



Chapter 1: Introduction



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Implications of the vote to leave the European Union

This chapter was written before the results of the EU Referendum were known. Leaving the European Union is unlikely to change the overall scale of current and future risks from climate change, but in some areas it may affect policies and programmes important to address climate-related vulnerabilities.

If such policies and programmes are changed, it will be necessary for UK measures to achieve the same or improved outcomes to avoid an increase in risk. The Adaptation Sub-Committee will consider the impact of the EU Referendum and the Government's response in its next statutory progress report on the UK National Adaptation Programme, to be published in June 2017.

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1.1 Introduction to the climate change risk assessment

1.1.1 Context and audience for the CCRA

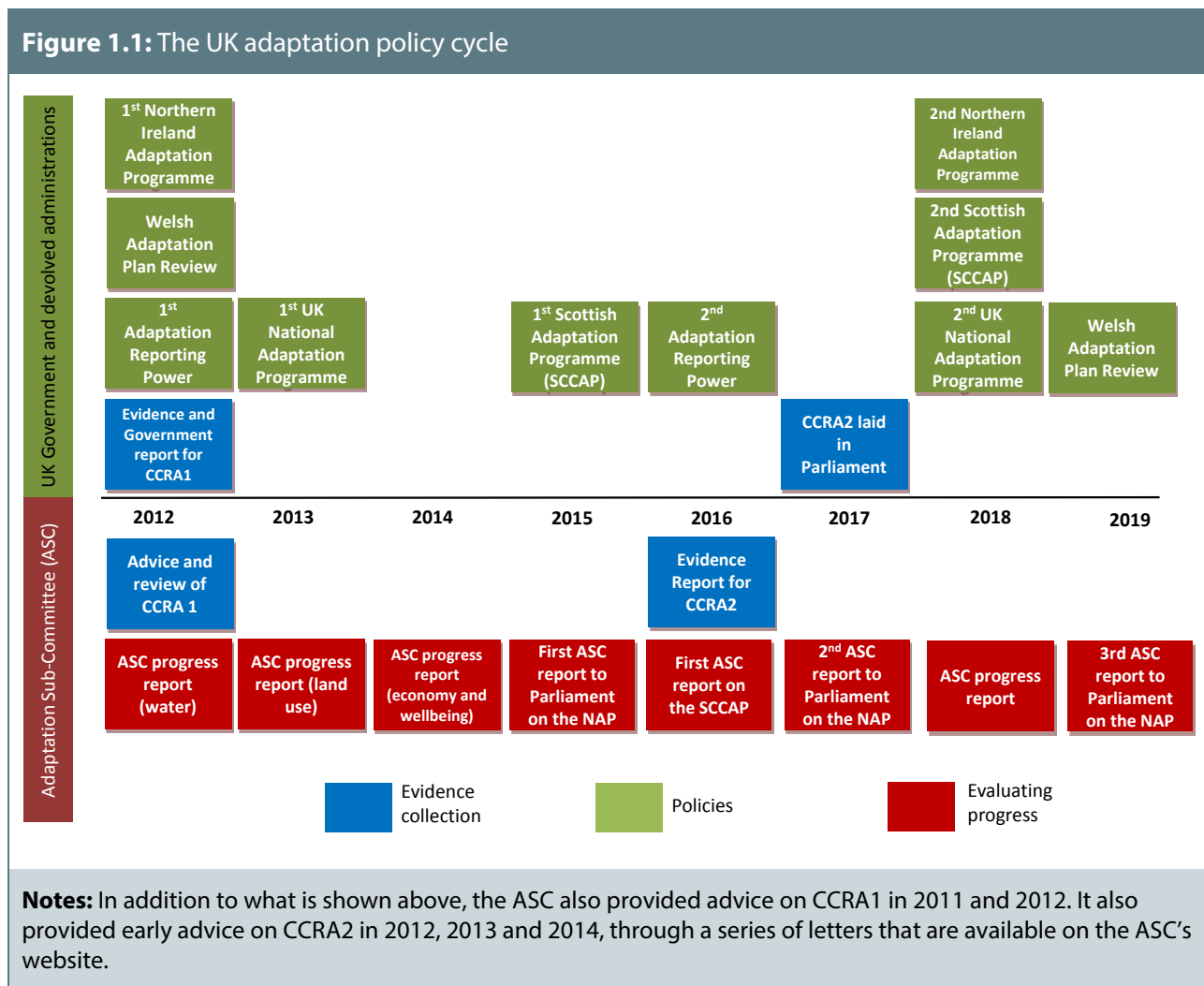
The UK Government is required under the 2008 Climate Change Act to publish a UK-wide Climate Change Risk Assessment (CCRA) every five years. The Act stipulates that the Government must assess 'the risks for the United Kingdom from the current and predicted impacts of climate change'.

The first CCRA was published by the Department for Environment, Food and Rural Affairs (Defra) in 2012.¹ For this second CCRA, due by January 2017, Defra has asked the Adaptation Sub-Committee of the Committee on Climate Change to prepare an independent Evidence Report setting out the latest evidence on the risks and opportunities to the UK from climate change. This report fulfils that request. The Government will formally lay the CCRA in Parliament by the end of January 2017.

The CCRA will feed in to the development of the next UK National Adaptation Programme, expected in 2018, as well as the national adaptation programmes of the devolved administrations. The intended audience for this report is the departments of the UK Government, departments of the devolved administrations, and their respective arm's length bodies. These key stakeholders have been involved throughout the process of designing and writing the CCRA Evidence Report. It should be noted however that the individual Evidence Report chapters are the product of their respective authors only, and the synthesis report and urgency scores represent the Adaptation Sub-Committee's (ASC's) interpretation of the evidence set out in the chapters.

Figure 1.1 sets out the statutory cycle of risk assessments and adaptation reports for the UK.

¹ <https://www.gov.uk/government/publications/uk-climate-change-risk-assessment-government-report>



1.1.2 Aims and approach

The aim of this report is to address the following question, set to the ASC by the UK Government and devolved administrations:

“Based on our latest understanding of current, and future, climate risks/opportunities, vulnerability and adaptation, what should the priorities be for the next UK National Adaptation Programme and adaptation programmes of the devolved administrations?”

In order to create an assessment that answers the question above, the UK Government and devolved administrations have asked that the following questions be covered in this report:

- How has our understanding of climate change, risks and opportunities changed since 2012?
- How does climate change interact with other socio-economic factors to affect the level of risk or opportunity?
- How might current and planned policies and other actions affect the overall level of risk or opportunity?
- What are the net effects of different risks or opportunities acting together?

- What is the urgency of action needed for different risks and opportunities?
- What are the uncertainties, limitations and confidence in the underlying evidence and analysis for different risks and opportunities?

In addressing these questions, the method for the Evidence Report looks at three different aspects of risk and opportunity (see Chapter 2 for a full description of the methodology). The first is to consider the current level of climate-related risk or opportunity and current actions. The second is to consider the potential range of future risks and opportunities, and how planned actions or autonomous adaptation may address these. The third is to use the analysis to draw conclusions about the benefits of further action in the next five years within each of the four countries of the United Kingdom.

This CCRA Evidence Report is using the concept of **urgency** to summarise the findings of the analysis and make conclusions that fulfil the overall aim. Urgency is defined here as *'a measure of the degree to which further action is needed in the next five years to reduce a risk or realise an opportunity from climate change'*. Much activity is already underway to reduce the risks and realise the opportunities from climate change in the UK, and this report seeks to assess the level of action in relation to the degree of risk, and whether further action would be beneficial in the next five years. Chapter 2 provides a detailed description of the methodology behind the urgency scoring in the Evidence Report. Each chapter of the Evidence Report provides the outputs of the urgency scoring approach for each risk and opportunity, and these are summarised together in an appendix to the Synthesis Report. In order to provide greater detail on the kinds of actions that might be needed in the next five years, urgency has been divided into four categories of action (see Box 1.1).

Box 1.1: Urgency categories in the CCRA2 Evidence Report

- **More action needed.** New, stronger or different government policies or implementation activities– over and above those already planned – are needed in the next five years to reduce long-term vulnerability to climate change.
- **Research priority.** Research is needed in the next five years to fill significant evidence gaps or reduce the uncertainty in the current level of understanding in order to assess the need for additional action.
- **Sustain current action.** Current or planned levels of activity are appropriate, but continued implementation of these policies or plans is needed to ensure that the risk continues to be managed in the future. This includes any existing plans to increase or change the current level of activity.
- **Watching brief.** The evidence in these areas should be kept under review, with long-term monitoring of risk levels and adaptation activity so that further action can be taken if necessary.

Across all of these four areas, capacity building is important to equip decision-makers and practitioners to make timely, well-evidenced and well-resourced decisions.

The assignment of different risks and opportunities to these categories is based on the expert judgement of the ASC, in consultation with the Evidence Report authors and the CCRA peer reviewers.

It is important to note that this report is a risk assessment and not an appraisal of potential

adaptation options. The report identifies specific areas where further action is felt to be needed, based on the available evidence. It does not take the further step of recommending what specific actions should be taken. This is a task for the UK Government and devolved administrations, following this assessment, in weighing up the costs and benefits of different options and setting objectives and actions in the next national adaptation programmes.

A very large number of people have contributed time, material and ideas to this report (see Annex 1.B). The ASC and its secretariat have led on the process and approach for developing the report, assigned the urgency scores and authored the various summary documents. Following an open competition in 2013, the ASC selected nine independent lead contributors to oversee the authoring of each of the Evidence Report chapters. Lead contributors were also supported on a voluntary basis by 65 contributing authors. The report has been peer-reviewed by an independent technical peer review panel of 25 individuals, a large number of government stakeholders and a selected group of non-government stakeholders. Contributions from each of these groups are acknowledged in the relevant chapters of the report.

1.1.3 Products and supporting material

Table 1.1 shows the various products that make up the CCRA2 Evidence Report.

Table 1.1: CCRA2 Evidence Report products		
Evidence Report product	Purpose	Intended audience
Synthesis Report	Written by the ASC, to provide a summary of the main conclusions of the Evidence Report, focusing on the results of the urgency scoring	Government ministers, officials, arm's length bodies, MPs and members of House of Lords, wider stakeholders
Urgency score tables	Written by the ASC, to provide 'look-up summaries' of the results and rationale for the urgency scoring, with sign posting back to the relevant sections in the main report	Government officials, policy and technical experts within arm's length bodies
Main CCRA Evidence Report, consisting of eight technical chapters	Written by chapter authors, to provide the detailed analysis that underpins the assessment of risks/opportunities and resulting urgency scores	Government officials, policy and technical experts within arm's length bodies
Country summaries	Written by the ASC, to summarise the most relevant findings from the UK-level Evidence Report for England, Northern Ireland, Scotland and Wales	Officials and arm's length bodies in each of the four UK countries
CCRA research projects	Written by consultants, to provide supporting evidence to inform the Evidence Report	CCRA authors and the ASC

The analysis for this Evidence Report has been conducted through a literature review of the available evidence. In addition to this, four research projects were commissioned specifically to provide further data and information on key aspects of the evidence base for the UK, and these have been published separately. The projects were funded with the support of the Natural Environment Research Council and the Environment Agency.

1. Sayers and Partners et al. (2015) for the ASC: Future projections of UK flood risk.
2. HR Wallingford et al. (2015) for the ASC: Updated projections of water availability in the UK.
3. AECOM et al. (2015) for the ASC: Aggregate assessment of climate change impacts on the goods and services provided by the UK's natural assets.
4. Met Office et al. (2015) for the ASC: Developing H++ climate change scenarios

1.1.4 Differences between CCRA1 and CCRA2 Evidence Reports

The first CCRA Evidence Report provided a comprehensive and detailed assessment of risks and opportunities for the UK from climate change. However, it assessed the potential impacts of climate change without taking account of current adaptation plans and activity. Results were summarised using magnitude and confidence scores. Only risks arising in the UK were summarised, rather than both domestic and international risks that could lead to UK impacts.

It is desirable to maintain consistency between assessments to be able to compare the reports and see how the evidence has changed in the intervening period. However, the process of creating CCRA1 also provided a learning opportunity for conducting risk assessments at the national level and various reviews produced a series of recommendations for future assessments (HR Wallingford, 2012; Wilby, 2012; Watkiss and Hunt, 2012). The approach for this Evidence Report has attempted to take those recommendations into account, and as a consequence, changes have been made to the method and structure of the report. This Evidence Report has also been produced with a smaller budget and team than was available for CCRA1. Table 1.2 provides an overall comparison between the CCRA1 and CCRA2 Evidence Reports. In addition, each individual chapter of this report provides a summary of the key differences between the two assessments for the risks and opportunities discussed, which are also summarised in the Synthesis Report.

Table 1.2: Differences in approach between the CCRA1 and CCRA2 Evidence Reports

Aspect of report	CCRA1 Evidence Report	CCRA2 Evidence Report
Coverage of risks and opportunities	100+ risks and opportunities, prioritised from a list of 700	Around 60 risks and opportunities, chosen by Government and the report authors
Metric for summarising the results	Focused on magnitude	Focused on urgency
Time periods covered	2020s, 2050s and 2080s	Current, 2020s 2050s and 2080s, post-2100 for sea-level rise
Type of analysis	Mix of existing data and new analysis to create 'response functions' for risks and opportunities	Mostly synthesis of existing analysis with some new data from four specially-commissioned research projects
Use of climate science	Used the UK Climate Projections, UKCP09, to explore different climate scenarios	Literature used to inform the Evidence Report is based on a mixture of studies that use UKCP09, the global CMIP5 model ensemble, single models and other scenario-based approaches
Consideration of drivers of risk	Results did not include effects of planned adaptation or socio-economic change (beyond population growth)	Results include analysis of the effects of adaptation and socio-economic change on risk/opportunity, where evidence exists
Spatial coverage	Covered England, Northern Ireland, Scotland and Wales. Did not quantify international risks	Covers England, Northern Ireland, Scotland and Wales. Includes a chapter on international dimensions
Products	11 sector reports, one synthesis report, three national summaries (~2,000 pages)	One synthesis report plus an Evidence Report of eight chapters, four national summaries, four research reports (~2,000 pages)
Authors	Authored by consultants led by HR Wallingford, signed off by Defra	Authored by independent academics and consultants led by the ASC, signed off by the ASC
Cost	£3 million over three years	£650K over three years
Funders	Defra, devolved administrations	Defra, devolved administrations, Natural Environment Research Council, Environment Agency

Peer review process	Defra-led stakeholder review process, review of the method by the Adaptation Sub-Committee and independent peer review of the sector reports and evidence report. Method and outputs also reviewed by the Defra Science Advisory Council.	Defra-led stakeholder review process including ASC-organised workshops and conferences on the method and outputs. Independent peer review of chapters and synthesis report, and external review by organisations who signed up to comment on the report. Method reviewed by the Defra Science Advisory Council and Economic Advisory Panel.
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1.1.5 Definition of risk

Traditionally, risk assessments define ‘risk’ as a function of probability and consequence and attempts are made to define these quantities as accurately as possible. However, studies that assess future risks, including climate change studies, have to cope with a large amount of uncertainty. Although all of the risks discussed in this report have some implicit likelihood associated with them, it cannot be quantified precisely. In some cases, probabilities are attributed to changes, based on an understanding of how the physics of the climate system may change in the future. Projections such as those presented in the UK Climate Projections (2009), give a current best estimate of what changes in the climate are more or less likely than others, but these probabilities do not include all sources of uncertainty, and only represent changes in the climate such as temperature and sea level, rather than impacts such as flooding.

In this report, therefore, ‘risk’ is taken to mean ‘the potential for consequences where something of value is at stake and where the outcome is uncertain’. While the authors have in many cases been able to provide some information on the magnitude of the impact arising from a given change, the resulting risk descriptors do not for the most part have probabilities associated with them. This reflects the current state of the evidence. Instead, there are a number of ways in which the risks and opportunities are presented:

- As a ‘best guess’ future estimate, either as a single figure or a range, for example: “The results show that for degrees of sea-level rise of 0.5 to 1 m, there may be 200 km or more of coastal sea defences that are particularly vulnerable to failure and it may not be cost-effective to maintain these in the future”, or “the number of hospitals located in areas at risk of flooding may increase by 4 to 27% by 2050 depending on the climate scenario”.
- As the change in probability of a specified event: “The Foresight Future Flooding study (2004) provides estimates for a 20% increase in the intensity of storms of less than six hours’ duration by 2100. The current 1:100-year storm would have a return period of 1:63 years, and the current 1:30 year storm would be 1:17.”
- As a qualitative statement giving a suggested direction of change: “It has been suggested that, depending on precipitation, conditions will become more suitable for Mediterranean, xeric or sub-tropical than temperate vegetation once the mean January temperature goes above 10°C and the mean July temperature goes above about 22°C”.

A lack of quantification of likelihood should not be taken to mean that the risks and opportunities presented in this report are very unlikely to occur. They may be very likely to occur. The choice of risks and opportunities presented reflects those thought to have the potential for most damage or benefit to the UK and have a reasonable chance of occurring.

Decision-makers in Government must assess their risk appetite in deciding what level of consequence to adapt to across each of the risks or opportunities. Over-adaptation can lead to wasted resources, whereas under-adaptation can lead to potentially irreversible economic, social and environmental consequences, or missed opportunities. The role of Government policy is to strike a balance between these two outcomes.

1.1.6 Next steps

Following publication of this Evidence Report in July 2016, the UK Government with the devolved administrations will formally lay the CCRA in Parliament by January 2017.

Both reports will then be used to inform the next round of national adaptation programmes for each of the four countries of the UK. The next UK National Adaptation Programme (covering England and the UK on reserved matters), Scottish Climate Change Adaptation Programme and the Northern Ireland Climate Change Adaptation Programme are due for publication as soon as practicable after the CCRA is published, which is likely to be in 2018 or 2019. The Welsh Government will also review its Adaptation Plan in 2019.

1.2 Observations and projections of UK climate

This section summarises our latest understanding of how the UK climate has changed in recent years and decades, and how it may change in the future. Some information on global climate is also discussed, to provide context for the UK assessment. This summary is supported by a more detailed description of our current understanding of climate science provided in **Annex 1.A**. Throughout the Evidence Report, past and future changes in climate are referenced to a number of alternative baseline periods, dependent on what has been used in the underlying source material. For example, future global warming levels are expressed below relative to a pre-industrial baseline, to provide a benchmark for potential levels of climate change. However, other baselines are often used in impact assessments and adaptation planning. For example, the UKCP09 national climate scenarios used a baseline of 1961-1990 to provide continuity with previous scenarios, while in some applications it may be preferable to use a more contemporary baseline, such as 1981-2010, to allow future changes to be referenced to more recent experience.

1.2.1 Global climate change

The 2014 Fifth Assessment Report of the Intergovernmental Panel on Climate Change (known as the IPCC AR5) concluded that observed warming of the climate system is unequivocal. The globally averaged surface temperature, combined over land and ocean, increased by 0.85°C between 1880 and 2012 (IPCC, 2013), with almost the entire globe contributing to the warming. In addition to a general upward trend, land and ocean surface temperatures show substantial variability on annual to decadal time scales. The IPCC AR5 reported that following a relatively rapid rise from the 1970s, global mean surface temperature showed a much smaller warming

trend since the late 1990s. However, 2014 was one of the warmest years on record and 2015 has been confirmed as the warmest year globally, 0.2°C above the previous warmest. Fourteen of the sixteen warmest years on the record have occurred since 2000. The chance of this happening in the absence of human-induced² warming has been estimated at around one in ten thousand.^{3 4} In 2015, global mean surface temperature was measured as 1°C above the 1851-1990 average for the first time.⁵

The extent and causes of the slowdown in warming since the late 1990s, often referred to as a warming hiatus or pause, have received much attention in the scientific literature, and remain under investigation. Recent evidence points to a significant role for internal (natural) climate variability, probably alongside some contribution from radiative forcing.⁶ Periods of slower, as well as more rapid, warming have occurred in the past. The influence of natural variability (for example through El Niño and La Niña events in individual years, or Atlantic and Pacific variability from decade to decade), together with short-term variations in natural and human-induced radiative forcing from year to year, serve to mask longer-term trends in surface temperature due to human-induced global warming. Other measures of global warming also support a continuing warming trend, such as ocean heat content and global sea level rise. Global mean sea level increased by 0.19m between 1901 and 2010 (IPCC, 2013). The recent trend has been higher, amounting to 3.2mm per year for the period 1993 to 2010.

The IPCC AR5 also assessed *future* climate projections from a new set of international climate models provided by different countries around the world (known as CMIP5, or the Fifth Coupled Model Intercomparison Project). These models were driven by four different scenarios of future greenhouse gas concentrations and aerosol emissions - Representative Concentration Pathways - called RCP2.6, 4.5, 6.0 and 8.5. These correspond to different levels of future radiative forcing due to human activities, and provide an important focus for current climate research and impacts analysis.

Projections of globally averaged surface temperature provide a convenient way of characterising the magnitude of future climate change, and associated uncertainties, expected in response to each of the RCPs. Using CMIP5 models, the IPCC AR5 provided such projections for the period 2081-2100 relative to a baseline of 1986-2005. These showed likely⁷ ranges of change that varied from 0.3 - 1.7°C for RCP2.6 to 2.6 - 4.8 °C for RCP8.5, the scenario with the highest radiative forcing. For a given RCP scenario, the IPCC AR5 ranges represent CMIP5 responses to one specific pathway for future carbon dioxide concentration.

² "Human-induced" refers to climate changes driven by human activities, including changes in atmospheric composition due to emissions of greenhouse gases or aerosols, or land use changes.

³ <http://www.nature.com/articles/srep19831>

⁴ <http://www.livescience.com/53468-how-likely-is-global-warm-streak.html>

⁵ <http://www.metoffice.gov.uk/news/releases/archive/2016/2015-global-temperature>

⁶ Radiative forcing refers to the effect on the radiation balance of the Earth, measured in Watts per square metre (Wm^{-2}), due to a change in one or more external drivers of climate change. Such drivers can include natural effects such as a change in solar output or a volcanic eruption, or human-induced changes in atmospheric greenhouse gases and aerosols. Footnote 11 provides a more detailed description.

⁷ In the specific case of global temperature projections, AR5 adjusted its quantitative language scale to interpret 5-95% probability ranges as *likely* rather than the usual interpretation of *very likely*, to account for limitations in the confidence attached to the underpinning climate model results.

Using different sets of climate models or different baselines leads to different results for scenarios of future global temperature change. For example, the UK Climate Projections (UKCP09) were produced using a methodology based on a larger number of climate projections, using models available at the time of the previous IPCC assessment, IPCC AR4. When driven by the same RCP concentration pathways, the corresponding UKCP09 ranges for the period 2081-2100 relative to a baseline of 1986-2005 are 1.0 - 1.9°C for RCP2.6 and 3.1 - 4.8°C for RCP8.5, which differ from the IPCC AR5 results to an extent dependent on choice of emissions scenario. These differences result from several methodological contrasts, including the use of different sets of climate model simulations, and application in UKCP09 of formal observational constraints derived from measures of model performance. Such differences underline that outcomes outside the likely ranges provided by either IPCC AR5 or UKCP09 cannot be ruled out.

The above 'concentration-driven' projections consider uncertainties in modelling the future physical response of climate, but not uncertainties arising from carbon cycle processes, which control how carbon emissions are converted into concentrations of carbon dioxide in the atmosphere. IPCC AR5 did not provide emissions-driven ranges for future global temperature rise that account for uncertainties in both carbon cycle and physical processes, but these are available from UKCP09. For 2080- 2099 relative to 1986-2005, the UKCP09 ranges broaden to 1.1 - 2.4°C for RCP2.6 and to 3.1 - 5.3°C for RCP8.5, when carbon cycle uncertainties are added.

It is also useful to express global temperature changes relative to a pre-industrial rather than a near-contemporary baseline, as this allows these projections to be related to international climate change policy agreements. IPCC AR5 did not provide global temperature projections referenced this way, but these are provided in Table 1.3 using the UKCP09 methodology, for each of the RCP scenarios. The results are presented as emissions-driven projections to give the most comprehensive view on the associated uncertainties, using a baseline of 1860 – 1899.⁸

⁸ This is slightly different from the period of 1851-1900 that is generally used to represent a pre-industrial climate in the IPCC AR5 report. This is because the UKCP09 climate simulations started in 1860, but this difference does not significantly influence the results.

Table 1.3: Projections of changes in global mean surface temperature for 2080-2099 compared to 1860-1899

RCP scenario	Change in global mean surface temperature
RCP 2.6	1.4 - 3.2°C
RCP 4.5	2.1 - 4.2°C
RCP 6.0	2.5 - 4.7°C
RCP 8.5	3.4 - 6.2°C

Source: Met Office, based on UKCP09 data.

Notes: These values are 5 - 95% probabilistic ranges from the UKCP09 method. They are interpreted here as *likely* ranges, based on the same interpretation of uncertainty in global temperature changes adopted by IPCC AR5. See also Figure 1.A7 and associated text in Annex 1.A for further details of these projections, and how they relate to other emissions scenarios and to the AR5 projections.

In December 2015, 195 countries reached a new international climate change agreement in Paris. The Paris Agreement’s aim is to keep the rise in global mean surface temperature ‘well below’ 2°C above pre-industrial levels (i.e. 1850 – 1900) and to ‘pursue efforts’ to limit the increase to 1.5°C. The agreement calls for global emissions to peak as early as possible and then fall to net zero later this century. The Agreement requires a global stocktake of national commitments every five years. Current voluntary national pledges are insufficient to reach the 2°C target, and if implemented in full would likely correspond to a rise in global mean surface temperature in the range 2.2 - 3.4°C, with a central estimate of 2.7°C (Jeffery et al., 2015). Significantly stronger national commitments will therefore be needed, and soon, to have a better than even chance of keeping global surface temperature rise to well below 2°C. Therefore, although UK national mitigation strategy is predicated on containing global warming to about 2°C, adaptation policy should consider a range of possible futures including those with greater warming.

1.2.2 UK climate change

Annual average UK land temperature increased by 0.9°C in 2005 – 2014 compared to 1961 – 1990, with 2014 being the warmest individual year. The bulk of the UK warming has occurred since 1970, with significant human influence detected in the increase in Central England Temperature (CET) since 1950 (Karoly and Stott, 2006). All of the top ten warmest years in the UK annual average temperature series have occurred since 1990 and the eight warmest years have all occurred since 2002 (Kendon et al., 2015a).

Annual rainfall over Scotland has increased since 1970, to a level more than 10% above the average observed during the early decades of the 20th century. Smaller increases have also occurred over Northern Ireland and England & Wales in more recent decades (Kendon et al., 2015a).

During the past few decades, the UK has seen increases in several indicators of high temperature extremes and heavy rainfall events (Brown et al., 2008; Jones et al., 2013; Kendon et al., 2015a); accompanied by increases in river water temperatures, winter runoff and the occurrence of high river flows (Watts et al., 2015). The period since 2000 accounts for two-thirds of hot-day records, and close to half of wet-day records, in monthly, seasonal and annual observations since 1910 (Kendon, 2014). The frequency of severe autumn and winter wind storms increased between 1950 and 2003 (Alexander et al., 2005), although storminess in recent decades is not unusual in the context of longer European records dating back to the early 20th century (Matulla et al., 2008). Attribution of regional extreme events to specific causes, such as human-induced climate change, is challenging. However, peer-reviewed studies suggest that the probability of occurrence of several recent seasonal events has been increased by human-induced climate change, including the autumn 2000 floods in England & Wales (Pall et al., 2011), the European heatwave of summer 2003 (Stott et al., 2004), and the record central England temperature of 2014 (King et al., 2015). In addition to the effects of long-term climate change, internal variability due to natural processes, such as variations in atmospheric circulation arising from coupling with the ocean on seasonal or longer time scales, can also be a key driver of individual high-impact events. The winter flooding of 2013/14 is one recent example in which internal variability may have played an important role (Huntingford et al., 2014), while human-induced climate change also increased the risk of the circulation and moisture drivers of the event (Schaller et al., 2016). The run of wet summers from 2007 to 2012 may have been influenced by variability associated with the Atlantic Multidecadal Oscillation (AMO). This is a broad pattern of surface temperature anomalies that exhibits substantial variability on decadal time scales, and is capable of exerting a significant influence on several aspects of European climate (Sutton and Dong, 2012).

Globally, the main drivers of changes in sea level during the 20th century were ocean thermal expansion and mass loss from glaciers, with mass loss from the Greenland and Antarctic ice sheets also making a contribution to changes during the past two decades. Regionally, changes are additionally influenced by changes in ocean density and circulation, and by gravitational effects of mass redistribution due to melting land ice. Due to the combined influence of these effects, average UK sea level has risen at a best-estimate rate of 1.4mm/year since 1901, which is close to the estimated rate for global sea level. Locally, the UK is also influenced by continuing vertical movements of the land as a delayed response to the melting of ice sheets following the last ice age, with a general pattern of subsidence in the south of the UK and uplift in the north.

Future UK climate change

Status of UKCP09

The 2009 UK Climate Projections (UKCP09) provide the current set of standard land and marine scenarios available for assessment of future UK climate change. The centrepiece of the land scenarios is a set of probabilistic projections representing uncertainties due to internal climate variability and the modelling of earth system components, based on modelling technology available at the time of their development. The projections were constructed from perturbed

parameter ensemble (PPE)⁹ simulations using variants of a single climate model from the Met Office Hadley Centre, combined with results from a set of international models called CMIP3, and a set of observational measures of model performance.

The probabilistic projections were provided for alternative 'low', 'medium' and 'high' emissions pathways, corresponding to the IPCC SRES B1, A1B and A1FI scenarios respectively. These predate the RCPs discussed in section 1.2.1, and were used extensively in IPCC AR4. For a given probability level, the projected warming is larger for the high emissions scenario compared to the medium or low cases, particularly during the second half of the 21st century. However, there is considerable overlap between the distributions of change for each of the different emissions pathways, because uncertainties in modelling the climate response are large. For a given emissions scenario, uncertainties in long-term UK changes arise from a range of potential outcomes for global average temperature, and also from a range of potential regional patterns of change for any given level of global temperature rise.

Uncertainties in future response patterns must therefore be accounted for, when considering UK risks associated with specific global warming outcomes. As an example, UKCP09 includes estimates of plausible ranges of UK change for the period 2070 – 2099 relative to 1961-1990, derived from the medium emissions scenario for projections which give a global average warming by the end of the century of approximately 4°C relative to pre-industrial conditions. These projections showed that long-term global warming close to 4°C implies probability distributions of annual UK temperature changes ranging from 2 - 3°C at the low end (defined as the probability level which gives only a 10% chance of a lower outcome) to an upper limit (defined as the level giving a 90% chance of a lower outcome) of more than 6°C in much of southern England, or more than 5°C in most other UK regions. The corresponding winter rainfall response ranges from little change at the 10% probability level, to substantial increases of 20 - 70% at the 90% probability level, dependent on location. Table 1.3 shows that global warming of 4°C is within the *likely*⁷ range of UKCP09 projections for the RCP6.0 and RCP8.5 scenarios, which is also the case for the medium and high scenarios of UKCP09.

A comparison between UKCP09 and the newer CMIP5 multi-model simulations concluded that the advice from the two sources is generally consistent in terms of credibility and projected outcomes (Sexton et al., 2016). UKCP09 continues to provide a valid assessment of 21st century UK climate, and all its outputs can still be used for adaptation planning. However, CMIP5 results imply a smaller risk of substantial future reductions in summer rainfall for England and Wales, and should be considered alongside UKCP09 for decisions that are being made now and in the future that are sensitive to summer rainfall. The exact change in risk cannot be quantified for this CCRA, because UKCP09 has not yet been updated to include CMIP5 results. However, new probabilistic projections incorporating CMIP5 results are planned for the forthcoming updated scenarios, UKCP18.

New research (Sexton and Harris, 2015) allows the UKCP09 projections to be expressed for individual years rather than 30-year averages, to help understand how climate change and natural variability might combine to create seasonal anomalies from year to year. Doing so

⁹ A perturbed parameter ensemble is a collection of model simulations derived from a single climate model, in which ensemble members differ in the values of parameters controlling important earth system processes in the model.

allows recent extreme seasons to be placed in the context of projected long-term changes. These results show, for example, that the cold winter of 2009 – 2010 and wet summer of 2012 are consistent with UKCP09 results, despite long-term expectations of an increasing frequency of warmer winters and drier summers.

Sea surface temperatures in the North Atlantic have cooled recently, following an unusually warm period since the 1990s. Some recent decadal forecasts suggest further cooling during the next few years, while others predict a persistence of relatively cool conditions compared to the previous warm period, but not further cooling. Either outcome may increase the near-term likelihood of drier UK summers compared to the previous 20 years. However, uncertainties in decadal prediction are currently considerable, and the expected impact of these cooler sea surface temperatures on UK summer rainfall is modest compared with the range of plausible near-term outcomes given by the seasonal projections derived from UKCP09.

While the *predictability* of internal climate variability on annual to decadal time scales may currently be limited, such variability can exert a potentially significant impact on UK climate in any given decade, for example by driving variations in atmospheric circulation and storms that temporarily oppose or enhance trends in extremes and impacts expected from longer-term climate change. This modulating influence is likely to be particularly important from the 2020s to the 2050s, during which the magnitude of decadal variability is expected to be larger with respect to the human-induced response than during the second half of the 21st century (Hawkins and Sutton, 2009).

Projections of global mean sea level from IPCC AR5 span a wider range than those from the earlier IPCC fourth assessment that were used in the UKCP09 marine projections. For 2081 – 2100 relative to 1986 – 2005, the IPCC AR5 *likely* ranges were 0.26 - 0.55m (RCP2.6 emissions scenario), 0.32 - 0.63m (RCP 4.5), 0.33 - 0.63m (RCP6.0) and 0.45 - 0.82m (RCP8.5). Projected regional changes in sea level differ from the global mean due to regional variations in ocean density changes, changes in ocean circulation and the gravitational effects of melting land ice. The latest IPCC projections suggest the regional change around the UK is near to the global mean change, which was also the case in the projections reported in UKCP09. Locally, the UK will continue to experience vertical land movements, with a similar pattern to that experienced during recent decades.

In situ changes in shelf sea temperature, salinity and currents were considered in UKCP09 using a single future projection. Recent work has added an initial estimate of uncertainties to the UKCP09 projection (Tinker et al., 2016), by using some of the climate model variants deployed in the land scenarios to drive simulations using a single shelf seas model. Further work has assessed how confidence in the model projections depends on variables, regions and seasons of interest (Tinker et al., 2015). The new ensemble confirms the general trend of warming in the shelf seas projected in UKCP09, with deviations from rates of warming from further offshore. A sizeable freshening (reduction in salinity) is also projected in some areas.

Projections of future climate extremes

Table 1.4 shows projected changes in the values associated with one in 20-year events for daily summer maximum temperature and 5-day winter rainfall accumulations, an indicator of flood events caused by large-scale weather systems. These were derived from the UKCP09 probabilistic projections (Brown et al., 2014), and show plausible changes by 2041 – 2060

relative to 1961 – 1990 ranging from little change (at the 10% probability level) to increases of 4.4 - 6.4°C for summer hot days (at the 90% probability level), and 14 - 24% for winter 5-day rainfall accumulations (90% probability level).

Table 1.4: Values of 20 year return period events for daily maximum surface temperature in summer (June-August), and accumulated rainfall over five consecutive days in winter (December-February)

City	Daily summer max temperature (°C)				5-day winter rainfall accumulation (mm)			
	1961-1990 observed	2041-2060 Low	2041-2060 Central	2041-2060 High	1961-1990 Observed	2041-2060 Low	2041-2060 Central	2041-2060 High
London	34.4	34.1	37.2	40.6	56.1	57.8	62.5	68.3
Cardiff	31.7	31.9	34.7	38.1	73.6	76.6	79.8	83.6
Belfast	25.9	26.5	28.5	30.9	70.3	70.6	76.9	84.6
Edinburgh	23.5	24.8	26.2	27.9	63.4	63.5	70.0	78.4

Source: Brown et al. (2014).
Notes: The values represent observed and projected estimates for 25x25km² spatial averages, for locations on the UKCP09 grid (Murphy et al., 2009) containing national capitals. In order to derive observational estimates, the 5km gridded station dataset of Perry et al. (2009) was interpolated to the UKCP09 grid. The observed estimates for 1961-1990 are compared with values for the 10th (low), 50th (central) and 90th (high) percentiles of probabilistic projections for 2041-2060 under the A1B emissions scenario.

CMIP5 simulations suggest that events similar to the southern European heatwave of summer 2003 will become common by the 2040s, and would represent extremely cold summers by the 2090s under the RCP6.0 or 8.5 scenarios.

Kendon et al. (2014) report the first UK climate change simulation that represents the dynamics of large convective storms, covering Wales and central and southern England. They find substantial increases in the intensity of hourly summer rainfall extremes, while future multi-year average summer rainfall reduces in line with UKCP09. Further kilometre-scale simulations using a range of models will be needed in the future, to assess uncertainties in projected changes in sub-daily rainfall.

Current evidence suggests that storm surges will not show large and significant changes in the future, but that extreme water levels will increase because the surges would occur on a higher average sea level (see above).

It is virtually certain that sea level rise will continue beyond 2100 (IPCC, 2013), to an extent which depends significantly on whether temperatures remain high enough and for long enough to cause an irreversible melting of the Greenland and West Antarctic ice sheets. By 2300, sea level rise relative to pre-industrial conditions may remain below 1m for peak-and-decline emissions scenarios similar to RCP2.6. For scenarios such as RCP8.5 in which radiative forcing at 2100

reaches levels corresponding to CO₂ concentrations between 700 and 1,500 parts per million, the projected sea level rise ranges from 1m to more than 3m by 2300. Beyond 2100 the forcing scenarios follow a range of pathways, and in the case of RCP8.5 the forcing during the 22nd century rises to a level corresponding to CO₂ concentrations above 1500 ppm.

This CCRA also includes an H++ scenario concept to represent low likelihood, high end outcomes that cannot be ruled out based on current understanding. In general, H++ scenarios can consist of both quantitative information derived from climate models, and qualitative narrative derived from theoretical insight, understanding of processes missing from models, and/or past observations. The scenarios are of low but unspecified probability, and are useful for thinking about the limits of different adaptation strategies or contingency planning. For sea level rise, the existing H++ scenario included in UKCP09 remains in use. This gives an upper limit of around 1.9 metres for sea level rise by 2100. Met Office (2015) for the ASC provides new H++ scenarios for aspects of UK terrestrial climate. It suggests that by the end of the 21st century, the UK could plausibly see heatwaves of 50 days duration with a mean temperature of almost 40°C and increasingly intense summer droughts with rainfall 60% below average. These droughts could be accompanied by severe reductions of up to 70% in 'Q95', an index of low river flow defining a level exceeded 95% of the time. Winter rainfall could increase by up to 100%, suggesting that winters like 2013/14, with 70% more than average rainfall, could conceivably be exceeded in most years by the 2080s. Daily intense rainfall could also increase in both summer and winter, with a possible increase of 60 to 80% compared to current intense rainfall events. As a result of this increased rainfall, peak river flows could be up to three times higher than they are now, by the 2080s. The H++ outcomes above are not designed to be linked to any specific future emissions scenario or level of global temperature rise, however most of them lie near or above the upper end of the range of outcomes in the UKCP09 high scenario. On the other hand, the UK is already at risk from what is considered to be a worst-case wildfire, but climate change increases the probability of such a fire occurring in the future. This H++ information should be considered alongside mainstream estimates of the likely range of future outcomes, such as those provided by UKCP09 or CMIP5.

Abrupt or irreversible changes in the climate

The IPCC AR5 assessed several unlikely but plausible climate surprises that would cause substantial disruption if they occurred, and are potentially abrupt (could take place over a few decades or less) or irreversible (natural recovery time would be significantly longer than the time taken to reach the perturbed state). These hypothetical events could impact the UK either via their effects on global aspects of climate change, or via remote effects on regional patterns of change. Annex 1.A provides more specific details on these changes.

During the 21st century, a near-complete collapse of the Greenland or Antarctic ice sheets is assessed as exceptionally unlikely. A substantial methane release from ocean sediments, or a collapse of the Atlantic meridional overturning circulation (AMOC), are both assessed as very unlikely. There is low confidence in projections of the collapse of large areas of tropical forest, though the possibility cannot currently be ruled out. Some degree of carbon release due to thawing permafrost can be expected, though the magnitude is highly uncertain.

Projections derived from existing climate models, such as UKCP09 and CMIP5, do not include the processes necessary to simulate changes in ice sheets, methane release from the oceans or permafrost carbon release. Many (though not all) of the processes influencing the AMOC are

included in current models, but they project steady rather than abrupt weakening in its future strength. A total loss of summer Arctic sea-ice by the mid-21st century is assessed as likely in AR5. Current model-based scenarios include most of the key processes driving future sea-ice changes, however the response of the atmospheric circulation and the effects on the UK remain uncertain. The UKCP09 H++ scenario for sea level assumes a dominant contribution from partial melting of the Greenland ice sheet, based on palaeoclimatic evidence.

Met Office (2015) for the ASC report that a hypothetical but very unlikely collapse of the AMOC could lead to a UK winter cooling of 4 - 5°C. This is outside the UKCP09 range, because none of the climate model simulations used in UKCP09 simulated a complete collapse of the AMOC.

In summary, the changes that have been seen in the UK climate over the past few decades, including an increase in average temperature, the number of hot days, heavy rainfall events and sea level rise, are consistent with the expected effects of global warming. Natural climate variability remains a key driver of individual extreme events in the UK, however attribution studies suggest that human influence significantly increased the risk of several recent events, including seasonal flooding or heatwave episodes and a record high in annual CET in 2014. The current projections of future climate for the UK reflect considerable uncertainty, but the likelihood is that average annual temperature and average winter rainfall will continue to increase over the next few decades, and that the risk of extremely hot summers and wet winters will also gradually rise. Sea levels around the UK will also continue to rise well beyond 2100, regardless of the level of climate change mitigation.

Annex 1.A: Observed and future climate for the UK

1.A1 IPCC Fifth Assessment Report

The IPCC Fifth Assessment Report (AR5) has been published since the first CCRA, drawing together new evidence from observations, theory, attribution studies and model projections.

Working Group I (IPCC, 2013) concluded that warming of the climate system is unequivocal. The globally averaged surface and ocean temperature, for land and ocean combined, increased by 0.85°C (90% uncertainty¹⁰ interval 0.65 to 1.06°C) from 1880 to 2012, and 2013 and 2014 were both amongst the warmest 10 years on record. Global sea level increased by 0.19 (0.17 to 0.21) metres between 1901 and 2010. During recent decades, global average temperature and specific humidity has increased in the troposphere, ocean heat content has increased, the extent of northern hemisphere snow cover and Arctic sea-ice has declined, and the mass of worldwide glaciers and the Greenland ice sheet has reduced (IPCC, 2013; Blunden and Arndt, 2014). Atmospheric concentrations of the greenhouse gases carbon dioxide (CO₂), methane and nitrous oxide have increased to levels unprecedented during at least the past 800,000 years. This has driven a positive anthropogenic radiative forcing¹¹ of the climate system since the industrial revolution, partially offset by a net cooling due to the effects of atmospheric aerosols, the magnitude of which is subject to considerable uncertainty.

Human influence is detected in warming of the atmosphere and ocean (*very likely*), changes in the global water cycle (*likely*), reductions in Arctic sea-ice cover (*very likely*) and northern hemisphere spring snow cover (*likely*), worldwide glacier retreat (*very high confidence*), global average sea level rise (*very likely, with high confidence*), and in some climate extremes. It is *extremely likely* that more than half of the observed increase in global average surface temperature since the mid-20th century was caused by anthropogenic forcing, and very likely that human activity has contributed to global scale changes in daily temperature extremes.¹²

The IPCC AR5 also reported results from new climate and earth system models provided by CMIP5, the Coupled Model Intercomparison Project Phase 5. CMIP5 included more than twice as many models as its predecessor (CMIP3), reported in the previous IPCC Fourth Assessment Report (AR4). CMIP5 models feature a more comprehensive treatment of forcing agents, particularly with respect to aerosols and land use change. CMIP5 projections were driven by four new Representative Concentration Pathways (RCPs), designed to achieve different targets for

¹⁰ Uncertainties in AR5 were assessed both quantitatively, using likelihood statements based on probability ranges derived from statistical analysis and expert judgement, and qualitatively, using confidence statements based on the robustness of the evidence (from theory and mechanistic understanding as well as from data and models), and the degree of agreement. For example, very likely corresponds to a probability exceeding 90%, and high confidence to robust evidence accompanied by high agreement.

¹¹ Radiative forcing measures the net change in the energy balance of the Earth system in response to a change in an external driver of climate change, such as an increase in the concentration of carbon dioxide. It is measured in AR5 as the downward minus upward change in radiative flux at the tropopause, after allowing stratospheric temperatures to adjust, while holding other state variables (e.g. tropospheric temperature, moisture and cloud cover) fixed at their unperturbed values. Radiative forcing is measured in watts per square metre (Wm⁻²), a positive value implying heating of the Earth system.

¹² See IPCC AR5 for full definitions of likelihood and confidence.

radiative forcing by 2100 relative to pre-industrial conditions (2.6, 4.5, 6.0. and 8.5 Wm⁻²). The RCPs represent a range of future climate policies, in contrast to the non-intervention IPCC Special Report on Emissions (SRES) scenarios used previously. In common with SRES, RCPs are not provided with attached probabilities.

CMIP5 provided long term climate simulations from 1860-2100 (in some cases extended to 2300), driven by: (a) *prescribed CO₂ concentrations*, allowing assessment of uncertainties in physical processes in determining the response to specific future CO₂ pathways; (b) *carbon emissions*, in which uncertainty in future CO₂ due to climate-carbon cycle interactions is also considered.

The latest scientific evidence relating specifically to UK climate is summarised below, focusing on key aspects of observations, future projections and current understanding based on IPCC AR5 and more recent developments.

1.A2 Observed UK climate

The latest data and understanding on observed UK climate is summarised below, updating selected aspects of the UK Trends report of Jenkins et al. (2008) with more recent observations, including material from the Met Office's 'State of the UK Climate 2014' report (Kendon et al., 2015a).

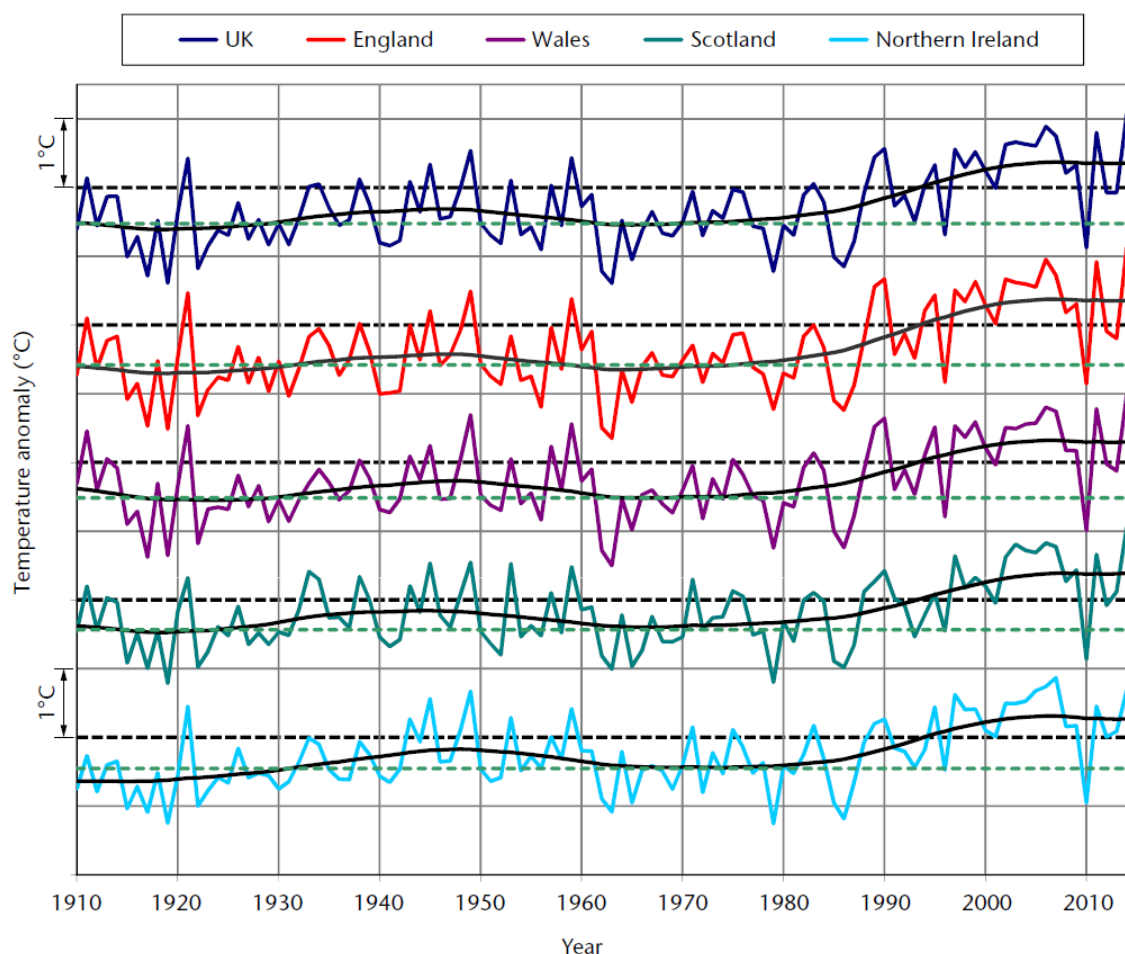
Mean temperature and rainfall trends

Annual average UK land temperature in the decade 2005 - 2014 was 0.9°C warmer than 1961-1990 (Kendon et al., 2015a), with 2014 being the warmest individual year. All of the top ten warmest years in the UK average temperature series have occurred since 1990, and the eight warmest years have all occurred since 2002 (ibid.).

National changes (Figure 1.A1) are similar to the UK average in England, Wales and Scotland, and slightly smaller in Northern Ireland (about 0.7°C). The bulk of the UK warming occurred between about 1970 and 2005, while the time series also shows the substantial influence of internal climate variability¹³ on annual to multi-decadal time scales.

¹³ Internal climate variability is used in this report to denote variations around the long-term average climate on spatial and temporal scales beyond those of individual weather events, and caused by natural processes rather than variations caused by natural or man-made changes in radiative forcing.

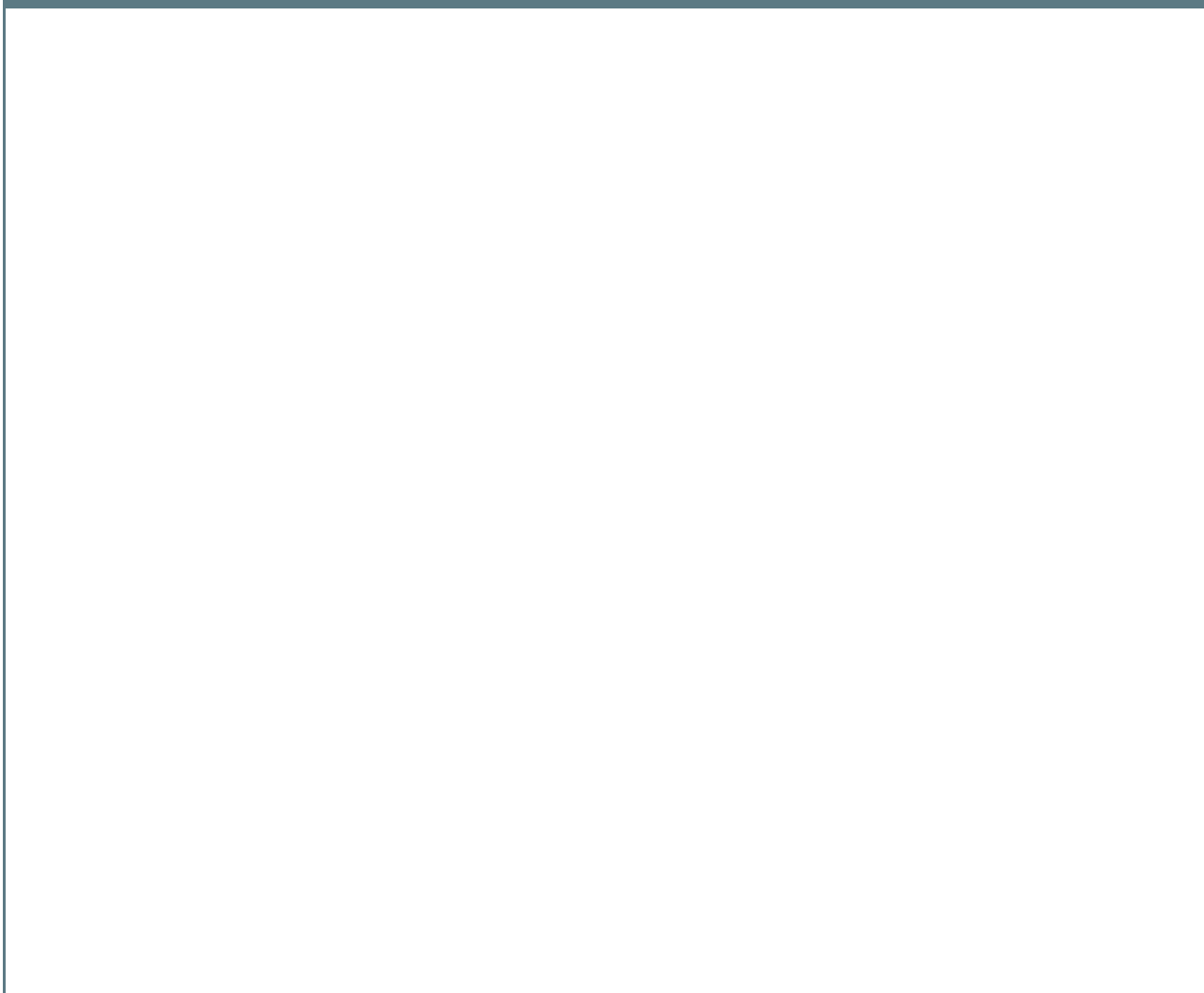
Figure 1.A1: Annual average temperature for the UK and its constituent countries, 1910 to 2014, expressed as anomalies relative to the 1981-2010 average.



Notes: The hatched black line is the 1981-2010 long-term average. The lower hatched green line is the 1961-1990 long-term average. Light grey grid-lines represent anomalies of +/- 1 °C.

Karoly and Stott (2006) demonstrated a significant human influence on the observed warming in the annual average value of Central England Temperature (CET) since 1950. During 1965-1995, a positive trend in the North Atlantic Oscillation (NAO), the dominant mode of winter climate variability for the North Atlantic and Western Europe, may also have contributed to the warming in winter (Scaife et al., 2005). The UK mean temperature in 2014 was 9.9°C, the warmest in the record back to 1910 (Kendon et al., 2015a). The CET value was also marginally above the previous highest value, in a longer record dating back to 1659 (Ibid).

Figure 1.A2: Annual rainfall totals from 1910-2014 expressed as a percentage of the 1981-2010 average



Notes: The dashed black line is the 1981-2010 long-term average. The lower dashed green line is the 1961-1990 long-term average. Light grey grid-lines represent anomalies of +/- 10%. Here, 'rainfall' is used to denote the sum of rain and frozen precipitation.

Annual rainfall over Scotland has increased since about 1970 (Figure 1.A2), to a level about 13% above the average for the early decades of the 20th century. All seasons contribute to the increase. Smaller increases in recent decades are observed for annual averages over Northern Ireland and England-Wales (Figure 1.A2), but there is no evidence of an overall change during the past century.

Although future global warming levels are often expressed relative to a pre-industrial baseline (for example, this is done in CCRA2 to benchmark evidence, as well as in the Copenhagen

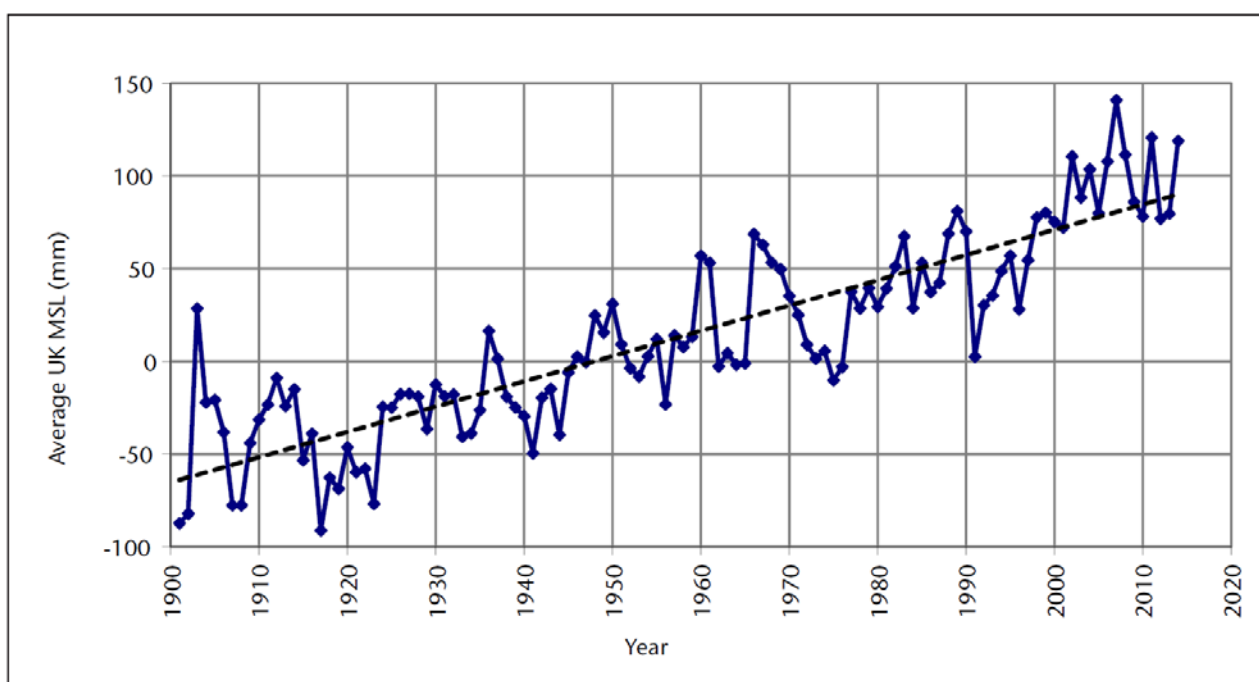
Accord¹⁴ on emissions targets), other baselines are often used in impacts assessments and adaptation planning. For example, the UKCP09 national climate scenarios were provided as changes relative to a baseline of 1961-90, in order to provide continuity with previous scenarios. In some applications, however, it may be preferable to use a more contemporary baseline, such as 1981-2010, in order to place future changes in the context of the most recent experience. It is therefore useful to be aware of how observed climate has changed between alternative baselines that might be used in adaptation studies. At the national scale, for example, observed changes in annual mean temperature, for 1981-2010 relative to 1961-90, amount to 0.58°C (England), 0.44°C (Scotland), 0.51°C (Wales), and 0.46°C (Northern Ireland). Annual rainfall for Scotland increased by 6.7% from 1961-90 to 1981-2010, whereas increases were smaller for England, Wales and Northern Ireland (3.2, 4.3 and 3.4% respectively). Changes vary with season and specific location for rainfall, temperature and other variables (see <http://www.metoffice.gov.uk/public/weather/climate>).

Sea level

Sea level changes are monitored by the UK national network of tide gauges. These capture both changes relative to the Earth's crust driven by the atmosphere and ocean, and also changes due to vertical movements in the land, which the UK continues to experience with a general pattern of subsidence in the south and uplift in the north (Shennan et al., 2009). Tide gauge trends since 1901 range from 0.8 mm/yr at Newlyn to 1.8 mm/yr at Lowestoft. A UK sea level index, computed using data from five stations (Aberdeen, North Shields, Sheerness, Newlyn and Liverpool), is shown in Figure 1.A3. This provides a national-scale best estimate of 1.4 ± 0.2 mm/yr for sea level rise since 1901 (Woodworth et al., 2009), corrected for vertical land movement. This is close to the estimate of 1.7 ± 0.2 mm/yr for global sea level rise suggested by AR5 (Church et al., 2013). In addition to a long term trend, UK sea level shows natural variability on a range of time scales.

¹⁴ <http://unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf#page=4>

Figure 1.A3: A UK sea-level index for the period since 1901, computed using sea-level data from Aberdeen, North Shields, Sheerness, Newlyn and Liverpool



Source: Woodworth et al. (2009).

Notes: UK sea level index for the period since 1901 computed from sea level data from five stations (Aberdeen, North Shields, Sheerness, Newlyn and Liverpool). The linear trend line has a gradient of 1.4mm/year.

The tide gauge network does not support construction of a UK index of sea-level extremes, which are primarily caused by storm surges. However, Haigh et al. (2010) found that extreme sea levels have increased during the past century in the English Channel, based on multidecadal data from 18 gauges. For the period 1916 - 2014, hourly data from Newlyn (P. Woodworth, pers. comm.) reveals a long-term trend of 2.0 mm/year in high waters (defined annually as the 99th percentile of hourly values), compared to trends of 1.8 mm/year in median sea level and 1.6 mm/year in extreme low waters (1st percentile of hourly values). More generally, Menéndez and Woodworth (2010) show that coastal extreme water levels worldwide have increased in line with changes in mean sea level since 1970, at most locations.

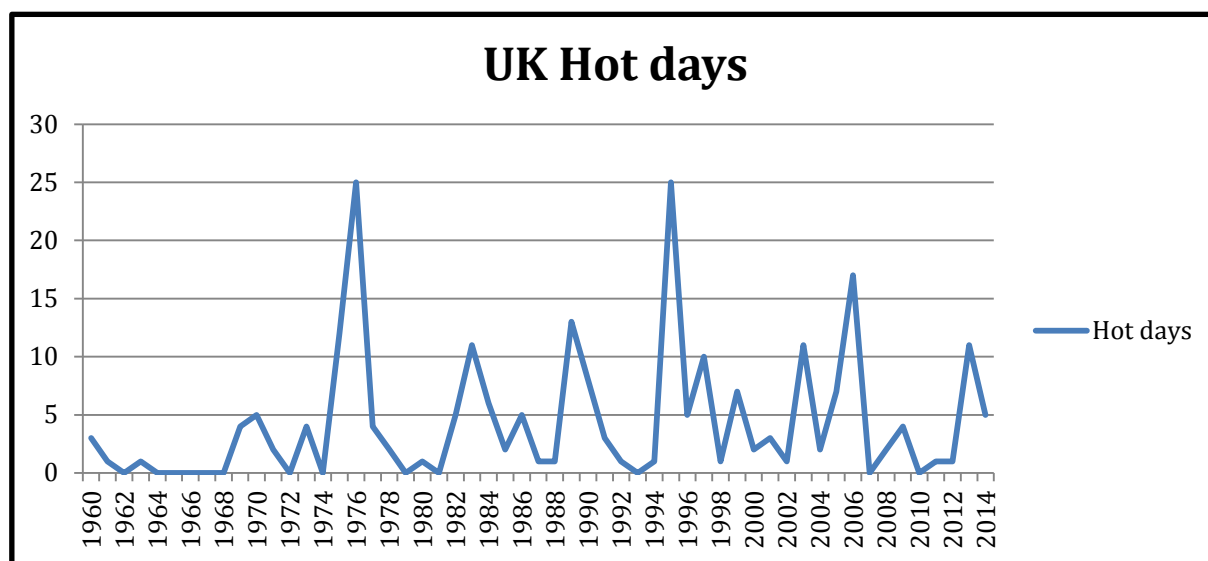
Extreme events

Alexander et al. (2005) found an increasing trend in the number of severe autumn and winter wind storms between the 1950s and 2003, although a downturn since the early 1990s was also apparent for January-March. Storminess in recent decades is not unusual in the context of longer records for north-west Europe, which showed similar levels in the early 20th century (Matulla et al., 2008).

Figure 1.A4 shows annual variations since 1960 in a measure of hot days, provided as a typical illustration of variability and change in UK extremes during the recent historical record. The indicator is defined as the total number of days on which the UK average daily maximum

temperature exceeded 23.6°C in a calendar year. This threshold represents the 99th percentile of values observed between 1961 and 1990. This indicator reflects national-scale climate extremes rather than localised high-impact weather events. For example, although 2003 saw the highest ever recorded temperature in the UK (38.5°C at Faversham), other years, such as 1976 and 1995, rank more highly in the metric of Figure 1.A4, because they both saw a UK mean temperature above 23.6°C over sustained periods of the summer, amounting to nearly a month in total.

Figure 1.A4: No. of UK hot days per year between 1960 - 2014

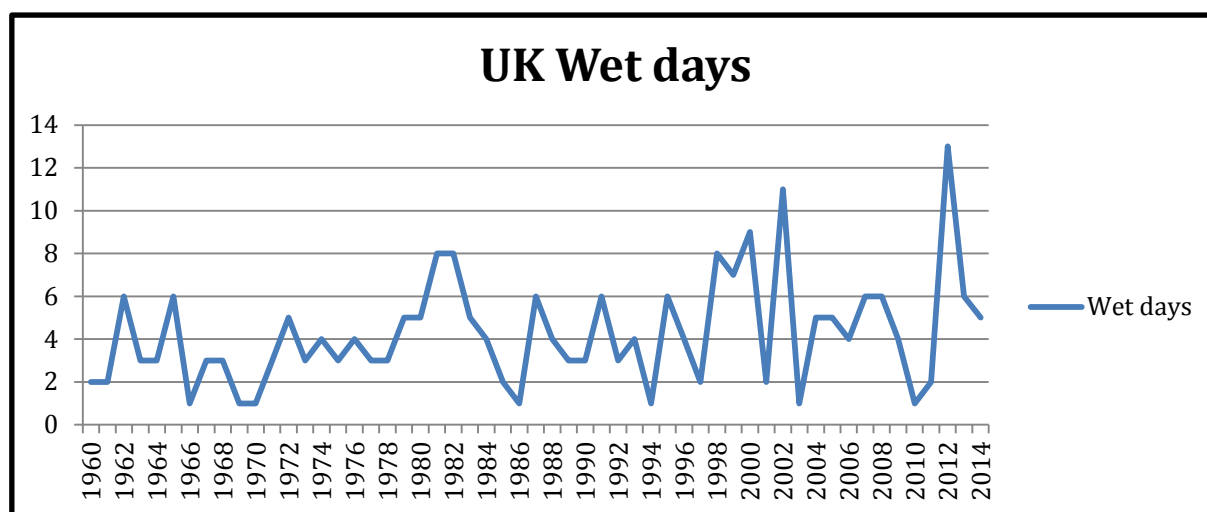


Source: Calculated using daily gridded observed maximum temperature data (Perry et al., 2009), available from <http://www.metoffice.gov.uk/climatechange/science/monitoring/ukcp09/>.

Notes: “Hot days” is defined here as the total number of days on which the UK average daily maximum temperature exceeded 23.6°C in a calendar year. This threshold represents the 99th percentile of values observed between 1961 and 1990. During this period, this threshold is exceeded, on average, on 3.65 days per year. During later periods, the average frequency of exceedance can change, dependent on the effects of climate variability and change relative to 1961-90.

Corresponding results for rainfall are shown in Figure 1.A5, in which extreme rainfall is defined as the annual count of days on which the UK average exceeds 13.6 mm, the 99th percentile of values during 1961-1990. The highest count of 13 days occurred in 2012, which saw record total annual rainfall in England (since 1910), and a particularly wet summer in which total UK rainfall exceeded 150% of the 1981-2010 average. However, the metric of Figure 1.A5 does not reflect so strongly the winter floods of 2013/14. This is partly because the event straddled two calendar years. In addition, the floods arose from persistently wet weather, rather than individual exceptional daily rainfall events.

Figure 1.A5: Number of UK wet days per year between 1960 - 2014



Source: (Redrawn from Figure 27 of Kendon et al., 2015a).

Notes: "Wet days" here is defined as the annual count of days on which the UK average exceeds 13.6 mm, the 99th percentile of values during 1961-1990.

Based on Figures 1.A4 and 1.A5, the average count during 1981-2010 was 4.63 for both UK hot days and UK wet days, compared with 3.65 for 1961-90. Statistical results from extreme value analysis suggest that the UK daily maximum and minimum temperature extremes have increased by just over 1°C since the 1950s (Brown et al., 2008), and that heavy seasonal and annual rainfall events have also increased (Jones et al., 2013). Kendon (2014) assessed record-breaking months, seasons and years at national and district levels since 1910, finding that the period since 2000 accounts for two-thirds of high temperature records and 45% of rainfall records, based on a weighted score accounting for area and duration.

Watts et al. (2015) reviewed observations of the UK water environment, finding evidence of:

- More winter rainfall falling as intense events during the last 30 years,
- Increases in winter runoff and high river flows during the last 40 years,
- Increases in river water temperatures over recent decades.

In all cases, *medium confidence* was ascribed to these results, and insufficient evidence to date has been found to link the observed changes to anthropogenic climate change.

Nevertheless, many of the observed changes described above are qualitatively consistent with expectations of a warmer and moister atmosphere under anthropogenic climate change. At the global scale, AR5 assessed it *very likely* that anthropogenic forcing had contributed to observed changes in temperature extremes since the middle of the 20th century. *Medium confidence* was assigned to a human contribution to a global-scale intensification of heavy rainfall, during the same period. At the UK scale, detection and attribution of extremes is challenging (e.g. Fowler and Wilby, 2010), being complicated by the greater role played by internal climate variability, the greater range of radiative forcing components that may be important and the challenges of representing the key driving processes realistically in climate models.

While individual observed events cannot be ascribed unambiguously to human influence, the change in odds can be estimated from climate model simulations, using the concept of fraction of attributable risk (FAR – Allen, 2003). Pall et al. (2011) concluded that anthropogenic forcing had *very likely* increased by at least 20% the risk of the floods that occurred in England and Wales in autumn 2000. Stott et al. (2004) found that human influence had at least doubled the risk of the European summer heatwave of 2003. In the region bounded by 10°E -40°W, 30°-50°N, containing most of the areas worst affected by the heatwave, average summer land temperature increased by 0.81°C between the decades 1990-1999 and 2003-2012. Christidis et al. (2014) found that this increase has reduced the return time for a similar heatwave from thousands of years to around a hundred years, based on attribution analysis of CMIP5 simulations. Also using CMIP5 simulations, King et al. (2015) concluded with 90% confidence that human influence had increased the likelihood of the record CET in 2014 by a factor of at least 13.

High-impact seasonal events and their drivers

The UK has recently seen several examples of monthly or seasonal climate events leading to significant impacts and disruption. The winter floods of 2013/14 were associated with the positive phase of the NAO, bringing a rapid succession of Atlantic low pressure systems into much of the UK. Huntingford et al. (2014) suggest that unusually heavy rainfall in Indonesia and the tropical west Pacific may have been partly responsible for the event, by forcing downstream strengthening of the North Atlantic jet stream via large-scale dynamical mechanisms. Schaller et al. (2016) ran a large ensemble of simulations of winter 2013-14 with and without anthropogenic effects on greenhouse gas concentrations, sea surface temperature and sea-ice extents. They found that human influence increased the risk of enhanced westerly flow and atmospheric moisture content, both of which increased the risk of extreme rainfall over southern England and 30-day peak flows in the River Thames. In contrast, the cold December of 2010 and March of 2013 were both associated with the negative phase of the NAO, bringing easterly winds to the UK, accompanied by a southward shift in the North Atlantic storm track. Maidens et al. (2013) identified cold sea surface temperatures (SSTs) in the North Atlantic as a key driver of the December 2010 event.

More generally, North Atlantic SSTs have been unusually warm since the 1990s. This reflects the positive phase of the Atlantic multidecadal oscillation (AMO), a pattern of northern hemisphere temperature anomalies centred on the North Atlantic that varies on time scales of a few decades (Knight et al., 2006). The AMO influences various aspects of European climate (Sutton and Dong, 2012), and may have played a role in driving the run of wet UK summers observed between 2007 and 2012. Observational and modelling evidence suggests that AMO-like variability can occur in the absence of externally-forced climate change, associated with variations in the AMOC (Delworth and Mann, 2000). However, anthropogenic aerosol emissions may also have influenced AMO variability during the 20th century, through their effects on solar heating of the ocean surface (Booth et al., 2012). The extent of potential human influence on recent variations in the AMO is a subject of current research.

Arctic sea-ice extent has continued to decline since 1979 (Stocker et al., 2013, using a data series to 2012). The most rapid reductions have occurred in summer and autumn, with the summer minimum extent dropping by about 11% per decade during this period. Francis and Vavrus (2012) suggest that the resulting reduction in poleward temperature gradient may lead to weaker average westerly winds in winter, potentially favouring the negative phase of the NAO.

Coumou et al. (2015) suggest a similar potential influence in summer, citing an observed reduction in the energy of eastward-travelling weather systems during recent decades. However, Screen et al. (2013) found only weak evidence of an impact on the NAO in winter, in climate model simulations assessing the influence of recent changes in sea-ice cover relative to that of internal variability. The influence of Arctic sea-ice on the atmospheric circulation is a topic of active debate (Gramling, 2015). Development of a consensus will require improved understanding of impacts on the Atlantic jet stream (Wallace et al., 2014), including meanders associated with large-amplitude planetary waves that are an important driver of monthly climate extremes in the northern hemisphere (Screen and Simmonds, 2014).

1.A3 Future UK climate change

This section assesses information on projected UK climate change available to inform the second CCRA.

The most recent national projections of climate change are provided through the 2009 UK Climate Projections, UKCP09. The UKCP09 land scenarios (Murphy et al., 2009) took the form of probabilistic projections representing uncertainties due to internal climate variability and the modelling of key Earth system processes. They were constructed from several ensembles of variants of a single climate model (HadCM3), designed to represent modelling uncertainties by perturbing model parameters within expert-specified ranges. These were combined with results from the CMIP3 ensemble of international climate models and a set of observational metrics of historical model performance (Sexton et al., 2012; Harris et al., 2013).

Flato et al. (2013) evaluated CMIP5 climate models, finding a general improvement compared to CMIP3. Areas of progress included better simulation of surface temperature at regional scales and rainfall at large (continental to global) scales, although rainfall at regional scales is simulated less well than at larger scales. There was also improvement in the simulation of rainfall extremes, partly because of a shift towards higher horizontal resolution in CMIP5 models. For particular climate variables of interest, there is typically a wide spread of performance between the CMIP3 and CMIP5 models, with considerable overlap between the two ensembles. Both ensembles exhibit a number of common systematic errors: the simulation of clouds remains a challenge, for example, despite the modest improvements found in CMIP5.

Sexton et al. (2016) evaluated UKCP09 in the light of CMIP5 results, in terms of both historical performance and projected changes. The historical evaluation focused on a perturbed parameter ensemble (PPE) of 17 coupled ocean-atmosphere variants of HadCM3 (Collins et al., 2011), a core modelling component of UKCP09. The PPE was found to be competitive with CMIP5 in its simulation of worldwide climate averages, across a range of standard model assessment variables. This reflected the status of HadCM3 as one of the best performing of the CMIP3 models.

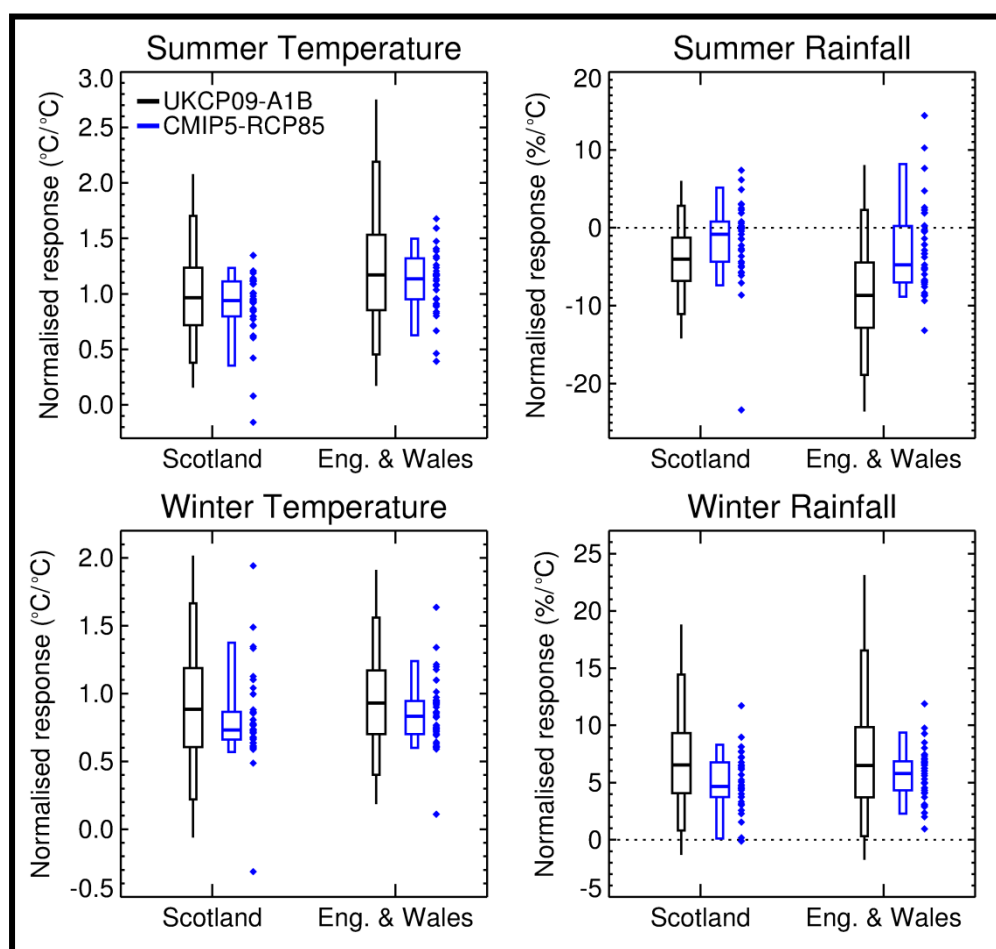
Several key drivers of UK climate variability were also considered. The PPE simulated the winter and summer NAO with skill comparable to CMIP5, although the AMOC is too weak in HadCM3, with some CMIP5 models giving better simulations of the observed overturning circulation. Despite some improvements relative to CMIP3 and the PPE, CMIP5 models show qualitatively similar systematic biases in sub-seasonal climate variability in winter. Too many storms pass over the UK in most models, as a consequence of a southward displacement error in the North Atlantic storm track, and the frequency of blocking anticyclones (often associated with cold spells in UK winters) is typically still underestimated.

Based on comparisons of distributions of equilibrium climate sensitivity (ECS),¹⁵ the range of long-term global temperature responses to anthropogenic forcing in CMIP5 was found to be consistent with UKCP09. Regional patterns of change were compared by considering projected UK changes *per degree of global temperature rise*, referred to in Figure 1.A6 below as ‘normalised response’. In Figure 1.A6, UKCP09 normalised projections for the A1B emissions scenario are compared against CMIP5 results from the RCP8.5 scenario, because CMIP5 did not include projections for SRES scenarios. However, Murphy et al. (2014) found that ranges of normalised response were similar (though not identical) in a recent PPE of simulations of HadCM3-based model variants for A1B and RCP8.5 emissions. This suggests that any substantial differences between UKCP09 and CMIP5 results in Figure 1.A6 are more likely to be due to the use of different sets of climate models. In practice, for winter changes in surface temperature and rainfall, no major differences were found between the UKCP09 probabilistic projections and the ensemble of changes simulated by CMIP5 models.

The climate models forming the basis of UKCP09 and CMIP3 share poor vertical resolution of the stratosphere, and, therefore, do not account well for dynamic coupling between the stratosphere and the troposphere. Scaife et al. (2012) examined the impact of improving and extending the representation of the middle atmosphere in a multi-model ensemble, analysing the detailed impact on European surface climate in two of the models. These showed a southward shift in the future change in the North Atlantic storm track and a larger increase in UK winter rainfall. Karpechko and Manzini (2012) also found a southward shift in the storm track response, but a drier response in UK winter rainfall. CMIP5 included several models with enhanced stratospheric resolution; however Sexton et al. (2016) found no evidence of a systematic shift in the UK winter rainfall response, compared with CMIP5 models lacking a well-resolved stratosphere. Changes in average near-surface wind speed from CMIP5 models revealed no clear signals for increases or reductions, also consistent with the UKCP09 advice (Sexton and Murphy, 2010). Nevertheless, stratosphere-troposphere interactions are a potentially significant driver of winter changes for the North Atlantic and Europe that should be accounted for in future generations of UK climate projections.

¹⁵ ECS is defined as the equilibrium (steady state) response of globally and annually averaged surface temperature to a doubling of CO₂ concentration in the atmosphere. It is a standard benchmark measuring the long term sensitivity of a climate model, or of the real climate system, to a sustained change in greenhouse gas concentrations.

Figure 1.A6: Future changes in winter and summer surface temperature and rainfall, per degree of global mean warming



Source: G. Harris (Met Office), following methodology of Sexton et al. (2016).

Notes: Probabilistic projections of this normalised response from UKCP09 in black. Lines, boxes and whiskers show the 1, 5, 25, 50, 75, 95 and 99% probability levels of normalised change, derived from statistical regression of projected changes relative to a 1961-1990 baseline under the A1B emissions scenario. Blue diamonds show changes from individual CMIP5 models, taken from the RCP8.5 scenario. Blue boxes and whiskers show 5th, 25th, 50th, 75th and 95th percentiles of the CMIP5 (non-probabilistic) distribution of changes, obtained by ranking and interpolation of the modelled outcomes. Results are shown for grid points of the HadCM3 global climate model corresponding approximately to England and Wales, and Scotland. It is not possible to show results for N Ireland, because there is no sufficiently co-located HadCM3 land point. CMIP5 is judged to show acceptable correspondence with UKCP09 where: (a) the 5th-95th percentile ranges of CMIP5 lie close to or within their UKCP09 counterparts and (b) several CMIP5 simulations support outcomes both above and below the UKCP09 central estimate.

For summer changes, Figure 1.A6 again shows reasonable consistency between UKCP09 and CMIP5, with the exception of rainfall over England and Wales. In this case, UKCP09 and CMIP5 agree to the extent that projected reductions are more likely than increases in the future. However, CMIP5 suggests smaller reductions, and contains few simulations simulating a drying beyond the 50% probability level given by UKCP09 for England or Wales. While CMIP5

simulations represent the latest available modelling advice, their results should not be interpreted quantitatively in terms of risk, because:

- The set of simulations was assembled on an opportunistic basis, and does not provide a systematic sample of possible climate models (e.g. Knutti et al., 2010).
- The CMIP5 results are typically provided (including in Figure 1.A6) on a simple 'one model one vote' basis, and do not account for variations in model quality.
- The ensemble is not screened to account for the sharing of components (and hence errors) between different models contributed to the CMIP5 archive (Masson and Knutti, 2011). Therefore, the ensemble cannot be treated as a set of fully independent outcomes (Pennell and Reichler, 2011).

In Figure 1.A6, for example, the CMIP5 models giving the largest increases in summer rainfall over England and Wales are two variants of one particular CMIP5 earth system model. In addition to being closely related, McSweeney et al. (2015) suggest that these two simulations are not suitable for use in regional downscaling, due to significant biases in their simulations over Europe and other regions.

In summary, Sexton et al. (2016) conclude that UKCP09 continues to provide a valid assessment of future UK climate, and all its outputs can still be used for adaptation planning. However, for decisions that are sensitive to future changes in summer rainfall, CMIP5 results should be considered alongside UKCP09. In particular, CMIP5 results imply a smaller risk of substantial future reductions in summer rainfall for England and Wales. The change in risk cannot be quantified for the second CCRA, because UKCP09 has not yet been updated to include CMIP5 results. However, new probabilistic projections incorporating CMIP5 results are planned for the forthcoming updated scenarios, UKCP18.

Scenarios and uncertainties

The UKCP09 projections were provided for alternative 'low', 'medium' and 'high' emissions pathways, corresponding to the SRES B1, A1B and A1FI scenarios respectively. Figure 1.A7 sets these in the context of the RCP scenarios, comparing projected future changes in global mean surface temperature (GMST) based on the central estimate (median) of probabilistic projections obtained using the UKCP09 method. Projections for each RCP scenario were obtained by driving the simple climate model of Harris et al. (2013) using the relevant future pathway of carbon emissions and aerosol forcing, and using the methods of UKCP09 to sample uncertainties in physical and carbon cycle drivers of past and future GMST change, and constrain the projections using observations of present day climate and historical patterns of GMST change. The changes are presented relative to a pre-industrial baseline of 1860-1899, rather than the UKCP09 baseline of 1961-1990, to allow the results to be related to global warming targets. While the central estimates show increasing divergence beyond 2050, substantial overlap remains between the broad ranges of change projected for alternative scenarios (shown in Figure 1.A7 for 2080 – 2099). Therefore, it is not possible to associate a single level of long-term GMST rise with a specific emissions pathway. Similarly, there is uncertainty in the timing of exceedance of any specific warming threshold because of uncertainties in both future emissions and climate model response (Joshi et al., 2011). However, uncertainties can be expressed using likelihood statements, conditional on the methodology used to provide the projections. In assessing GMST uncertainties derived from climate models, AR5 adjusts its quantitative language scale to

interpret 5-95% ranges as *likely* rather than *very likely*, to account for limitations in the confidence attached to the model results. We follow the same approach in Figure 1.A7 (though not in other parts of this report), interpreting 5-95% probabilistic ranges from the UKCP09 method as *likely*. On this basis, the projections of Figure 1.A7 suggest that warming by 2081-2100 is *likely* to lie in the range 1.4-3.2°C under RCP2.6, the scenario implying the highest degree of greenhouse gas mitigation, whereas for the highest emissions scenarios (A1FI and RCP8.5), the corresponding ranges are 3.3 - 6.1°C and 3.4 - 6.2°C, respectively. The central estimates of warming for 2081-2100 are well above 2°C for all scenarios apart from RCP2.6, for which the value is 2.3°C.

For the RCPs, AR5 gives GMST changes for 2080-2099 relative to 1986-2005, derived from CMIP5 models (Stocker et al., 2013). When re-based relative to this more contemporary baseline, the corresponding UKCP09 changes are somewhat larger than those of AR5. For RCP2.6, the UKCP09 central estimate of warming for 2080-2099 relative to 1986-2005 is 1.6°C, compared to an average warming of 1.0°C from CMIP5 models. The corresponding changes are 2.4°C (UKCP09) and 1.8°C (AR5) for RCP4.5, and 4.1°C (UKCP09) and 3.7°C (AR5) for RCP8.5. These differences result from the combined effects of several methodological contrasts, including the use of different sets of climate model simulations, the consideration in UKCP09 of additional lines of evidence arising from uncertainties in the effects of carbon cycle changes, and application in UKCP09 of a set of formal observational constraints.

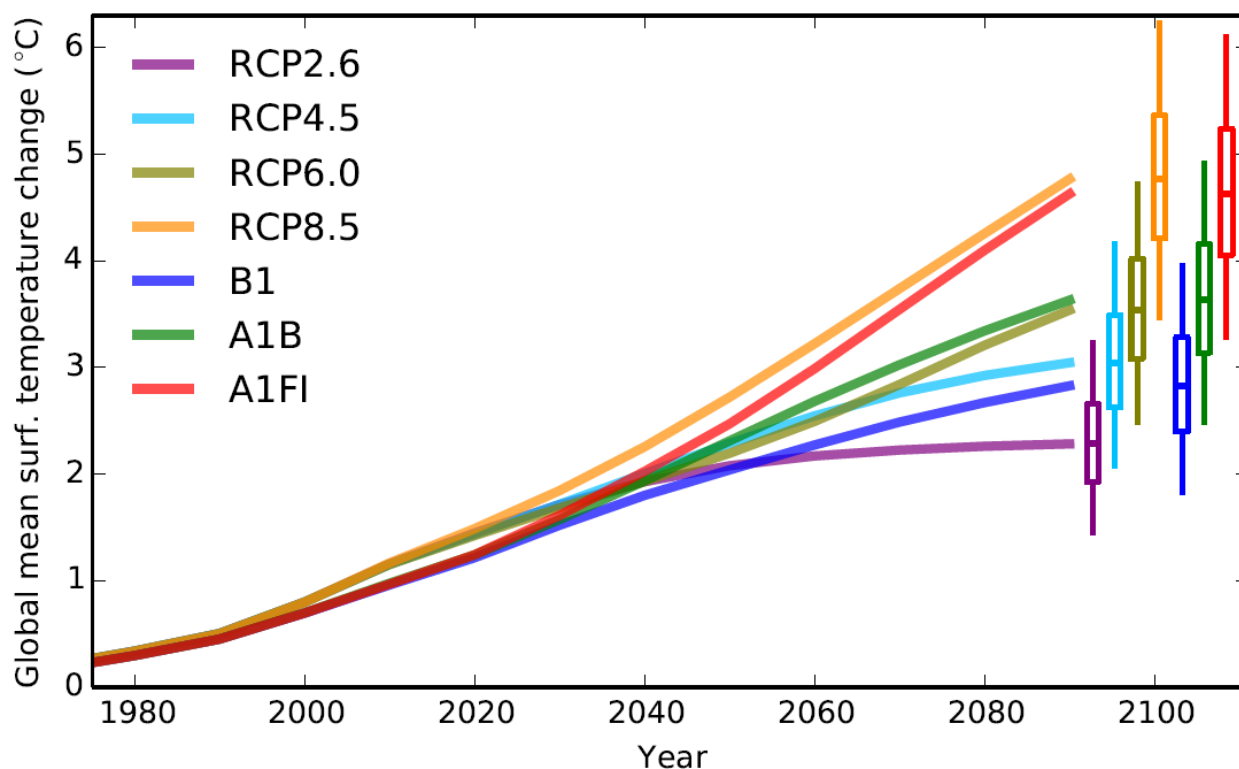
The contrasting treatment of carbon cycle information arises because the AR5 results are derived from “concentration-driven” projections that consider uncertainties in modelling the future physical response of climate, but not uncertainties arising from carbon cycle processes, which control how carbon emissions are converted into concentrations of carbon dioxide in the atmosphere. In “emissions-driven” projections such as UKCP09, however, ranges of future climate response can be produced that account for uncertainties in both carbon cycle and physical processes. The main effect of accounting for uncertainties in carbon cycle feedbacks in UKCP09 can be estimated by reproducing the projections using the same concentration-driven approach used in AR5, which relies on a single estimate of carbon cycle effects. The main impact of reverting to this concentration-driven method is to reduce the upper end of the *likely* range. For 2080-2099 relative to 1986-2005, the upper limit reduces from 2.4°C to 1.9°C under RCP2.6, and from 5.3°C to 4.8°C for RCP8.5, bringing them close to the corresponding upper limits in AR5.

However, the central estimates of change for UKCP09 reduce by only 0.1 - 0.2°C (dependent on the specific RCP scenario) when the concentration-driven approach is adopted, and remain 0.2 - 0.5°C warmer than the corresponding AR5 results. The lower ends of the UKCP09 *likely* ranges are also warmer than their AR5 counterparts, by 0.5 - 0.7°C. The largest difference is for RCP2.6, for which UKCP09 gives a lower limit of 1.0°C for 2081-2100 relative to 1986-2005, compared with 0.3°C in AR5. These differences illustrate the dependence of the projected ranges on the set of climate models used to produce them. In RCP2.6, the warmer value for low-end responses in UKCP09 occurs partly because its projected GMST changes continue to warm slowly following the peak in radiative forcing around 2050 in the RCP2.6 concentration scenario (G. Harris, pers. comm.), whereas some of the CMIP5 simulations show small reductions after 2050 (Collins. et al., 2013). For the other RCP scenarios, in which external forcing increases throughout the 21st

century, an important driver of GMST change is the transient climate response (TCR¹⁶). CMIP5 models sample a 5-95% probability range of TCR values from 1.2-2.4°C (Stocker et al., 2013), whereas the corresponding UKCP09 range is 1.5-2.5°C (G. Harris, pers. comm.), similar to CMIP5 at the upper end but 0.3°C higher at the low end. This difference in TCR distributions may contribute to the warmer projections found in UKCP09 for the 5% and 50% probability levels, subject to further research.

In summary, the results of Figure 1.A7 provide broad ranges of potential GMST outcomes relative to pre-industrial conditions, but they are conditional on the climate models and methodology used to produce them, which are taken from UKCP09. Results from CMIP5 models underline that outcomes below the low (5% probability) end of the UKCP09 ranges cannot be ruled out.

¹⁶ TCR is defined as the annual mean rise in global mean surface temperature, averaged over 20 years, centred on the time of CO₂ doubling in a climate model simulation in which CO₂ increases at 1% per year. It measures both the strength and rapidity of the GMST response to greenhouse gas forcing.

Figure 1.A7: Projected changes in global mean surface temperature


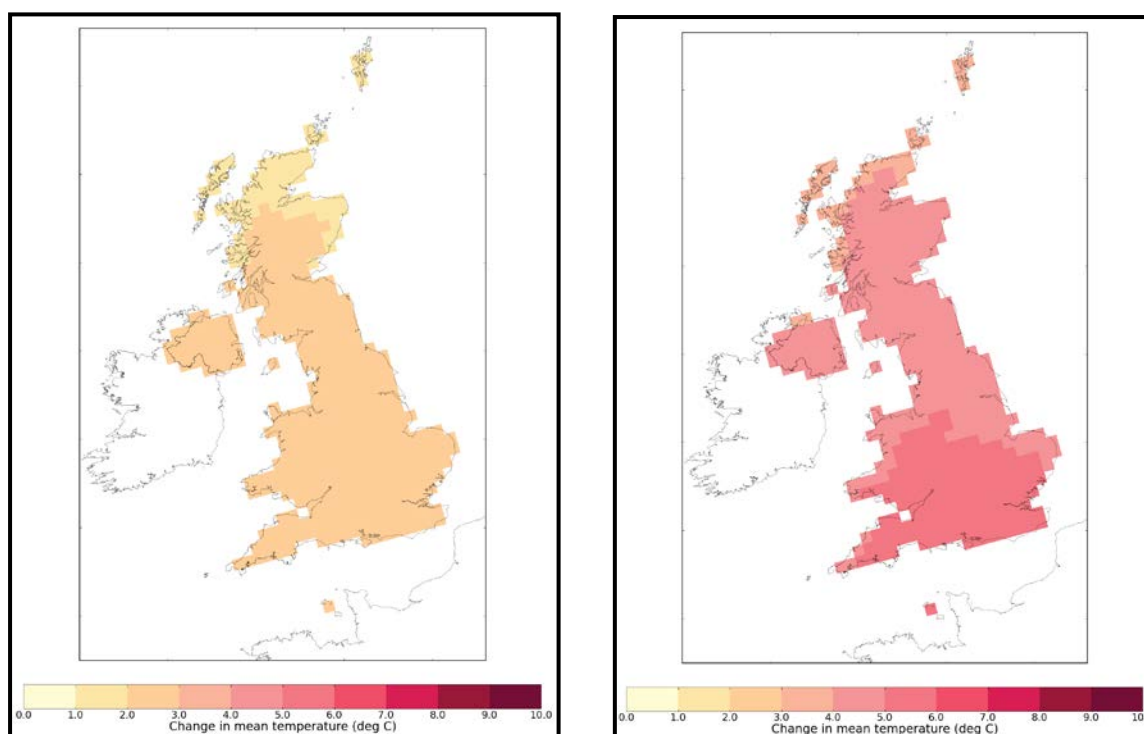
Source: G. Harris (Met Office), based on Harris et al. (2013).

Notes: This plot shows projections for twenty year periods relative to 1860-1899, based on the UKCP09 methodology. The baseline is slightly different from the AR5 baseline of 1851-1900 because the UKCP09 climate model simulations started in 1860, but this is expected to have a negligible impact on the results. Boxes and whiskers show 5, 25, 50, 75 and 95% probability levels of the UKCP09 distributions of change for 2080 - 2099. Solid curves show time-dependent changes for the 50% probability level (median), referred to in the text as the 'central estimate'. The results consider uncertainties in converting carbon emissions to atmospheric CO₂ concentrations, as well as in the physical response of climate to raised CO₂ levels.

Focusing on specific future global temperature outcomes sidesteps uncertainties in future emissions and in the response of global temperature to any specific emissions scenario. At regional scales, however, additional sources of uncertainty arise from internally generated climate variability (e.g. Hawkins and Sutton, 2009), and from the spatial pattern of the response to externally-forced climate change (e.g. Rowell, 2012). This implies that a range of regional changes are plausible, for any given level of global warming. This is illustrated for the UK in Figure 1.A8, based on results for the 2080s derived from UKCP09. These results show plausible ranges of UK change relative to 1961-90, for projections which give a global average warming close to 4°C by the 2080s relative to pre-industrial conditions. The results were obtained from projections for the medium emissions scenario, but the ranges are likely to provide a good indication of uncertainties conditioned on a 4°C warming in other emissions pathways with steady increases in radiative forcing (e.g. Murphy et al., 2014). Potential warming at the 10% probability level lies in the range 2-3°C over most of the UK, falling below 2°C in parts of

northern Scotland. The 50% probability level (not shown in Figure 1.A8) lies in the range 3-4°C over northern Scotland, and 4-5°C in most locations to the south. The corresponding upper estimates (90% probability level in Figure 1.A8) exceed 6°C over much of southern England, 5°C over most of the rest of the UK, or 4°C in coastal regions of northern Scotland. For summer heatwaves conditioned on a 4°C global warming, Clark et al. (2010) found that increases in the intensity of once in 20 year events ranged from 1.6°C to 10.5°C in Northern Europe, based on a large subset of the perturbed parameter ensemble simulations used to provide UKCP09.

Figure 1.A8: Uncertainty in changes in annual mean temperature according to the UKCP09 probabilistic projections, for a global average temperature rise of 4°C



Source: Derived from the UKCP09 probabilistic projection methodology (Murphy et al., 2009; Sexton et al., 2012; Harris et al., 2013). See <http://ukclimateprojections.metoffice.gov.uk/22614>.

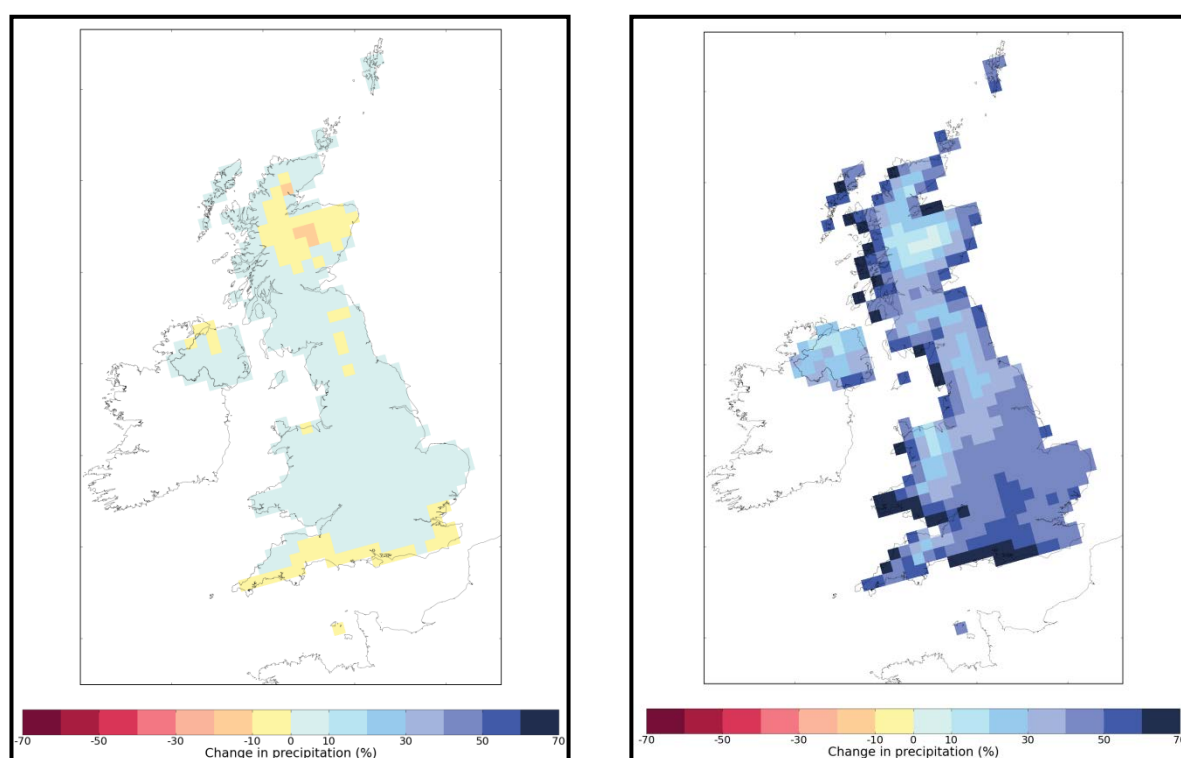
Notes: Left and right panels show lower (10% probability level) and upper (90% probability level) estimates respectively of ranges of plausible regional warming for the 2080s (2070-99) relative to 1961-90, derived from the medium emissions scenario for 25 km grid squares. Uncertainties are calculated by weighting alternative projections according to how consistent they are with a global average warming of 4°C relative to pre-industrial conditions, thus providing an estimate of ranges of future UK changes conditioned on this potential long-term outcome for global temperature.

Corresponding results for winter rainfall are shown in Figure 1.A9. For most of the UK, plausible responses by the 2080s relative to 1961-90 range from little change at the 10% probability level, to significant increases of varying magnitude at the 90% level, for scenarios consistent with a warming of approximately 4°C relative to pre-industrial climate. Increases at the 90% level typically exceed 20% of baseline rainfall, and reach 70% in some coastal locations. In the

Cairngorm region, reductions locally exceeding 10% are seen at the lower end of the plausible range, with modest increases (locally less than 10%) at the upper end.

For a 2°C global warming, corresponding ranges of plausible UK changes were derived from the UKCP09 low emissions scenario. These are somewhat narrower than their 4°C warming counterparts (especially for annual temperature), but still significant. For example, Clark et al. (2010) suggest that increases in heatwave intensity of up to 6°C cannot be ruled out. These results underline the importance of considering a range of potential climate impacts and risks, even for future scenarios focused on specific global temperature targets.

Figure 1.A9: Uncertainty in changes in winter rainfall according to the UKCP09 probabilistic projections, for a global average temperature rise of 4°C



Source: Derived from the UKCP09 probabilistic projection methodology (Murphy et al., 2009; Sexton et al., 2012; Harris et al., 2013). See <http://ukclimateprojections.metoffice.gov.uk/22614>.

Notes: Left and right panels show lower (10% probability level) and upper (90% probability level) estimates respectively of ranges of change for the 2080s (2070-99) relative to 1961-90, for 25 km grid squares. Rainfall changes are expressed as percentage changes relative to baseline climatology values. Uncertainties are calculated by weighting alternative projections according to how consistent they are with a global average warming of 4°C relative to pre-industrial conditions, thus providing an estimate of ranges of future UK changes conditioned on this potential long-term outcome for global temperature.

Beyond UKCP09: extensions and new information

The UKCP09 probabilistic projections were presented as thirty-year averages, in order to emphasise long-term climate change signals. Sexton and Harris (2015) extend the methodology

to account for internal climate variability on one to 30-year time scales, allowing the projections to be expressed in terms of individual seasons. Subject to satisfactory evaluation of simulated variability, this supports assessment of changing future risks of high-impact events and allows recent extreme seasons to be placed in the context of long-term climate change. For example, Sexton and Harris conclude that the cold winter of 2009/10 and wet summer of 2012 are consistent with UKCP09 results, despite expectations of an increasing frequency of warmer winters and drier summers in the future arising from projected trends in multi-year climate averages.

National climate scenarios, including UKCP09, are derived from climate model simulations started from pre-industrial conditions, reflecting the standard approach used in IPCC assessments. Consequently, their simulations of internal climate variability are not constrained by recent analyses of the observed state of the climate system. However, a number of worldwide modelling groups have developed experimental decadal prediction systems in which climate models are initialised from recent observations (e.g. Smith et al., 2013). These systems aim to capture potential predictability of low frequency variability that may arise from initialising slowly-varying components of the climate system, particularly the world oceans, while also accounting for the response to externally-forced climate change. AR5 assessed a multi-model ensemble of decadal predictions provided by CMIP5. They found enhanced skill in global mean temperature predictions out to two years ahead, and in regional temperature forecasts in some ocean areas, including the North Atlantic (Kirtman et al., 2013).

This raises the question of whether initialised predictions with enhanced skill in the North Atlantic could offer more precise information on the evolution of UK climate during the coming decade, compared with uninitialised scenarios such as UKCP09. Using three versions of the Met Office decadal prediction system, Hermanson et al. (2014) suggest that the North Atlantic sub-polar gyre region (south of Greenland) is likely to cool during the next few years. This may increase the likelihood of drier UK summers compared to the previous 20 years, during which the North Atlantic has generally been unusually warm. However, the impact found by Hermanson et al. is modest, compared with the range of plausible outcomes given by UKCP09 for the corresponding period (Sexton and Harris, 2015). The latest Met Office near-term prediction (for 2016 – 2020), using a new climate model, does not predict further cooling in the sub-polar gyre, although the forecast does suggest persistence of relatively cool conditions compared with most other regions of the world oceans. In summary, initialised decadal forecasts show some promise for enhanced predictability of near-term future climate in the North Atlantic region, but uncertainties in these forecasts are considerable, and they are currently viewed as experimental products requiring expert advice, in particular regarding their reliability for use as regional predictions. See <http://www.metoffice.gov.uk/research/climate/seasonal-to-decadal/long-range/decadal-fc>.

Some impact studies or adaptation decisions require nationwide assessments of changes affecting natural resources or distributed infrastructure networks. In such cases the UKCP09 probabilistic projections are often unsuitable, due to the limited set of variables available and a lack of spatial coherence in the data. More flexible datasets are needed, supporting access to a wider set of variables with full spatial, temporal and inter-variable coherence. Several applications (e.g. Prudhomme et al., 2012a; Sanderson et al., 2012; McColl et al., 2012; Palin et al., 2013) have therefore used results from a perturbed parameter ensemble of eleven high resolution regional climate model (RCM) simulations, derived from the HadCM3 model. These

simulations, driven by the SRES A1B emissions scenario, formed one of the modelling components of UKCP09 (Murphy et al., 2009). In some applications, a more robust basis for decisions can be achieved by combining alternative sources of evidence to account for different influences on future impacts. In projections of fluvial flooding, for example, Kay and Jones (2012) showed that considering a range of plausible realisations of internal climate variability using daily time series from the RCM simulations (or from the UKCP09 weather generator of Jones et al. (2010)) can provide more robust uncertainty estimates than relying solely on changes in long-term climate averages ('change factors') from the RCM simulations, applied to a single realisation of internal variability. On the other hand, while the RCM simulations confer greater flexibility in this sense, they only sample a subset of the plausible range of change factors covered by the probabilistic results (Sexton et al., 2010). Kay and Jones (2012) also show that considering a wider range of change factors from the probability distributions can also broaden the spread of changes in flooding.

Additional RCM projections for the A1B scenario are available from the European Union ENSEMBLES project (van der Linden and Mitchell, 2009), which used a multi-model ensemble of RCMs driven by several global models. The Euro-Cordex project (Jacob et al., 2014) has assembled an archive of new multi-model RCM simulations driven by CMIP5 global models, for the RCP2.6, 4.5 and 8.5 scenarios. These results provide opportunities to augment the UKCP09 RCM ensemble to obtain a larger set of plausible realisations of 21st century climate for distributed impacts analyses.

A major upgrade to the UK Climate Projections, UKCP18, is due for release in 2018, and will feed in to the next UK Climate Change Risk Assessment due in 2022. More information on UKCP18 can be found at <http://ukclimateprojections.metoffice.gov.uk/24125>.

Projected changes in UK extremes

Christidis et al. (2014) used CMIP5 simulations to assess future changes in the risk of the summer average temperature in southern Europe exceeding an anomaly of 2.3°C relative to 1961-1990, as experienced in the heatwave summer of 2003. They found that such events are projected to become common by the 2040s, confirming the earlier results of Stott et al. (2004). Furthermore, simulations using the two RCP scenarios with the largest anthropogenic forcing (RCP6.0 and 8.5) suggest that such events would represent extremely cold summers by the 2090s.

In UKCP09, probabilistic information on 21st century extremes was restricted to changes in the typical warmest, coolest or wettest day in a season, for 30-year time slices. The results showed very broad uncertainty ranges (Murphy et al., 2009), reflecting a large contribution from internal variability in addition to climate modelling and statistical uncertainties in the UKCP09 methodology. Brown et al. (2014) provided a method for obtaining projections of rare sub-seasonal local events, such as the future intensities of 20-year return period events for daily maximum temperature, or 5-day rainfall accumulations. This was done by applying the UKCP09 probabilistic methodology to the statistical parameters of extreme value distributions (EVD), accounting for future climate change by allowing the EVD parameters to depend on global average temperature. As with other UKCP09-related information, the resulting projections are consistent with the underpinning climate modelling, and conditional on its limitations.

Table 1.A1: Values of 20-year return period events for daily maximum surface temperature in summer (June-August), and accumulated rainfall over five consecutive days in winter (December-February)

City	Daily summer max temperature (°C)			5-day winter rainfall accumulation (mm)				
	1961-1990 Observed	2041-2060 Low	2041-2060 Central	2041-2060 High	1961-1990 Observed	2041-2060 Low	2041-2060 Central	2041-2060 High
London	34.4	34.1	37.2	40.6	56.1	57.8	62.5	68.3
Cardiff	31.7	31.9	34.7	38.1	73.6	76.6	79.8	83.6
Belfast	25.9	26.5	28.5	30.9	70.3	70.6	76.9	84.6
Edinburgh	23.5	24.8	26.2	27.9	63.4	63.5	70.0	78.4

Source: from Brown et al. (2014).

Notes: For each national capital, estimated observed values for 1961-1990 are compared with values for the 10th (low), 50th (central) and 90th (high) percentiles of probabilistic projections for 2041-2060 under the A1B emissions scenario. The values represent 25x25km² spatial averages, for locations on the UKCP09 grid (Murphy et al., 2009) containing national capitals. In order to derive observational estimates, the 5km gridded station dataset of Perry et al. (2009) was interpolated to the UKCP09 grid. Projections are obtained by applying the UKCP09 methodology to predict future changes in parameters controlling the properties of statistical EVD. The examples provided show cases where the results are robust to plausible variations in the methodology, based on sensitivity tests assessing the degree of consistency between the global and regional modelling components of UKCP09.

Projected values for once in 20-year events are shown in Table 1.A1, focusing on summer daily maximum temperature and five-day rainfall totals in winter. The latter metric is an indicator of flooding events caused by large-scale weather systems (Frei et al., 2006). The observed and projected estimates in Table 1.A1 represent values for 25km boxes on the UKCP09 grid (Figure 1.2a of Murphy et al., 2009) that contain national capitals. Projected changes for 2041-2060 show central estimates exceeding observed values for 1961-1990 by 2.6°C to 3.0°C for extreme summer hot days, and 6 to 7 mm (i.e. 8-11%) for 5-day winter rainfall. The upper ends of the uncertainty ranges suggest that changes of approximately twice the central estimate cannot be ruled out. The lower ends show only modest changes relative to the baseline values.

At the spatial resolutions of long-term climate change simulations (such as those of UKCP09, CMIP5 and Euro-Cordex), the dynamics of atmospheric convection cannot be resolved, and is instead parameterised through bulk relationships to grid-scale model variables. This is a practical choice currently necessitated by limitations of computational resources. However, Kendon et al. (2014) report the first UK climate change simulation in which the dynamics of larger convective storms is explicitly represented, using a 1.5 km resolution regional model derived from weather forecasting experience. Using 13 year historical and future simulations for a domain covering Wales and central and southern England, they found substantial increases in the intensity of hourly summer rainfall extremes. These increases were not captured in a coarser 12 km simulation in which convection is parameterised. Ban et al. (2015) find a similar result in a

corresponding study for the Alpine region. In winter, sub-daily rainfall extremes increase substantially in both the 1.5 km and 12 km simulations of Kendon et al. (2014). The greater similarity between the two model resolutions in winter probably reflects the dominant influence of large-scale moisture convergence (rather than local convection) in driving the peak rainfall intensities.

UKCP09 did not provide projections of how anthropogenic forcing might change the future characteristics of rainfall at sub-daily time scales, so a direct comparison with Kendon et al. (2014) is not possible. However, Kendon et al. (2015b) report a substantial reduction in future *multi-year average* summer rainfall in the 1.5 km simulation discussed above, consistent with UKCP09 (see Figure 1.A6). Previous studies have suggested that extreme daily summer rainfall could increase even if average rainfall reduces (e.g. Christensen and Christensen, 2002), due, at least in part, to the 7% per degree increase in the water-holding capacity of the atmosphere in a warmer climate (Trenberth et al., 2003). However, Kendon et al. (2014) suggest that positive feedback¹⁷ between condensational heating and vertical motion in storms may enhance increases in extreme rainfall in their 1.5 km simulation, compared to models relying on parameterised convection.

Kendon et al. (2015b) caution that further kilometre-scale simulations using a range of models are needed to assess the robustness of their results, and that moving to this resolution does not address all sources of bias in modelled convection. For example, smaller showers are still not represented in the UK simulations, leading to a tendency for heavy rainfall to be too intense (Kendon et al., 2012). Nevertheless, such simulations provide a new opportunity to account for convective storm dynamics in regional climate projections and thus include a potentially important driver of extreme rainfall absent from previous scenarios.

One of the CCRA2 research projects (HR Wallingford (2015) for the ASC) provides projections of water availability for the UK, looking both at public water supply and other uses of water. The public water supply assessment builds on current water company plans to look at water availability in the 2050s and 2080s under low and high population projections and with different climate change scenarios. The climate scenario information previously available from the Future Flows project (Prudhomme et al., 2012b) relied mainly on climate changes projected by the 11-member UKCP09 RCM ensemble (see above). In HR Wallingford (2015) for the ASC, a broader range of future river flow and groundwater trajectories is obtained. This is achieved by driving selected Future Flows hydrological models, and all available Future Flows groundwater models, using the full range of plausible climate change scenarios available from the UKCP09 probability distributions. Under the most testing combination of scenarios, the project suggests a public water supply deficit of up to 6,000 megalitres per day (Ml/day) by the 2080s; currently public water supply provides about 18,000 Ml/day. The projected deficit is both the result of increasing demand because of a larger population and also a reduction in water availability as the climate changes. Other uses of water also face a deficit by the end of the century, though the scale of the deficit depends on the volume of water that is deemed necessary to be left in the environment to support good ecological status.

¹⁷ A climate feedback is an interaction in which one climate quantity causes a change in a second, which then leads to an additional change in the first. A positive (negative) feedback is one in which the second change enhances (weakens) the first.

Another CCRA2 research project (Met Office (2015) for the ASC) asks how far climate change could go, looking at the plausible limits of cold extremes, heatwaves, low and high rainfall, low and high flows, droughts, windstorms and wildfires. The assessment uses the H++ concept originally developed in the sea level rise and storm surge component of UKCP09 (see Lowe et al. (2009) and discussion of marine and coastal projections below). An H++ scenario represents a high-end outcome, or range of outcomes, that cannot be ruled out based on current understanding. In general, H++ scenarios can consist both of quantitative information derived from model projections or idealised sensitivity studies, and qualitative narrative derived from sources such as theoretical insight, understanding of processes missing from models, or past observations. The scenarios identified are of low but unspecified probability, and are useful for thinking about contingency planning. In practice, much of the quantitative information from this project is obtained by considering the upper extremes of ranges available from mainstream climate projection products, such as the UKCP09 probability distributions, CMIP5 global models, or the UKCP09 or ENSEMBLES regional models. One notable exception is for cold extremes, where simulations of the consequences of a hypothetical shutdown of the AMOC are also considered.

In their new H++ scenarios, Met Office (2015) for the ASC finds that by the end of the century, the UK could plausibly see heatwaves of 50 days duration with a mean temperature of almost 40°C and increasingly intense summer droughts with rainfall 60% below average, but little change in the chance or intensity of longer droughts. In these summer droughts, low flows would be severely reduced, with Q95 (a measure of low flow) up to 70% lower than now. At the same time, winter rainfall could increase by up to 100%, suggesting that winters like 2013/14, with 70% more than average rainfall, could be exceeded in most years by the 2080s. Daily intense rainfall could also increase in both summer and winter, with a possible increase of 60 to 80% compared to current intense rainfall events. As a result of this increased rainfall, peak river flows could be up to three times bigger than they are now by the 2080s. The number of windstorms could also increase by 50 to 80%. Finally, for wildfires the project concludes that the UK is already at risk from a worst-case fire, but that climate change increases the probability of such a fire occurring. This H++ information should be considered alongside estimates of the likely range of future outcomes. The project also considered plausible but very unlikely scenarios of extreme cooling caused by AMOC collapse and other factors (see Section 1.A4).

A third CCRA2 research project (Sayers and Partners (2015) for the ASC) describes projections of future flood risk, broadening the assessment to consider surface water and groundwater flooding, as well as updating information on coastal and river flooding that was the focus of the first CCRA. This project assesses flood likelihoods for the 2020s, 2050s and 2080s, based on climate trajectories leading to 2 or 4°C of global warming by the 2080s, supplemented by H++ scenarios (see above). Results are provided for the whole UK, and at national and regional levels. Alternative population projections are also considered. Information on climate projections is derived from UKCP09 and other sources. These include new results on sub-daily rainfall changes (e.g. Kendon et al. (2014), discussed above) to assess surface flooding, and results from the FD2020 project (Reynard et al., 2009). In FD2020, projections from both CMIP3 global climate models and the UKCP09 RCM ensemble were used to assess peak river flows for England and Wales. The results show that significant additional investment and adaptation action will be needed to counter the increase in UK flood risk projected under a 2°C rise in global mean temperatures. Even the most ambitious adaptation scenarios considered will not be able to avoid the large increase in UK flood risk implied by a 4°C rise in global temperatures. Long

stretches of current coastal flood defence structures in England would become highly vulnerable to failure as sea levels rise, making it increasingly difficult and costly to manage the risk of widespread coastal inundation.

Marine and coastal projections

The AR5 global mean sea level projections span a wider range than those from the earlier IPCC fourth assessment (Meehl et al., 2007), which were used in the UKCP09 marine projections. For 2081-2100 relative to 1986-2005, the AR5 *likely* ranges were 0.26-0.55m (RCP2.6 emissions scenario), 0.32-0.63m (RCP 4.5), 0.33-0.63m (RCP6.0) and 0.45-0.82m (RCP8.5), based on evidence from CMIP5 model projections in combination with information on glacier and ice sheet contributions from process-based models and the published literature (Church et al., 2013). The regional change in sea level differs from the global mean due to regional variations in ocean density changes and changes in ocean circulation (e.g. Lowe and Gregory, 2006). It is also now more clearly recognised that the water from melting land ice has a spatial pattern, which is related to changes in the gravity field of the earth as mass is redistributed (Mitrovica et al., 2011). The latest IPCC projections suggest the regional change around the UK is near to the global mean change, which was also the case in earlier projections and reported in UKCP09. Locally, the UK will continue to experience vertical land movements, with a similar pattern to that experienced during recent decades.

Although CCRA2 focuses mainly on the period up to 2100, it is prudent in the case of sea level rise to look further into the future, using evidence from climate models and palaeoclimatic sea level records. AR5 assessed that it is *virtually certain* that sea-level rise will continue beyond 2100, although the magnitude will depend on the emission pathway followed and other sources of uncertainty, as for changes during the 21st century. Even setting emissions to zero at 2100 would likely lead to subsequent sea level increases.

The AR5 assessment highlights the few available process-based models that go beyond 2100. The IPCC grouped long term sea level rise scenarios based on their CO₂-equivalent¹⁸ concentration in 2100. By 2300, these indicate a global mean sea level rise above the pre-industrial level to be less than 1m, for greenhouse gas concentrations that peak and decline and remain below 500 parts per million (ppm), as in scenario RCP2.6. For scenarios with radiative forcing between 700 ppm and 1500 ppm CO₂-equivalent in year 2100, as in the RCP8.5 scenario, the projected sea level rise ranges from 1m to more than 3m by 2300. Beyond 2100 the forcing scenarios follow a range of pathways, and in the case of RCP8.5 the CO₂-equivalent concentration rises above 1500 ppm during the 22nd century.

The amount of sea level rise after 2100 will depend significantly on whether temperatures remain high enough and for long enough to cause an irreversible melting of the Greenland ice sheet and the West Antarctic ice sheet. There is some evidence that the point at which loss of parts of the West Antarctic ice sheet becomes inevitable may already have been passed (Joughin et al., 2014; Rignot et al., 2014). Melting from each of these ice sheets could contribute around 10-20cm per century to sea level rise during the next few hundred years, although there is

¹⁸ Equivalent CO₂ concentration refers to the concentration of carbon dioxide, for a given period, that would cause the same total radiative forcing as some mixture of carbon dioxide and other forcing components, such as other greenhouse gases or a combination of greenhouse gases and aerosols.

considerable uncertainty over the rate of melting, and over the global warming threshold that would trigger irreversible collapse of the Greenland ice sheet in the longer term (see Section 1.A4).

In UKCP09, an H++ sea level rise scenario was constructed from additional lines of evidence, such as palaeoclimatic evidence (e.g. Rohling et al., 2008) and physical constraints on the rates of outlet glacier and fast ice stream flow into the oceans (Pfeffer et al., 2008). Whilst the IPCC report did not formally develop an updated H++ scenario, it did state that a rise above the likely range could occur, without quantifying the likelihood. At present there is insufficient evidence to change the UK H++ level from 1.9m by 2100, with further increases beyond (Palmer et al., 2015), but it is important to emphasize that this represents a very low probability outcome on the basis of current evidence (Hinkel et al., 2015).

The biggest risk of inundation comes from storm surge events, notably when they happen close to a high tide and with a strong onshore wind. Consistent with recent observations, current work suggests that storm surges will not show large and significant changes in the future, but that extreme water levels will increase because the surges occur on a higher time mean sea level (Lowe et al., 2009). There is also now research showing that future mean sea level changes might cause variations in the tidal cycle (e.g. Pickering et al., 2012), including the amplitude as seen at the coast.

In situ changes in shelf sea temperature, salinity and currents were considered in UKCP09 using a single future projection, but the lack of information on uncertainties held back impacts analysis in this area (Pinnegar et al., 2012). Recent work has added an initial estimate of uncertainties to the UKCP09 projections (Tinker et al., 2016) and has also demonstrated when and where there is confidence in the model projections (Tinker et al., 2015). The general trend continues to be one of warming in the shelf seas, with deviations from offshore rates of warming. Salinity also changes, with a sizeable freshening (reduction in salinity) expected in some areas. Temperature changes on the shelf are influenced mainly by the atmosphere, whereas salinity change is strongly affected by both the atmosphere and ocean. These results account for some of the uncertainties associated with the driving climate modelling, by using global and regional PPE simulations taken from the UKCP09 land scenarios to drive a shelf seas model. However, it remains to add quantification of uncertainties arising from the shelf sea modelling.

1.A4 Understanding climate drivers and events

Current understanding is summarised here on selected climate research topics relevant to understanding the current climate, and the status and credibility of future projections. This provides a qualitative context for the quantitative data available for the risk assessments in CCRA2.

Global warming hiatus

Following a period of relatively rapid rise from the 1970s, AR5 reported that GMST has risen only modestly during the past 15 years or so, and more slowly than the long-term trend predicted by climate model simulations (e.g. Fyfe et al., 2013). This phenomenon has become known as the global warming “hiatus”, “pause” or “slowdown”. It has provoked considerable interest in the climate science community and the media, creating challenges for public communication (Hawkins et al., 2014). Incomplete observational coverage may have led to an underestimation

of the recent observed trend in the extratropical northern hemisphere (Cowtan and Way, 2014; Saffioti et al., 2015), however data gaps alone do not explain the difference in trend between the hiatus and pre-hiatus period reported in AR5, for which the dominant causes are found at low latitudes (Gleisner et al., 2015).

With *medium confidence*, AR5 attributed the discrepancy between modelled and observed trends during 1988 - 2012 to a cooling due to internal (natural) variability of the climate system and a reduction in external forcing, in roughly equal measure (Flato et al., 2013). While the external forcing from the major greenhouse gases has continued to increase during this period, a reduction in the total external forcing may have arisen from factors not included in CMIP5 models, including eruptions of minor volcanoes (e.g. Santer et al., 2014), the extended and deeper recent solar minimum (e.g. Kaufmann et al., 2011), or neglect or underestimation of aspects of the forcing due to anthropogenic aerosols (Schmidt et al., 2014). The Pacific Decadal Oscillation (PDO¹⁹) has been in a predominantly negative phase since the late 1990s, and has been highlighted as a key factor in explaining the warming slowdown in several recent studies, both in relation to GMST (e.g. Dai et al., 2015) and to many of its spatial features, including winter cooling over north-western North America (Kosaka and Xie, 2013) and an increase in the odds of cold winters over Europe (Trenberth et al., 2014). A pronounced strengthening in Pacific trade winds during the past two decades, and consequent redistribution of heat from the surface of the ocean to deeper levels, has been identified as a key driver of the negative PDO pattern and the warming hiatus (England et al., 2014). This strengthening in trade winds is unprecedented in the 20th century historical record, and is outside the envelope of CMIP5 simulations of recent changes. Recent modelling studies suggest that the recent warming trend in Atlantic SSTs may have amplified the increase in Pacific trade winds through the influence of the atmospheric circulation (McGregor et al., 2014), and that warming in the tropical Atlantic played a key role in driving observed tropics-wide changes in SST during the past 30 years, including cooling in the eastern Pacific and warming in the western Pacific and Indian oceans (Li et al., 2015).

Increased ocean heat uptake across multiple ocean basins, especially the Atlantic and Southern Oceans, has also been suggested as a cause of the GMST slowdown (Chen and Tung, 2014; Drijfhout et al., 2014). However, Smith et al. (2015a) find that analyses of ocean heat content during the early 2000s are not consistent with their estimate of the net planetary heating, suggesting instead that a reduction in the latter between 1999 and 2005 may have contributed to the GMST slowdown. Potential drivers of reduced net heating include minor volcanoes, the recent solar minimum or aerosol forcing (see above).

Karl et al. (2015) used one surface temperature dataset, recently updated using new bias corrections to SST measurements, to argue that there was no detectible difference between the GMST trend during 1950 - 1999 and that during 2000 - 2014, and therefore no post-1998 hiatus. However, their conclusion may be sensitive to their choice of baseline period, as there was also

¹⁹ The PDO is a pattern and time series representing the leading mode of observed variability in sea surface temperatures (SSTs) in the North Pacific Ocean. It is closely related to the Interdecadal Pacific Oscillation (IPO), a broader pattern defined over the whole Pacific basin. The negative phase of the PDO is associated with cool SSTs in the tropical Pacific and along the North American coast, with warm SSTs in the interior of the North Pacific. The PDO is associated with a range of impacts on worldwide climate, broadly similar to those of El Niño events.

an extended warming hiatus from the mid-1940s to about 1975, to which the effects of aerosol forcing and the PDO (predominantly in its negative phase during that period) are both likely to have contributed (Trenberth, 2015).

In summary, the extent and causes of the slowdown in warming remain under investigation, with recent literature pointing to a significant role for internal variability, probably alongside some contribution from external forcing. From CMIP5 models, the central estimate of the current forced trend in GMST is about 0.2°C per decade. Roberts et al. (2015) used the CMIP5 pre-industrial simulations to show that internal variability can offset this trend over a 10-year period with a probability of about 5%, and over a 20-year period with a probability of less than 1%. They also found that an existing 15-year hiatus could potentially continue for another 5 years with a probability of about 15%. However, 2014 was one of the warmest years in a record dating back to 1850, and 2015 was the warmest year in the record, at $0.75 \pm 0.1^\circ\text{C}$ above the 1961 - 1990 average, and around 1°C above the average for 1851 - 1900. The exceptional warmth in 2015 was partly due to the development of a strong El Niño event in the tropical Pacific (<http://www.metoffice.gov.uk/news/releases/archive/2016/2015-global-temperature>). However, it is currently premature to predict an end to the warming pause with confidence, due to the challenges associated with predictability of the driving phenomena (Smith et al., 2015b). Nevertheless, observations and climate models show that 10-15 year hiatus periods can occur as a manifestation of internal decadal climate variability, and GMST in each of the last three decades has been successively warmer than any preceding decade since 1850 (IPCC, 2013). Furthermore, several other indicators (including ocean heat content, sea level rise, Arctic sea-ice cover, northern hemisphere snow cover and atmospheric humidity) have shown trends in recent decades consistent with continuing global warming (see Section 1.A1).

Implications for long-term warming

The recent warming hiatus has been used in some studies to suggest that current climate models overestimate the global climate response to increasing concentrations of greenhouse gases (Otto et al., 2013; Lewis, 2013; Lewis and Curry, 2014). However, evidence from other studies questions such a conclusion:

- Olson et al. (2013) show that estimates of equilibrium climate sensitivity (ECS, defined in section 1.A3) derived from observed historical changes since the industrial revolution are subject to considerable uncertainty, because the historical record consists of only a single realisation of internal climate variability. This can lead to a significant discrepancy between the estimated ECS and the true value, since different realisations of past internal variability with identical statistical properties can give rise to a broad range of ECS values in studies of this type.
- Johansson et al. (2015) investigate how the accumulation over time of observations (of land and ocean surface temperature and ocean heat content) affects probability distributions of ECS. While adding the hiatus period leads to a reduction in their most likely value from 2.8°C to 2.5°C , the lower bound of their 90% range for ECS remains stable at around 2.0°C . The effects of internal variability also cause their ECS estimates to shift back and forth over time, leading to their conclusion that impact of the hiatus on ECS cannot yet be determined.
- Marotzke and Forster (2015) find no substantive relationship between simulated trends in CMIP5 models since 1900 (up to and including the hiatus period) and the long-term

response of the model to greenhouse gas forcing. They suggest that comparisons between simulated and observed historical trends do not provide a basis to conclude that climate models systematically overestimate the response to increasing greenhouse gas concentrations.

- England et al. (2015) attempted to screen CMIP5 projections by selecting only simulations that captured a slowdown in warming between 1995 and 2015, but found that future GMST projections were statistically indistinguishable from those of the full ensemble.

AR5 assessed uncertainties in ECS using several lines of evidence, concluding that ECS is *likely* in the range 1.5°C to 4.5°C with *high* confidence (Bindoff et al., 2013). A related metric of the global climate system response to an imposed external forcing is the transient climate response (TCR, see Section 1.A3). The TCR is particularly relevant to understanding changes in GMST during the 21st century under emissions scenarios implying a steady increase in external forcing. Bindoff et al. concluded with high confidence that TCR is likely in the range 1.0°C to 2.5°C. Two of the main lines of evidence in the AR5 assessments of TCR and ECS consisted of:

- Results from three-dimensional global climate models, in which ECS and TCR are predicted ‘bottom-up’ by simulating the interactions between a detailed set of Earth system processes.
- ‘Top-down’ assessments derived from the use of simple models based on global energy balance principles. These infer estimates of TCR or ECS consistent with historical global changes in temperature, radiative forcing and (in some cases) ocean heat content (e.g. Otto et al., 2013; Lewis, 2013; Lewis and Curry, 2014; Johansson et al., 2015, discussed above).

For TCR, both lines of evidence gave consistent results, however for ECS the CMIP5 models indicated a lower bound of 2°C, whereas some of the estimates derived from the instrumental record support lower values, leading to the AR5-assessed lower bound of 1.5°C. Cloud feedbacks provide the largest source of uncertainty in ECS in CMIP5 models (Vial et al., 2013), as in earlier multi-model ensembles. Several recent studies (e.g. Clement et al., 2012; Fasullo and Trenberth, 2012; Sherwood et al., 2014; Tian, 2015) suggest potential ‘emergent constraints’ on ECS. These are statistical relationships between ECS and biases in simulated properties of present climate observables related to cloud or convection, which can then be used to constrain ECS. These approaches generally show that models with ECS values of 3°C or higher agree better with the observations than those with lower values. In addition, some CMIP5 models with relatively high ECS values show good general performance in their historical simulations, when assessed against a wider range of climatological variables. These results, coupled with other lines of evidence, led AR5 to conclude that the upper end of the *likely* ECS range should remain at 4.5°C, unchanged from the value assessed by AR4.

An important current challenge is to reconcile the difference in the lower bound of ECS between results from complex climate models and those based on the instrumental record. Regarding the latter class of methods, one factor may be the influence of historical internal variability, discussed above. A second factor may arise from neglect of complicating factors in some methods based on global energy balance criteria. Shindell (2014) finds that the efficacy²⁰ of the

²⁰ Efficacy is a measure of how effectively a radiative forcing from a given driver changes the equilibrium global mean surface temperature, compared to an equivalent radiative forcing from CO₂, which has an efficacy of 1.0.

forcing due to aerosols and ozone is substantially larger than that due to CO₂, an issue neglected in many simple model studies. When this is accounted for, the distribution of TCR inferred from historical temperature changes is shifted to higher values. Andrews et al. (2015) find that climate feedbacks in CMIP5 models strengthen with time as patterns of surface warming evolve, suggesting that estimates of TCR or ECS derived from the historical record may not be representative of longer-term future changes. These caveats do not question the usefulness of ECS estimates based on simple models and the instrumental record, but they do emphasise the importance of avoiding an overconfident interpretation of results from any particular study. This applies particularly to impacts dependent on short periods of observations, such as the hiatus period.

Climate surprises and missing processes

Collins et al. (2013) assessed in AR5 a number of unlikely but plausible ‘climate surprises’, consisting of Earth system components or phenomena potentially susceptible to abrupt or irreversible change. Here, *abrupt* denotes a large-scale change that occurs over a few decades or less, persists for at least a few decades and would cause substantial disruption to human or natural systems if it occurred. A change is defined as *irreversible* if the recovery time due to natural processes is significantly longer than the time taken to reach the perturbed state. Table 1.A2 summarises the AR5 assessment of several plausible events, drawing also on recent evidence from a Met Office report by Good et al. (2014).

Table 1.A2: Earth system components or events proposed in the climate science literature as being potentially susceptible to abrupt or irreversible changes

Event	Potentially abrupt?	Irreversible?	Assessed likelihood during 21 st century	Do current climate model projections include the main processes that might cause the event?
Atlantic Meridional Overturning Circulation (AMOC) collapse	Yes	Unknown	<i>Very unlikely</i> , that the AMOC will undergo a rapid transition, with <i>high confidence</i> .	Many but not all influences on AMOC are included, although model-dependent biases are present in the simulations. Current models simulate a steady weakening (of uncertain magnitude) in AMOC strength during the coming century, but not a collapse. Freshwater input from melting land ice is a further source of potential

The driver could be a man-made change in an aerosol species or a different greenhouse gas, or a natural event such as a volcanic eruption or the solar cycle.

Table 1.A2: Earth system components or events proposed in the climate science literature as being potentially susceptible to abrupt or irreversible changes				
Event	Potentially abrupt?	Irreversible?	Assessed likelihood during 21 st century	Do current climate model projections include the main processes that might cause the event?
				weakening, not included in CMIP5 or UKCP09 models.
Ice sheet collapse	No	Irreversible for millennia	A near-complete disintegration of the Greenland or Antarctic ice sheets during the 21st century is <i>exceptionally unlikely, with high confidence</i> .	No. CMIP5 and UKCP09 models prescribed ice sheet extents as constant through time, and did not simulate their dynamics.
Permafrost carbon release	No	Irreversible for millennia	Possible that permafrost will become a net source of atmospheric greenhouse gases (<i>low confidence</i>). The contribution of thawing permafrost to the global carbon cycle is expected to rise relatively smoothly with temperature.	No. However, Burke et al. (2013) used soil temperatures saved from CMIP5 simulations to estimate future permafrost carbon release using a simple offline modelling approach. Results suggest a positive feedback contribution to future atmospheric CO ₂ concentrations, but with a highly uncertain magnitude.
Methane release from ocean sediments	Yes	Irreversible for millennia	Warming could release frozen carbon stored in methane hydrates in ocean shelves, shelf slopes and deep ocean sediments. Catastrophic release assessed <i>very unlikely, with high confidence</i> .	No. Initial estimates suggest a small positive contribution to anthropogenic warming during the 21 st century, with potential for a larger contribution on millennial time scales.
Tropical forest dieback	Yes	Reversible within centuries	<i>Low confidence</i> in projections of the collapse of large	Many relevant physical and ecosystem processes are included, but some are

Table 1.A2: Earth system components or events proposed in the climate science literature as being potentially susceptible to abrupt or irreversible changes

Event	Potentially abrupt?	Irreversible?	Assessed likelihood during 21 st century	Do current climate model projections include the main processes that might cause the event?
			areas of tropical forest.	either poorly understood or missing from current models, limiting confidence in the assessment. Land use changes are included in some CMIP5 models, but not in CMIP3 or UKCP09. To date, few models account for feedbacks between vegetation changes and fire risk.
Total loss of summer Arctic sea ice	Yes	Reversible within years to decades	<i>Likely</i> that the Arctic ocean becomes nearly ice-free in September before mid-century under high forcing scenarios such as RCP8.5 (<i>medium confidence</i>).	Yes, although the response of atmospheric circulation to Arctic sea ice loss is uncertain (section 1.A2).

Source: Assessments in columns 2 to 5 are drawn from detailed surveys of evidence from AR5 (in particular section 12.5.5 of Collins et al. (2013), and from a Met Office Hadley Centre Climate Programme report (Good et al., 2014). The likelihood and confidence statements are derived from IPCC AR5, and follow the definitions of uncertainty given in Box TS.1 of Stocker et al. (2013).

The hypothetical events in Table 1.A2 would all cause major climate impacts in their regions of origin. In general, impacts on the UK would occur both via effects of the events on globally averaged aspects of climate change (such as atmospheric CO₂ concentration and global temperature rise, or global sea-level rise), and also via effects on patterns of climate change remote from the sites of the events.

The only event assessed as likely during the 21st century is the near-disappearance of summer Arctic sea ice cover by the middle of the century. This occurs in UKCP09 modelling as well as in CMIP5 (Sexton et al., 2016). While the effects of reduced sea ice in increasing local and global surface warming are well understood, the impact on atmospheric circulation, and how this might affect the UK, remains uncertain (see Section 1.A2).

Effects of a hypothetical but *very unlikely* collapse of the AMOC have been investigated in climate model experiments (e.g. Jackson et al., 2015), in which the largest impacts are found in the northern hemisphere. Results from Met Office (2015) for the ASC suggest a potential cooling

of average UK temperature amounting to 4 to 5°C in winter. Met Office (2015) combined AMOC collapse with other plausible but very unlikely assumptions, including a prolonged minimum in solar output during the 21st century (discussed below), and selection of a response to future greenhouse gas emissions at the low end of the UKCP09 projections, in order to construct extreme cold winter scenarios. For example, under this set of assumptions, UK average winter temperatures during the 2080s could be -4°C. However, the modelling underpinning CMIP5 and UKCP09 indicates only a partial weakening of the AMOC (see Table 1.A2), and these effects are accounted for alongside other processes in changes projected for the UK.

Direct observations of the AMOC (available since 2004) have shown a weakening during the period 2004 - 2012 (Smeed et al., 2013), at a rate considerably larger than the longer-term rate of decline projected by climate models during the 21st century (Cheng et al., 2013). Indirect observations (of density changes that drive the AMOC) suggest that the recent weakening may have been in progress since the late 1990s (Robson et al., 2014), raising the possibility that the recent decline could continue, leading to a significant weakening (but not a complete collapse) of the AMOC during the next few decades. However, Roberts et al. (2014) point out that recent observed reductions in density are similar in magnitude to previous increases, thought to have driven an increase in the AMOC during the early 1990s (Robson et al., 2012). They also use a comparison of the recent direct observations with eight-year trends from CMIP5 models to assess the potential role of internal variability, concluding that the observed trend since 2004 is not significantly different from internal variability, and that a longer period of continuous observations will be needed to detect any influence of anthropogenic forcing on the AMOC. Therefore, the implications of the recent decline remain uncertain.

Potential carbon release through the melting of permafrost or destabilisation of ocean methane hydrates is not accounted for in UKCP09 or CMIP5 projections, with the former likely to play a significant role in determining CO₂ concentrations and global warming during the 21st century. CMIP5 Earth system models and the UKCP09 probabilistic projections do account for the uncertain effects of projected changes in tropical forest, as a component of their representation of the global carbon cycle. In UKCP09, carbon cycle feedbacks are accounted for insofar as they affect global CO₂ concentration and future global mean temperature changes, and are an important driver of uncertainty in the latter (Harris et al., 2013). However, effects on regional patterns of change (e.g. Murphy et al., 2014) were not accounted for. Carbon cycle uncertainties, particularly in how land storage will respond to elevated atmospheric CO₂, remain highly uncertain in CMIP5 (Ciais et al., 2013). Furthermore, some important processes are not yet included in Earth system models, limiting the confidence that can be placed in current projections. For example, only two CMIP5 models account for the effects on plant growth of the nitrogen cycle, which can either limit future carbon uptake by vegetation or stimulate it, depending on changes in nitrogen availability.

While complete collapse of the Greenland or Antarctic ice sheets during the 21st century is assessed as *exceptionally unlikely* (Table 1.A2), ice sheets are recognised as the largest and most uncertain potential source of future sea level rise on the millennial time scale. Rignot et al. (2014) and Joughin et al. (2014) report rapid retreat in the grounding line of several glaciers in West Antarctica during recent decades, concluding that there is no obvious physical obstacle to further retreat in the future, leading eventually to instability of the marine ice sheet in this sector of West Antarctica. This is expected to contribute significantly to future sea level rise, on a time scale of several centuries. Cornford et al. (2015) project a maximum increase of close to 0.5m by

2200 in dynamic simulations of the West Antarctic ice sheet (WAIS), while DeConto and Pollard (2016) provide the first ice sheet model simulation to account for the destabilising effects of future atmospheric warming on buttressing ice shelves and marine-terminating ice cliffs. They predict an Antarctic contribution of around 1m to sea level rise by 2100, if emissions increase rapidly during the 21st century. Feldmann and Levermann (2015) predict a long-term increase of 3m if the entire marine ice sheet discharges into the ocean, although the time scale (of centuries to several millennia) is highly uncertain. Joughin et al. (2014) stress the uncertainty in the time scale (200 to 900 years) for complete collapse of the Thwaites Glacier, a key component of the WAIS.

Analysis of sediment cores by Reyes et al. (2014) showed that the south Greenland ice sheet was much smaller during the period 400,000-410,000 years ago, when global temperature was a few degrees warmer than at present. The global warming threshold leading to an irreversible melting of the Greenland ice sheet (GIS) is uncertain. Robinson et al. (2012) suggest a 95% credible interval of 0.8-3.2°C, for warming relative to pre-industrial conditions. While complete melting of the GIS would contribute about 7m to global sea level rise, this would probably take several millennia to occur. Simulations by Ridley et al. (2005) suggested that melting half the GIS would take 800 years, while those of Vizcaino et al. (2015) suggest a contribution of 0.5m by 2300 under the RCP8.5 scenario. Freshwater runoff from melting Greenland ice will potentially contribute to future weakening of the AMOC, but this mechanism is not included in standard climate model projections from UKCP09 or CMIP5, due to the lack of dynamic ice sheet components in the underpinning earth system models.

Another potential climate surprise is raised by the recent decline in solar activity. This has led to a statistical assessment of an 8% probability of a return to Maunder Minimum-like conditions during the next 40 years (Lockwood, 2010). Ineson et al. (2015) report a climate model study of the regional surface climate impacts of a potential future Maunder Minimum. They find little impact on GMST, but a winter cooling over northern Eurasia and the eastern United States. The model response resembles the negative phase of the NAO (see Section 1.A2), consistent with the expected dynamic effects of a reduction in ultraviolet solar irradiance. For a high-end estimate of the latter, the simulated winter cooling during the second half of the 21st century is comparable to the difference in projected response between the RCP4.5 and RCP6.0 scenarios, and about 30% of the difference between the RCP8.5 and 4.5 responses.

The discussion in this section underlines that the data available for quantitative risk analysis from climate model projections does not cover all possible low-probability events, and is conditional on the scope and understanding of Earth system processes encoded in current climate models. This knowledge is incomplete in a number of aspects, and subject to change as new observations, research and insight become available.

Annex 1.B: Acknowledgements

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