convective events in a warmer moister environment.

In terms of heavy winter rainfall, the 1.5km model showed very similar changes compared to a coarser 12km model (Kendon et al 2014). In particular, Chan et al 2014 found very similar changes in hourly rainfall extremes, although there was some suggestion that the better representation of orography may lead to greater increases in multi-hourly rainfall extremes over mountains in winter in the 1.5km model. In general, however, these results suggest that coarser resolution RCMs are likely to be sufficient for projecting changes in heavy rainfall in winter.

## 5.5 Physical limits

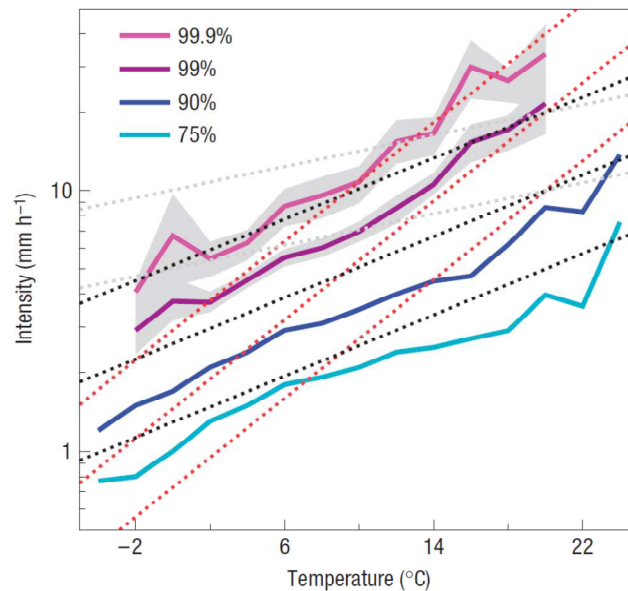
There are a number of factors that may constrain changes in heavy precipitation, including the amount of moisture in the atmosphere, atmospheric stability, the ability of the troposphere to radiate away latent heat released by precipitation (Allen and Ingram, 2002) and changes to circulation patterns. Different driving factors may work together to enhance heavy rainfall or counter each-other to reduce the impacts of increased temperatures on rainfall intensities.

The link between temperature and the atmospheric moisture holding capacity is described by the thermodynamic Clausius-Clapeyron relationship, which suggests a 6-7% increase in atmospheric moisture for 1 degC rise in temperature assuming relative humidity stays constant. This sets a scale for change in precipitation extremes. The results from recent climate models (CMIP5) appear to reinforce this relationship at a global scale (Lau et al., 2013), although this was not the case in earlier climate models (CMIP2) that had a lower gradient of change in precipitation over change in temperature (Allen and Ingram, 2002).

There is some evidence that hourly rainfall intensities may exceed the Clausius-Clapeyron relationship (Lenderink and Van Meijgaard 2008). This seems to be a property of convective rainfall (Berg et al 2013), with one possible explanation being through the dynamic amplification of rain-bearing systems, where the induced circulation drives greater convergence of moisture into the system and hence heavier rainfall (Met Office and CEH, 2014). Figure 5.13 plots heavy rainfall intensities observed in the Netherlands against the Clausius-Clapeyron relationship. This shows that intense rainfall in the Netherlands can follow a steeper CC relationship (2x) as shown by the dotted red lines compared to the 99.9 and 99 percentile rainfall intensities.

The CONVEX project also found that extreme summer hourly precipitation intensities over the southern UK were linked to temperature and that this relationship also followed Clausius-Clapeyron. This provides a good physical basis for estimating H++ sub-daily intensities based on degrees warming. Importantly, however, results from the 1.5km model suggest that this relationship cannot simply be extrapolated into the future due to more complex changes in atmospheric circulation conditions. The CONVEX project concluded that although changes to intense precipitation are dominated by local changes in temperature and associated increases in atmospheric moisture, changes in large scale circulation can have important regional effects, and may serve to suppress

precipitation intensities in the future. As such, although they are important, regional surface temperatures may not provide an adequate predictor of changes in precipitation intensity.



**Figure 5.13. Percentiles of observed maximum 1 hour rainfall intensity (mm/hour) on a logarithmic scale as a function of temperature for a 99-year record from De Bilt, The Netherlands.**

Notes: Solid colour lines are the different percentiles. Grey bands, plotted only for the 99 and 99.9th percentile, are 90% confidence intervals. Dotted lines are the exponential relations given by 0.5 (light grey), 1 (black) and 2 (dark red) times the Clausius–Clapeyron relation. From Lenderink and Van Meigaard 2008.

## 5.6 Other evidence

### *Palaeo analogue / evidence*

Palaeo analogue evidence was not considered for rainfall as evidence of erosion and sedimentation (for example from lake sediment cores) is highly sensitive to land use change as well as the precipitation signal. Spatial analogues have been considered in both the research literature and industry studies (see following sections).

### *Spatial analogues*

The use of spatial analogues can be useful for communicating potential changes in climate but need to be used with care and are associated with considerable uncertainties. As we know from the CONVEX results, temperature is an important driver of changes in rainfall extremes, but changes in circulation patterns can have important regional effects. In an ongoing UKWIR project on extreme rainfall for sewer design,



temperature is used to identify spatial analogues for future conditions in the UK<sup>33</sup>. Preliminary results from this work suggested potential uplifts of 70 to 90 percent on 6 hourly rainfall totals in the south east of England (Dale, *pers comm.*).

### *Industry data*

#### *The use of precipitation ‘uplifts’ on seasonal or extreme daily rainfall*

UKCP09 monthly and seasonal change factors have been used directly in studies related to river flooding, groundwater flooding and water resources (see Section 5). Environment Agency guidance for flood risk management suggests using UKCP09 change factors for high probability events ( $p > 20\%$ ) and a 40 percent uplift on extreme rainfall events ( $p < 20\%$ ) for the 2080s; it did not propose a H++ rainfall scenario (Environment Agency, 2011). Forthcoming UKWIR guidance for drainage engineers will propose the use of higher rainfall uplifts for the 2080s based on a mixture of evidence from the CONVEX project and use of spatial analogues (Dale, *pers. comm.*).

## **5.7 H++ scenarios**

A number of quantitative indicators for increases seasonal and daily precipitation are summarised in Figure 5.14. For daily rainfall the H++ range is a 60 to 80 % increase in rainfall event depths and for the winter season (DJF) it is a 70 to 100% increase in 30 yr average winter rainfall. The rationale for these ranges is described below and in both cases they are subject to caveats related to the relative skill of global, regional and higher resolution models of resolving important physical processes.

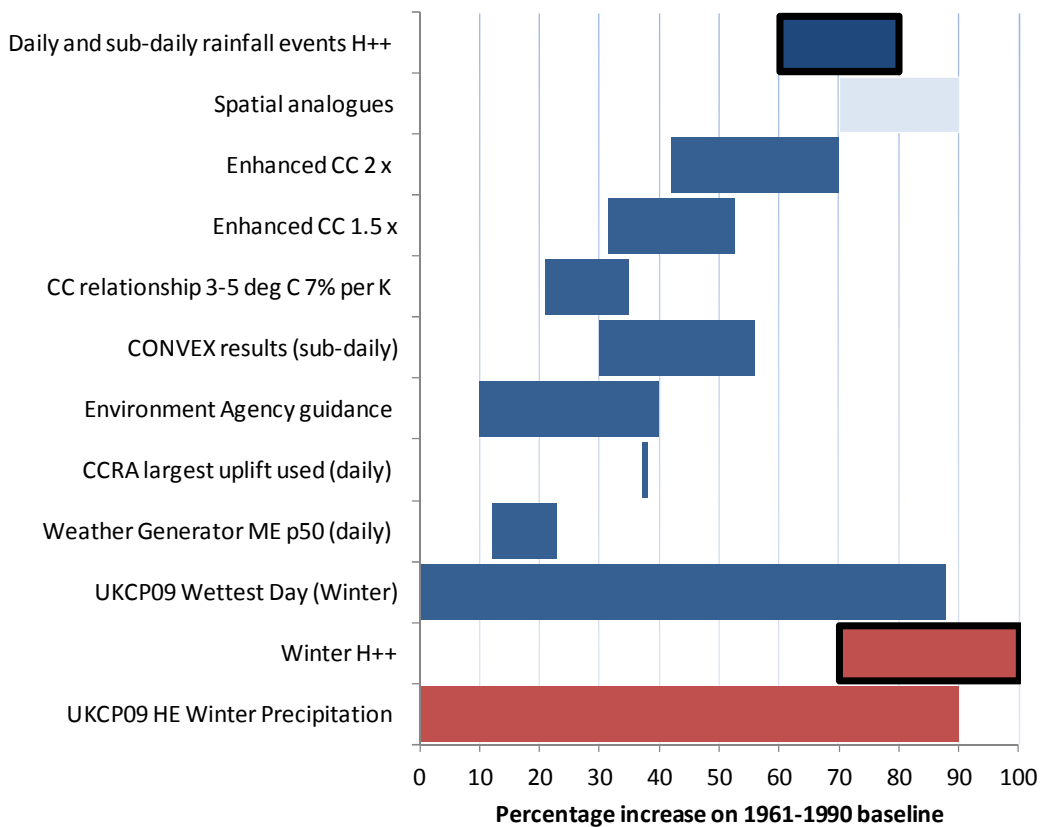
### *Winter rainfall*

- The wettest winters (Dec-Jan-Feb) in the historical record were 2013/14, 1994/95, 1989/90, 1914/15, 2006/07. The recent winter of 2013/14 is a useful benchmark with a 70% increase in seasonal rainfall (nationally, noting the increases were far greater in some regions).
- The UKCP09 2080s high emissions scenario project changes of around 70% for 30-year average annual winter rainfall (at the 90 % probability level) and changes of up to 90% for individual grid squares compared to the 1961-90 average. **A high end scenario of 70-100% more winter precipitation on average across the UK by the 2080s suggests that winters similar to 2013/14, would be**

---

<sup>33</sup> The future circulation regime is not used in the selection – so it is likely that the circulation conditions for the spatial analogue may not match those over the UK in future. For reliable future projections, ensembles of high resolution climate models are needed that physically represent the key processes driving future changes.

**exceeded in most years in the 2080s.** *This is based on expert opinion/interpretation of the data available and is subject to a number of caveats. In particular the unusual meteorological conditions experienced in 2013/14 (Met Office and CEH, 2014; Huntingford et al., 2014) are not well represented in climate models, which form the main source of evidence for this part of the assessment.*



**Figure 5.14. A summary of “high-end” ranges of precipitation uplifts presented in UKCP09 and other literature as well as H++ ranges (bold) for daily and sub-daily rainfall (any season) in blue and winter rainfall (Dec-Jan-Feb) in red (Grey bars indicate lower confidence).**

*Daily and sub-daily rainfall*

- The highest recorded 24 hour rainfall in the UK was 316 mm at Seathwaite Farm in Cumbria in 2009. Around 200 mm in 5 hours was recorded at Otterham, near Boscastle in August 2004 and there are several historical events with similar or greater rainfall intensities recorded in the 20th century.
- Evidence from Regional Climate Models suggests a two to threefold increase in extreme daily rainfall. The CONVEX project, which used a high resolution climate

model, suggests a two to five-fold increase in the frequency of heavy sub-daily rainfall in summer and a two to eleven-fold increase in winter but greater increases in frequency can't be ruled out. Large increases in precipitation over the UK may be limited by physical constraints as well as changes in circulation.

- Environment Agency guidance suggests that UKCP09 uplifts (which reach 70 to 80% in the tails of the UKCP09 high emissions scenario) are appropriate for rainfall events with probabilities less than 20 % (or 1 in 5 years) and thereafter plus 40% is an appropriate H++ scenario for flood and coastal erosion risk. There is some evidence from CONVEX and spatial analogues (UKWIR, 2015) that uplifts could be greater than 40% for these rare events; **therefore a H++ range of 60-80% is proposed for daily rainfall in winter or summer.** *Similar to the H++ winter rainfall this sits at the upper end of what is indicated by the evidence and is subject to caveats such as warming of at least four degrees and an enhanced 2x Clausius-Clayperon relationship.*

## Chapter 6 High flows

### 6.1 Summary of the High ++ ‘high flow’ scenarios

The H++ ‘high flow’ or flood scenarios are for increases in peak river flow and are presented as a range of percentage increases in peak flow for different regions of the UK. The approach for high flows deviates from the standard H++ methodology because substantive NERC, Defra and Environment Agency research projects have already been completed on the impacts of climate change on river flows, including the development of H++ scenarios. However, this section still covers most of the H++ steps including the use of UKCP09, consideration of other climate models and physical factors that influence flooding.

**The High ++ high river flow scenarios are presented on a regional basis at the end of this chapter. The ‘lower end’ of the 2080s H++ scenarios for regions in England and Wales range from a 60% to 120% increase in peak flows compared to a 1961-1990 baseline. The lower end of the H++ scenarios for regions in Scotland and Northern Ireland range from 55% to 125%. The upper limit is 290% for all cases.**

### 6.2 Background

In 2011 the EA released guidance to flood managers (Environment Agency 2011), which provided information on the range of flood changes under climate change that might be expected in an average catchment in each of 12 river-basin regions across England. This included ‘H++ river flow scenarios’ for each region (Table 3 of the EA guidance; see Table 6.1 for an example). The guidance was based on research by CEH, funded by Defra/EA (projects FD2020 and FD2648; Reynard et al. 2009 and Kay et al. 2011a), which used the UKCP09 sampled data for river basins, along with a sensitivity-based approach to estimating flood changes from climatic changes. The H++ scenarios provided in the EA guidance represent a high-end estimate of change in a type of catchment that is particularly sensitive to changes in climatic inputs (‘Enhanced-High’). Such catchments are more likely to occur in some river basin regions than others (Figure 2 of the EA guidance), but they cannot currently be completely ruled out anywhere.

	Total potential change anticipated for the 2020s	Total potential change anticipated for the 2050s	Total potential change anticipated for the 2080s
<b>Upper end estimate</b>	25%	30%	<b>50%</b>
<b>Change factor</b>	10%	15%	<b>20%</b>
<b>Lower end estimate</b>	0%	0%	<b>5%</b>
<b>H++</b>	<b>35%</b>	<b>45%</b>	<b>75%</b>

**Table 6.1: Potential changes in peak river flows for the Northumbria river basin region (Environment Agency 2011).**

Note that the H++ high flow scenarios in the EA guidance, and those derived for this project, are presented as percentage changes in flows (from a baseline period of approximately 1961-2001) rather than absolute values of flows. The latter are not appropriate for high flows as, even under the current climate, there is always a chance of a flood event occurring that is larger than any previously experienced at a particular location on a river. Also, the uniqueness of every river catchment, in terms of area, soils, geology, land cover, topography and orientation as well as climatology, means that generic absolute scenarios are impossible. When applying the H++ high flow scenarios, it is thus important that a reliable baseline flood frequency curve is developed, to which the percentage changes can be applied. This would usually be done via one of the Flood Estimation Handbook (FEH) methods, which are discussed briefly later in this chapter.

### **6.3 Approach**

The derivation of the H++ high flow scenarios for the EA 2011 guidance for river basin regions in England was re-assessed, to decide how best to provide H++ high flow scenarios for CCRA2 which are as consistent as possible both with the H++ scenarios for other variables within CCRA2 and with the original EA guidance. In particular, an H++ range was preferred, rather than a single number as in the EA guidance. It was decided that a method similar to that used for the original EA guidance should be applied to derive the 'H++ lower end' numbers, thus providing regionally varying values for three time-slices (2020s, 2050s and 2080s), but that the 'H++ upper end' should go further into the tails of the UKCP09 distributions and be taken as the maximum across all regions of the UK (for the 2080s under the high emissions scenario). The H++ high flow scenarios thus derived are then discussed in the context of a review of other, more recent, sources of evidence (e.g. from CMIP5).

The final method had to be applied to derive values for all river basin regions across the UK, not just those in England; the Adaptation Sub-Committee (ASC) requested UK-wide consistency wherever possible. This was straightforward for the West Wales river basin region, which was covered in project FD2648, and for river basin regions across Scotland, which were covered in similar research by CEH funded by SEPA (project *R10023PUR*; Kay et al. 2011b), so directly equivalent numbers could be derived for these regions. For river basin regions in Northern Ireland though, there has been no equivalent research using UKCP09 scenarios and the sensitivity-based modelling approach, and such an approach could not be fully developed within the time and budget constraints of this project. However, it was considered reasonable to assume that the range of response types in Northern Ireland is the same as that derived from modelling catchments in England, Wales and Scotland, and that the same FD2020 (average and standard deviation) response surfaces for each response type are applicable in Northern Ireland. The UKCP09 sampled data for the three river basin regions in Northern Ireland have thus been downloaded and overlaid on the 'Enhanced-High' response surfaces, allowing derivation of H++ high flows scenarios for Northern Ireland using region-specific UKCP09 projections, as for the rest of the UK.

What is not known is the chance of any catchment in Northern Ireland being of the 'Enhanced-High' type. Looking at the decision trees for England and Wales (Kay et al. 2011a) and Scotland (Kay et al. 2011b), it is likely that the best estimate of the response type of most gauged catchments in Northern Ireland would be Neutral, due to their high annual rainfall and relatively small catchment area. This is consistent with the pattern across the rest of the UK, where the best estimate of the response type for many catchments in western England, Wales and Scotland is 'Neutral', whereas catchments further to the east are more variable in type. Thus the H++ high flow scenarios have a lower (but currently unquantifiable) chance of occurring for any individual catchment in Northern Ireland, compared to the chance for a catchment in the Anglian, Northumbria, Thames or South-East England regions for example.

Further research is required to better identify catchment-by-catchment differences in response to climatic changes, and thus provide more catchment-specific information on the potential impacts of climate change on flood peaks. A new project to address precisely this issue is just being initiated by EA via FCERM.

## **6.4 Physical limits**

The concept of a probable maximum flood (PMF) for river flooding has always been controversial but the Flood Studies Report (FSR; NERC, 1975) introduced a procedure for estimating PMF based on an extension to the design hydrograph method. PMF can be defined as the flood of near-zero exceedance probability and it is assumed to be caused by the most extreme combination of antecedent catchment wetness, rainfall and runoff response possible. The concept is still used by UK reservoir engineers when assessing flood safety at dam sites (Institution of Civil Engineers, 1996). The recommended procedure relies on a statistical estimate of probable maximum precipitation (PMP) deriving from the FSR which is routed via the unit hydrograph and losses model. The unit hydrograph time-to-peak is reduced to represent the more rapid and intensive response that may occur in exceptional conditions, and optional changes to the percentage runoff allow for higher than normal runoff from frozen ground. The estimation of PMF is gradually being superseded by the use of probabilistic risk assessment within the reservoir industry, reflecting a general feeling that the concept of an upper limit and, more importantly, the methods in current use are outdated.

## **6.5 Review of other evidence**

A recent review of historical changes in UK river flows (Hannaford 2015) describes several recent major flood events and includes a review of changes in high flows and flood indicators. Significant trends are seen in many UK Benchmark catchments (Fig. 3 of Hannaford 2015), and such changes are considered relatively consistent with future projections of changes in flows.

To our knowledge no other study published to date has applied the UKCP09 Sampled Data to look at changes in fluvial flood peaks, but Charlton and Arnell (2014) used them to look at changes in the high flow measure Q5 (the flow exceeded 5% of the time), as well as median flow Q50 and low flow measure Q95, for six catchments in England. They found that the range of changes for Q5 was large but mostly positive, and varied significantly between catchments. Of particular interest here is that some catchments had significantly larger increases than others at higher percentiles (up to approximately a 50% increase at about the 95<sup>th</sup> percentile, for the 2080s under medium emissions). Although changes in Q5 cannot be directly translated into changes in flood peaks, the fact that both the median and range of changes in Q5 for each catchment are larger than for Q50 (which are larger than for Q95), is suggestive of even greater changes in flood

peaks (in terms of median and range), and greater sensitivity of some catchments than others. This is consistent with the results of Kay et al. (2014a) for flood peaks.

Several studies have used time-series from the UKCP09 11-member Regional Climate Model (RCM) ensemble to look at impacts on floods in specific catchments in Britain. Bell et al. (2012) used data from the UKCP09 RCM ensemble to drive a distributed hydrological model (Grid-to-Grid) for the Thames Basin, and looked at changes in (5- and 20-year return period) flood peaks throughout the basin for the 2080s (A1B emissions). They found significant spatial variation in impacts, and significant variation between ensemble members. In some locations, increases in the 20-year return period fluvial flood peak of over 150% were simulated by a member of the RCM ensemble (but this was not always the same member). As the UKCP09 RCM ensemble only has 11 members, the range of impacts from it would be expected to be smaller than that from a much larger ensemble like the UKCP09 Sampled Data, but the amount of difference is likely to vary between catchments. This is confirmed by Kay and Jones (2012), who compare use of the various UKCP09 products, including RCM time-series, for modelling impacts on 20-year return period flood peaks in nine catchments in Britain. For the Enhanced-High catchment modelled by Kay and Jones (2012), the maximum modelled change in flood peaks from direct use of RCM time-series was ~50%, whereas the maximum from modelling using Sampled Data delta changes was significantly higher, at over 250%. This compares to a maximum of over 135% from modelling using time-series produced by the UKCP09 weather generator (although this was only from a 100-member ensemble). The fact that the RCM ensemble is only available for A1B (medium) emissions also reduces the impacts compared to the H++ high flows scenarios presented here, which are for A1F1 (high) emissions for the 2080s.

Cloke et al. (2013) used a range of methods, including both direct forcing of a hydrological model with UKCP09 RCM data and use of response surfaces, to investigate changes in the annual frequency of exceeding a given flood warning level for the Severn at Montford. They found a wide range of uncertainty from the UKCP09 RCM ensemble, as well as from two alternative climate model ensembles, but it is difficult to translate these results into changes in flood peaks. While the 'Future Flows' project produced flow time-series for a large number of catchments across Britain using UKCP09 RCM data for 1951-2098 (Prudhomme et al. 2013), no studies have so far published results on changes in fluvial flood peaks using these flow time-series data.



More recent work, using high resolution RCM data (from the CONVEX project) to drive a gridded hydrological model over southern Britain, suggests that use of very high resolution (1.5km) RCM data tends to project larger increases in flood peaks (for all seasons except summer) than use of data from the 12km RCM in which the 1.5km RCM is nested (Kay et al. 2015). However, the availability of only one set of high resolution RCM runs, covering a relatively short period (~13 years), together with increased baseline biases from use of the 1.5km RCM data compared to the 12km RCM data, means that the suitability of this data set for flood risk research remains unclear. It is also possible that smaller, faster responding catchments may show different results to those covered by the gridded modelling above (where mapped river points had a drainage area threshold of 50km<sup>2</sup>).

A global-scale study using CMIP5 data (Dankers et al. 2014) showed increases in flood hazard (measured as 5-day mean peak flows with a 30-year return period) for more than half of the global land grid points in most of the 45 model experiments (5 CMIP5 GCMs x 9 global hydrology/land surface models), for the period 2070-2099 under RCP8.5. It is difficult to distinguish the results for the UK from the global maps presented, particularly in terms of the percentage change in the 30-year return period peak flow, but it looks like the mean impact is an increase of perhaps 10-20% and that a lot of the models agree on an increase, compared with high agreement on decreases in much of the rest of Europe. Another global study, using 11 CMIP5 GCMs, showed similar results for the change in flood frequency over Europe, with the 100-year return period flood peak occurring more frequently in future in Britain but less frequently over much of the rest of Europe (Hirabayashi et al. 2013). But the presented changes in flood return period cannot be readily translated into changes in flood peaks, for comparison with other studies. The apparently opposite potential impacts in Britain, compared to much of the rest of Europe, shown by the latter two global studies may be related to the influence of atmospheric rivers (synoptic features that transport water vapour polewards) on the climate of western Europe, and the fact that these are projected to increase in both magnitude and frequency in future (Lavers et al. 2013).

### ***FEH methods for deriving baseline flood frequency curves***

As the H++ high flow scenarios are provided as percentage changes in flood peaks, a brief outline is provided below of the Flood Estimation Handbook (FEH) methods that would usually be used to estimate baseline flood frequency for a catchment of interest in the UK.

The national standard methods for UK flood frequency estimation are presented in the FEH (Institute of Hydrology, 1999) and its subsequent updates (Kjeldsen, 2007; Environment Agency, 2008). Flood frequency curves for any site on the UK river network, gauged or ungauged, can be derived from the improved FEH statistical method, which combines flood peak data from hydrologically similar sites to form a pooling-group using the analysis of L-moments (Hosking and Wallis, 1997). Thus the approach to regionalisation is flexible and not based on the prior definition of geographical regions. A key feature of the FEH statistical approach is the importance of hydrological judgement in the refinement of the estimation procedure for each subject site. While the method has been successfully automated to provide spatial consistency over a wide area, for use in flood risk mapping for example (Morris, 2003), flood estimation on a site-by-site basis is still recommended.

The improved FEH statistical method is flexible and a number of different variants exist depending on the extent of the data available. The method requires the estimation of the index flood (the median annual flood at the site of interest, termed QMED) and a flood growth curve that relates QMED to floods of longer return period. QMED can be estimated from at-site data or, for ungauged or poorly gauged sites, using catchment descriptors together with adjustment from suitable donor catchments. Pooling-groups are constructed using data from the site of interest (if available) and other hydrologically similar sites to derive the flood growth curve. FEH flood growth curves are catchment specific rather than being regionally averaged. Various further adjustments can be applied if the site of interest lies within a permeable catchment or is urbanised. The method makes use of instantaneous flow peaks for about 1000 gauging stations from the NRFA Peak Flow data set, which can be accessed on-line and is regularly updated ([http://www.ceh.ac.uk/data/nrfa/peakflow\\_overview.html](http://www.ceh.ac.uk/data/nrfa/peakflow_overview.html)). The original FEH statistical method was extended to allow the use of historical data pre-dating the installation of river flow gauging structures (Bayliss and Reed, 2001) and further research on this subject is ongoing.

The FEH analysis included examination of possible trend but found little evidence of non-stationarity in the peak flow series (Robson and Reed, 1999). Thus the methods assume that the underlying data series are stationary, although it is recognised that the UK climate is highly variable and 'flood rich' and 'flood poor' periods have been identified (Robson *et al.*, 1998; Hannaford and Marsh, 2008). There is a high degree of uncertainty

associated with statistical flood frequency estimates (Kjeldsen, 2014) and this is the subject of ongoing research.

## **6.6. H++ scenarios**

The H++ high flow scenarios derived for the UK are given in Table 6.2, as percentage changes in fluvial flood peaks. The scenarios are based on using the UKCP09 Sampled Data for UK river-basin regions, combined with a sensitivity-based approach to estimating flood changes from climatic changes (Kay et al. 2011a). They represent high-end estimates of change in a type of catchment that was identified as being particularly sensitive to changes in climatic inputs: 'Enhanced-High' (Reynard et al. 2009; Prudhomme et al. 2013). Such catchments are more common in some regions than others (Kay et al. 2011a, b). The scenarios are provided as a range, with the lower end of the range given for each of 23 river-basin regions and for three 30-year time-slices (2020s, 2050s and 2080s). The upper end of the range is given for the UK as a whole and only for the 2080s time-slice.

The use of the UKCP09 Sampled Data — which provides climate projections as sets of 10,000 change factors for each river-basin region, for a set of overlapping 30-year time-slices and for three emissions scenarios (Murphy et al. 2009) — enables probabilistic impact ranges to be estimated. Thus the lower end of the H++ range has been taken as the 90<sup>th</sup> percentile from the 'Enhanced-High' impact curves for 50-year return period flood peaks, using high (A1F1) emissions for the 2080s but medium (A1B) emissions for the 2020s and 2050s. The upper end of the H++ range is taken as the maximum, over all of the river-basin regions, of the 100<sup>th</sup> percentile from the 'Enhanced-High' impact curves for 50-year return period flood peaks, using high (A1F1) emissions for the 2080s.

The upper end value, 290%, comes from the South-East England river-basin region, but the 100<sup>th</sup> percentile impact values for the 2080s under high emissions are also high for the Argyll and West Highland river-basin regions (225% and 250% respectively). These three regions also have the highest H++ lower end values (Table 6.2). This regional pattern, with higher impacts in regions to the far south east and far north west of the UK and lower impacts for regions in between, is shown in Kay et al. (2014a,b). The differences are due to regional differences in the UKCP09 climate change projections (see Fig. 3 in Kay et al. 2014a, b).

River-basin region	2020s (2010-2039)	2050s (2040-2069)	2080s (2070-2099)
H++ (lower end):			
<b>Northumbria</b>	20	35	65
<b>Humber</b>	20	35	65
<b>Anglian</b>	25	40	80
<b>Thames</b>	25	40	80
<b>South East England</b>	30	60	120
<b>South West England</b>	25	50	105
<b>Severn</b>	25	45	90
<b>Dee</b>	20	30	60
<b>North West England</b>	25	45	95
<b>West Wales</b>	25	50	100
<b>Orkney and Shetland</b>	30	55	110
<b>North Highland</b>	25	40	80
<b>North East Scotland</b>	15	25	55
<b>Tay</b>	20	35	75
<b>Forth</b>	25	45	90
<b>Tweed</b>	20	35	75
<b>Solway</b>	25	45	95
<b>Clyde</b>	25	50	100
<b>Argyll</b>	30	65	125
<b>West Highland</b>	30	65	125
<b>North East Ireland</b>	20	40	80
<b>Neagh Bann</b>	15	30	70
<b>North West Ireland</b>	20	35	75
H++ (upper end):			
<b>max over all regions</b>			290

**Table 6.2: H++ high flow scenarios for the UK, expressed as percentage changes in fluvial flood peaks (50-year return period) compared to 1961-1990. The lower end of the H++ range is given for each of 23 river-basin regions and three 30-year time-slices. The upper end of the H++ range is given for the UK as a whole and only for the 2080s time-slice. [Note that all values are rounded to the nearest 5%.]**

All of the values in Table 6.2 are based on an average ‘Enhanced-High’ catchment, represented by an average ‘response surface’ for the Enhanced-High type (Reynard et al. 2009). But any individual ‘Enhanced-High’ catchment could have a response in a range around that average. This range is illustrated by a standard deviation (sd) surface (Reynard et al. 2009), which can be used alongside the average response surface. If 1\*sd is applied when calculating the H++ upper end value, to allow for an Enhanced-High catchment potentially being more extreme than the average, then the upper end value increases from 290% to 325%. A more extreme example of an Enhanced-High catchment would likely have an even higher 100<sup>th</sup> percentile increase in flood peaks. Furthermore, while the overall method accounts for possible bias in the median impact estimated from response surfaces compared to direct hydrological modelling of the

catchment (Kay et al. 2014c), the possibility of a wider impact range from direct hydrological modelling is not incorporated. This could further increase the derived H++ scenarios.

## Chapter 7 Windstorms

### 7.1 Summary of the H++ windstorm scenario

Windstorms are intense extratropical cyclones that bring strong winds that can damage property and lead to loss of life. Examples of windstorms that have affected the UK include the Great October Storm of 1987, which inflicted 6.3Bn USD of damage (indexed to 2012 values) and 22 lives lost (Roberts *et al.* 2014).

The H++ scenario for windstorm is based on an analysis of the CMIP5 model projections. **The CMIP5 climate model projection suggest a plausible H++ scenario for a 50-80% increase in the days of strong winds over the UK by 2070-2100 compared to the period 1975-2005.** The caveats are that the scenario is based on the CMIP5 climate model simulations, which contain biases in the position of North Atlantic storm track and systematically under-represent the number of intense cyclones.

The data sources for windstorm analysis are summarised in Annex 2.

### 7.2 Historical data

#### *Paleoclimate data*

Paleoclimatology considers aggregate measures of storminess through proxies such as salt marsh inundation and coastal erosion (e.g. May *et al.* 2012). However, it was considered that these aggregate measures are too coarse to be able to construct a H++ scenario for windstorm.

#### *Historical Windstorms in the UK and NW Europe*

Historical records of windstorms before instrumental records exist primarily through their impacts on coastal areas. Lamb (1991) collated records of such windstorms, including major events such as the "Grote Mandrenke" (Great Drowning of Men) in 1362. Strong south-westerly gales lead to extensive coastal flooding and estimated deaths of 11,000 to 30,000 in Northern Germany. The strong winds over England led to the toppling of the bell towers in London, Bury St. Edmunds and Norwich.

Other notable windstorms occurred in November 1570, January 1607 and October 1634. Strong south-westerly gales in early November 1570 led to the "All Saints Flood". Extensive coastal flooding occurred along the North Sea coastline from France to

Denmark, which led to the loss of 100,000 lives. Strong gales in January 1607 are thought to have led to flooding in the Bristol Channel and the loss of 2,000 lives (Horsburgh and Morrit, 2006). A windstorm and associated coastal flooding in October 1634 led to an estimated 6,000 deaths in Northern Germany.

The Great Storm of 1703 is often regarded as most severe windstorm of which we have good written records. The windstorm occurred on the 7-8 December 1703 (current calendar) and left a path of destruction across Wales and Southern England, the Netherlands, Denmark and Northern Germany. The impacts of the windstorm were recorded in a number of written accounts, including Daniel Defoe's book "The Storm". The Great Storm of 1703 led to destruction of buildings across Wales and Southern England, including the collapse of the first Eddystone lighthouse. The Royal Navy was particularly affected with the loss of thirteen ships. Estimates of loss of life from the windstorm range from 1,500 to 10,000 deaths. Lamb (1991) was able to construct rudimentary weather maps from the small number of surface pressure measurements made at that time, which suggested the 1703 storm developed at the end of a period of enhanced storminess during the start of December 1703. Surface winds may have reached an average velocity of over 100 mph, with wind gusts potentially reaching higher values.

Other notable events include a windstorm in December 1717 which led to extensive flooding and storm damage along the North Sea coastline. 11,000 deaths are reported to have occurred, mostly in Northwest Germany.

#### *Windstorms in the instrumental record*

The introduction of instrumental networks across the UK and Europe during the 19th Century enabled a more quantitative analysis of windstorms. Notable windstorms include:

*1839, 6-7 January, Night of the Big Winds (Irish: Oíche Na Gaiithe Móire):* 400 deaths and substantial property damage across Ireland and Great Britain. The central pressure of windstorm was measured at 918hPa and gusts were estimated to have been over 100 mph.

*1953, 31 January:* Strong gales in the North Sea led to extensive coastal flooding along the eastern coastline of the UK, the Netherlands and Northern Germany. The flooding led to 2000 deaths, including 350 deaths in the UK.

1962, 16-17 February: South-easterly gales in the North Sea lead to coastal flooding and 340 deaths in the region around Hamburg.

1976, 2-3 January, *Capella Storm*: A mobile windstorm developed to the west of Northern Ireland, moved across Britain and into Denmark. 60 lives were lost and there was extensive damage to property across Ireland, the UK, the Netherlands and Northern Germany. The insurance loss in the UK alone was estimated to be £126M at 1976 prices.

1987, 16 October, *Great October Storm of 1987*: The windstorm developed rapidly and crossed over Southern England and into the North Sea. There was extensive damage to property and 22 were lives lost. Wind gusts measured 115mph on the Sussex coast. Total insurance losses reached 6.3Bn USD (indexed to 2012 values).

1990, 25 January 1990, *Daria, Vivian and Wiebke*: The months of January and February 1990 were particularly stormy. *Daria* developed on 25 January and moved across the UK and Northern Germany inflicting total insurance losses of 8.2Bn USD (indexed to 2012 values). Cyclones *Vivian* and *Wiebke* developed during 26 and 28 February 1990 inflicting further insurance losses of 7.0Bn USD (indexed to 2012 values).

1993, 8 January, *Braer storm*: Passed to the northwest of Scotland and so caused little damage on land (apart for the sinking of the eponymous MV *Braer*). Notable as the central pressure of the storm reached 914hPa, the lowest pressure recorded in a Northern Hemisphere extratropical cyclone.

1999, 26 and 27 December, *Cyclone Lothar and Cyclone Martin*: Two very intense windstorms passed over Northern France within a period of a few days in December 1999. Total insurance losses from the two storms reached 11.3Bn USD (indexed to 2012 values).

2007, 18 January, *Cyclone Kyrill*: *Kyrill* developed in the North Atlantic and rapidly crossed the UK, the Netherlands and Northern Germany. *Kyrill* led to 47 deaths and total insurance losses reached 8.2Bn USD (indexed to 2012 values).

In recent years, windstorms have continued to affect the UK. Windstorms include *Friedhelm* (8 December 2011) and *Ulli* (3 January 2012) which affected Central



Scotland, Christian (the St Jude's Day storm; 28 October 2013) and the series of windstorms in January and February 2014 that led to coastal flooding in the UK and extensive damage to the railway infrastructure at Dawlish (Kendon and McCarthy, 2014).

### *Observed trends of European Storminess*

One key question is whether there are long term trends of storminess over the UK and Europe in the instrumental record. Feser et al (2014) provide a comprehensive review of studies of long term storminess from observations, which include long-term records of wind speed, mean sea level pressure and sea level height. Analysis of long term winds records in the UK and Ireland (Hammond, 1990; Sweeney, 2000; Hickey, 2003, Ciavola et al. 2011) have found large decadal variations in storminess, but no significant long term trends. In contrast, Esteves et al. (2011) found a significant decrease in storminess over the period 1929-2002 at Bidston Observatory.

Studies of long term changes in European storminess have also been performed using estimates of geostrophic winds from weather stations, gridded mean sea level pressure datasets and atmospheric reanalysis. Using pressure differences to estimate geostrophic winds between weather stations was pioneered by the WASA Group (1998). Alexandersson et al. (1998, 2000) found large decadal variability in storminess as measured by geostrophic winds, with a maxima in activity in the late 19th century, a comparative lull during the 1960s and an increase in activity in the 1990s. These results were confirmed by later analysis using different measures of storminess (Matulla et al. 2007; Hanna et al. (2008), Wang et al. 2009, 2011). Cornes and Jones (2012) studied changes in storminess using the EMULATE gridded mean sea level pressure dataset, and also found similar results.

Until recently, atmospheric reanalysis have only been constructed after the middle of the 20th Century. However, the 20th Century Reanalysis (Compo et al. 2011) assimilates long term records of mean sea level pressure from 1871 onwards, enabling long term analyses to be performed. Significant increases in storminess have been found in the 20th Century Reanalysis in the Baltic (Donat et al. 2011) and the high latitude North Atlantic and Northern Europe (Wang et al. 2013). However, the consistency of the 20th Century reanalysis is a subject of current debate (Kruger et al. 2013, 2014; Wang et al. 2014; Dangendorf et al. 2014). In particular, Krueger et al. (2013) suggested that long term changes in storminess may be influenced by changes in the density of weather stations over time, and so caution should be exercised in interpreting the 20<sup>th</sup> Century Reanalysis. In summary, the historical evidence is important for suggesting that long

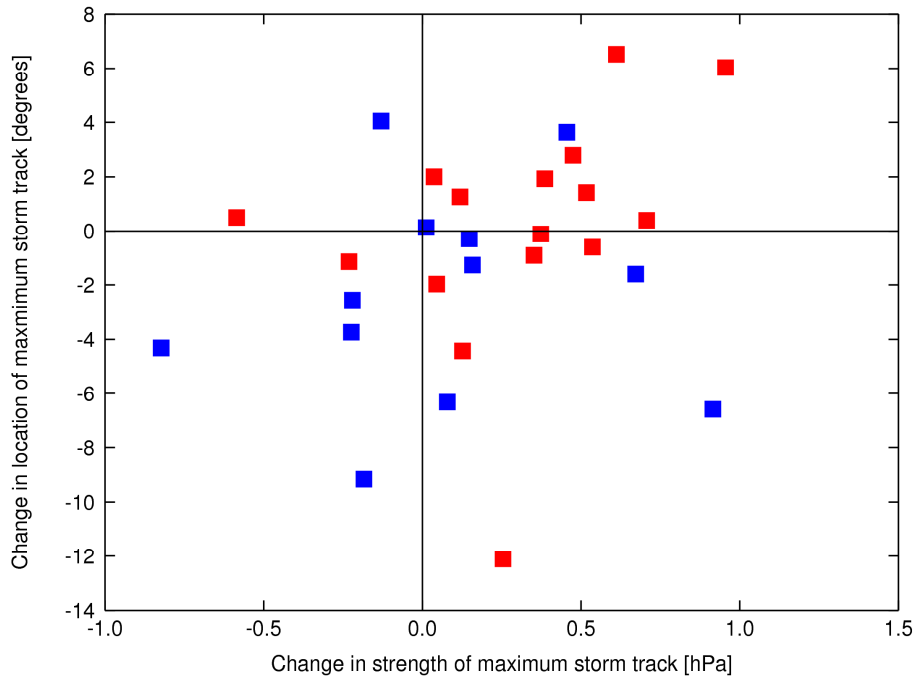
term trends in storminess over the instrumental records are relatively small (and generally statistically insignificant) compared to the large decadal variability.

### **7.3 UKCP09**

Changes in windstorms (i.e. extreme winds) were not explicitly considered in UKCP09, so it is not possible to construct a H++ windstorm scenario from the UKCP09 projections. However, changes in the North Atlantic storm tracks (as measured by mean sea level pressure variance) in the HadCM3 ensemble and the CMIP3 climate model were considered in a supplementary report (Murphy et al. 2009). The analysis found large inter-model spread in the responses of the North Atlantic storm track around the UK, with some CMIP3 models moving the North Atlantic storm track to the north and some models moving the storm tracks to the south. This was in contrast to the HadCM3 climate model ensemble used in the UKCP09 projections, where the North Atlantic storm track tended to move southwards under anthropogenic forcing. This analysis has been updated for CMIP5 climate models and the results are discussed below.

### **7.4 Evidence from CMIP5 models**

Since UKCP09, the CMIP5 inter-model comparison project has provided a major advance in the assessment of future windstorm risk. For the first time in the CMIP process model output has been archived at sub-daily frequencies, allowing a systematic assessment of extra-tropical cyclones and their associated wind extremes. Assessing how the location, severity and number of extratropical cyclones might respond to climate change is essential for understanding how risks from damaging winds might change over the UK. Such an assessment has been performed by a number of groups worldwide, and their results are discussed later in this chapter. Despite the improvement in the resolution of the state-of-the-art climate models used in CMIP5 there are still numerous processes that are known to be not well represented in these models, such as mesoscale circulations embedded within extra-tropical cyclones. Recent evidence relating to these processes is discussed in Section on *Other Evidence*.



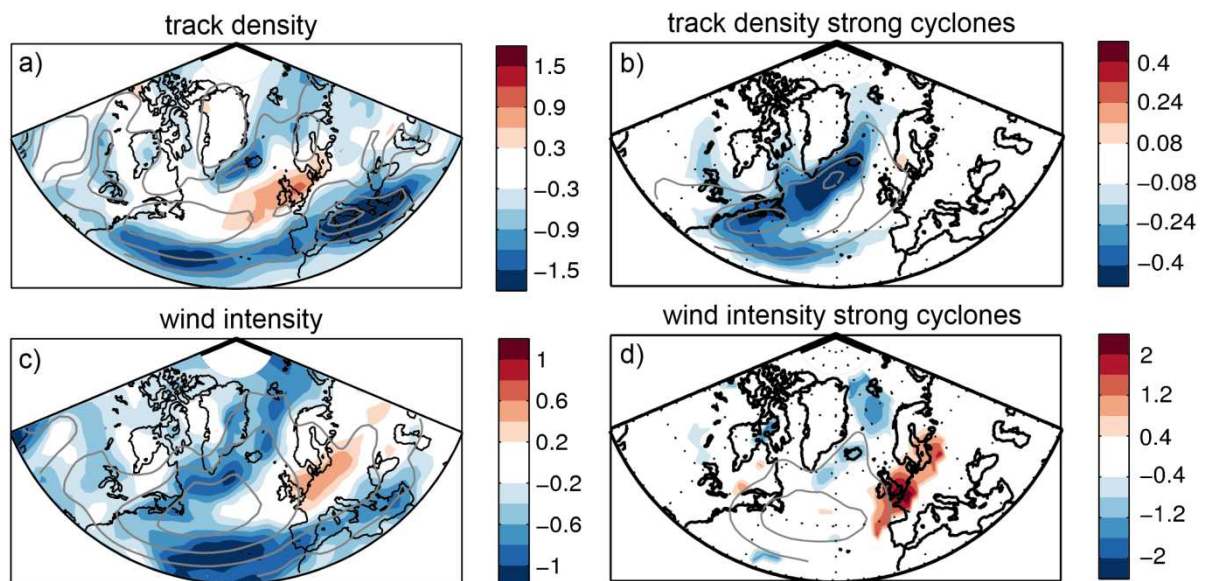
**Figure 7.1:** Climate change responses of the latitude and strength of the DJF storm track at 0E. Blue and red squares represent CMIP5 (RCP8.5) and CMIP3 (SRESA1B) models respectively and the climate change response is defined as the difference between late 21<sup>st</sup> century and late 20<sup>th</sup> century values. The measure of the storm track is the 2-6 day bandpass-filtered mean sea level pressure.

### *CMIP5 models*

The ability of the CMIP5 models to simulate North Atlantic cyclones in present-day conditions was assessed by Zappa et al. (2013a). They find that many of the CMIP5 models show an improvement over the CMIP3 models in their representation of the North Atlantic storm track. However, there is still a systematic deficit in the number of intense cyclones in the CMIP5 Historical simulations. Furthermore, the North Atlantic storm track in the CMIP5 Historical simulations also tends to be located southwards of the observed North Atlantic storm track. The biases in the historical simulations reduce confidence in the CMIP5 climate projections of the North Atlantic storm track.

The CMIP5 future projections of North Atlantic cyclones for the end of the 21st century have been assessed by numerous authors (Harvey et al., 2012; Mizuta, 2012; Chang et al., 2013; Zappa et al., 2013b). These studies utilise both traditional grid-point based statistics (such as the variance of bandpass-filtered sea level pressure) and cyclone tracking algorithms to characterise properties of the storm tracks. Cyclone tracking algorithms, which require the use of the sub-daily data available in CMIP5, provide detailed information on both the number and intensity of cyclones and therefore provide

a means of evaluating changes in intense windstorms. The traditional grid-point based statistics are less useful for this purpose as they combine information from all cyclones without distinguishing between their intensity. Two key questions are generally considered in these studies: how do the storm track responses compare between CMIP3 and CMIP5, as measured by the grid-point based statistics, and what extra information do the cyclone tracking algorithms reveal about changes in intense windstorms in CMIP5?



**Figure 7.2:** CMIP5 multi-model mean DJF RCP8.5 responses of cyclone track density from (a) all cyclones and (b) the subset of strong cyclones only. The same but for cyclone intensity measured by wind speeds in the lower troposphere (at a height of 850hPa) from (c) all cyclones and (d) the subset of strong cyclones only. Units in (a) and (b) are cyclones per month per unit area with a contour interval of 4 and 1 cyclones per month respectively. The units in (c) and (d) are  $\text{ms}^{-1}$  with a contour interval of  $4 \text{ms}^{-1}$  in (c) and the two contours in (d) indicating  $30 \text{ms}^{-1}$  and  $35 \text{ms}^{-1}$ . Strong cyclones are defined as those with intensities greater than the 90<sup>th</sup> percentile in the Historical simulations of each CMIP5 model. Figure kindly provided by Giuseppe Zappa; the corresponding plots for RCP4.5 are published in Zappa et al. (2013b).

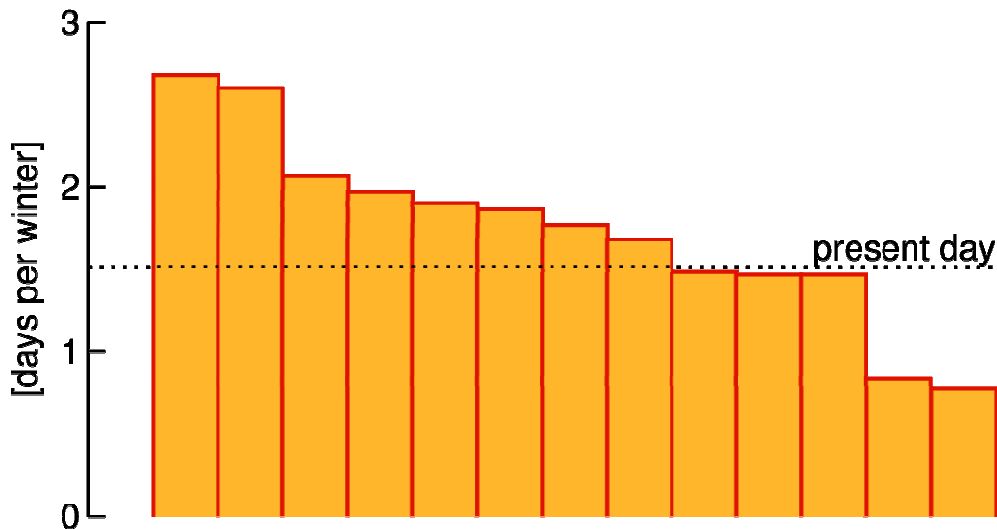
The studies of Harvey et al. (2012); Zappa et al. (2013b) and Chang et al. (2013) compare the CMIP3 and CMIP5 storm track responses using the traditional grid-point based diagnostics. There is in general a good agreement in the responses in CMIP3 and CMIP5. In each case the multi-model mean response consists of a tri-polar pattern over the eastern Atlantic, with an increase in storminess over the UK and decreases to the north and south. Relative to the present-day storm track this represents an increase of its southern flank together with a decrease in the subtropics, which may result in an increase of storm activity over the UK. Figure 7.1 shows the responses of the latitude and strength of one measure of the storm track at 0E for both the CMIP3 and CMIP5

models. As noted in the UKCP09 (Murphy et al. 2009) the CMIP3 models show little consistency as to the sign of the shift; the responses in the CMIP5 models however are more consistent with 10 of the 13 models exhibiting a southward shift.

The studies of Zappa et al. (2013b); Chang et al. (2013) and Mizuta (2012) analyse the CMIP5 storm track responses using cyclone tracking algorithms. Regarding the full set of all North Atlantic cyclones, Zappa et al. (2013b) find that both the frequency of cyclones and their mean intensity respond with a qualitatively similar pattern to the grid-point based statistics: there is a tri-polar pattern over the eastern Atlantic with increases over the UK and decreases to the north and south. They present detailed results only for RCP4.5, Figures 2a and c show the corresponding results for RCP8.5. Therefore the tri-polar pattern of storm track response obtained from the grid-point based statistics, can be due to a combination of both increased frequency and increased intensity of cyclones. Chang et al. (2013) provide less detail on the geographical distribution of changes, but consistent with the results of Zappa et al. (2013b) find a slight southward shift in the mean latitude of cyclones in the East Atlantic in the RCP4.5 scenario.

Regarding only those cyclones associated with strong winds, Zappa et al. (2013b) subset their cyclone database based on the maximum 850 hPa wind speed associated with each cyclone. Those cyclones where the maximum wind speed is greater than the value of the 90th percentile from the Historical simulation of that model are classed as strong cyclones. In this way the impact of model biases present in both the present-day and future simulations are avoided. Figures 7.2b and 7.2d show the corresponding RCP8.5 multi-model mean changes in track density and mean wind intensity for the strong cyclones. Over the UK there is little change in the track density of strong cyclones but an approximately 5% increase in the mean intensity of the strong cyclones of the present-day mean.

## Number of Strong Wind Days CMIP5 Models



**Figure 7.3: The number of strong wind days per extended winter for the late 21st century (2069-2099, RCP8.5) for 13 CMIP5 models. A strong wind day is defined as one where the daily mean wind speed in the lower troposphere (i.e. at 850 hPa) and averaged over the UK (8W-2E, 50N-60N) is greater than the 99th percentile of the HIST (1975-2005) simulations (this corresponds to 1.51 strong wind days per extended winter). An extended winter is defined as October to February.**

These published studies focus on the multi-model mean storm track responses. An H++ scenario should consider the range of model spread around the multi-model mean in order to estimate possible values in the tails of the distribution. The analysis here focuses on the 13 CMIP5 models identified by Zappa et al. (2013a) as having a reasonable representation of the present-day North Atlantic storm track. Figure 7.3 shows the change in the number of strong wind days over the UK for the 13 CMIP5 RCP8.5 simulations. A strong wind day in this analysis is defined as one where the daily mean wind speed at 850 hPa is greater than the 99th percentile from the corresponding historical simulations. The wind speed at 850 hPa is used as it provides an estimate of likely maximum surface wind gusts. According to the CMIP5 models considered, the frequency of windstorms and strong wind days over the UK could increase or decrease by the end of the 21st century. **The largest changes in the CMIP5 climate models suggest that the frequency of strong winds over the UK might increase by 50-80%.** The sensitivity of the results to the choice of region was tested by repeating the analysis with a larger Northwest European box. A very similar spread in projections was found, which suggests the conclusions are largely insensitive to small variations in the choice of region.

### *Other evidence*

Haarsma et al. (2013) present a novel mechanism by which the occurrence of strong windstorms over the UK during early Autumn may increase in future. Their very high resolution (25km) global climate model simulations suggest that changes in tropical Atlantic SSTs may yield more frequent and intense tropical cyclones positioned so as to recurve and hit Europe after extra-tropical transition. This mechanism will not be captured by the CMIP5 models which have insufficient resolution to resolve tropical cyclones. However, this work is in its infancy; it has only been identified in one model to date, and further work is needed to quantify this risk.

An additional question to consider is whether the clustering of windstorms might change in response to climate change. Windstorms tend to cluster in time (Mailier et al. 2006) and clustered windstorms have greater socioeconomic impacts (e.g. Lothar and Martin in Northern France, December 1999) through the failure of already weakened or damaged infrastructure and processes such as demand surge. The impacts of climate change on clustering were studied in the ECHAM5 climate model by Pinto et al. (2013), who found a decrease in clustering in Western Europe in response to climate change. These results are, however, only from one climate model. It is not yet clear how well climate models represent clustering, or how robust climate projections are, hence it is presently difficult to incorporate changes in clustering into a H++ scenario.

One other issue concerns the relatively low resolution of climate models. Climate models typically have horizontal resolutions of the order of 100km and relatively low resolution in the vertical. This means that current climate models fail to capture key smaller scale processes, such as sting jets (Browning and Field, 2004) which are important for generating damaging surface winds. Furthermore, low resolution climate models may not adequately capture the representation of latent heat release in windstorms (Willison *et al.*, 2013). An additional area of uncertainty is that damage from windstorms is often caused by the wind-gusts rather than by the sustained winds. However, modelled wind-gusts are not routinely output from climate model simulations. These are areas of current research, and the H++ scenario presented here might be revised with the advent of higher resolution climate models (Shaffrey et al. 2009, Mizielinski et al. 2014).

## **7.5 Physical limits**

It is difficult to construct quantitative physical arguments for how intense an extratropical cyclone might become over the UK in response to climate change. Extratropical cyclones primarily derive their energy from (i) the available potential energy in the equator-to-pole temperature gradient and (ii) from the release of latent energy from moist processes (e.g. the formation of rainfall). However, it is difficult to use these ideas to provide constraints on intensity of individual extratropical cyclones, which will largely depend on the efficiency of the extratropical cyclone to convert these potential energies into kinetic energy.

An alternative approach was adopted by Economou et al (2014), who performed an extreme value analysis on the central pressures of extreme extratropical cyclones over the North Atlantic. This approach suggested that a most likely lower bound on central pressures in Southern England would be 942hPa. There is a relationship between central pressure and the winds generated by an extratropical cyclone. However, this relationship is not straightforward, making it difficult to infer what an upper bound on surface winds might be.

## **7.6 Summary on Windstorms**

- The UK has experienced many extreme windstorms in the past, which have had substantial socioeconomic impacts. In the historical record these impacts have mostly been through the large loss of life from coastal flooding and shipwreck. Extreme windstorms since the 1960s have mostly had their greatest impact in terms of damage to property, where insurance losses can amount to many billions of pounds and they can still lead to loss of life.
- Analysis of the instrumental records suggest that long term trends in storminess over the UK and NW Europe are small, and generally statistically insignificant, relative to the decadal variability.
- CMIP5 climate model projections suggest that the number of strong wind days (i.e. greater than the 99% percentile) might increase or decrease by the 2070-2100. Some climate model projections suggest that the number of strong wind



days might increase. **A plausible H++ windstorm scenario is thus a 50-80% increase in the number of windstorms over the UK by 2070-2100 compared to 1975-2005.** The caveats are that the scenario is based on the CMIP5 climate model simulations, which contain biases in the position of North Atlantic storm track and systematically under-represent the number of intense cyclones.

## Chapter 8 Cold snaps

This chapter deals with cold winters and presents ranges of temperature changes for the coldest days of winter, along with seasonal mean temperature changes. The data sets used are similar with those used for heat waves in Chapter 3 and are described in detail in Annex 2. We refer to the cold snap scenarios as L-- to emphasise that they are at the opposite end of the scale to the extreme warm summer temperatures in H++.

### ***8.1 Summary of L-- cold snap and cold winter scenarios***

The L-- cold winter scenarios span a range of time scales (1 day to a season) and encompass the entire UK. The time scales of the L-- scenarios are relevant for a variety of purposes. Periods of prolonged cold weather can lead to frozen water pipes which can then burst, and disrupt transport due to ice and snow. There is also a link to health impacts, with winter mortality at its greatest during cold winters.

Under long-term future warming conditions, future cold winters and cold days in the UK are likely to be less severe, occur less frequently and last for a shorter period of time than present day events. In UKCP09 winter temperatures increase under all scenarios (Section 8.4) thereby providing no evidence for more severe cold conditions in the UK. So, the L-- scenario considers two mechanisms that, were they to occur, would lead to a cooling of UK winter temperatures. These are a slowdown or collapse of the Atlantic Meridional Overturning Circulation (AMOC) and reductions in solar output (Section 8.5).

**Under the L-- scenario for the 2020s, UK average winter temperature (for December, January and February) would be 0.3°C. UK average temperature on the coldest day would be around -7°C.**

The temperatures for the 2080s are colder than those of 1962/63 and are similar to the coldest winters at the end of the Little Ice Age. This assessment is subject to a number of caveats. First, the AMOC slowdown is highly unlikely during the 21<sup>st</sup> century and the evidence has 'low confidence' associated with it. Secondly, the estimates were derived by adding several different climate effects together and onto a baseline based on the 1962/63 winter. The validity of this assumption, and in particular whether these events could occur together and the effects linearly combined, should be explored in future

work. Finally the effect of volcanic activity, which can exacerbate cooling on timescales of several years, is not considered. Large volcanic eruptions have played a significant role in past climate but are complex to include. Their effects are usually temporary and/or short-lived (Section 8.6).

## 8.2 Historical data

There are several different data sources which can be studied to examine how periods of cold weather have changed in the past and provide guidance on suitable L--scenarios (Table 8.1). Northern hemisphere annual average temperatures have been estimated using a wide range of proxy data, such as tree ring widths, composition of lake sediments and pollen samples. Some of these proxy records cover the past 2000 years (Masson-Delmotte et al., 2013).

**Table 8.1 Summary of evidence and data sources used to identify cold winters and create L-- cold scenarios.**

Evidence	Description and Confidence	Confidence
Palaeo	Proxy data; northern hemisphere annual mean temperatures	Medium
Central England Temperature series	Instrument based. Monthly data from 1659, daily min/max from 1878	High
National Climate Information Centre	UK-wide gridded temperatures from 1910	High
Weather Stations	Longest record is at Oxford (about 160 years)	High
Solar output	Climate model simulations	Medium
Atlantic Meridional Overturning Circulation slowdown	Climate model simulations	Low
UK climate projections, UKCP09	Climate model simulations	Medium

The Central England Temperature record (CET; Parker et al., 1992) dates back to 1659, and is the longest instrumental series of this kind in the world. Monthly mean temperatures are available over the entire series. Gridded temperatures based on weather station records are available from 1910. Briefly, for this study data from the UK weather and climate station network were gridded by regression and interpolation to a 5

km × 5 km grid, taking into account factors such as latitude, longitude, coastal proximity and local topography (Perry and Hollis, 2005; Perry et al., 2009). These data have been aggregated to the 25 km × 25 km grid used by the UKCP09 climate projections by simply averaging all 5 km data within each 25 km grid box. Monthly data are available from 1910 and daily data from 1960.

Before these data sources are analysed and changes in winter temperatures are discussed, the next section briefly describes the North Atlantic Oscillation (NAO), which exerts a strong control on UK climate, especially during winter.

### *The North Atlantic Oscillation*

The North Atlantic Oscillation (NAO) is a major driver of north European climate during winter. There is a semi-permanent area of high pressure over the Azores and an area of low pressure over Iceland which modulates the strength and direction of winds across the Atlantic into Europe. The exact positions and strengths of these two pressure systems vary both within and between years, and are known as the North Atlantic Oscillation (NAO). The NAO exists all year, but has the largest influence on European climate during the winter months (November to February).

The NAO is represented by the NAO index, which is based on the sea level pressure difference between the subtropical high and polar low (Osborn, 2011). Pressure is measured at Iceland and the Azores. A positive value of the NAO index corresponds to higher pressure in the Azores and lower pressure near the poles. A negative value represents the reverse. The positive phase of the NAO is associated with a stronger storm track, so winters in the UK tend to be mild and wet. A negative phase of the NAO implies mid-latitude cyclones take a more southerly storm track allowing Arctic air to reach northern Europe, resulting in colder, drier winters. Some studies have examined possible links between the NAO and other large scale modes of atmospheric variability, such as the El Niño-Southern Oscillation (ENSO). For example, the seasonal cycle of the NAO appears to be enhanced during ENSO events, but weaker when the ENSO is decaying toward a neutral phase (Polonsky et al., 2004).

Climate models run for long periods reproduce the broad scale features of the NAO, but there are substantial differences between individual models. Models do not reproduce observed changes in the NAO index, such as the positive trend between 1960 and 2000 (Christensen et al., 2013). Currently, the reasons for interannual and multi-decadal

changes in the sign and magnitude of the NAO index are not fully understood. The effect of this is not so problematic here as the model and observations have reasonable agreement with respect to the statistics of warm and cool days.

### *Reconstructions of past climate*

A wide variety of proxy data have been used to reconstruct the Earth's climate over timescales ranging from tens of millions of years to hundreds of years (Masson-Delmotte et al., 2013). In this section, the focus is on temperatures reconstructed for the past 2000 years. Annual mean temperatures for both hemispheres have been reconstructed from a variety of sources, including tree rings, pollen and lake sediments. These reconstructions show that the climate was warm during 950-1250 AD (The Medieval Climate Anomaly, also known as the Medieval Warm Period). The climate was considerably colder between 1450 and 1850 AD, a period known as the Little Ice Age (LIA). During the LIA, annual average temperatures in the northern hemisphere were roughly 1.0 to 1.3°C colder than the present day<sup>34</sup>.

The LIA appears to have been caused by several different factors. The Earth's orbital configuration resulted in low summer insolation (the total amount of solar radiation received) across the northern hemisphere. This reduced insolation acted as the trigger for the LIA to start around the end of the thirteenth century (Miller et al., 2012) by allowing Arctic sea ice to expand, leading to an increased albedo effect. The cooling was further reinforced by several large sulphur-rich volcanic eruptions. Changes in solar output are thought to have been unimportant. Another study of decadal and centennial scale variability in northern hemispheric temperatures over the past millennium concluded that volcanic eruptions and changes in greenhouse gas levels were the most important factors, and any changes in solar output had only a small impact (Schurer et al., 2014).

### *Changes in the coldest and warmest days and months in winter in the Central England Temperature record*

As stated above, monthly mean temperatures from the Central England Temperature record (CET) are available from 1659. Monthly mean temperatures for the consecutive months of December, January and February have been averaged to calculate winter

---

<sup>34</sup> These approximate temperature changes were estimated from proxy temperature reconstructions shown in Figure 5.7 of the IPCC 5<sup>th</sup> Assessment Report (Masson-Delmotte et al., 2013).

mean temperatures. The winter mean temperatures are shown as anomalies (i.e. differences) from the 1961-1990 mean in Figure 2.3. The 1961-1990 period was also used as a baseline for the UKCP09 climate projections (Murphy et al., 2009).

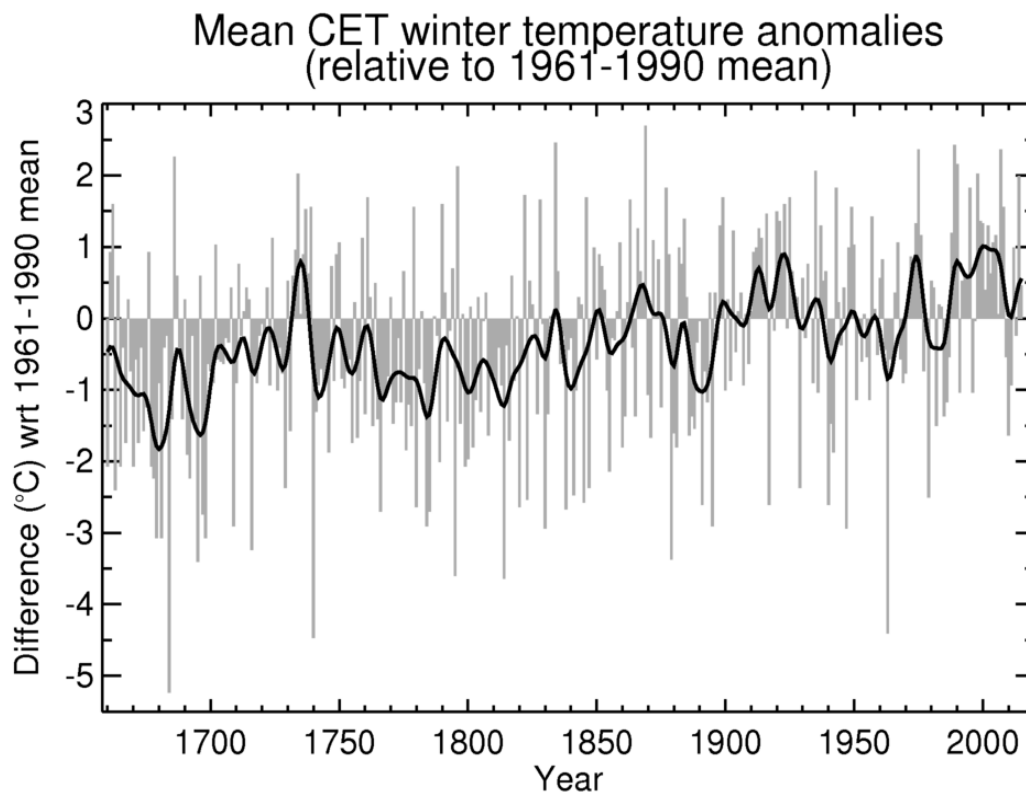
The very cold winter of 1962/1963 can be seen clearly, with only two previous winters (1683/1684 and 1739/1740) colder in the CET. The temperature anomaly of the cold winter of 2009/2010 is comparable to winter anomalies 200 years earlier.

From the anomalies shown in Figure 8.1, it can be seen that there has been a slow rise in winter mean temperatures throughout the period (1660-2014). Warm winters have become more frequent and cold winters less frequent, especially after about 1970. Using the Mann-Kendall trend estimator (Sen, 1968), a positive trend of 0.039°C per decade in the winter mean temperatures shown in Figure 8.1 was found. The trend over the period 1660-1900 was smaller, but the uncertainty bounds included zero. The trend for the period 1900-2014 was not significant at the 5% level. Overall, there is some evidence of an upward trend in winter temperatures in the CET, but the value of the trend is very dependent on the time period chosen, and is hard to distinguish from zero.

A closer examination of the temperature anomalies in Figure 8.1 reveals a few interesting features. Temperatures of the warmest winters (those with a positive anomaly of 2°C or more in Figure 8.1) appear to have remained approximately the same throughout the period shown. Temperatures of warm winters (an anomaly larger than 0°C but less than 2°C) have become higher; before 1750, the anomaly was around 0.5°C, but has increased to around 1.5°C in the early 21<sup>st</sup> century. There is an increased frequency of warm winters from 1970. The winters of 1833/34 and 1868/69 are (at the time of writing) the warmest in the CET.

Changes in the temperatures of the coldest winters in the CET are different to the changes in the warmest winters discussed above. The temperatures of the coldest winters in the twentieth century are generally higher than the coldest winters of the preceding centuries. The frequency of cold winters after 1970 is greatly reduced compared with earlier periods. Using the full CET record of monthly mean temperatures, Christidis and Stott (2012) calculated that the chances of a winter like 2009/10 occurring have reduced by approximately a factor of 2 owing to the human influence on climate. An analysis of the circulation patterns of the 2009/10 winter by Cattiaux et al. (2010)

showed that, in the absence of anthropogenic warming, temperatures would have been comparable to those of the 1962/63 winter.

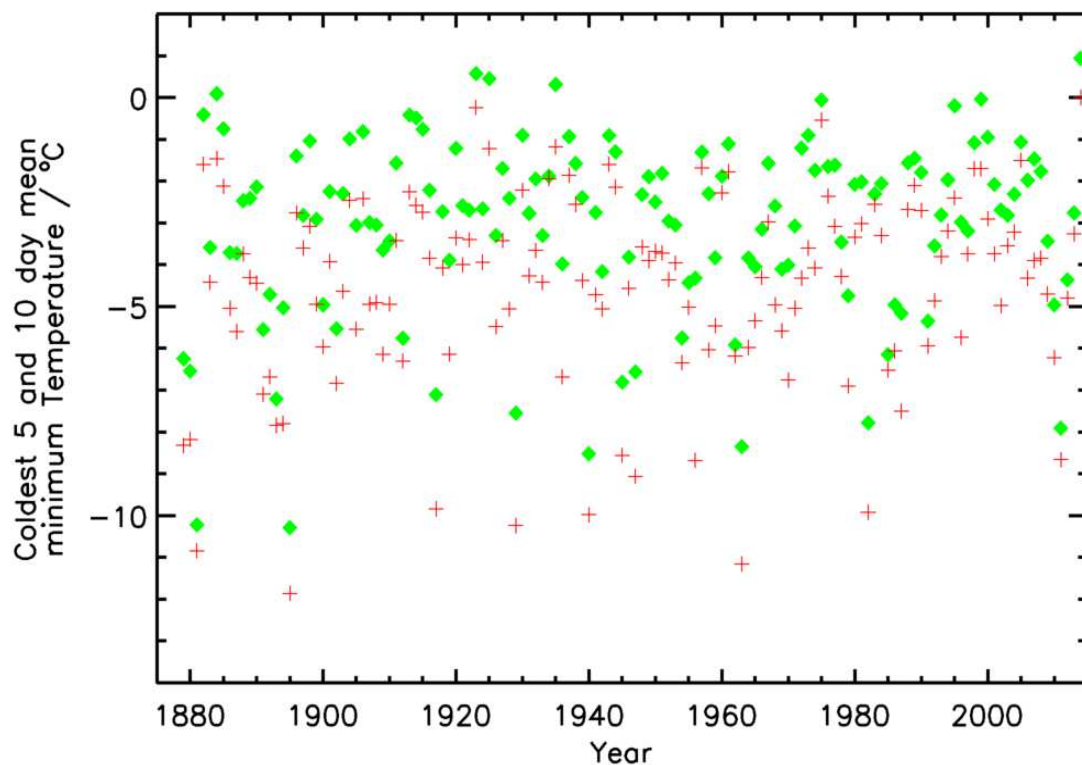


**Figure 8.1. Winter mean temperature anomalies in the Central England Temperature record for the years 1660-2015 relative to the 1961-1990 mean. The grey bars show individual anomalies for each year. The black line is a smoothed version created with a 21-term binomial filter (Parker, 2009).**

As well as cold winters, changes in shorter cold spells are also of interest. The average minimum temperatures of the coldest 5 and 10 day periods in each year in the Central England Temperature Record are shown in Figure 8.2. These temperatures were calculated using daily minimum temperatures from the CET which are available from 1878. The coldest values are found at the beginning, whereas the warmest values occurred in 2014.

Changes in the highest and lowest temperatures in winter are similar to those seen for winter as a whole (Figure 8.1). There is no significant trend in the highest winter temperatures. Temperatures for recent decades are generally similar to temperatures at the beginning (i.e. 1880-1900). However, the lowest temperatures of the 5 day periods in winter (red crosses) have warmed, from about  $-11^{\circ}\text{C}$  in the late 1800s to about  $-6^{\circ}\text{C}$ .

Similarly, the lowest temperatures of the 10 day periods (green diamonds) have warmed from  $-10^{\circ}\text{C}$  to about  $-5^{\circ}\text{C}$ .



**Figure 8.2. Coldest 5 day (red crosses) and 10 day (green diamonds) periods in the Central England Temperature record for the period 1878 – 2014. The mean 5 and 10 day values were calculated from the time series of daily minimum temperatures.**

The analysis of seasonal mean and daily minimum temperatures for 5-10 day periods from the Central England temperature record shows that the changes are not a simple linear increase. The highest temperatures in winter have remained approximately constant, despite the observed warming over the whole period. The lowest temperatures have increased, and cold winters have become less frequent, particularly in the last few decades. Despite these trends, December 2010 was one of the coldest in the CET, with a mean monthly temperature of  $-0.7^{\circ}\text{C}$ ; only December 1890 was colder ( $-0.8^{\circ}\text{C}$ ). This shows that cold winters are still possible due to natural variability even when there is an underlying warming trend.

#### *Changes in the coldest and warmest days and months in winter for the UK as a whole*

In this section, changes in UK-wide winter temperatures inferred from the gridded NCIC data are analysed and discussed. Winter is defined as the consecutive months of December, January and February. Trends in the gridded temperatures for winter have



been analysed by Jenkins et al. (2009). Significant upward trends were found for both minimum and maximum temperatures averaged over the winter period between 1961 and 2006. The temperature changes ranged from about 2°C in south-east England to about 1.2°C in Scotland.

The analysis of the CET showed that cold winters had warmed, and cold winters had become less frequent in recent decades. Using the NCIC gridded data, a very cold winter was defined as a winter with a mean daily minimum temperature less than or equal to 0°C. This threshold is arbitrary, but any winter whose mean minimum temperature is below freezing would be considered to be very cold. In such a winter, there would be many impacts such as freezing of water pipes, snowfall, ice on roads and pavements etc. Thresholds for the impact of cold temperatures on health are more uncertain than the impacts from heat (see CCRA1, Wade et al., 2012) and vary regionally; hence, it was decided not to choose a health related threshold for this work.

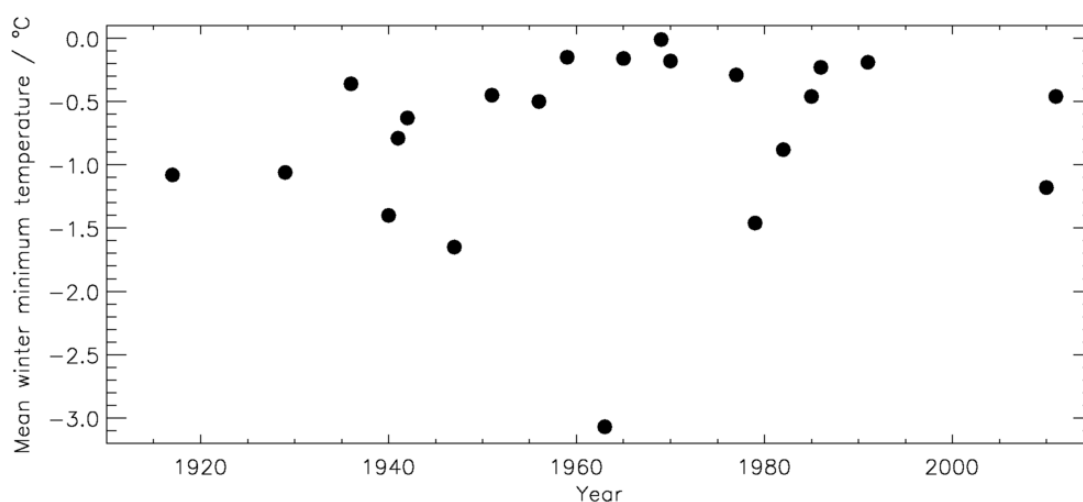
From the NCIC data, there have been 22 very cold winters since 1910 which are listed in Table 8.2. Very cold winters have occurred throughout the twentieth and early twenty-first centuries. Very cold winters were relatively infrequent between 1910 and the mid-1930s, and between the 1990s and 2000s. During these periods, the NAO had positive values in most years, leading to milder winters (Osborn, 2011). Between about 1940 and 1980, the NAO had mostly negative values, and a number of very cold winters occurred during this period. From 1980 to 2008, the NAO was again mostly positive, and there were a smaller number of very cold winters. The very cold winter of 2009/2010 was associated with a record negative NAO index (Osborn, 2011). The sign and magnitude of the NAO has a strong influence on winter temperatures in the UK, as discussed above.

**Table 8.2. Very cold winters, defined as a winter with a mean daily minimum temperature (T<sub>min</sub>) of 0°C or colder in the NCIC record (which begins in 1910). Winter is defined as the consecutive months of December, January and February. The year refers to January and February. T<sub>min</sub> refers to the mean daily minimum temperature from December to February.**

Year	T <sub>min</sub>	Year	T <sub>min</sub>	Year	T <sub>min</sub>	Year	T <sub>min</sub>
1917	-1.08	1947	-1.65	1969	-0.01	1986	-0.23
1929	-1.06	1951	-0.45	1970	-0.18	1991	-0.19
1936	-0.36	1956	-0.50	1977	-0.29	2010	-1.18
1940	-1.40	1959	-0.15	1979	-1.46	2011	-0.46
1941	-0.79	1963	-3.07	1982	-0.88		
1942	-0.63	1965	-0.16	1985	-0.46		

The only time three consecutive very cold winters occurred in the NCIC was 1939/1940, 1940/1941 and 1941/1942. Two consecutive very cold winters occurred in 1969 and 1970, 1985 and 1986 and 2010 and 2011 (Table 8.2). The winter of 1962/1963 is by far the coldest in this record (winter mean temperature of  $-3.07^{\circ}\text{C}$ ).

The mean winter daily minimum temperatures for the years listed in Table 2.2 are plotted in Figure 8.3. There is no significant trend in these temperatures, and the temperatures of the most recent cold winters (2009/2010 and 2010/2011) lie within the range of temperatures of the previous very cold winters. However, very cold winters have occurred less frequently in recent decades than earlier periods.



**Figure 8.3. UK mean winter daily minimum temperatures from the NCIC records for the period 1910 – 2013. Only very cold winters (where the mean temperature is  $0^{\circ}\text{C}$  or colder) are shown.**

### *UK Cold Climate Extremes*

The coldest days and nights in the UK have been identified from weather stations by the NCIC, and the coldest days and nights for each part of the UK are shown in Table 8.3. Most of the record cold temperatures occurred during the cold winters of 1982, 1995 and 2010. Interestingly, none of these records happened during the coldest winters of 1946/47, 1962/1963 or 1978/79.

**Table 8.3. UK record cold days and nights using data from individual weather stations.**

UK Region	Coldest Daily Minimum / °C	Date	Coldest Daily Maximum / °C	Date
<b>Scotland</b>	-27.2	10.01.1982 11.02.1895 30.12.1995	-15.9	29.12.1995
<b>England</b>	-26.1	10.01.1982	-11.3	23.12.2010
<b>Northern Ireland</b>	-23.3	21.01.1940	-11.3	11.01.1982
<b>Wales</b>	-18.7	24.12.2010	-8.0	12.01.1987

### *Summary*

The NCIC UK mean and CET both show that cold winters have occurred throughout the historical record, and that cold winters are still possible despite the warming of the planet since preindustrial times. The characteristics of cold winters are often very different. For example, 1946/47 was characterised by persistent heavy snowfall between January and early March, whereas 1962/63 had much colder temperatures during a similar period but less snowfall. Using monthly mean temperatures from the CET, the winter of 2010/11 was characterised by one of the coldest Decembers on record, whereas January and February 2011 were relatively mild. In contrast, January and February were very cold during the winter of 1946/1947 and all three winter months during the winter of 1962/1963 were consistently cold.

## **8.3 UKCP09**

Under warming conditions, future cold winters and cold days in the UK are likely to be less severe, occur less frequently and last for a shorter period of time than present day events. In UKCP09, 30-year average mean winter temperatures increase under all scenarios (Murphy et al., 2009). For the medium emissions scenario, the 30-year 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 by the 2080s.

Under the Low emissions scenario at the 10 % probability level and at the regional scale, 30-year average winter (Dec-Jan-Feb) warming is less at 0.2 to 0.5°C in the 2020s and 1.0 to 1.4°C in 2080s<sup>35</sup>. Gridded data for this specific scenario were used for estimation of the L-- cold winter described in Section 8.6.

<sup>35</sup> The range represents different rates in different UKCP09 administrative regions <http://ukclimateprojections.metoffice.gov.uk/23672?emission=low>

## **8.4 Physical limits**

When considering cold extremes, two additional climatic events with low probabilities but potentially high impacts should be considered: a prolonged solar minimum and a slowdown or collapse of the Atlantic Meridional Overturning Circulation (AMOC). Both of these events would cause a cooling of temperatures over the UK. The possible effects of these two events on UK winter mean temperatures are discussed in the following sections. The recent reductions in Arctic sea ice and its potential effect on the probability of cold winters occurring over Europe and the UK are also briefly discussed.

### *Prolonged solar minimum*

Correlations between meteorological variables and solar variability have suggested an influence of solar irradiance on the Earth's climate (Gray et al. (2010) and references therein). For example, Ineson et al. (2011) noted that weaker westerly winds over Europe have been observed in winters when the sun is less active, i.e., at the minimum phase of the 11-year sunspot cycle. These authors suggested that low solar activity increases the chance of cold winters in northern Europe and the United States, and mild winters over southern Europe and Canada, but with little change in global mean temperatures.

A future decline in solar activity would not offset the overall warming caused by anthropogenic greenhouse gas emissions (Ineson et al., 2015). However, variability in ultraviolet (UV) solar irradiance is linked to modulation of the North Atlantic Oscillation (NAO). Ineson et al. (2011) showed that the response of surface pressure patterns at a solar minimum during winter closely resembled the negative phase of the NAO. Temperatures over north-east Europe were also anomalously cold during these periods. Lockwood (2010) calculated an 8% chance of a return to a period of prolonged low solar output by 2060. Given the continuing decline in solar output since about 1990, Ineson et al. (2015) suggested that the 8% estimate is probably too small, and could be between 15 and 20%.

Ineson et al. (2015) have examined the effects of a prolonged solar minimum on European winter temperatures during the twenty-first century. They used the Met Office Hadley Centre general circulation model HadGEM2-CC (Martin et al., 2011) which includes a representation of the carbon cycle. The HadGEM2-CC model has 60 vertical levels and an upper boundary at 84 km, and so can simulate important stratospheric

processes and their effects on the troposphere. Future greenhouse gas emissions were taken from the RCP8.5 scenario (a high emissions scenario; van Vuuren et al., 2011; Taylor et al., 2012). Three simulations with no reduction in solar output, and three more with the reduction were completed. Ineson et al. (2015) used two different estimates of future solar output; here, the change in UK winter average temperatures was calculated from simulations with the larger reduction in solar UV fluxes.

**Table 8.4. 30-year mean UK winter (Dec-Feb) temperature changes (°C) from the solar minimum simulations. The temperatures are the differences between the control (no change in solar output) run and simulations with reduced solar output. All the changes are negative, showing that reduced solar output results in colder UK 30-year mean winter temperatures. The simulations were run in pairs, so the same initial conditions were used to start simulations with and without the reduced solar UV flux. The decades are 30 year periods indicated by the central decade, so, for example, the 2050s means the period 2040-2069.**

30-year time period	Ensemble Member			Ensemble Mean
	1	2	3	
2010-2039	-0.35	-0.54	-0.66	-0.52
<b>2020-2049</b>	-0.39	-0.52	-0.47	-0.46
<b>2030-2059</b>	-0.39	-0.32	-0.11	-0.28
<b>2040-2069</b>	-0.49	-0.26	-0.14	-0.30
<b>2050-2079</b>	-0.90	-0.25	-0.40	-0.52
<b>2060-2089</b>	-0.71	-0.49	-0.50	-0.57
<b>2070-2099</b>	-0.70	-0.58	-0.76	-0.68

The reductions in UK winter mean temperatures are relatively modest, and would offset the effects of global warming by at most a decade (Table 8.4). Low solar activity does not guarantee cold conditions in any specific European winter. Solar variability acts only to bias the intrinsic year-to-year variability, which remains substantial for Europe and the UK (Ineson et al., 2015). For example, in the Central England temperature (CET) record (Parker et al., 1992), many cold winters occurred at the beginning of this record (1659 to approximately 1715), which is roughly the end of the Maunder minimum (a period when sunspots became very rare and solar output was reduced). However, the winter of 1685/1686 is one of the warmest in the CET (Figure 8.1). Other studies have shown that changes in solar output have had at most a small effect on climate (Miller et al., 2012; Schurer et al., 2014). Given projected increases in greenhouse gas emissions and the associated warming of the planet, a sustained reduction in solar output would not offset the warming caused by increasing levels of greenhouse gases.

*Effects of a slowdown of the Atlantic Meridional Overturning Circulation (AMOC)*

An analysis in the most recent IPCC assessment of the AMOC under four emissions scenarios shows that it is very likely that the AMOC will weaken during the 21st century (Collins et al., 2013) and that the weakening tends to increase with higher levels of warming associated with greater greenhouse gas emissions. However, it also finds that the current generations of global climate models suggest that a sudden slowdown or collapse of the AMOC is very unlikely during the 21<sup>st</sup> century (Weaver et al., 2012; Collins et al., 2013). They consider a collapse due to global warming beyond 2100 to be unlikely. Some caution must be placed on these conclusions because there is some evidence that many of the current generation of climate models might be overly stable with respect to their AMOC response.

**Table 8.5. UK winter mean temperatures in simulations of a slowdown of the AMOC. The columns headed Control and Change show the long-term UK mean winter temperatures and the mean change after the AMOC slowdown occurred. The temperature changes are all negative, indicating they are colder in the simulation with a weakened AMOC than the control simulation. The model resolutions are approximate.**

Model / Reference	Model Resolution / km (approx.)	CO <sub>2</sub> level / ppm	Temperature / °C	
			Control	Change
HadCM3 <sup>(1,2)</sup>	300	286	3.9	-5.2 <sup>b</sup>
HadCM3 <sup>(2)</sup>	300	500 – 710 <sup>a</sup>	7.1	-4.5 <sup>b</sup>
HadGEM3 <sup>(3)</sup>	150	345	4.6	-4.9 <sup>c</sup>
HadGEM3 <sup>(3)</sup>	80	345	5.3	-4.1 <sup>c</sup>

<sup>a</sup>CO<sub>2</sub> levels from the IS92a scenario between 2050 and 2100. <sup>b</sup>Temperature differences calculated using the first 10 years of the perturbation run only, when the AMOC strength was similar to that in the simulations using HadGEM3. <sup>c</sup>Temperature differences averaged over 30-60 years; the averaging period was determined by the length of the simulation and the period for which the AMOC was stable following the initial slowdown. References: (1) Vellinga and Wood (2002); (2) Vellinga and Wood (2008); (3) Jackson et al. (2015).

Nevertheless, as a slowdown during the next century cannot be ruled out and because the climatic and economic consequences of a large slowdown of the AMOC are likely to be severe and wide-ranging (Kuhlbrodt et al., 2009; Link and Tol, 2011), so an assessment of the impacts on UK temperatures is expedient. Four simulations of a slowdown of the AMOC were analysed, and the effects on mean winter temperatures in the UK are summarised in Table 8.5. Despite the differing models and initial climatic conditions used in the simulations, the changes in winter mean temperatures are reasonably consistent.

An important caveat is that we have not assessed whether the pattern of temperature change seen in hypothetical AMOC collapse experiments is related to the transient climate response. As we will link these AMOC cooling patterns with models from the lower tail of the UKCP09 ensemble, which tend to have lower transient climate response values, this assumption must be kept in mind.

## **8.5 Other evidence**

The decline of Arctic sea ice has been linked to recent colder winters in Europe and Asia (Mori et al., 2015). The rapid warming of the Arctic has reduced the temperature gradient between mid-latitudes and the Arctic. It has been argued that a reduction in this temperature gradient leads to reduced westerly wind speeds and a slower movement of the jet stream (Francis and Vavrus, 2012), as well as an increased amplitude (or “waviness”) of the jet stream (Francis and Vavrus, 2014). However, another study found no evidence of an influence of a warm Arctic on cold European winters (Woolings et al., 2014).

A slower jet stream would lead to increased persistence of weather patterns over the UK, including cold winters (as well as warm winters). A reduction in the speed of the jet stream has not been detected (Barnes, 2013), but it could still change in the future. It is now recognised that large amplitude slow-moving waves in the jet stream can be associated with extreme weather (Screen and Simmonds, 2014). However, it is still not clear whether the jet stream has slowed, how it may change under a warming climate, and whether reductions in Arctic sea ice are linked to any changes in the jet stream (Woolings et al., 2014).

An analysis of 22 CMIP5 global climate model simulations by Mori et al. (2015) showed that projected warming of the climate will overcome any possible effects of reductions in Arctic sea ice on European and Asian winter temperatures, should these effects even exist.

## **8.6 L-- cold scenarios**

The analyses of the NCIC data and the CET show that the mean temperatures of very cold winters have increased over the historical period owing to warming since preindustrial times (approximately 1850). Cold winters have occurred less frequently in

the last few decades, whereas warm winters have become common (Figure 8.1). An analysis of monthly mean temperatures from the CET shows that the characteristics of the coldest winters are often very different. Some had mild Decembers but January and February were very cold (for example, 1946/47, 1978/79) whereas others had a very cold December but milder temperatures during January and February (2010/11). December, January and February were all unusually cold during the winter of 1962/63.

An important decision is how to represent an L-- winter. The three coldest winters in the CET record are 1683/84, 1739/40 and 1962/63 (Figure 8.3). The winter of 1683/84 is the coldest in the series, but occurred toward the end of the Little Ice Age, when temperatures were generally lower, by about 1.1°C compared to the 1961-1990 average. The anomalies for the winters of 1739/40 and 1962/63 are similar, at -4.5°C and -4.4°C respectively. The winter of 1962/63 and coldest day (12<sup>th</sup> January 1987) are used to represent an L-- winter, as gridded temperature data from the NCIC are available for these two periods and they are suitable anomalies to apply to the standard 1961-1990 baseline.

An L-- winter and an L-- coldest day for the 2020s (2010-2039) and 2080s (2070-2099) have been constructed using the data summarised in Table 8.6. These L-- scenarios are expressed using mean temperatures, because minimum and maximum temperatures were not archived from some of the climate model simulations. First, a baseline winter was defined as the average winter temperatures for the period 1961-1990, which is the same period used in the UKCP09 climate projections. This calculation used the gridded temperatures created by Perry et al. (2009). Next, the baseline winter temperatures were subtracted from the actual winter mean temperatures (again using the gridded data created by Perry et al. (2009)) for 1962/63. The winter temperatures for 1962/63 are now expressed as anomalies relative to this baseline.

From the gridded temperature data, the coldest day for the UK as a whole (identified by calculating UK average temperatures from daily mean values in the NCIC record) was 12<sup>th</sup> January 1987. On this day, record daily minimum temperatures were recorded in Wales (Table 8.3). The baseline winter temperatures were subtracted from the actual temperatures for this day, to create a set of anomalies for the coldest day.

The L-- winter scenario for the 2020s was created as follows. Gridded changes in winter average temperatures from the UKCP09 projections under the low emissions scenario for the 2020s at the 10% probability level were added to the baseline. Then, the



1962/63 anomalies were added onto this revised baseline to create the L-- winter scenario. A similar procedure was used to create the L-- coldest day for the 2020s, using the same revised baseline and then adding the anomalies for the 12<sup>th</sup> January 1987. These scenarios are therefore event based and describe cold conditions over specific time periods.

**Table 8.6. Observations and model data used to create two possible L-- winter scenarios for the 2020s and 2080s.**

Variable	Description of the effect on winter temperature	Type <sup>a</sup>
<b>Baseline</b>	Observed winter mean temperature for 1962/63	Gridded <sup>b</sup>
<b>Coldest Day</b>	Coldest day (UK-average; 12 <sup>th</sup> January 1987)	Gridded <sup>b</sup>
<b>UKCP09</b>	Low emission scenario, 10 <sup>th</sup> %ile, 2020s and 2080s	Gridded
<b>AMOC</b>	-4.7°C	Single value <sup>c</sup>
<b>Solar</b>	-0.68°C (2080s)	Single value <sup>d</sup>

<sup>a</sup>"Gridded" means observed temperatures on the 25 km grid used by the UKCP09 climate projections.

<sup>b</sup>Created by averaging all values from the 5 km grid within each 25 km grid box.

<sup>c</sup>Winter mean temperature change from the four AMOC slowdown simulations (Table 8.5)

<sup>d</sup>Ensemble average of winter mean values from Table 8.4.

For the 2080s, temperature changes from the hypothetical solar (Table 8.4) and AMOC (Table 8.5) experiments were also included. The average temperature change from the AMOC experiments (Table 8.6) and the ensemble mean temperature change from the solar experiments for the 2020s (Table 8.6) were added to every model grid point in the baseline. Next, the UKCP09 winter mean temperature changes for the 2080s under the low emissions scenario at the 10% probability level were added to the baseline. Finally, the anomalies for the 1962/63 winter and coldest day (12<sup>th</sup> January 1987) were added.

UK average temperatures for the L--cold scenarios in the 2020s and 2080s are listed in Table 8.7.

**Table 8.7. UK average temperatures for winter and a coldest day. All temperatures represent daily averages**

Variable	Time Period	
	2020s	2080s
<b>Winter mean</b>	0.3°C	-4°C
<b>Coldest day</b>	-7.0°C	-11°C

In the L-- scenario for the 2020s, UK mean winter temperature is 0.3°C over all land points. For the L--coldest day scenario, temperatures are well below freezing over the entire UK, averaging -7°C.

For the 2080s L-- scenario, average winter temperatures and the temperatures of the coldest day are much lower than those for the 2020s owing to the effects of the reduced solar output and AMOC slowdown. Average winter temperatures are about -4°C, and temperatures of the coldest day are around -11°C over the land area.

**Under the L-- scenario for the 2080s, winter temperatures in December, January and February would be -4°C over averaged over the UK and temperatures on the coldest days would be around -11°C.**

The effects of volcanic eruptions, whether large and explosive or smaller and sulphur-rich have not been included in the L-- winters. These effects are not simple to include. Large eruptions cause a temporary cooling of global mean temperatures; for example, the eruption of Mt Pinatubo in 1991 was followed by a cooling of global mean temperatures of 0.5°C (Hansen et al, 1992), whereas smaller eruptions have more of a local effect. In the case of the Little Ice Age, the effect of multiple smaller volcanic eruptions appeared to amplify an existing cooling trend (Miller et al., 2012). Any future volcanic emissions would have to be much larger and prolonged to offset the continued warming of the planet resulting from anthropogenic greenhouse gas emissions.

## Chapter 9 Other hazards, wildfires and combined events

This chapter provides a brief review of the implications of H++ type scenarios for other hazards, with a short review of wildfires as an example of an important risk that is highlighted in the National Risk Register.

### 9.1 Other hazards

The UK is exposed to a range of hazards that can be broadly classified as space weather (e.g. geo-magnetic storms), atmospheric (e.g. wind storms, hail storms and lightning), geophysical (e.g. landslides, earthquakes), shallow earth (e.g. subsidence), hydrological (e.g. floods, droughts) or biophysical (e.g. wildfires, bio-hazards) (Gill and Mallamud, 2014). Many hazards are linked, which raises the issue of whether the H++ scenarios presented in this report could occur together, increasing the risks for people, infrastructure and the environment. A full analysis of the correlations between these events was outside the scope of this report and this was agreed at the inception stage (Met Office, 2014). A summary of important hazards linked to climate change is provided in Table 9.1 with comments of the relevance of H++ type scenarios.

### 9.2 Systemic risks

Most climate risks faced by the UK are due to a combination of climate and socio-economic factors and many may be exacerbated by inter-linkages and interdependencies in systems. These are referred to as systemic risks and are relevant to H++ scenarios because it will often be a combination of extreme weather events and other factors that have the greatest impact. For example, deaths related Pakistan's 2015 heat wave, where temperatures reached 45°C, have been linked to power cuts that have restricted the use of air-conditioning units and fans and abstention from drinking water in the fasting month of Ramadan. Deaths have been greatest amongst the poorest communities with limited access to resources<sup>36</sup>. The second CCRA will consider systemic risks when assessing the potential impacts of heat waves, floods and droughts. The H++ type scenarios may be included in these assessments.

---

<sup>36</sup> <http://www.bbc.co.uk/news/world-asia-33251100>

**Table 9.1 A summary of selected hazards and their links to H++ scenarios**

Hazard Group	Hazard	H++ Relevance	Links (+ strength)
<b>Atmospheric</b>	Storm	Windstorms are often associated with heavy rainfall e.g. storms in 2013/14. (Huntingford, et al. 2014)	Floods (++) (river, coastal and pluvial flooding)
	Snow storm	Cold winters can be associated with heavy snowfall.	Floods (+) (river flooding)
	Meteorological drought	Low rainfall causes meteorological drought and is a key factor in other types of drought.	Low flows (+++)
	Heat waves	Heat waves are associated with land-atmospheric feedbacks due to dry soils. High temperatures are linked to both heat waves and hydrological drought.	Drought (++) Also clearly linked to impacts such as rail buckling.
<b>Hydrological</b>	Flood	High flows. Increases in peak flows caused heavy rainfall and wet antecedent conditions. Both H++ wet winter and heavy rainfall scenarios are relevant.	High rainfall (+++) (wet winters and heavy rainfall events)
	Hydrological drought	Low flows	Low rainfall (+++)
<b>Geophysical</b>	Landslide	High rainfall (Ch 6) can trigger shallow landslides. Both winter rainfall and event H++ scenarios are relevant to landslide risk assessment	High rainfall (++)
	Snow avalanche	Cold winters can be associated with heavy snowfall. Only relevant in Scotland.	Cold winters (+)
<b>Shallow Earth</b>	Regional subsidence	None. Although high rates of subsidence may increase rates of relative sea level rise.	n/a
	Local subsidence	Low rainfall and dry soils are linked to subsidence with impacts of buildings, roads and pipes.	Low rainfall (++) Heat waves (+)
<b>Biophysical</b>	Wildfires	Low rainfall and heat waves contribute to wild fires.	Low rainfall (+) Heat waves (+)

### **9.3 Wildfires**

This section considers wildfires by reviewing the evidence that links climate change to an increase in the frequency of fires. It provides a qualitative assessment to come up with H++ scenario and suggests the types of research required to come up with a more quantitative assessment of future risks.

**Under the H++ scenario described in this section, the UK would experience high-risk fire danger conditions coincident in multiple critical locations, particularly in the south-east of England.**

Wildfires are a global hazard, receiving increasing attention as a result of large-scale disasters with high-level impacts across the world in recent years. This attention has prompted the development of global climate change risk assessments for wildfires, summarised in the latest IPCC report (Settele et al., 2014). Along with recent studies (for e.g. Betts et al., 2013; Moritz et al., 2012; Gonzalez et al., 2010; Pechony and Shindell, 2010; Flannigan et al., 2005) current conclusions are that significant portions of the globe are likely to see increases in fire danger under climate change, although some regions may see decreases in fire danger, particularly when vegetation interactions and feedbacks are taken into account. It is also clear that there is a considerable degree of uncertainty in projections due to the highly interlinked nature of climate, vegetation, human interaction and wildfire.

The current threat to the UK from wildfire has been highlighted by its inclusion in the National Risk Register in recent years, prompted by high-impact fires such as Swinley Forest in 2011. Of interest to multiple stakeholders in the UK is the potential for increases in fire risk in the future to allow appropriate adaptive and mitigative action to be taken. The aim of this work is to provide an assessment of high-end scenarios of fire risk for the UK by the end of the century in line with other 'H++' scenarios provided for the Climate Change Risk Assessment (CCRA). These scenarios should lend insight and context to decision makers considering the longer-term evolution of land and fire management in the UK to guide costly investment, as well as provide further indication of the high-impact changes that could be avoided by limiting climate change.

Research regarding wildfire the UK is less advanced than research on many of the other risks considered in the CCRA. It is highly multi-disciplinary and our knowledge of the relevant systems and how they interact is still limited. In addition projections of wildfire are not sufficiently developed so as to have high confidence in a model-based assessment. However, it is still useful to consider multiple approaches as used in other H++ assessments. Therefore this assessment will consider the following evidence supporting H++ scenarios for wildfire in the UK:

1. Historical events
2. Temporal and spatial analogues
3. Model simulations

As with all high-end scenarios, expert judgement is a key ingredient, and for this reason an initial activity in this assessment was to convene a group of experts representing

different stakeholders in UK wildfire research. The following sections address the evidence base for high-end wildfire scenarios in the UK; followed by an outline of the expert discussion mainly with regard to the question ‘what does an H++ scenario for wildfire in the UK look like?’ A final section recommends further research needed to address this question with greater confidence.

### **What evidence do historical events give to H++ scenarios of wildfire in the UK?**

It is useful to consider historical fire events, the meteorological and climatological conditions that accompanied them, and the impact of the events. These events provide clear demonstration of the current risk and can be useful analogues of future risk. In this instance we consider a series of 3 events: The 2011 Swinley Forest fires have already been discussed and provide a useful case study of potential damage to critical infrastructure; in addition the hot and dry years of 2003 and 1995 demonstrate a clear link of such weather to wildfire incidence and allow us to consider future occurrence of such events.

In the record heat wave year of 2003 fires in the UK were not nearly as damaging as fires in southern Europe; however fire incidence was much greater than is usually expected. For instance, 870 ha were lost in the Pirbright Ranges, Surrey over 4 days. This area is designated as Special Protection Area (SPA), Special Area of Conservation (SAC) and Site of Special Scientific Interest (SSSI) and the event caused significant ecological damage. The fire also closed local roads, and led to the evacuation of military homes and concerns about Farnborough Airport flight path. The fire had regional implications on major infrastructure and reduced Fire and Rescue resources to respond to other emergencies (Rural Development Initiatives, 2012). Similarly devastating fires affected areas of moorland in the north of the UK.

The years of 1995 of 2003 saw the driest springs and warmest summers in recent years and suffered far greater than the average number of wildfires; the number of primary fires recorded by the Fire and Rescue Services during these years disproportionately account for almost 40% of fires in the entire nine year period between 1995 and 2004 (Table 9.2). By 2040 the temperatures experienced in 1995 and 2003 are expected to be around average, and to be considered a cool year by the end of the century (Stott et al., 2004). Consequently it may be expected that based on temperature alone the number of fires in these years will also become the norm or low risk.

**Table 9.2: Number of wildfire recorded in the UK 1995-2004**

Calendar Year	1995	1996	1997	1998	1999	2000	2001	2002	2003*	2004*
Primary wildfires **	627	511	380	107	197	183	118	169	303	155
Secondary wildfire ***	13,510	7,629	6,060	3,456	5,721	4,081	6,097	5,466	13,100	5,360
* Excluding incidents not recorded during industrial action Nov 2002 and Jan/Feb 2003 ** Primary fires include grassland and heathland fires where 5+ fire appliances attended *** Secondary fires include grass, straw and stubble fires where >5 fire appliances attended Source: Fire Directorate, Communities and Local Government Fire Statistics, HM Government (19 June 2006)										

### **What evidence do temporal and spatial analogues give to H++ scenarios of wildfire in the UK?**

In consultation the expert team advised that conducting analogue studies in this context may have limited use and therefore they are not considered in detail here. The incidence of wildfire is heavily dependent on the vegetation present and also on human interaction. Vegetation and human interaction in warmer or drier periods in the UK past would have been significantly different. It may be useful in future to consider how appropriate spatial analogues from the Mediterranean region may be. It is certainly useful to consider the practices that may be adapted from any fire-prone region in the face of increasing fire risk in the UK.

In addition to analogues on such a large scale, it is also useful to consider transporting knowledge and experience within the UK. Considerable work has evaluated the present day and future fire risk to the Peak District National Park (McMorrow and Lindley, 2006). The situation of the Park was considered to make it particularly vulnerable to climate change, and it is also vulnerable to visitor pressure and hence risk of fire ignition. The Park could therefore be seen as a useful analogue for future fire risk in more northerly peatlands as they experience increased drying and visitor pressure.

### **What evidence do model simulations give to high-end wildfire scenarios in the UK?**

The meteorological drivers of wildfire are well understood, and a variety of indices exist for different regions to help predict fire risk based on a meteorological or climate forecast. For instance the McArthur Forest Fire Danger Index (FFDI, Luke and McArthur, 1978) is a weather-based index derived empirically in south-eastern Australia. It indicates the probability of a fire starting, its rate of spread, intensity, and difficulty of suppression. Originally the calculation took the form of a set of cardboard wheels, into

which the user dialled the observations. Later, Noble et al. (1980) converted the FFDI into a form suitable for use by computers.

$$\text{FFDI} = 2.\exp(0.987\log D - 0.45 + 0.0338T + 0.0234V - 0.0345H)$$

H = relative humidity from 0-100 (%)

T = daily maximum air temperature (°C)

V = daily mean wind-speed 10-metres above the ground (km/hr)

D = drought factor in the range 0-10

The drought factor (D) is calculated as:

$$D = 0.191(I+104)(N+1)^{1.5} / [3.52(N+1)1.5+R-1]$$

N = No. of days since the last rain (days)

R = Total rainfall in the most recent 24h with rain (mm)

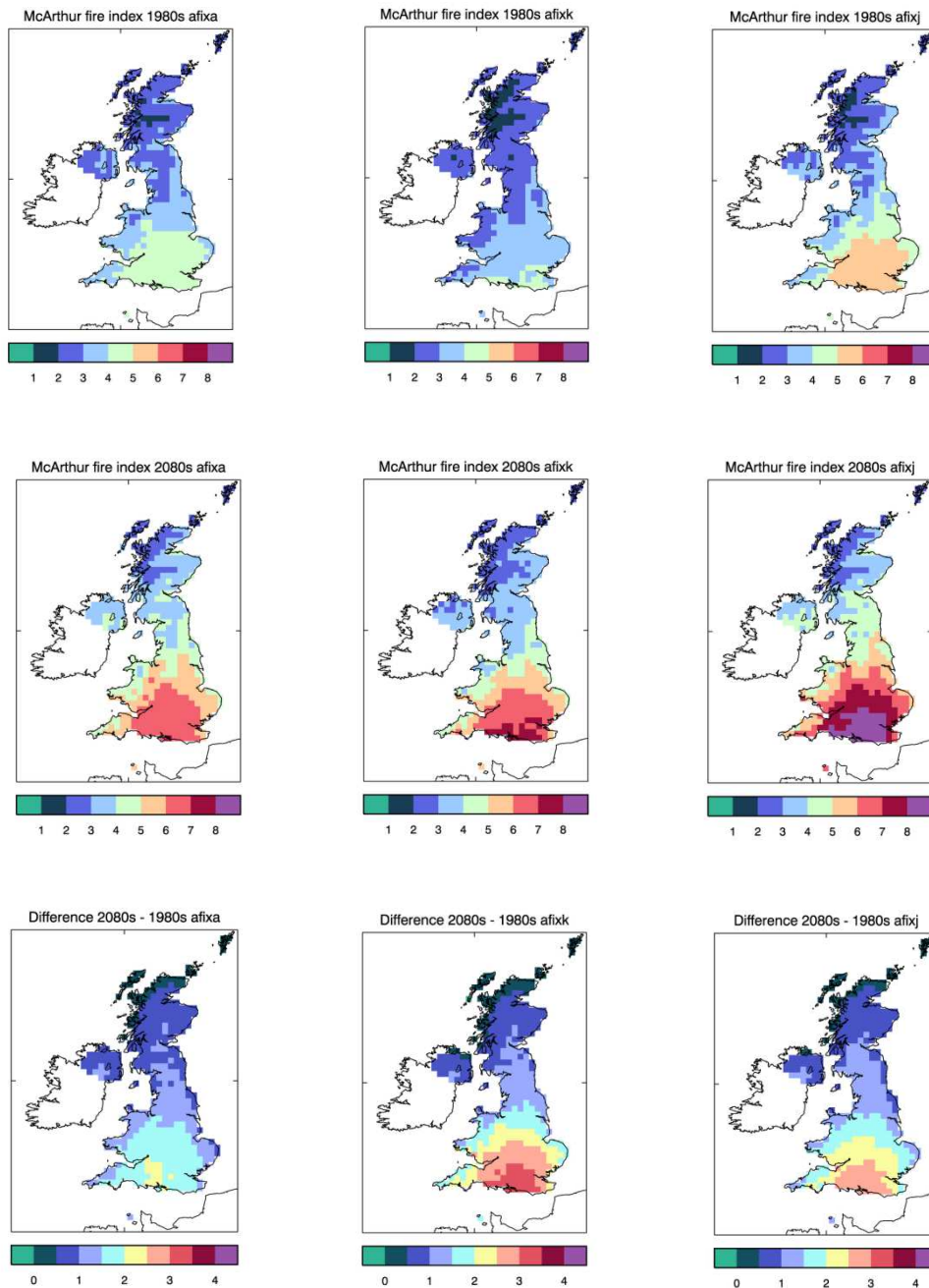
I = Amount of rain needed to restore the soil's moisture content to 200mm (mm).

A constant of 120mm has been substituted here, as suggested by Sirakoff (1985).

The previous CCRA chapter for the Biodiversity and Ecosystem Services Sector (Brown et al., 2012) concluded that wildfires and forest fires are likely to increase in frequency although it is not possible to be confident about the size of the increase. This conclusion was based on use of the 11-member Regional Climate Model (HadRM3) ensemble associated with UKCP09. The ensemble is made up of model variations each with slightly different parameter perturbations and therefore allows us to consider a degree of uncertainty in modeling. Data from ensemble were used to calculate the McArthur Forest Fire Danger Index (FFDI; Dowdy et al., 2009, Golding and Betts, 2008) across the UK for the present day and the 2080s.

As a first approximation of plausible high-end projections we take the regional climate simulations that showed greatest change in fire danger (FFDI) and project greatest future fire danger (Figure 9.1). The changes are expected to be greatest in the south of England, however some increases in fire risk are expected across the whole of the UK. Of particular importance is the projected changes for locations of strategic and asset vulnerability and the Southeast is shown here to be at greater risk. The absolute changes are small, however it is important to note the percentage increase in fire risk in some locations and the potential for strain on resources.





**Figure 9.1: Projected future FFDI values (2080s), change in FFDI (1980s-2080s) and % change in FFDI (1980s-2080s) for the 3 ensemble members showing greatest future FFDI values.**

It is also important to note that these values are annual average values only and therefore do not provide any quantitative information on future incidence of extreme fire weather or changes in fire risk seasonality. However it is expected that as the annual average FFDI increases the occurrence of extreme FFDI will also increase. Further work using these simulations is necessary to quantify these expected changes.

Finally it is not clear how appropriate the use of the FFDI is as an index for predicting long-term changes in wildfire risk in the UK. The FFDI was developed in Australia, and therefore an index more tuned to the climate, environment and vegetation of the UK might provide a more robust estimate of fire risk and variability. Given the limitations of this index-based approach it is also useful to draw on the conclusions of work presented here on high-end scenarios for heat-waves and drought, those being the major meteorological drivers of wildfire.

The H++ scenario on heatwaves concludes that all measures of extreme heat considered are predicted to increase. Changes in the hottest day of summer also showed that absolute temperatures in excess of 40°C are entirely possible, which, in an index such as the FFDI would increase the maximum fire danger significantly. Of particular importance to wildfires are prolonged periods of sustained high temperature with the night-time temperatures remaining high and therefore allowing no respite to firefighters.

The H++ scenario for meteorological droughts shows a less robust signal, suggested that future summer meteorological droughts in England and Wales could be more or less severe. The largest changes suggest the possibility of a significant increase in 6 month duration summer droughts, and the likelihood is that summer drought will increase, which together with increased incidence and duration of heatwave is significant for wildfire occurrence. Winter droughts are also important for UK wildfire occurrence as they can determine the amount of dead fuel available for burning for spring and early summer fires. The results here suggest no significant change in winter droughts, however, the possibility remains of some longer dry periods lasting several years similar to the most severe long droughts on record.

### **What does an H++ scenario for wildfire in the UK look like in reality?**

It is not possible to separate the question of wildfire in the UK from human interaction. Wildfires are usually caused by human activity, either by accident or on purpose, and therefore wildfires frequently occur in areas containing or close to assets of value to humans, either residential or industrial areas, or natural areas popular for public access. For this reason it is important to note that a high-end scenario for wildfire does not necessarily mean a scenario of greatest fire danger, but a scenario where wildfire has greatest impact.

It was clearly expressed by decision-makers present in this group that the situation already exists in the UK for a 'worst case' fire scenario. The right fuels are present in locations that would threaten significant infrastructure and assets, all it requires is the right weather. End of century timescales were considered irrelevant here as it could happen next year.

Moreover it was highlighted that for fire risk the variable of most importance was location of the fire, i.e. close to critical national infrastructure. A Wildfire Threat Analysis scoping study for Swinley Forest demonstrated this point by simulating potential fires at the site of the 2011 damaging fires. They show that if the wind had strengthened, the fire would have been pushed southwest into houses at Crowthorne and to the doorstep of Broadmoor High Security Hospital. A change in wind direction would have allowed the fire to spread northwest into the Transport Research Laboratory or eastwards into Swinley Forest and beyond (McMorrow et al, 2014). Both of these scenarios would have been incredibly costly and are in themselves considered high-risk scenarios. In addition it is the capacity of the fire service that would determine the impact of the fire; should multiple large fire events happen in two critical locations the capacity of the fire service to respond adequately would be challenged. It is therefore of value to consider the changing likelihood of multiple events across the country.

In considering changing fire risk related to climate change it is important to also consider the impacts on fire risk of other events, which may themselves change, for instance impacts on vegetation and soils from drought, pests, flooding. In general the discussions held demonstrated the complex and interactive nature of wildfire in the UK, and hence the value of a more holistic approach to risk assessment than can be achieved here. However, the following evidence provides a basis of current knowledge that will help to inform such an approach.

### **Conclusions and recommendations for future work on wildfires**

This assessment has highlighted the challenges in providing high-end scenarios for wildfire in the UK. The tight linkages between climate, vegetation, human management and interaction require much further study and understanding. However, this assessment has pulled out several key tasks, which would begin to address this:

1. Quantification of changes in projected extreme fire risk is necessary. The annual statistics presented here hide many features of the climate simulations so statistics

based on daily fire risk are needed. In addition further simulations of wildfire risk derived from potential high-end drought and heat climate scenarios would help to identify the more extreme situations that are plausible in the future. This information is particularly needed to understand where the challenge may fall, i.e. longer fire seasons or fire danger covering greater areas therefore stretching response resources, increased likelihood of multiple locations experiencing high fire danger, or increased likelihood of consecutive years with high fire danger.

2. From an ecological point of view it is necessary to better understand the tolerances of local vegetation to increasing incidence of fire, and to highlight any thresholds relevant to ecology. It would also be useful to consider the adaptive capacity of vegetation to potential new fire regimes.

3. Further research that would aid the development H++ scenarios also includes using a fire-spread model to conduct risk assessments for locations where critical infrastructure has been identified. A similar model for heathland is essential. This research is also necessary to highlight priority areas for adaptation and mitigation.

The opinion that 'the situation already exists in the UK for a 'worst case' fire scenario' is striking. Indeed, based on the limited evidence presented here, it is likely that climate change will steadily tip the balance in favour of such a scenario occurring. The recommended future work will tell by how much the scales may be tipped, and also help to establish more firmly the locations most vulnerable and most at risk.

## Chapter 10 References

### Summary and Chapter 1

Allen M.R, Stott P.A, Mitchell J.F.B, Schnur R, Delworth T.L 2000 Uncertainty in forecasts of anthropogenic climate change. *Nature*. 407, 617–620. doi:10.1038/35036559.

Jenkins, G., Perry, M and Prior, J. 2009. The climate of the United Kingdom and recent trends [<http://ukclimateprojections.metoffice.gov.uk/>]

King, D., Schrag, D., Dadi, Z., Ye Qi and Ghosh, A. 2015. Climate change: A risk assessment. Cambridge University Centre for Science and Policy. [<http://www.csap.cam.ac.uk/media/uploads/files/1/climate-change--a-risk-assessment-v10-spreads.pdf>]

Mastrandrea, M.D., C.B. Field, T.F. Stocker, O. Edenhofer, K.L. Ebi, D.J. Frame, H. Held, E. Kriegler, K.J. Mach, P.R. Matschoss, G.-K. Plattner, G.W. Yohe, and F.W. Zwiers, 2010: Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties. Intergovernmental Panel on Climate Change (IPCC). Available at <<http://www.ipcc.ch>>

Murphy, J; Sexton, D; Jenkins, G; Boorman, P; Booth, B; Brown, C; Clark, R; Collins, M; Harris, G; Kendon, E; Betts, R; Brown, S; Howard, T; Humphrey, K; McCarthy, M; McDonald, R; Stephens, A; Wallace, C; Warren, R; Wilby, R; Wood, R. (2009). *UK Climate Projections Science Report: Climate change projections*. Met Office Hadley Centre, Exeter.

Ranger, N., Reeder, T., Lowe, J. 2013. *Addressing 'deep' uncertainty over long-term climate in major infrastructure projects: four innovations of the Thames Estuary 2100 Project*. EURO J Decis Process. doi:10.1007/s40070-013-0014-5.

Wade, S.D., Townend, I., Udale-Clarke, H., Rance, J., Betts, R., Hames, D. and Nash, E. (2012) *The UK Climate Change Risk Assessment Evidence Report*. Prepared for Defra.

### Heatwaves and cold snaps

Australian Government (2009). The exceptional January-February 2009 heatwave in south-eastern Australia. Special Climate Statement 17, Bureau of Meteorology, Melbourne, Victoria.

Brown SJ, Murphy JM, Sexton DMH, Harris GR. 2014. Climate projections of future extreme events accounting for modelling uncertainties and historical simulation biases. *Clim. Dyn.*, 43, 2681-2705.

Christensen JH, Christensen OB. 2007. A summary of the PRUDENCE model projections of changes in European climate by the end of this century. *Clim. Change*, 81, Issue 1 Supplement, 7-30.

Christidis, N., and P. A. Stott. 2012. Lengthened odds of the cold UK winter of 2010/2011 attributable to human influence. In "Explaining Extreme Events of 2011 from a Climate Perspective", edited by T. C. Peterson, P. A. Stott and S. Herring, *Bull. Amer. Meteor. Soc.*, 93, 1041-1067.

Collins M, Booth BBB, Bhaskaran B, Harris GR, Murphy JM, Sexton DMH, Webb M. 2011. Climate model errors, feedbacks and forcings: a comparison of perturbed physics and multi-model ensembles. *Clim. Dyn.*, 36, 1737-1766.

Della-Marta, PM, Haylock MR, Luterbacher J, Wanner H. 2007. Doubled length of western European summer heat waves since 1880, *J. Geophys. Res.*, 112, D15103, doi:10.1029/2007JD008510.

Dobney K, Baker CJ, Quinn AD, Chapman L. 2009. Quantifying the effects of high summer temperatures due to climate change on buckling and rail related delays in south-east United Kingdom. *Meteorol. Appl.*, 16, 245-251.

Donat, MG, et al. 2013. Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century: The HadEX2 dataset, *J. Geophys. Res. Atmos.*, 118, 2098-2118, doi:10.1002/jgrd.50150.

El Fadli KI et al. 2013. World Meteorological Organization Assessment of the Purported World Record 58°C Temperature Extreme at El Azizia, Libya (13 September 1922). *Bull. Amer. Meteor. Soc.*, 94, 199-204.

Gray LJ et al. 2010. Solar influences on climate. *Rev. Geophys.*, 48, RG4001, doi:10.1029/2009RG000282.

Hartmann, D.L., A.M.G. Klein Tank, M. Rusticucci, L.V. Alexander, S. Brönnimann, Y. Charabi, F.J. Dentener, E.J. Dlugokencky, D.R. Easterling, A. Kaplan, B.J. Soden, P.W. Thorne, M. Wild and P.M. Zhai, 2013: Observations: Atmosphere and Surface. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 159-254.

Ineson S, Scaife AA, Knight JR, Manners JC, Dunstone NJ, Gray LJ. and Haigh JD. 2011. Solar forcing of winter climate variability in the northern hemisphere. *Nature Geosci.*, 4, 753-757.

Ineson S., A. C. Maycock, L. J. Gray, A. A. Scaife, N. J. Dunstone, J. W. Harder, J. R. Knight, M. Lockwood, J. C. Manners, R. A. Wood. 2015. Regional climate impacts of a possible future grand solar minimum. *Nature Comm.*, 6, doi:10.1038/ncomms8535.

Jackson LC, Kahana R, Graham R, Ringer M, Woollings T, Mecking J, Wood R. 2015. Climate impacts over Europe of a slowdown of the AMOC in a high resolution GCM. *Clim. Dyn.*, doi:10.1007/s00382-015-2540-2.

King D, Schrag D, Dadi Z, Ye Q, Ghosh A. 2015. *Climate Change: A Risk Assessment*. <http://www.csap.cam.ac.uk/projects/climate-change-risk-assessment/> [downloaded 24/7/15].

Kington J. 2010. *Climate and Weather*. HarperCollins, London.

Kuhlbrodt T et al. 2009. An integrated assessment of changes in the thermohaline circulation, *Clim. Change*, 96, 489–537.

- Link PM, Tol RSJ. 2011. Estimation of the economic impact of temperature changes induced by a shutdown of the thermohaline circulation: an application of FUND, *Clim. Change*, 104, 287-304.
- Lockwood M. 2010. Solar change and climate: An update in the light of the current exceptional solar minimum, *Proc. Roy. Soc. A*, 466, 303-329.
- Manley G. 1974. Central England temperatures: 1659 to 1973. *Q. J. Roy. Met. Soc.*, 100, 389-405.
- Masson-Delmotte, V., M. Schulz, A. Abe-Ouchi, J. Beer, A. Ganopolski, J.F. González Rouco, E. Jansen, K. Lambeck, J. Luterbacher, T. Naish, T. Osborn, B. Otto-Bliesner, T. Quinn, R. Ramesh, M. Rojas, X. Shao and A. Timmermann, 2013. Information from Paleoclimate Archives. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Miralles DG, Teuling AJ, van Heerwaarden CC, de Arellano JVG. 2014. Mega-heatwave temperatures due to combined soil desiccation and atmospheric heat accumulation. *Nature Geosci.*, 7, 345-349.
- Murphy JM et al. 2009. UK Climate Projections Science Report: Climate Change Projections, Met Office Hadley Centre, Exeter, UK.
- Ngar-Cheung L, Nath MJ. 2014. Model simulation and projection of European heat waves in present-day and future climates. *J. Climate*, 27, 3713-3730.
- Osborn T.J. 2011. Winter 2009/2010 temperatures and a record-breaking North Atlantic Oscillation index. *Weather* 66, 19-21.
- Parker DE, Legg TP, Folland CK. 1992. A new daily Central England Temperature Series, 1772-1991. *Int. J. Climatol.*, 317-342.
- Perkins SE, Alexander LV. 2013. On the measurement of heat waves. *J. Climate*, 26, 4500-4517.
- Perry M, Hollis D. 2005. The generation of monthly gridded datasets for a range of climatic variables over the United Kingdom, *Int. J. Climatol.*, 25, 1041-1054.
- Perry M, Hollis D, Elms M. 2009. The Generation of Daily Gridded Datasets of Temperature and Rainfall for the UK, National Climate Information Centre Climate Memorandum No 24, Met Office, Exeter, UK.
- Piani C, Haerter JO, Coppola E. 2010. Statistical bias correction for daily precipitation in regional climate models over Europe. *Theor. Appl. Climatol.*, 99, 187-192.
- Quesada B, Vautard R, Yiou P, Hirschi M, Seneviratne SI. 2012. Asymmetric European summer heat predictability from wet and dry southern winters and springs. *Nature Clim. Change*, 2, 736-741.
- Seneviratne SI et al. 2012. Changes in climate extremes and their impacts on the natural physical environment *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (A Special Report of Working Groups I and II of the*

Intergovernmental Panel on Climate Change), eds C B Field et al (Cambridge: Cambridge University Press), pp 109–230.

Schoetter R, Cattiaux J, Douville H. 2014. Changes of western European heat wave characteristics projected by the CMIP5 ensemble. *Clim. Dyn.*, doi:10.1007/s00382-014-2434-8.

Schurer AP, Tett SFB, Hegerl GC. 2014. Small influence of solar variability on climate over the past millennium. *Nature Geoscience*, 7, 104–108.

Stott PA, Stone DA, Allen MR. 2004. Human contribution to the European heatwave of 2003. *Nature*, 432, 610-614.

Taylor, K.E., R.J. Stouffer, G.A. Meehl. 2012. An Overview of CMIP5 and the experiment design. *Bull. Amer. Meteor. Soc.*, 93, 485-498.

van Vuuren DP et al. 2011. The representative concentration pathways: an overview. *Clim. Change*, 109, 5-31.

Vellinga M, Wood RA. 2002. Global climatic impacts of a collapse of the Atlantic thermohaline circulation. *Clim. Change*, 54, 251-267.

Vellinga M, Wood RA. 2008. Impacts of thermohaline circulation shutdown in the twenty-first century. *Clim Change*, 91, 43-63.

Weaver AJ et al. 2012. Stability of the Atlantic meridional overturning circulation: A model intercomparison, *Geophys. Res. Lett.*, 39, L20709, doi:10.1029/2012GL053763.

Wetter O., Pfister C. 2013. An underestimated record breaking event – why summer 1540 was likely warmer than 2003. *Clim. Past*, 9, 41–56.

Wetter O. et al. 2014. The year-long unprecedented European heat and drought of 1540 – a worst case. *Clim. Change*, 125, 349-363.

## **Low rainfall**

Alexander, L. V., and P. D. Jones. 2000. "Updated Precipitation Series for the UK and Discussion of Recent Extremes." *Atmospheric Science Letters* no. 1 (2):142-150. doi: DOI 10.1006/asle.2001.0016.

Allan, R. P. 2011. "CLIMATE CHANGE Human influence on rainfall." *Nature* no. 470 (7334):344-345. doi:10.1038/470344a.

Buntgen, U., W. Tegel, K. Nicolussi, M. McCormick, D. Frank, V. Trouet, J. O. Kaplan, F. Herzig, K. U. Heussner, H. Wanner, J. Luterbacher, and J. Esper. 2011. "2500 Years of European Climate Variability and Human Susceptibility." *Science* no. 331 (6017):578-582. doi: DOI 10.1126/science.1197175.

Carlson, T. N. 1991. *Mid-latitude Weather Systems*: Harper Collins Academic.

Hannaford, J., B. Lloyd-Hughes, C. Keef, S. Parry, and C Prudhomme. 2011. "Examining the large-scale spatial coherence of European drought using regional indicators of precipitation and streamflow defici." *Hydrological Processes* no. 25:1146-1162.



Hannaford, Jamie, Benjamin Lloyd-Hughes, Caroline Keef, Simon Parry, and Christel Prudhomme. 2009. The Spatial Coherence of European Droughts – Final Report. Environment Agency.

Hulme, M., G. J. Jenkins, X. Lu, J. R. Turnpenny, T. D. Mitchell, R. G. Jones, J. Lowe, J. M. Murphy, D. Hassell, P. Boorman, R. McDonald, and S. Hill. 2002. Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report. Tyndall Centre for Climate Change Research.

James, R. W. 1951. "The Structure of Steady-State Anticyclones." Australian Journal of Scientific Research, Series A: Physical Sciences no. 4:329-343.

Jenkins, G. J., J. M. Murphy, D. M. H. Sexton, J. A. Lowe, P. Jones, and C.G. Kilsby. 2009. UK Climate Projections: Briefing report. Met Office Hadley Centre, Exeter, UK. .

Lloyd-Hughes, B. 2014. "The impracticality of a universal drought definition." Theoretical and Applied Climatology no. 117 (3-4):607-611. doi: DOI 10.1007/s00704-013-1025-7.

Lloyd-Hughes, B., L. C. Shaffrey, P. L. Vidale, and N. W. Arnell. 2013. "An evaluation of the spatiotemporal structure of large-scale European drought within the HiGEM climate model." International Journal of Climatology no. 33 (8):2024-2035. doi: Doi 10.1002/Joc.3570.

Marsh, T.J. 2004. "The UK drought of 2003 - an overview." Weather no. 59 (8):224-230.

Marsh, T.J., G. Cole, and R. Wilby. 2007. "Major droughts in England and Wales, 1800–2006." Weather no. 62 (4):87-93.

Marsh, T.J., and M. Lees. 1985. The 1984 Drought. Institute of Hydrology.

Marsh, T.J., R.A. Monkhouse, N.W. Arnell, M.L. Lees, and N.S. Reynard. 1994. The 1988-92 drought. Institute of Hydrology.

Marsh, T.J., S. Parry, M.C. Kendon, and J. Hannaford. 2013. The 2010-12 drought and subsequent extensive flooding.: Centre for Ecology & Hydrology.

McSweeney, C. F., R. G. Jones, R. W. Lee, and D. P. Rowell. 2014. "Selecting CMIP5 GCMs for downscaling over multiple regions." Climate Dynamics:1-24. doi: 10.1007/s00382-014-2418-8.

Petrov, V., C. G. Soares, and H. Gotovac. 2013. "Prediction of extreme significant wave heights using maximum entropy." Coastal Engineering no. 74:1-10. doi: DOI 10.1016/j.coastaleng.2012.11.009.

Rahiz, M., and M. New. 2012. "Spatial coherence of meteorological droughts in the UK since 1914." Area no. 44 (4):400-410. doi: DOI 10.1111/j.1475-4762.2012.01131.x.

Rodda, J.C., and T.J. Marsh. 2011. The 1975-76 Drought - a contemporary and retrospective review. Centre for Ecology & Hydrology.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl. 2012. "An Overview of Cmpip5 and the Experiment Design." Bulletin of the American Meteorological Society no. 93 (4):485-498. doi: Doi 10.1175/Bams-D-11-00094.1.

Woollings, T., J. M. Gregory, J. G. Pinto, M. Meyers, and D. J. Brayshaw. 2012. "Response of the North Atlantic storm track to climate change shaped by ocean-atmosphere coupling." *Nature Geoscience* no. 5 (5):313-317. doi: Doi 10.1038/Ngeo1438.

### **Low flows**

Environment Agency. (2013a). Environmental Flow Indicator (Vol. LIT 7935 811630, pp. 4).

Environment Agency. (2013b). Guidance for run-of-river hydropower (Vol. LIT 8836, pp. 8).

Hannaford, J. (2015). Climate-driven changes in UK river flows: A review of the evidence. *Progress in Physical Geography*, 39(1), 29-48. doi: 10.1177/0309133314536755

Hay, L. E., Wilby, R. L., & Leavesley, G. H. (2000). Comparison of delta change and downscaled GCM scenarios for three mountainous basins in the United States. *Journal of the American Water Resources Association*, 36(2), 387-397.

Jones, P. D., & Lister, D. H. (1998). Riverflow reconstructions for 15 catchments over England and Wales and an assessment of hydrologic drought since 1865. *International Journal of Climatology*, 18(9), 999-1013. doi: 10.1002/(sici)1097-0088(199807)18:9<999::aid-joc300>3.0.co;2-8

Keller, V. D. J., et al. (2015). "CEH-GEAR: 1 km resolution daily and monthly areal rainfall estimates for the UK for hydrological use." *Earth Systems Science Data Discussion* 8(1): 83-112 doi: 10.5194/essdd-8-83-2015.

Lang Delus, C., Laaha, G., Koffler, D., Stahl, K., Hisdal, H., Prudhomme, C., . . . Jakubowski, W. (2014, October 2014). Towards a pan-European assessment of low flow indices. Paper presented at the FRIEND-Water 2014 - Hydrology in a Changing World: Environmental and Human Dimensions, Montpellier.

Ledbetter, R., Anderton, S. and Prudhomme, C. (2015). Performance of water supply systems during extreme drought - draft final report.

Marsh, T., Cole, G., & Wilby, R. (2007). Major droughts in England and Wales, 1800–2006. *Weather*, 62(4), 87-93. doi: 10.1002/wea.67

Moore, R. J. (1985). "The probability-distributed principle and runoff production at point and basin scales." *Hydrological Sciences Journal* 30(2): 273-297.

Moore, R. J. (2007). The PDM rainfall-runoff model. *Hydrology and Earth System Sciences*, 11(1), 483-499.

Murphy, J. M., Sexton, D. M. H., Jenkins, G. J., Booth, B. B. B., Brown, C. C., Clark, R. T., . . . Wood, R. A. (2009). UK Climate Projections Science Report: Climate Change Projections (pp. 190). Exeter, UK: Met Office Hadley Centre.

Parry, S., Lloyd-Hughes, B., Hannaford, J., Prudhomme, C., & Keef, C. (2011). The spatial coherence of European droughts – summaries of major historical droughts (Vol. SC070079/R4; SCHO1211BUVV-E-E, pp. 34): Environment Agency.

Prudhomme, C., Crooks, S., Jackson, C., Kelvin, J., Mackay, J., & Young, A. (2012). Future Flows and Groundwater Levels - Final report - Science Report/Project Note – SC090016/PN9 (Vol. PN9, pp. 90). Wallingford: CEH.

Prudhomme, C., Haxton, T., Crooks, S., Jackson, C., Barkwith, A., Williamson, J., . . . Watts, G. (2013). Future Flows Hydrology: an ensemble of daily river flow and monthly groundwater levels for use for climate change impact assessment across Great Britain. *Earth Systems Science Data*, 5(1), 101-107. doi: 10.5194/essd-5-101-2013

Tanguy, M., Dixon, H., Prosdocimi, I., Morris, D. G., & Keller, V. D. J. (2014). Gridded estimates of daily and monthly areal rainfall for the United Kingdom (1890-2012) [CEH-GEAR]. Retrieved from: <http://dx.doi.org/10.5285/5dc179dc-f692-49ba-9326-a6893a503f6e>

Thompson, N., et al. (1982). The Meteorological Office Rainfall and Evaporation Calculation System: MORECS (July 1981). *Hydrological Memorandum N 45*. Bracknell, UK, Met. Office. 45.

## Heavy rainfall

Allen, M.R. and Ingram, W.J. (2002) Constraints on future changes in climate and the hydrologic cycle. *Nature*. 419.

Allen M.R, Stott P.A, Mitchell J.F.B, Schnur R, Delworth T.L 2000 *Uncertainty in forecasts of anthropogenic climate change*. *Nature*. 407, 617–620. doi:10.1038/35036559.

Brown, S. J., Murphy, S.J., Sexton, D.M.H. and Harris, G. (2014). Climate projections of future extreme events accounting for modelling uncertainties and historical simulation biases. *Clim. Dyn.* 43:2681-2705. DOI 10.1007/s00382-014-2080-1.

Berg P, Moseley C and Haerter J O (2013) Strong increase in convective precipitation in response to higher temperatures. *Nature Geoscience*, 6, 181-185.

Chan SC, EJ Kendon, HJ Fowler, S Blenkinsop and NM Roberts (2014) Projected increases in summer and winter UK sub-daily precipitation extremes from high resolution regional climate models. *Environ. Res. Lett.* 9, 084019

Collier, C. and Hardaker (1996). *Estimating probable maximum precipitation using a storm model approach*. *J. of Hydrology* 183 (1996) 277-306.

Environment Agency (2011). *Adapting to Climate Change: Advice for Flood and Coastal Erosion Risk Management Authorities*. Environment Agency, UK.

Fenn, C.R., Bettess, R., Golding, B. And Farquharson, F.A. 2005. The Boscastle flood of 16<sup>th</sup> August 2004: Characteristics, causes and consequences. Proceedings of the 40<sup>th</sup> Defra Flood and Coastal Management Conference. [http://eprints.hrwallingford.co.uk/78/1/HRPP341\\_The\\_Boscastle\\_flood\\_of\\_16\\_August\\_2004\\_Characteristics%2C\\_causes\\_and\\_consequences.pdf](http://eprints.hrwallingford.co.uk/78/1/HRPP341_The_Boscastle_flood_of_16_August_2004_Characteristics%2C_causes_and_consequences.pdf)

Hand, W.H., Fox, N.I. and Collier, C.G. (2004). *A study of twentieth-century extreme rainfall events in the United Kingdom with implications for forecasting*. *Meteorol. Appl.* 11, 15–31 (2004) DOI:10.1017/S1350482703001117

Haarsma, R.J., W. Hazeleger, C. Severijns, H. de Vries, A. Sterl, R. Bintanja, G.J. van Oldenborgh and H.W. van den Brink, *More hurricanes to hit Western Europe due to global warming*. Geophys. Res. Lett., 2013, doi:10.1002/grl.50360.

Huntingford, C. et al. *Potential influences on the United Kingdom's floods of winter 2013/14*. Nature Climate Change 4,769-777 (2014) doi:10.1038/nclimate2314

Hurford, A.P. et al. (2012). *Validating the return period of rainfall thresholds used for Extreme Rainfall Alerts by linking rainfall intensities with observed surface water flood events*. Journal of Flood Risk Management: Volume 5, Issue 2, June 2012.

IPCC, United Nations Intergovernmental Panel on Climate Change (2013b). *Technical Summary: The Physical Science Basis. Contribution of Working Group I to the IPCC Fifth Assessment Report*.

Jones, M.R. et al. (2014) *Objective classification of extreme rainfall regions for the UK and updated estimates of trends in regional extreme rainfall*. Int. J. Climatol. 34: 751–765 DOI: 10.1002/joc.3720

Jones, M.R. et al. (2013) *An assessment of changes in seasonal and annual extreme rainfall in the UK between 1961 and 2009*. Int. J. Climatol. 33: 1178–1194

Kay, A.L., Crooks, S.M., Pall, P. Stone, D.A. (2011). *Attribution of Autumn/Winter 2000 flood risk in England to anthropogenic climate change: A catchment-based case study*. Journal of Hydrology 406, 97-112.

Kay, A.L., Crooks, S., Davies, H.N., Prudhomme, C. and Reynard, N.S. (2011). *Practicalities for implementing regionalised allowances for climate change on flood flows*. Report to Department for Environment, Food and Rural Affairs, Technical Report FD2648, CEH Wallingford, May 2011, 209pp.

Kay, A.L., Crooks, S.M., Davies, H.N. and Reynard, N.S. (2011). *An assessment of the vulnerability of Scotland's river catchments and coasts to the impacts of climate change: Work Package 1 Report*. Report to Scottish Environment Protection Agency, project R10023PUR, CEH Wallingford, August 2011, 219pp.

Kendon, M., (2014). *Has there been a recent increase in UK weather records?* Weather, 69: 327–332, DOI: 10.1002/wea.2439  
<http://onlinelibrary.wiley.com/doi/10.1002/wea.2439/abstract>

Kendon, E.J. et al., 2014. *Heavier summer downpours with climate change revealed by weather forecast resolution model*. Nature Climate Change. DOI: 10.1038/NCLIMATE2258

Kershaw T, Sanderson M, Coley D, Eames M: *Estimation of the urban heat island for UK climate change projections*. Build Serv Eng Res Technol 2010, 31:1-13.

Met Office and CEH (2014). *The Recent Storms and Floods in the UK*. Available at: [http://www.metoffice.gov.uk/media/pdf/n/i/Recent\\_Storms\\_Briefing\\_Final\\_07023.pdf](http://www.metoffice.gov.uk/media/pdf/n/i/Recent_Storms_Briefing_Final_07023.pdf).

Murphy, J; Sexton, D; Jenkins, G; Boorman, P; Booth, B; Brown, C; Clark, R; Collins, M; Harris, G; Kendon, E; Betts, R; Brown, S; Howard, T; Humphrey, K; McCarthy, M; McDonald, R; Stephens, A; Wallace, C; Warren, R; Wilby, R; Wood, R. (2009). *UK Climate Projections Science Report: Climate change projections*. Met Office Hadley Centre, Exeter.

- Lau, W.K.M., Wu, H.T and Kim, K.M. (2103). *A canonical response of precipitation characteristics to global warming from CMIP5 models*. *Geo. Phys. Res. Letters*, 40, 3163–3169, doi:10.1002/grl.50420, 2013.
- Lui, C, et al. (2012) *Co-variation of temperature and precipitation in CMIP5 models ad satellite observations*. *Geo. Phys. Res. Letters*, 39, doi:10.1029/2012GL052093.
- Lenderink and Van Meijgaard (2008). *Increase in hourly precipitation extremes beyond expectations from temperature changes*. *Nature Geoscience*, 1, 511–514. doi:10.1038/ngeo262
- Osborn, T. J., Hulme, M., Jones, P. D. & Basnett, T. A. *Observed trends in the daily intensity of United Kingdom precipitation*. *Int. J. Climatol.* 20, 347–364 (2000).
- Otto, E.E.L., Rosier, S.M., Allen, M.A., Massey, N.R., Rye, C.J., Quintana, J.I. (2014) Attribution analysis of high precipitation events in summer in England and Wales over the last decade. *Climatic Change*. Available at: <http://rd.springer.com/article/10.1007/s10584-014-1095-2/fulltext.html> (Accessed: 19/11/2014)
- Pall., P., Aina, T., Stone, D.A., Stott, P.A., Nozawa, T., Hilberts, A.G.J., Lohmann, D., Allen, M.R. (2011). *Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000*. *Nature* 470, 382-386.
- Perry, M.C. and Hollis, D.M., (2005). The generation of monthly gridded datasets for a range of climatic variables over the UK. *International Journal of Climatology*, 25. pp. 1041-1054.
- Ranger, N., Reeder, T., Lowe, J. 2013. *Addressing 'deep' uncertainty over long-term climate in major infrastructure projects: four innovations of the Thames Estuary 2100 Project*. EURO J Decis Process. DOI 10.1007/s40070-013-0014-5
- Reynard, N.S., Crooks, S., Kay, A.L. and Prudhomme, C. (2009). *Regionalised impacts of climate change on flood flows*. Report to Department for Environment, Food and Rural Affairs, Technical Report FD2020, CEH Wallingford, November 2009, 113pp.
- Roberts, J.F., Champion, A.J., Dawkins, L.C., Hodges, K.I., Shaffrey, L.C., Stephenson, D.B., Stringer, M.A., Thornton, H.E., and Youngman, B.D.: *The XWS open access catalogue of extreme European windstorms from 1979 to 2012*, *Nat. Hazards Earth Syst. Sci.*, 14, 2487-2501, doi:10.5194/nhess-14-2487-2014, 2014.
- Rodda, J.C. and Marsh, T.J. 2011. *The 1975-76 Drought - a contemporary and retrospective review*. CEH report.
- Sanderson, M. (2010) *Changes in the frequency of extreme rainfall events for selected towns and cities*. Met Office report prepared for Ofwat.
- Stewart, E.J., Jones, D.A., Svensson, C., Morris, D.G., Dempsey, P., Dent, J.E., Collier, C.G., and Anderson, C.A., 2013. *Reservoir Safety - Long Return Period Rainfall (two volumes)*. Joint Defra/Environment Agency Flood and Coastal Erosion Risk Management R&D Programme, R&D Technical Report WS 194/2/39/TR.
- Stewart, E.J., Morris, D.G., Jones, D.A., Gibson, H.S., 2012. Frequency analysis of extreme rainfall in Cumbria, 16-20 November 2009. *Hydrology Research*, 43(5). 649-662, doi:10.2166/nh.2012.033

Tramblay, Y. Et al., (2013). *Non-stationary frequency analysis of heavy rainfall events in southern France*. Hydrological Sciences Journal – Journal des Sciences Hydrologiques, 58 (2) 2013 <http://dx.doi.org/10.1080/02626667.2012.754988>

Wade, S.D., Townend, I., Udale-Clarke, H., Rance, J., Betts, R., Hames, D. and Nash, E. (2012) *The UK Climate Change Risk Assessment Evidence Report*. Prepared for Defra.

Wilby, R., Betts, R. and McCarthy, M. *Causes of the Urban Heat Island and observations*. Annex 7 of UKCP09 report.

Zappa, G., Shaffrey, L.C., and Hodges K.I. 2013a: *The Ability of CMIP5 Models to Simulate North Atlantic Extratropical Cyclones*. J. Climate, **26**, 5379–5396.

Zappa, G., Shaffrey, L.C., Hodges K.I., Sansom, P., and Stephenson, D., 2013b: *A Multimodel Assessment of Future Projections of North Atlantic and European Extratropical Cyclones in the CMIP5 Climate Models*. J. Climate, **26**, 5846-5862.

### High flows

Bayliss, A.C. and Reed, D.W. (2001). The use of historical data in flood frequency estimation. Report to MAFF, CEH Wallingford.

Bell, V.A., Kay, A.L., Cole, S.J., Jones, R.G., Moore, R.J., Reynard, N.S (2012). How might climate change affect river flows across the Thames Basin? An area-wide analysis using the UKCP09 Regional Climate Model ensemble. *Journal of Hydrology*, **442-443**, 89–104, doi:10.1016/j.jhydrol.2012.04.001.

Charlton, M.B., Arnell, N.W. (2014). Assessing the impacts of climate change on river flows in England using the UKCP09 climate change projections. *Journal of Hydrology*, **519**, 1723-1738.

Cloke, H.L., Wetterall, F., He, Y., Freer, J.E., Pappenberger, F. (2014). Modelling climate impacts on floods with ensemble climate projections. *Quarterly Journal of the Royal Meteorological Society*, **139**, 282-297.

Dankers, R., Arnell, N.W., Clark, D.B., Falloon, P.D., Fekete, B.M., Gosling, S.N., Heinke, J., Kim, H., Masaki, Y., Satoh, Y., Wada, Y., Wisser, D. (2014). First look at changes in flood hazard in the Inter-Sectoral Impact Model Intercomparison Project ensemble. *PNAS*, **11**(9), 3257-3261.

Environment Agency (2008). Improving the FEH statistical procedures for flood frequency estimation. Final research report R&D Project SC050050. Environment Agency, Bristol.

Environment Agency (2011). Adapting to Climate Change: Advice for Flood and Coastal Erosion Risk Management Authorities. Environment Agency, UK.

Hannaford, J. and Marsh, T.J. (2008) High-flow and flood trends in a network of undisturbed catchments in the UK. *International Journal of Climatology*, **28**(10). 1325-1338. [10.1002/joc.1643](https://doi.org/10.1002/joc.1643)

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., Kanae, S. (2013). Global flood risk under climate change. *Nature Climate Change*, **3**, 816-821, doi:10.1038/nclimate1911.

Hosking, J.R.M., and Wallis, J.R. (1997). Regional frequency analysis: an approach based on L-moments. Cambridge University Press, Cambridge, U.K.

Institute of Hydrology (1999). Flood Estimation Handbook (five volumes). Centre for Ecology & Hydrology, Wallingford.

Institution of Civil Engineers (1996). Floods and reservoir safety (3<sup>rd</sup> ed.). Thomas Telford, London.

Kay, A.L., Crooks, S., Davies, H.N., Prudhomme, C. and Reynard, N.S. (2011a). Practicalities for implementing regionalised allowances for climate change on flood flows. Report to Department for Environment, Food and Rural Affairs, Technical Report FD2648, CEH Wallingford, May 2011, 209pp.

Kay, A.L., Crooks, S.M., Davies, H.N., Prudhomme, C. and Reynard, N.S. (2014a). Probabilistic impacts of climate change on flood frequency using response surfaces. I: England and Wales. *Regional Environmental Change*, **14**(3), 1215–1227, doi:10.1007/s10113-013-0563-y.

Kay, A.L., Crooks, S.M., Davies, H.N. and Reynard, N.S. (2011b). An assessment of the vulnerability of Scotland's river catchments and coasts to the impacts of climate change: Work Package 1 Report. Report to Scottish Environment Protection Agency, project R10023PUR, CEH Wallingford, August 2011, 219pp.

Kay, A.L., Crooks, S.M., Davies, H.N. and Reynard, N.S. (2014b). Probabilistic impacts of climate change on flood frequency using response surfaces. II: Scotland. *Regional Environmental Change*, **14**(3), 1243–1255, doi:10.1007/s10113-013-0564-x.

Kay, A.L., Crooks, S.M. and Reynard, N.S. (2014c). Using response surfaces to estimate impacts of climate change on flood peaks: assessment of uncertainty. *Hydrological Processes*, **28**(20), 5273–5287, doi:10.1002/hyp.10000.

Kay, A.L., Jones, R.G. (2012). Comparison of the use of alternative UKCP09 products for modelling the impacts of climate change on flood frequency. *Climatic Change*, **114**(2), 211–230, doi:10.1007/s10584-011-0395-z.

Kay, A.L., Rudd A.C., Davies, H.N., Kendon, E.J. and Jones, R.G. (2015). Use of very high resolution climate model data for hydrological modelling: baseline performance and future flood changes. *Climatic Change*, doi:10.1007/s10584-015-1455-6.

Kjeldsen, T.R. (2007). The revitalised FSR/FEH rainfall-runoff method. FEH Supplementary Report No. 1. Centre for Ecology & Hydrology, Wallingford.

Kjeldsen, T.R. (2014). How reliable are UK design floods? *Journal of Flood Risk Management*, doi:10.1111/jfr3.12090

Lavers, D.A., Allan, R.P., Villarini, G., Lloyd-Hughes, B., Brayshaw, D.J., Wade, A.J. (2013). Future changes in atmospheric rivers and their implications for winter flooding in Britain. *Environmental Research Letters*, **8**, 034010.

Morris, D.G. (2003). Automation and Appraisal of the FEH Statistical Procedures for Flood Frequency Estimation. Report to Defra. CEH, Wallingford, UK.

Murphy, J; Sexton, D; Jenkins, G; Boorman, P; Booth, B; Brown, C; Clark, R; Collins, M; Harris, G; Kendon, E; Betts, R; Brown, S; Howard, T; Humphrey, K; McCarthy, M;

McDonald, R; Stephens, A; Wallace, C; Warren, R; Wilby, R; Wood, R. (2009). *UK Climate Projections Science Report: Climate change projections*. Met Office Hadley Centre, Exeter.

NERC (1975). Flood Studies Report (five volumes). Natural Environment Research Council, London, UK.

Prudhomme, C., Crooks, S., Kay, A.L., Reynard, N.S. (2013) Climate change and river flooding: Part 1 Classifying the sensitivity of British catchments. *Climatic Change*, **119**(3-4), 933-948, doi: 10.1007/s10584-013-0748-x.

Prudhomme, C., Haxton, T., Crooks, S., Jackson, C., Barkwith, A., Williamson, J., Kelvin, J., Mackay, J., Wang, L., Young, A., Watts, G. (2013). Future Flows Hydrology: an ensemble of daily river flow and monthly groundwater levels for use for climate change impact assessment across Great Britain. *Earth System Science Data*, **5**, 101-107.

Reynard, N.S., Crooks, S., Kay, A.L. and Prudhomme, C. (2009). Regionalised impacts of climate change on flood flows. Report to Department for Environment, Food and Rural Affairs, Technical Report FD2020, CEH Wallingford, November 2009, 113pp.

Robson, A.J., Jones, T.K., Reed, D.W. and Bayliss, A.C. (1998). A study of national trend and variation in UK floods. *International Journal of Climatology*, **18**, 165–182.

Robson, A.J. and Reed, D.W. (1999). Statistical procedures for flood frequency estimation. Volume 3 of the Flood Estimation Handbook, Institute of Hydrology, Wallingford, UK.

Smith, A., Bates, P., Freer, J., Wetterhall, F. (2014). Investigating the application of climate models in flood projection across the UK. *Hydrological Processes*, **28**, 2810-2823.

## Windstorm

Alexandersson H, Schmith T, Iden K, Tuomenvirta H. 1998. Long-term variations of the storm climate over NW Europe. *Global Atmos. Ocean Syst.* 6: 97–120.

Alexandersson H, Tuomenvirta H, Schmith T, Iden K. 2000. Trends of storms in NW Europe derived from an updated pressure data set. *Clim. Res.* 14: 71–73

Browning, K. and M. Field, 2004: Evidence from Meteosat imagery of the interaction of sting jets with the boundary layer, *Meteorol. Appl.* 11, 277–289.  
DOI:10.1017/S1350482704001379

Chang, E. K. M., Guo, Y. & Xia, X. 2013 CMIP5 multimodel ensemble projection of storm track change under global warming. *J. Geophys. Res.* **117**, p. D23 118.

Ciavola P, Ferreira O, Haerens P, Van Koningsveld M, Armaroli C, Lequeux Q. 2011. Storm impacts along European coastlines. Part 1: The joint effort of the MICORE and ConHaz Projects. *Environ. Sci. Policy* 14: 912–923, doi: 10.1016/j.envsci.2011.05.011.

Compo GP, Whitaker JS, Sardeshmukh PD, Matsui N, Allan RJ, Yin X, Gleason BE, Vose RS, Rutledge G, Bessemoulin P, Bronnimann S, Brunet M, Crouthamel RI, Grant



AN, Groisman PY, Jones PD, Kruk MC, Kruger AC, Marshall GJ, Maugeri M, Mok HY, Nordli Ø, Ross TF, Trigo RM, Wang XL, Woodruff SD, Worley SJ. 2011. Review article: The twentieth century reanalysis project. *Q. J. R. Meteorol. Soc.* 137: 1–28, doi: 10.1002/qj.776.

Cornes RC, Jones PD. 2012. An examination of storm activity in the northeast Atlantic region over the 1851–2003 period using the EMULATE gridded MSLP data series. *J. Geophys. Res.* 116: D16110, doi: 10.1029/2011JD016007.

Dangendorf S, Muller-Navarra S, Jensen J, Schenk F, Wahl T, Weisse R. 2014. North Sea storminess from a novel storm surge record since AD 1843. *J. Clim.*, doi: 10.1175/JCLI-D-13-00427.1.

Donat MG, Renggli D, Wild S, Alexander LV, Leckebusch GC, Ulbrich U. 2011. Reanalysis suggests long-term upward trends in European storminess since 1871. *Geophys. Res. Lett.* 38: L14703, doi: 10.1029/2011GL047995.

Economou T, Stephenson DB, Ferro CAT., 2014: Spatio-temporal modelling of extreme storms, *Annals of Applied Statistics*, DOI:10.1214/14-AOAS766.

Esteves LS, Williams JJ, Brown JM. 2011. Looking for evidence of climate change impacts in the eastern Irish Sea. *Nat. Hazards Earth Syst.* 11: 1641–1656, doi: 10.5194/nhess-11-1641-2011.

Feser, F., Barcikowska, M., Krueger, O., Schenk, F., Weisse, R. and Xia, L., 2014: Storminess over the North Atlantic and northwestern Europe—A review. *Q.J.R. Meteorol. Soc.* doi: 10.1002/qj.2364

Haarsma, R. J., Hazeleger, W., Severijns, C., Vries, H., Sterl, A., Bintanja, R., Oldenborgh, G. J. & Brink, H. W., 2013: More hurricanes to hit Western Europe due to global warming. *Geophys. Res. Lett.*: 40, pp. 1783–1788.

Hammond J.M. 1990. Storm in a teacup or winds of change? *Weather* 45: 443–448, doi: 10.1002/j.1477-8696.1990.tb05582

Hanna, E. John Cappelen, Rob Allan, Trausti Jónsson, Frank Le Blancq, Tim Lillington, and Kieran Hickey, 2008: New Insights into North European and North Atlantic Surface Pressure Variability, Storminess, and Related Climatic Change since 1830. *J. Climate*, **21**, 6739–6766.

Harvey, B. J., Shaffrey, L. C., Woollings, T. J., Zappa, G. & Hodges, K. I. 2012 How large are projected 21st century storm track changes? *Geophys. Res. Lett.* 39: L052873.

Hickey KR. 2003. The storminess record from Armagh Observatory, Northern Ireland, 1796–1999. *Weather* 58: 28–35.

Horsburgh, K. and M. Horritt, 2006: The Bristol Channel floods of 1607– reconstruction and analysis, *Weather*, 61, 272-278

Kendon, M. and M. McCarthy, 2015: The UK's wet and stormy winter of 2013/2014, *Weather*, 70, 40-47.

- Krueger O, Schenk F, Feser F, Weisse R. 2013. Inconsistencies between long-term trends in storminess derived from the 20CR reanalysis and observations. *J. Clim.* 26: 868–874, doi: 10.1175/JCLI-D-12-00309.1.
- Krueger O, Feser F, Barring L, Kaas E, Schmith T, Tuomenvirta H, von Storch H. 2014. Comment on 'Trends and low frequency variability of extra-tropical cyclone activity in the ensemble of twentieth century reanalysis' by Xiaolan L. Wang, Y. Feng, G. P. Compo, V. R. Swail, F. W. Zwiers, R. J. Allan, and P. D. Sardeshmukh, *Climate Dynamics*, 2012. *Clim. Dyn.* 42: 1127–1128, doi: 10.1007/s00382-013-1814-9.
- Lamb, H. H.: *Historic Storms of the North Sea, British Isles and Northwest Europe*, Cambridge University Press, 1991.
- Mailier, P.J., David B. Stephenson, Christopher A. T. Ferro, Kevin I. Hodges, 2006: *Monthly Weather Review*, 134, no. 8.
- Matulla C, Schoner W, Alexandersson H, von Storch H, Wang X. 2007. European storminess: Late nineteenth century to present. *Clim. Dyn.* 31: 125–130, doi: 10.1007/s00382-007-0333-y.
- May, S. M. M. Engel, D. Brill, P. Squire, A. Scheffers, and D. Kelletat, 2012: *Coastal Hazards from Tropical Cyclones and Extratropical Winter Storms Based on Holocene Storm Chronologies*, Coastal Hazards, Coastal Research Library, 1000, pp 557-585
- Mizuta, R. 2012 Intensification of extratropical cyclones associated with the polar jet change in the CMIP5 global warming projections. *Geophys. Res. Lett.* 39: L19707
- Mizielinski, M. S., Roberts, M. J., Vidale, P. L., Schiemann, R., Demory, M.-E., Strachan, J., Edwards, T., Stephens, A., Lawrence, B. N., Pritchard, M., Chiu, P., Iwi, A., Churchill, J., del Cano Novales, C., Kettleborough, J., Roseblade, W., Selwood, P., Foster, M., Glover, M., and Malcolm, A.: High-resolution global climate modelling: the UPSCALE project, a large-simulation campaign, *Geosci. Model Dev.*, 7, 1629-1640, doi:10.5194/gmd-7-1629-2014, 2014.
- Murphy, J; Sexton, D; Jenkins, G; Boorman, P; Booth, B; Brown, C; Clark, R; Collins, M; Harris, G; Kendon, E; Betts, R; Brown, S; Howard, T; Humphrey, K; McCarthy, M; McDonald, R; Stephens, A; Wallace, C; Warren, R; Wilby, R; Wood, R. (2009). *UK Climate Projections Science Report: Climate change projections*. Met Office Hadley Centre, Exeter.
- Pinto, J. G., N. Bellenbaum, M. K. Karremann, and P. M. Della-Marta (2013), Serial clustering of extratropical cyclones over the North Atlantic and Europe under recent and future climate conditions, *J. Geophys. Res. Atmos.*, 118, 12,476–12,485, doi:10.1002/2013JD020564.
- Shaffrey, L.C. and co-authors, 2009: UK-HiGEM: The new UK High Resolution Global Environment Model. Model description and Basic Evaluation. *J. Climate*, 22, 1861-1896.
- Sweeney J. 2000. A three-century storm climatology for Dublin 1715–2000. *Irish Geogr.* 33: 1–14, doi: 10.1080/00750770009478595
- Roberts, J. F., Champion, A. J., Dawkins, L. C., Hodges, K. I., Shaffrey, L. C., Stephenson, D. B., Stringer, M. A., Thornton, H. E., and Youngman, B. D. 2014: The XWS open access catalogue of extreme European windstorms from 1979 to 2012, *Nat. Hazards Earth Syst. Sci.*, 14, 2487-2501, doi:10.5194/nhess-14-2487-2014.

Wang XL, Zwiers F, Swail V, Feng Y. 2009. Trends and variability of storminess in the northeast Atlantic region, 1874–2007. *Clim. Dyn.* 33: 1179–1195, doi: 10.1007/s00382-008-0504-5.

Wang XL, Wan H, Zwiers FW, Swail VR, Compo GP, Allan RJ, Vose RS, Jourdain S, Yin XG. 2011. Trends and low-frequency variability of storminess over western Europe, 1878–2007. *Clim. Dyn.* 37: 2355–2371, doi: 10.1007/s00382-011-1107-0.

Wang XL, Feng Y, Compo GP, Swail VR, Zwiers FW, Allan RJ, Sardeshmukh PD. 2013. Trends and low frequency variability of extra-tropical cyclone activity in the ensemble of twentieth century reanalysis. *Clim. Dyn.* 40: 2775–2800, doi: 10.1007/s00382-012-1450-9.

Wang XL, Feng Y, Compo GP, Zwiers FW, Allan RJ, Swail VR, Sardeshmukh RD. 2014. Is the storminess in the Twentieth Century Reanalysis really inconsistent with observations? A reply to the comment by Krueger et al.. (2013b). *Clim. Dyn.* 42: 1113–1125, doi: 10.1007/s00382-013-1828-3.

WASA Group. 1998. Changing waves and storms in the northeast Atlantic? *Bull. Am. Meteorol. Soc.* 79: 741–760, doi: 10.1175/1520-0477(1998)079<0741:CWASIT>2.0.CO;2.

Zappa, G., Shaffrey, L. C. & Hodges, K. I. 2013a The Ability of CMIP5 Models to Simulate North Atlantic Extratropical Cyclones. *J. Clim.* 26, pp. 5379–5396.

Zappa, G., Shaffrey, L. C., Hodges, K. I., Sansom, P. G. & Stephenson, D. B. 2013b A Multi-model Assessment of Future Projections of North Atlantic and European Extratropical Cyclones in the CMIP5 Climate Models. *J. Clim.* 26, pp. 5846–5862.

## **Section 8: Other hazards**

Betts, R.A., N. Golding, P. Gonzalez, J. Gornall, R. Kahana, G. Kay, L. Mitchell, and A. Wiltshire, 2013: Climate and land use change impacts on global terrestrial ecosystems, fire, and river flows in the HadGEM2-ES Earth System Model using the Representative Concentration Pathways. *Biogeosciences Discussions*, 10, 6171-6223. doi:10.5194/bgd-10-6171-2013.

Brown, I., Ridder, B., Alumbaugh, P., Barnett, C., Brooks, A., Duffy, L., Webbon, C., Nash, E., Townend, I., Black, H. and Hough, R. (2012) *Climate Change Risk Assessment for the Biodiversity and Ecosystem Services Sector*.

Dowdy, A.J., Mills, G.A., Finkele, K. and de Groot, W. (2009). Australian fire weather as represented by the McArthur Forest Fire Danger Index and the Canadian Forest Fire Weather Index, CAWCR Technical Report No. 10. Centre for Australian Weather and Climate Research, Melbourne. Available from [http://www.cawcr.gov.au/publications/technicalreports/CTR\\_010.pdf](http://www.cawcr.gov.au/publications/technicalreports/CTR_010.pdf)

Flannigan, M.D., B.D. Amiro, K.A. Logan, B.J. Stocks, B.M. Wotton, 2005: Forest fire and climate change in the 21<sup>st</sup> Century. *Mitigation and adaptation strategies for global change* 11:847-859.

Gill, J.C. and Malamud, B.D. 2014. Reviewing and visualising the interactions of natural hazards. *Rev. GeoPys.*, 52, 680-722, doi:10.1002/2013RG000445

- Golding, N. and Betts, R. (2008). Fire risk in Amazonia due to climate change in the HadCM3 climate model: potential interactions with deforestation. *Global Biogeochemical Cycles* 22, GB4007, 10 pp.
- Gonzalez, P., R.P. Neilson, J.M. Lenihan, and R.J. Drapek, 2010: Global patterns in the vulnerability of ecosystems to vegetation shifts due to climate change. *Global Ecology and Biogeography*, 19(6), 755-768.
- Huntingford, C. et al. 2014. *Potential influences on the United Kingdom's floods of winter 2013/14*. *Nature Climate Change* 4,769-777 (2014) doi:10.1038/nclimate2314
- McMorrow, J. and S. Lindley (2006) Modelling the spatial risk of Moorland Wildfire, Final Report, Moors for the Future small grant. Accessed Feb 2015  
[http://www.moorsforthefuture.org.uk/sites/default/files/documents/2006\\_McMorrow%20et%20al\\_MFF%20Fire%20risk%20map.pdf](http://www.moorsforthefuture.org.uk/sites/default/files/documents/2006_McMorrow%20et%20al_MFF%20Fire%20risk%20map.pdf)
- McMorrow, J., Ayles, J., Kazmierczak, A., Gazzard, R., Morison, J. and A. Moffat (2014) Wildfire threat analysis in the forest-urban interface – a scoping study for the Swinley forest area. In: Institution of Fire Engineers, Fire-related Research conference (Re14); 13 Nov 2014-13 Nov 2014; Fire Service College, Moreton-in-Marsh,. 2014.
- Moritz, M.A., Parisien, E. Battlori, M.A. Krawchuk, J. Van Dorn, D.J. Ganz, and K. Hayhoe, 2012: Climate change and disruptions to global fire activity. *Ecosphere*, 3(6), 49, doi:10.1890/ES11-00345.
- Pechony, O. and D.T. Shindell, 2010: Driving forces of global wildfires over the past millennium and the forthcoming century. *Proceedings of the National Academy of Sciences of the United States of America*, 107(45), 19167-19170.
- Rural Development Initiatives (2012), Building our Resilience to Wildfires. Project Plan, April 2010, Prepared by Rural Development Initiatives on behalf of the South East England Regional Wildfire Group and Home Counties Operational Wildfire Group Partnerships accessed Feb 2015  
[http://www.climatesoutheast.org.uk/images/uploads/building\\_our\\_resilience\\_to\\_wildfires\\_2012.pdf](http://www.climatesoutheast.org.uk/images/uploads/building_our_resilience_to_wildfires_2012.pdf)
- Settele, J., R. Scholes, R. Betts, S.E. Bunn, P. Leadley, D. Nepstad, J.T. Overpeck, and M.A. Taboada, 2014: Terrestrial and inland water systems. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 271-359.
- Stott, P.A., Stone, D.A. and M.R. Allen (2004) Human contribution to the European heatwave of 2003. *Nature*, Vol. 432, pg 610-61

## Annex 1 Caveats and guidance

The caveats associated with each H++ scenario are highlighted in each chapter and some initial guidance of H++ use was provided in Chapter 1. This Annex provides a check list of 10 key points for consideration by potential users of H++ scenarios.

1. H++ scenarios provide a high-end range of possible changes in climate suitable for sensitivity testing and long term planning that cannot be ruled out based on current understanding and may occur at some point in the future, without being tied to a specific time frame (e.g. 2080s).
2. They are based on information from different sources including historical observations, global and regional climate models and consideration of limiting physical arguments. Setting the lower and upper limits of the H++ scenarios presented was based mostly on expert opinion of individual authors and may change, subject to further interpretation or expert elicitation based on the available evidence.
3. By their very nature, extremes on time scales of hours, days and seasons are associated with the occurrence of unusual weather or the unusual persistence of a regime of weather. Most H++ scenarios presented relied heavily on climate models, which may not always have sufficient skill in modelling key processes. Users should refer to specific caveats presented in each chapter and recognise that models have limited skill in reproducing the most unusual events.
4. Each H++ scenario presented has specific limitations, for example the cold snap scenarios excluded cooling due to volcanic activity and the heat waves scenarios excluded explicit consideration of the Urban Heat Island effect. Users should refer to specific caveats presented in each chapter.
5. The results are presented in relation to specific spatial scales or with reference to specific catchment types (e.g. “Enhanced-high” catchments, which are particularly sensitive to increases in rainfall). More or less severe scenarios may be possible at local scales and users should refer back to guidance within individual chapters.
6. The H++ scenarios should be used in conjunction with UKCP09 (Murphy et al., 2009) or more recent CMIP5 models. We consider good practice to present them alongside the likely range where this has been quantified.
7. H++ scenarios are not appropriate for some aspects of engineering design or as a replacement to existing statutory methods for including climate change in long term planning. In such cases H++ scenarios could be complimentary and help decision makers consider more extreme or longer term changes.

8. There is a history of scenarios that are much more severe (for many events this means much higher) than the mean being misrepresented in the media or elsewhere as disaster predictions. Therefore careful presentation is needed, which will often be tailored for specific audiences.
9. Climate change projections, including more extreme scenarios, represent just one dimension of future risks and users should also consider other dimensions, such as socio-economic change or technological innovation that may reduce or exacerbate future threats and opportunities related to climate change.
10. H++ scenarios should be used in conjunction with appropriate qualitative or quantitative decision making methods such as *minimax*, robust decision making or real options to inform adaptation decisions. More pilot study research is needed on application of H++ to specific problems to understand how they can be used to design flexible adaptation plans or “adaptive pathways” to manage future risks.

#### *Concluding comments on H++ for hazard and risk assessment*

H++ scenarios have been developed for cold snaps, heat waves, wind storms, heavy rainfall, floods, low flows and droughts. They are relevant to a wide range of hazards and for incorporation to risk assessments and adaptation plans. The H++ scenarios developed may be considered in the second CCRA. Further research is recommended on (i) H++ landslides and subsidence, (ii) correlation between events and (iii) pilot case studies on the use of H++ in a number of sectors, particularly in estimating the consequences of such scenarios in terms of social, economic and environmental impacts.

It is important to note that this project was an experiment in constructing H++ scenarios. The results were produced by a number of research teams who had flexibility to each interpret the methodology in a manner appropriate to their specialist area. This means that the reliance on any particular element of the methodology varies from scenario to scenario. Compared to earlier work with sea-level rise a greater reliance was placed in the new H++ scenarios on UKCP09 and CMIP5 climate model results. This could be for several reasons, including the greater familiarity of the researchers with these tools, availability of particular datasets and a lack of precision with some paleo data. Observations were used, sometimes in helping to construct the H++ scenario and sometimes in either filtering model results or putting the H++ into context. Limiting physical arguments were more difficult to apply but were sometimes used as a sense check on the model findings.

## Annex 2 Data Sources

### *Heatwaves and cold snaps*

A wide range of observed and modelled data have been used in this study, which are described in the following sections.

#### Historical Observations

##### *NCIC monthly and seasonal UK mean temperatures*

The National Climate Information Centre (NCIC) produces UK-wide and regional climatological data. Weather station values, including digitised records historical observations, are interpolated onto a regular grid and then regional and UK-wide values are calculated by taking an average of all the grid points within a given area. Maximum and minimum temperatures are available at monthly and seasonal timescales from 1910 and are constantly updated.

##### *Central England Temperature Record*

The Central England Temperature Record (CET) is representative of a roughly triangular area of the United Kingdom enclosed by Lancashire, London and Bristol. Monthly mean temperatures in the CET were first constructed by Manley (1974) and have been further refined and extended by Parker et al. (1992). Monthly mean temperatures are available from 1659. The CET is constantly updated.

##### *Gridded surface temperatures*

Gridded data sets of daily maximum, mean and minimum temperatures have been generated from the archive of UK weather observations held at the Met Office. Regression and interpolation techniques were used to generate temperatures on a regular grid from the irregular station network, taking into account factors such as latitude and longitude, altitude and terrain shape, coastal influence, and urban land use. This approach alleviates the impact of station openings and closures on homogeneity, but the impacts of a changing station network cannot be removed entirely, especially in areas of complex topography or sparse station coverage. The methods used to generate the monthly and daily gridded temperatures are described in more detail by Perry and Hollis (2005) and Perry et al. (2009).

## *Climate Models*

### *Perturbed Physics Ensemble*

Seventeen versions of the Hadley Centre's climate model HadCM3 (Gordon et al., 2000) were used to simulate climate for the period 1950-2099. Observed levels of greenhouse gases and aerosols were used up to 1989, and from 1990 emissions were taken from the SRES A1B scenario (Nakicenovic et al., 2000). These different versions of the HadCM3 model were created by perturbing multiple parameters within the model away from their standard values within ranges given by experts. One member of this ensemble is the standard model; i.e., with no parameter perturbations. This ensemble is described in greater detail by Collins et al. (2011), and is referred to as a "perturbed physics ensemble", or PPE.

Eleven members of the HadCM3 ensemble were dynamically downscaled using the regional model HadRM3 for the same period (1950-2099). This model has a horizontal resolution of 25 km, and was forced at the boundary using meteorological data from the global climate model. The same parameter perturbations used in the global model ensemble were also applied to the regional model, so each global model was downscaled using an equivalent regional model. The regional model was executed over Europe, but only results for the UK will be analysed here. Further details of the regional climate model ensemble can be found in Murphy et al. (2009).

### *CMIP5 Multi-Model Ensemble (also used for low rainfall analysis)*

The Coupled Model Intercomparison Project Phase 5 (CMIP5) consisted of a series of both short- and long-term climate simulations which were designed to help answer key scientific questions for the 5<sup>th</sup> Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2013). Over 30 different models were used to simulate a wide range of scenarios. The studies referenced here analysed projections of future climate using Representative Concentration Pathways (RCPs). There are four scenarios, ranging from aggressive mitigation (RCP2.6) to high emissions (RCP8.5).

### ***Additional data used for low rainfall***



HadUKP (Alexander and Jones 2000) is a series of datasets of UK regional precipitation, which incorporates the long-running England & Wales Precipitation (EWP) series beginning in 1766, the longest instrumental series of this kind in the world.

### ***Additional data used high rainfall***

The Met Office and the Environment Agency maintain rainfall observation networks including Tipping Bucket Rain (TBR) and collection gauges. While the land observation networks provides a reasonably dense network it is not sufficient to record all localised events and sites at high or inaccessible locations are under-represented. Data from this network has been used to create a number of gridded rainfall data products and models for estimating extreme rainfall, most notably the Depth-Duration-Frequency (DDF) model FORGEX, which is used in the UK's Flood Estimation Handbook<sup>37</sup>. The Met Office Radar network has been operational since 1985 and provides another source of information particularly related to spatial extent of events. Radar rainfall typically underestimates rainfall depth and is normally used in conjunction with ground observations (e.g. Fenn et al., 2005).

The National Climate Information Centre (NCIC) maintains a dataset which contains gridded daily rainfall data at a resolution of 5 km (Perry and Hollis, 2005). In this dataset, rainfall data are available at every land point in the UK, and it is available freely for use with the UKCP09 climate projections. The NCIC gridded data were generated using the irregularly spaced rain gauge data and a regression model which accounts for the many parameters which could influence local rainfall amounts, such as altitude, distance from the coast, local topography, and urbanisation. Gridded daily rainfall data from 1958 to 2007 have been created, and these data have also been aggregated from the 5 km NCIC grid to the same 25 km grid used by the regional climate model.

Some information on baseline and future heavy rainfall is included in UKCP09 (Murphy et al., 2009) based on analysis of the sampled data and use of the UKCP09 weather generator (Jones et al., 2009). These data were incorporated into the CCRA as indicators of potential impacts on pluvial flooding, Combined Sewer Overflow (CSO) spill frequency and rainfall erosivity/soil erosion (Wade et al., 2012). Data from the 11-member RCM ensemble were also released alongside the UKCP09 climate projections. They were generated using a medium emissions scenario (A1B; IPCC, 2000). Daily rainfall data are available from each of the 11 versions of the RCM for the period 1950 –

---

<sup>37</sup> A new version of FEH, called FEH13 will be released in the summer 2015 (Stewart, pers. comm.)

2099. RCM data have been processed further by CEH to estimate changes in river flooding as part of the Future Flows project (Section 5).

***Additional data used for low flows***

Catchment average daily rainfall data was calculated from the CEH-GEAR 1-km gridded daily areal rainfall dataset for the period 1961-2012 (Keller et al., 2015; Tanguy et al., 2014). Catchment average monthly potential evapotranspiration PET was derived from the Met Office Rainfall and Evaporation Calculation System MORECS (Thompson et al., 1982), and monthly PET distributed evenly throughout the months for the period 1961-2010. Daily gauged river flow time series were obtained from the National River Flow Archive when available and from relevant water companies otherwise.