Developed at the request of:

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Climate: Observations, projections and impacts: United Kingdom

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The country reports were written by a range of climate researchers, chosen for their subject expertise, who were drawn from institutes across the UK. Authors from the Met Office and the University of Nottingham collated the contributions in to a coherent narrative which was then reviewed. The authors and contributors of the reports are as above.

Developed at the request of:

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Research conducted by:

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UNITED KINGDOM · CHINA · MALAYSIA

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Climate: Observations, projections and impacts

United Kingdom

We have reached a critical year in our response to climate change. The decisions that we made in Cancún put the UNFCCC process back on track, saw us agree to limit temperature rise to 2 °C and set us in the right direction for reaching a climate change deal to achieve this. However, we still have considerable work to do and I believe that key economies and major emitters have a leadership role in ensuring a successful outcome in Durban and beyond.

To help us articulate a meaningful response to climate change, I believe that it is important to have a robust scientific assessment of the likely impacts on individual countries across the globe. This report demonstrates that the risks of a changing climate are wide-ranging and that no country will be left untouched by climate change.

I thank the UK's Met Office Hadley Centre for their hard work in putting together such a comprehensive piece of work. I also thank the scientists and officials from the countries included in this project for their interest and valuable advice in putting it together. I hope this report will inform this key debate on one of the greatest threats to humanity.

The Rt Hon. Chris Huhne MP, Secretary of State for Energy and Climate Change

There is already strong scientific evidence that the climate has changed and will continue to change in future in response to human activities. Across the world, this is already being felt as changes to the local weather that people experience every day.

Our ability to provide useful information to help everyone understand how their environment has changed, and plan for future, is improving all the time. But there is still a long way to go. These reports – led by the Met Office Hadley Centre in collaboration with many institutes and scientists around the world – aim to provide useful, up to date and impartial information, based on the best climate science now available. This new scientific material will also contribute to the next assessment from the Intergovernmental Panel on Climate Change.

However, we must also remember that while we can provide a lot of useful information, a great many uncertainties remain. That's why I have put in place a long-term strategy at the Met Office to work ever more closely with scientists across the world. Together, we'll look for ways to combine more and better observations of the real world with improved computer models of the weather and climate; which, over time, will lead to even more detailed and confident advice being issued.

Julia Slingo, Met Office Chief Scientist

Introduction

Understanding the potential impacts of climate change is essential for informing both adaptation strategies and actions to avoid dangerous levels of climate change. A range of valuable national studies have been carried out and published, and the Intergovernmental Panel on Climate Change (IPCC) has collated and reported impacts at the global and regional scales. But assessing the impacts is scientifically challenging and has, until now, been fragmented. To date, only a limited amount of information about past climate change and its future impacts has been available at national level, while approaches to the science itself have varied between countries.

In April 2011, the Met Office Hadley Centre was asked by the United Kingdom's Secretary of State for Energy and Climate Change to compile scientifically robust and impartial information on the physical impacts of climate change for more than 20 countries. This was done using a consistent set of scenarios and as a pilot to a more comprehensive study of climate impacts. A report on the observations, projections and impacts of climate change has been prepared for each country. These provide up to date science on how the climate has already changed and the potential consequences of future changes. These reports complement those published by the IPCC as well as the more detailed climate change and impact studies published nationally.

Each report contains:

- A description of key features of national weather and climate, including an analysis of new data on extreme events.

- An assessment of the extent to which increases in greenhouse gases and aerosols in the atmosphere have altered the probability of particular seasonal temperatures compared to pre-industrial times, using a technique called 'fraction of attributable risk.'

- A prediction of future climate conditions, based on the climate model projections used in the Fourth Assessment Report from the IPCC.

- The potential impacts of climate change, based on results from the UK's Avoiding Dangerous Climate Change programme (AVOID) and supporting literature.
  For details visit: http://www.avoid.uk.net

The assessment of impacts at the national level, both for the AVOID programme results and the cited supporting literature, were mostly based on global studies. This was to ensure consistency, whilst recognising that this might not always provide enough focus on impacts of most relevance to a particular country. Although time available for the project was short, generally all the material available to the researchers in the project was used, unless there were good scientific reasons for not doing so. For example, some impacts areas were omitted, such as many of those associated with human health. In this case, these impacts are strongly dependant on local factors and do not easily lend themselves to the globally consistent framework used. No attempt was made to include the effect of future adaptation actions in the assessment of potential impacts. Typically, some, but not all, of the impacts are avoided by limiting global average warming to no more than 2 °C.

The Met Office Hadley Centre gratefully acknowledges the input that organisations and individuals from these countries have contributed to this study. Many nations contributed references to the literature analysis component of the project and helped to review earlier versions of these reports.

We welcome feedback and expect these reports to evolve over time. For the latest version of this report, details of how to reference it, and to provide feedback to the project team, please see the website at www.metoffice.gov.uk/climate-change/policy-relevant/obs-projections-impacts

In the longer term, we would welcome the opportunity to explore with other countries and organisations options for taking forward assessments of national level climate change impacts through international cooperation.

Summary

Climate observations

- There has been warming over the UK since 1960 with greater warming in summer than winter.
- Since 1960 there has been a decreasing trend in the frequency of cool nights and cool days and an increasing trend in the frequency of warm nights and warm days.
- There has been a general increase in summer temperatures averaged over the country as a result of human influence on climate, making the occurrence of warm summer temperatures more frequent and cold summer temperatures less frequent.

Climate change projections

- For the A1B emissions scenario the UK is projected to experience temperature increases of up to around 3°C in the south and 2.5°C further north. The agreement between models is moderate in the south of the UK and low further north.

- Europe shows a strong contrast in projected precipitation changes, with large decreases in the south and large increases in the north. The UK falls towards the northern region with generally increasing precipitation, with projected increases of up to 10%, though some southern parts of the UK may experience decreases of up to 5%. There is generally good agreement between ensemble members over the north of UK, but moderate agreement further south, indicating uncertainty in the position of the transition zone between increasing and decreasing precipitation over Europe.

Climate change impacts projections

Crop yields

- A definitive conclusion on the impact of climate change on crop yields in the UK cannot be drawn from the studies included here. There is some indication from global- and regional-scale studies for a difference in yield changes between the north and south of the UK. For instance, yield increases are projected for Northern Ireland and Scotland but declines projected in the South of England with climate change.

Food security

- The UK is currently a country with extremely low levels of undernourishment. Global-scale studies included here generally project that the UK is likely to remain food secure over the next 40 years, largely due to its high adaptive capacity associated with an ability to import food.

- Simulations from the AVOID programme project that population increases coupled with potential declines in crop yields by the 2080s could increase exposure to undernourishment in the UK, and that structural adjustment will be instrumental in decreasing exposure.

Water stress and drought

- Global- and national-scale studies included here project that the vulnerability to water stress with climate change is mainly focussed in the south and south-east of the UK. These regions are projected to experience an increase in the frequency of droughts and water stress with climate change. However, the rest of the UK may be relatively unaffected by changes in water availability with climate change.

- Recent simulations by the AVOID programme project that the UK could experience a moderate increase in water stress with climate change, although the median estimate of the models used suggests no increase in water stress with climate change for the UK by 2100.

Pluvial flooding and rainfall

- Rainfall extremes are generally projected to increase, particularly during winter, with changes during summer are more uncertain.

Fluvial flooding

- Several European-scale and national-scale assessments suggest an increase in flood risk with climate change in the UK.

- Simulations from the AVOID programme support this. For the UK as a whole, the projections show a much greater tendency for increasing flood risk, particularly later in the century and particularly in the A1B scenario.

- However, national-scale studies have also shown that the UK exhibits a high degree of spatial variability in the sensitivity of rivers to changes in climate, and projections of changes in flood hazard show large uncertainty, which is mainly due to climate modelling uncertainty.

- This supports conclusions from the IPCC AR4 but now more regional detail across the UK is available.

Coastal regions

- Several global-scale and regional-scale assessments suggest that without adaptation, the UK could experience major impacts on coastal flooding from sea level rise (SLR).

- For example, one study shows that by the 2080s under a high SLR scenario and without adaptation, the average annual number of people flooded in the UK could be around 986,300; this is greatly reduced with adaptation (raising of flood dykes and the application of beach nourishment), to around 5,600.

- New work also demonstrates the potential benefits of climate change mitigation policy. For example, one study shows that aggressive mitigation policy could avoid an exposure of around 51,000 people to SLR in the UK, relative to un-mitigated climate change.

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Chapter 1 – Climate Observations

Rationale

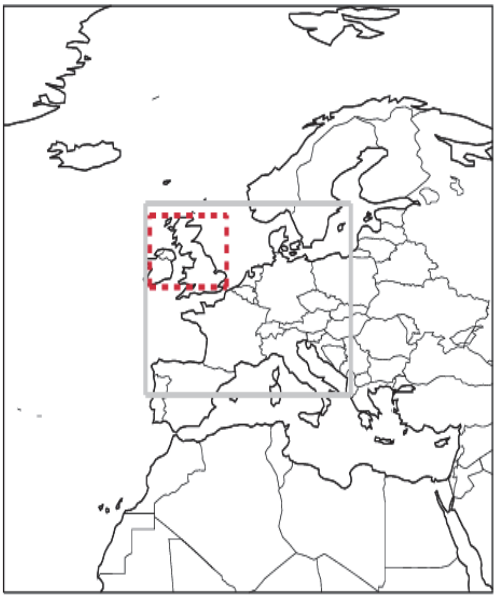


Figure 1. Location of boxes for the regional average time series (red dashed box) in Figures 3, 4, 5 and 7 and the attribution region (grey box) in Figure 6.

Present day weather and climate play a fundamental role in the day to day running of society. Seasonal phenomena may be advantageous and depended upon for sectors such as farming or tourism. Other events, especially extreme ones, can sometimes have serious negative impacts posing risks to life and infrastructure and significant cost to the economy. Understanding the frequency and magnitude of these phenomena, when they pose risks or when they can be advantageous and for which sectors of society, can significantly improve societal resilience. In a changing climate it is highly valuable to understand possible future changes in both potentially hazardous events and those reoccurring seasonal events that are depended upon by sectors such as agriculture and tourism. However, in order to put potential future changes in context, the present day must first be well understood both in terms of common seasonal phenomena and extremes.

The purpose of this chapter is to summarise the weather and climate from 1960 to present day. This begins with a general climate overview including an up to date analysis of changes in surface mean temperature. These changes may be the result of a number of factors including climate change, natural variability and changes in land use. There is then a focus on extremes of temperature, precipitation and storms selected from 2000 onwards, reported in the World Meteorological Organization (WMO) Annual Statement on the Status of the Global Climate and/or the Bulletin of the American Meteorological Society (BAMS) State of the Climate reports. This is followed by a discussion of changes in moderate extremes from 1960 onwards using an updated version of the HadEX extremes database (Alexander et al. 2006) which categorises extremes of temperature and precipitation. These are core climate variables which have received significant effort from the climate research community in terms of data acquisition and processing and for which it is possible to produce long high quality records for monitoring. No new analysis is included for storms (see the methodology section that follows for background). For seasonal temperature extremes, an attribution analysis then puts the seasons with highlighted extreme events into context of the recent climate versus a hypothetical climate in the absence of anthropogenic emissions (Christidis et al, 2011). It is important to note that we carry out our attribution analyses on seasonal mean temperatures over the entire country. Therefore these analyses do not attempt to attribute the changed likelihood of individual extreme events. The relationship between extreme events and the large scale mean temperature is likely to be complex, potentially being influenced by *inter alia* circulation changes, a greater expression of natural internal variability at smaller scales, and local processes and feedbacks. Attribution of individual extreme events is an area of developing science. The work presented here is the foundation of future plans to systematically address the region's present and projected future weather and climate, and the associated impacts.

The methodology section provides details of the data shown here and of the scientific analyses underlying the discussions of changes in the mean temperature and in temperature and precipitation extremes. It also explains the methods used to attribute the likelihood of occurrence of seasonal mean temperatures.

Climate overview

The United Kingdom (UK) is located between 50° to 60°N, with westerlies from the Atlantic dominating between high pressure to the south and the Icelandic Low to the north. It is composed of one large island and a large number of small islands, so there is a maritime influence on the climate. As well as this, there is relatively high ground in the west, including mountains in Wales, north-west England and Scotland, where the mountains reach up to 1300m above sea level.

The Gulf Stream is an ocean current from the Atlantic which has a warming effect on the UK, especially bringing mild winters for its latitude. Latitude and altitude are the main influences on the temperature, with mean temperature decreasing with increasing latitude and altitude. The combination of southerly latitude and the urban heat island effect means that London is the warmest place in the UK, with an annual mean temperature of 11°C, ranging from 5°C in January to 18°C in July. In the winter, coastal areas are milder as their temperatures are moderated by the relatively warm sea, so coastal areas of south-west England are the mildest in winter. Further north, Manchester has an annual mean temperature of 9.5°C, Edinburgh 8.5°C, and Stornoway in the far north-west 8°C. Scotland has very mountainous terrain, and the annual mean temperature reduces to 6°C at Braemar in central Scotland at an altitude of 340m, with a January mean of only 1°C. Frost can occur anywhere in the UK, but is most common away from the coast.

The UK weather is very changeable and cloud and rain occur frequently at all times of the year. The high ground in the west of the UK leaves the east in a rain shadow from the prevailing westerlies, so that there is a distinct west-east pattern to average rainfall amounts. The orographic enhancement means that the wettest places are in west Scotland, north-west England and north Wales, with annual average rainfall of over 3000 mm in places. More typical of western locations are the annual average amounts, decreasing from north to south, of Stornoway (1170 mm), Glasgow (1050 mm), Manchester (810 mm) and Exeter (760 mm). In the east, annual average rainfall amounts are 670 mm at Edinburgh and 610 mm at London, with parts of East Anglia having totals down to 500 mm. Autumn and winter tend to be the wettest seasons, with the rainfall coming from frontal systems. In the summer there is still a moderate amount of rainfall, much of which comes as heavy showers from convective activity.

Occasionally, the continental influence of Europe can bring settled spells of hot weather in summer, and cold spells in winter. In the winter, snow storms occasionally bring disruption to southern England, but snow is most common in Scotland and at higher altitudes. Heavy rain can lead to flooding, and dry spells can also be a problem. Atlantic storms bring strong winds in autumn and winter.

Analyses of long-term features in the mean temperature

CRUTEM3 data (Brohan et al., 2006) have been used to provide an analysis of mean temperatures from 1960 to 2010 over the UK using the median of pairwise slopes method to fit the trend (Sen, 1968; Lanzante, 1996). The methods are fully described in the methodology section. In concert with increasing global average temperatures (Sánchez-Lugo et al. 2011), there is a spatially consistent warming signal for temperature over the UK as shown in Figure 2. Grid boxes in which the 5^{th} to 95^{th} percentiles of the slopes are of the same sign can be more confidently regarded as showing this signal: they are widespread for summer (June to August) but more sporadic for winter (December to February). Regionally averaged trends (over grid boxes included in the red dashed box in Figure 1) show warming signals with higher confidence. For winter this trend is 0.23 ^{o}C per decade (5^{th} to 95^{th} percentile of slopes: 0.04 to 0.42 ^{o}C per decade) and for summer this trend is 0.28 ^{o}C per decade (5^{th} to 95^{th} percentile of slopes: 0.16 to 0.40 ^{o}C per decade).

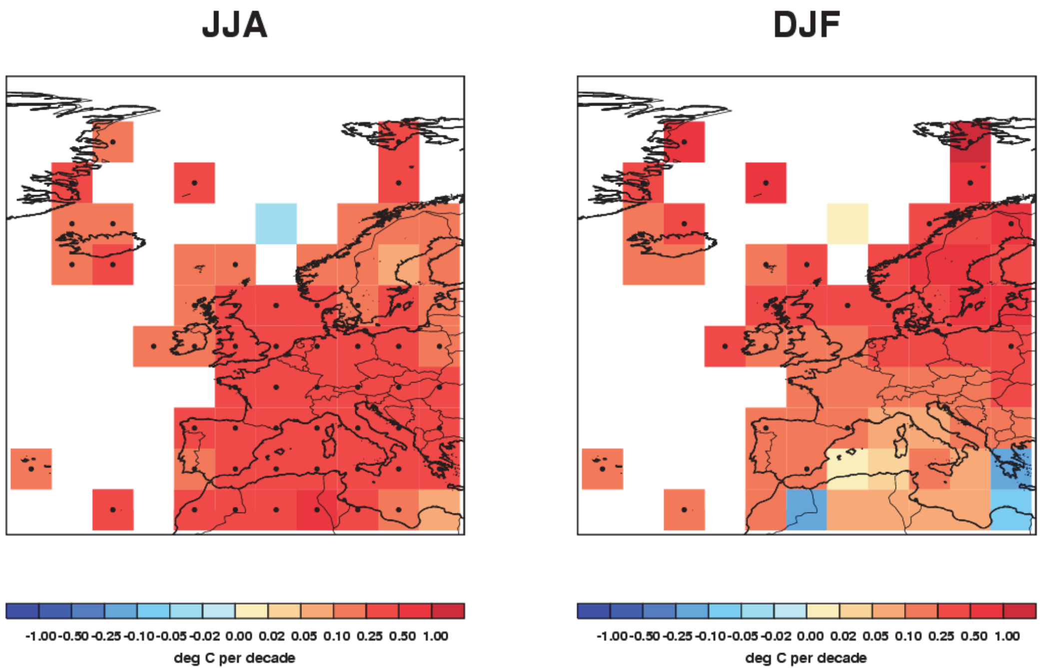


Figure 2. *Decadal trends in seasonally averaged temperatures for the UK and surrounding regions over the period 1960 to 2010. Monthly mean anomalies from CRUTEM3 (Brohan et al. 2006) are averaged over each 3 month season (June-July-August – JJA and December-January-February – DJF). Trends are fitted using the median of pairwise slopes method (Sen 1968, Lanzante 1996). There is high confidence in the trends shown if the 5th to 95th percentiles of the pairwise slopes do not encompass zero because here the trend is considered to be significantly different from a zero trend (no change). This is shown by a black dot in the centre of the respective grid-box.*

Temperature extremes

Both hot and cold temperature extremes can place many demands on society. While seasonal changes in temperature are normal and indeed important for a number of societal sectors (e.g. tourism, farming etc.), extreme heat or cold can have serious negative impacts. Importantly, what is ‘normal’ for one region may be extreme for another region that is less well adapted to such temperatures.

Table 1 shows selected extreme events since 2000 that are reported in WMO Statements on Status of the Global Climate and/or BAMS State of the Climate reports. The heat wave of summer 2003 and the cold spell of December 2010 are highlighted below as examples of temperature extremes which affect the UK.

Year	Month	Event	Details	Source
2003	Jun-Aug	Heat wave	At many locations, temperatures almost reached 40°C. Across France, Italy, The Netherlands, Portugal, Spain and the UK over 21,000 deaths were related to the heat.	WMO (2004)
2006	Jul	Heat wave	Western Europe experienced a summer heat wave; warmest European mean temperature for July	WMO (2007)
2008/9	Dec-Feb	Cold	The most prolonged spell of freezing temperatures and snowfall across the UK since winter 1981/82. The worst snowstorm experienced since Feb 1991.	WMO (2010)
2009	Dec	Cold	Coldest December since 1995.	WMO (2010)
2010	Dec	Cold	Coldest winter since 1978/1979; coldest December in 100 years.	WMO (2011)

Table 1: *Selected extreme temperature events reported in WMO Statements on Status of the Global Climate and/or BAMS State of the Climate reports since 2000.*

Recent extreme temperature events

Heat wave, summer 2003

The summer of 2003 was one of the warmest on record across parts of Europe, and in parts of Central Europe was likely the warmest since 1540 (Levinson and Waple, 2004).Two distinct periods of exceptional heat occurred during the summer season— the first in June and the second during the first half of August. The heat waves resulted from strong high pressure over Western Europe. Such "blocking highs" can persist for many days in Europe during summer. In 2003, heated air from the south reinforced the strength and persistence of the heat wave, and nearly all the sun's radiation was converted to heat because of the soil and vegetation dryness. The August heat wave was the more serious of the two, because it coincided with the normal peak in summer temperatures and was accompanied by an almost complete absence of rainfall. At many locations, temperatures rose above 40°C. In France, Italy, The Netherlands, Portugal, Spain and the United Kingdom over 21,000 additional deaths were related to the unrelenting heat (WMO, 2004).

Several weather records were broken in the United Kingdom, with the UK recording its highest temperature of 38.5 °C at Brogdale near Faversham, in Kent, on 10th August. Across the UK, on three consecutive days 32 °C was exceeded from 4-6th August, and then again on five consecutive days between 8-12th August; temperatures failed to reach 32 °C at any real-time stations on 7th August (UK Met Office, 2011a).

There were over 2,100 excess deaths in England and Wales, with those worst affected being over the age of 75. The impact was greatest in the London region where deaths in those over 75 years increased by 59% compared to 2002 (Johnson et al., 2005). Other impacts caused by the heat wave included disruption to transport networks. For example, the BBC reported that delays were caused on the railways due to speed restrictions imposed at noon each day while temperatures were above 30°C (BBC, 2003).

The heat wave had a major effect on mortality in the UK, but not to the extent of that observed in France where high temperatures were maintained for much longer (Johnson et al, 2005).

Extreme cold, December 2010

Severe winter weather affected Western and Central Europe throughout the first three weeks of December 2010, with the UK experiencing the coldest December for more than 100 years and the second coldest in the 352-year Central England Temperature series (Maier et al., 2011). Across much of the country temperatures regularly fell to between -10 and -20 °C overnight and many places also saw temperatures struggling to get above freezing by day (UK Met Office, 2011d).

This extreme cold weather was due to advection of cold arctic air associated with a strongly negative Arctic Oscillation (Maier et al., 2011). The UK experienced two spells of severe winter weather with very low temperatures and significant snowfalls. The first of these spells lasted for two weeks from 25th November and saw persistent easterly or north-easterly winds bring bitterly cold air from northern Europe and Siberia. This spell of snow and freezing temperatures occurred unusually early in the winter, with the most significant and widespread snowfalls experienced in late November and early December since late November 1965 (UK Met Office, 2011e).

From 9th-15th December conditions were milder with a gradual thaw of lying snow. However, a second spell of severe weather began on 16th December as very cold Arctic air pushed down across the UK from the north. The UK remained under bitterly cold Arctic air until Boxing Day, with daytime temperatures again failing to rise above freezing. While there was little further snowfall, lying snow remained until 27th December (UK Met Office, 2011e).

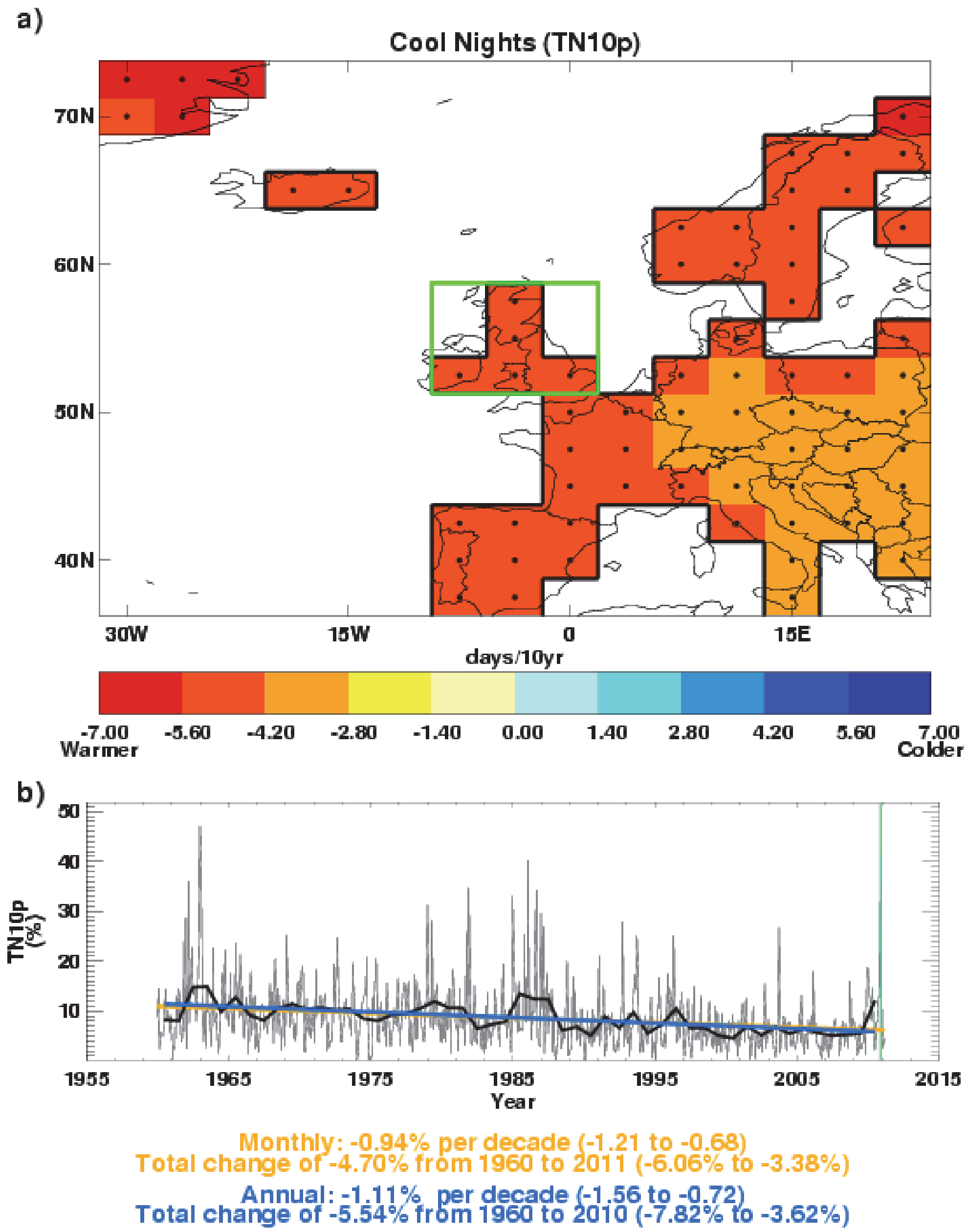
Mean temperatures over the UK were 5.0 °C below average for December (UK Met Office, 2011f), and on 28th December, the lowest temperature ever recorded in Northern Ireland was measured with -18°C at Castlederg (Maier et al., 2011).

The freezing conditions caused widespread impacts throughout the UK, with the emergency services, local authorities, transport networks and utilities all under great pressure. Snowfalls caused the most problems for transport, with road, rail and air all badly affected. Schools were also closed and hospital admissions increased markedly due to accidents and falls on the ice. The freezing temperatures also caused problems with water supplies (UK Met Office, 2011e).

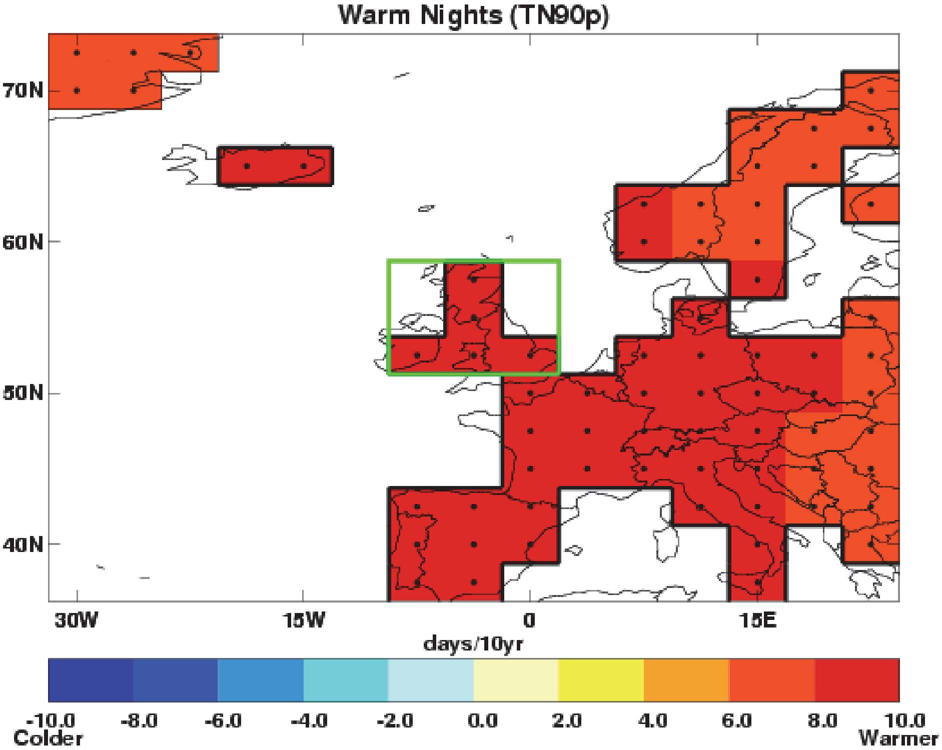
Analysis of long-term features in moderate temperature extremes

ECA&D data (Klein Tank et al. 2002) have been used to update the HadEX extremes analysis for the UK from 1960 to 2010 using daily maximum and minimum temperatures. Here we discuss changes in the frequency of cool days and nights and warm days and nights which are moderate extremes. Cool days/nights are defined as being below the 10th percentile of daily maximum/minimum temperature and warm days/nights are defined as being above the 90th percentile of the daily maximum/minimum temperature. The methods are fully described in the methodology section.

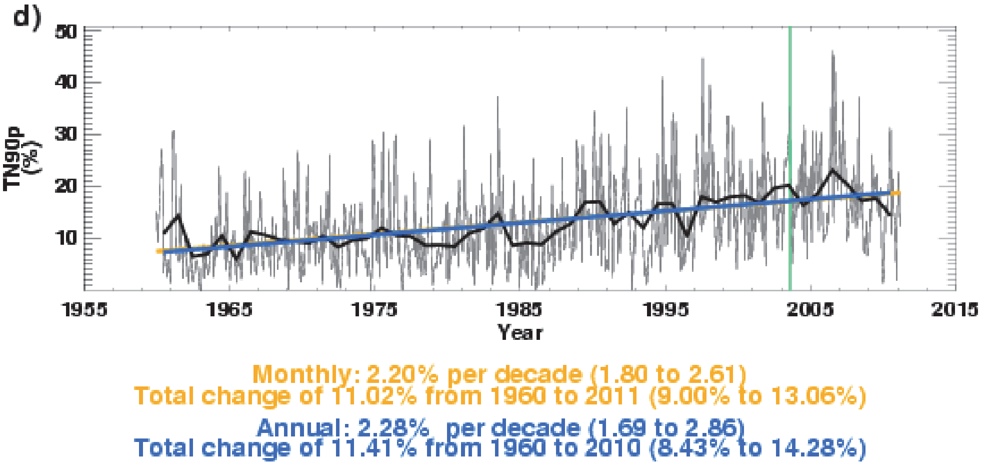
The trends in the temperature indices over the period from 1960 are consistent with a warming signal. The numbers of cool nights and cool days are decreasing, and the numbers of warm nights and warm days are increasing, with higher confidence in the trend being different to zero throughout the country. The variation in the size of the trend is small and there is no clear difference across the UK (Figure 3).


a)
Cool Nights (TN10p)
70N
60N
50N
40N
30W
15W
0
15E
days/10yr
-7.00
Warmer
-5.60
-4.20
-2.80
-1.40
0.00
1.40
2.80
4.20
5.60
7.00
Colder
b)
TN10p (%)
50
40
30
20
10
1955
1965
1975
1985
1995
2005
2015
Year
Monthly: -0.94% per decade (-1.21 to -0.68)
Total change of -4.70% from 1960 to 2011 (-6.06% to -3.38%)
Annual: -1.11% per decade (-1.56 to -0.72)
Total change of -5.54% from 1960 to 2010 (-7.82% to -3.62%)

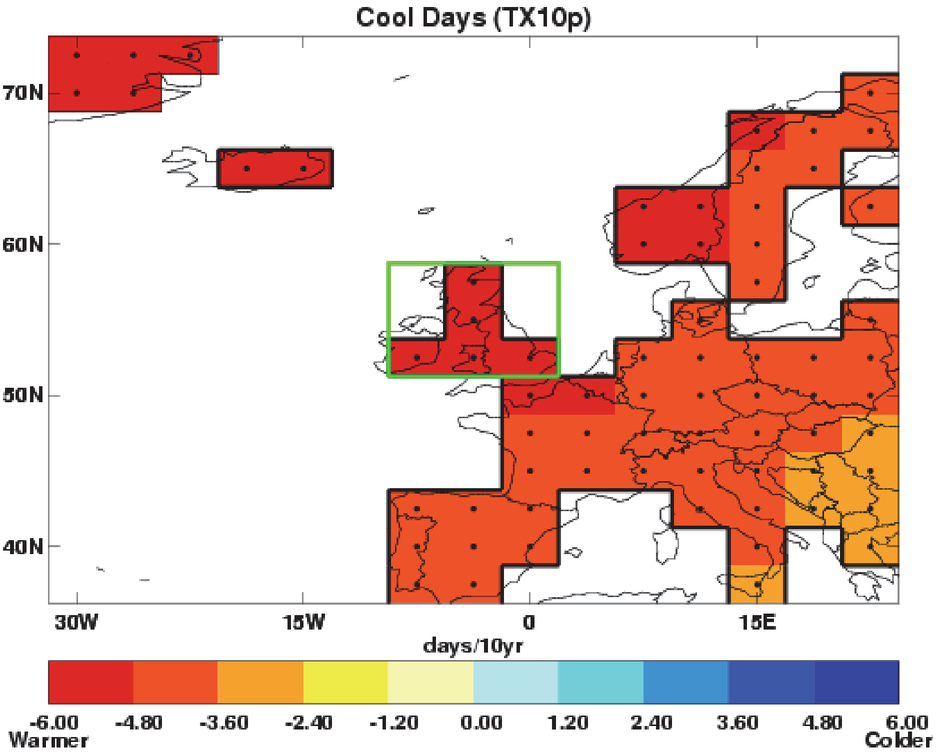
c)


Warm Nights (TN90p)
70N
60N
50N
40N
30W
15W
0
15E
days/10yr
-10.0
Colder
-8.0
-6.0
-4.0
-2.0
0.0
2.0
4.0
6.0
8.0
10.0
Warmer

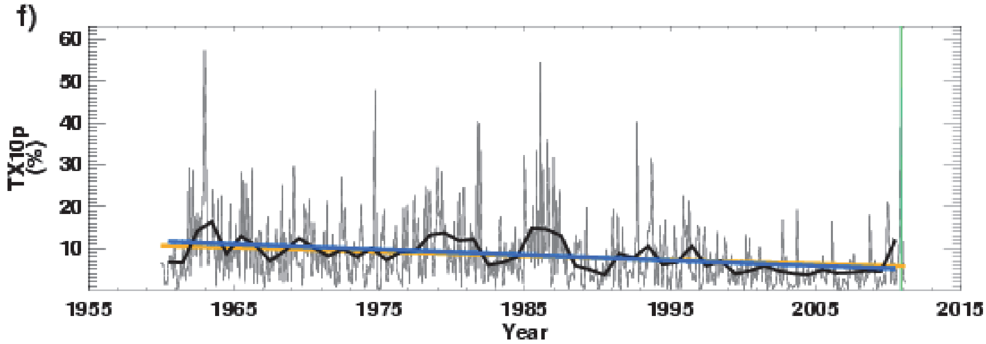
d)


TN90p (%)
50
40
30
20
10
1955
1965
1975
1985
1995
2005
2015
Year
Monthly: 2.20% per decade (1.80 to 2.61)
Total change of 11.02% from 1960 to 2011 (9.00% to 13.06%)
Annual: 2.28% per decade (1.69 to 2.86)
Total change of 11.41% from 1960 to 2010 (8.43% to 14.28%)

e)



f)



Monthly: -0.96% per decade (-1.23 to -0.68)
Total change of -4.78% from 1960 to 2011 (-6.17% to -3.41%)

Annual: -1.30% per decade (-1.80 to -0.79)
Total change of -6.48% from 1960 to 2010 (-9.02% to -3.95%)

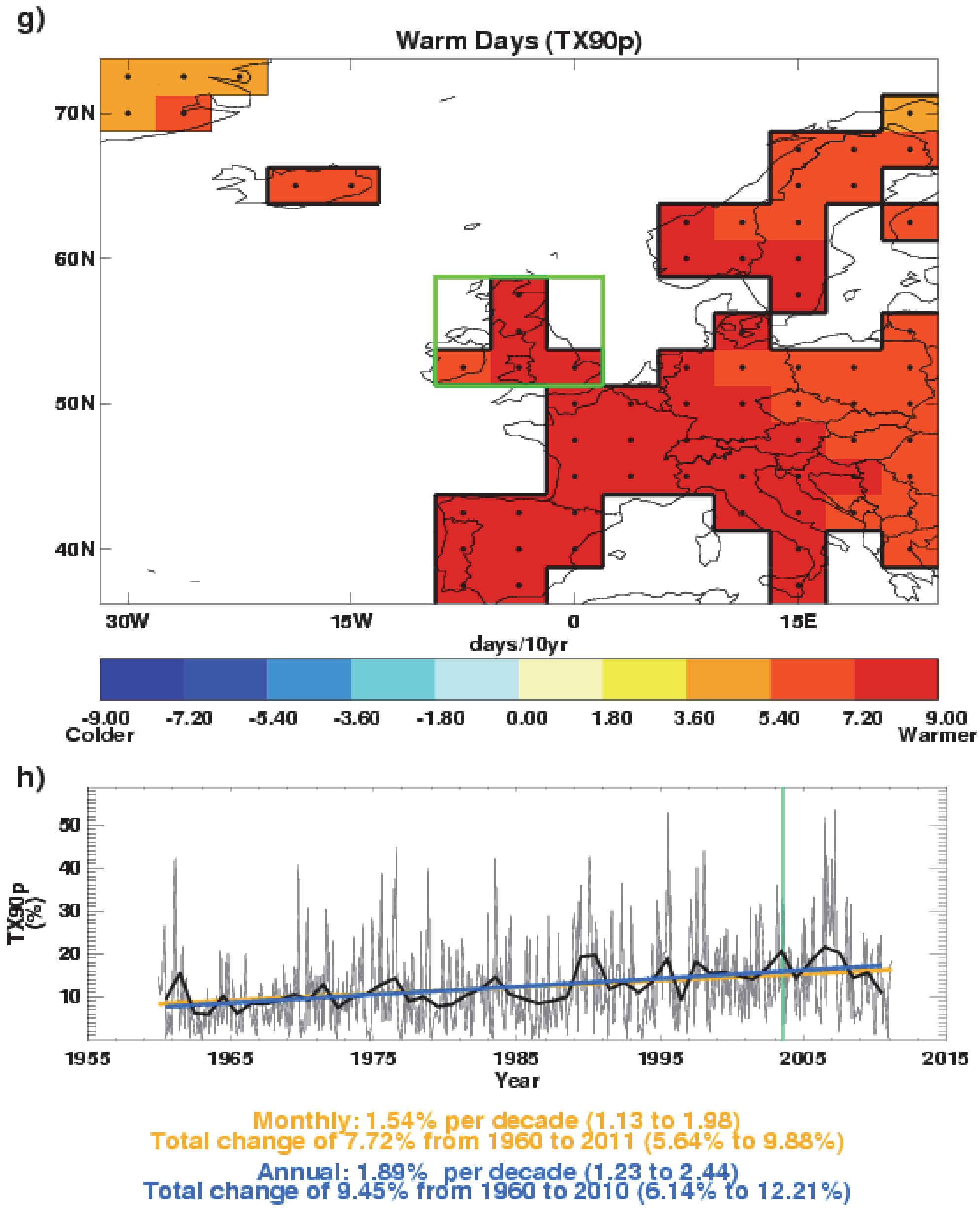


Figure 3. *Change in cool nights (a,b), warm nights (c,d), cool days (e,f) and warm days (g,h) for the UK over the period 1960 to 2010 relative to 1961-1990 from the ECA&D dataset (Klein Tank et al. 2002). a,c,e,g) Grid-box decadal trends. Grid-boxes outlined in solid black contain at least 3 stations and so are likely to be more representative of the wider grid-box. Trends are fitted using the median of pairwise slopes method (Sen 1968, Lanzante 1996). High confidence in a long-term trend is shown by a black dot if the 5th to 95th percentile slopes are of the same sign. Differences in spatial coverage occur because each index has its own decorrelation length scale (see the methodology section). b,d,f,h) Area averaged annual time series for 9.375° W to 1.875° E and 48.75° to 58.75° N as shown by the green box on the map and red box in Figure 1. Thin and thick black lines show the monthly and annual variations respectively. Monthly (orange) and annual (blue) trends are fitted as described above. The decadal trend and its 5th to 95th percentile confidence intervals are stated along with the change over the period for which there are data available. All the trends have higher confidence that they are different from zero as their 5th to 95th percentile slopes are of the same sign. The green vertical lines show the dates of the cold December of 2010 for the cool days and cool nights, and the heat wave in 2003 for the warm days and warm nights.*

The winter time-series show a decrease in the number of cool days and cool nights, but this has higher confidence in the number of cool days than cool nights (Figure 4). The cold winters of 2009 and 2010 stand out clearly from the previous decade. The summer time-series for the numbers of warm days and nights show a clear increase over the period (Figure 5). The heat wave of 2003 is clearly visible in the number of warm nights, but it is not so clear in the number of warm days.

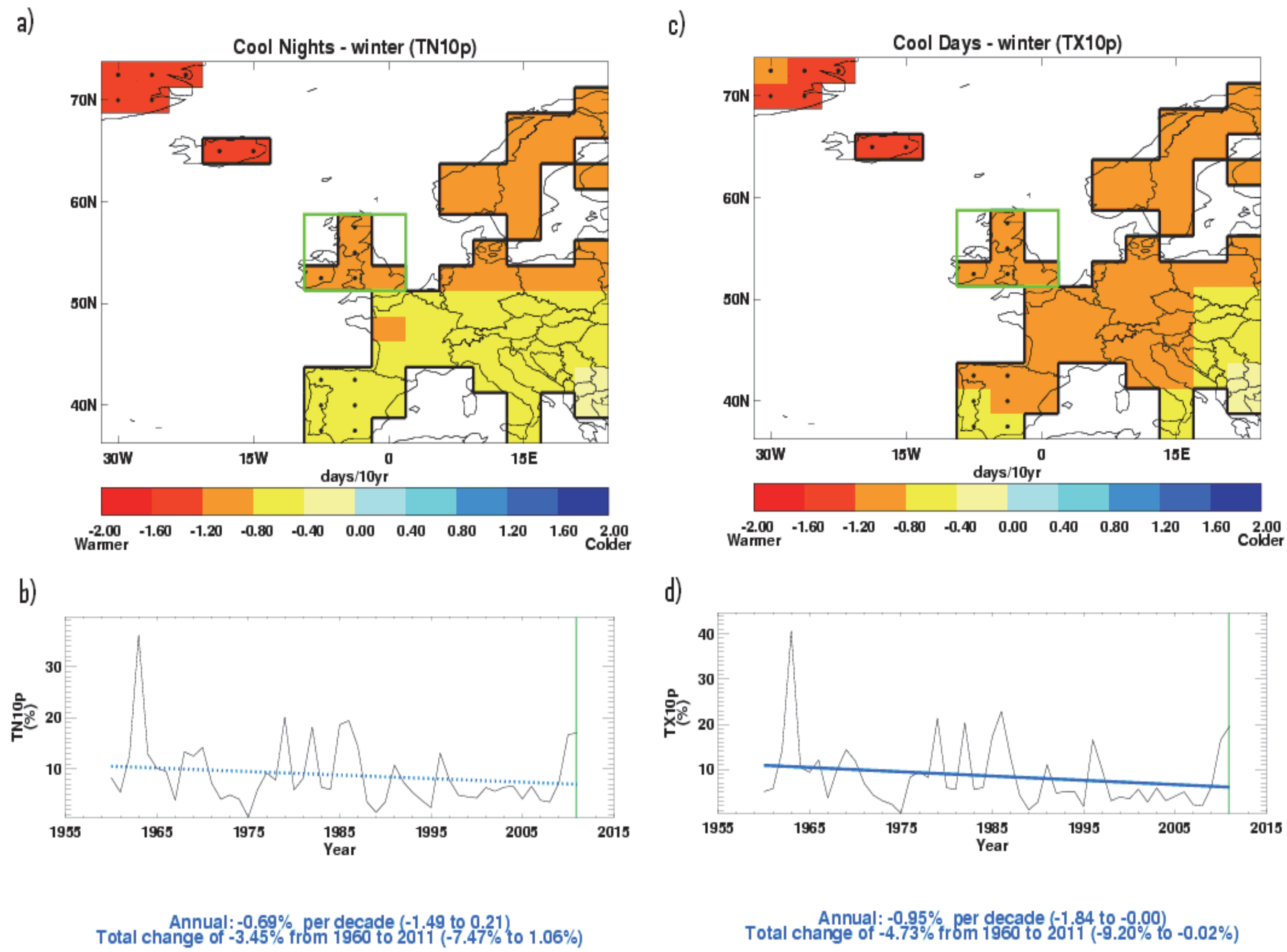


Figure 4. *The decadal change in cool nights (a,b), cool days(c,d) for winter in the UK. The maps and time-series have been created in exactly the same way as Figure 3. The vertical lines show the dates of the cold winters of 2010/11. There is lower confidence that the trend in the number of cool nights is different from zero, as the 5th to 95th percentile slopes are of different signs, and hence it is marked with a dotted line.*

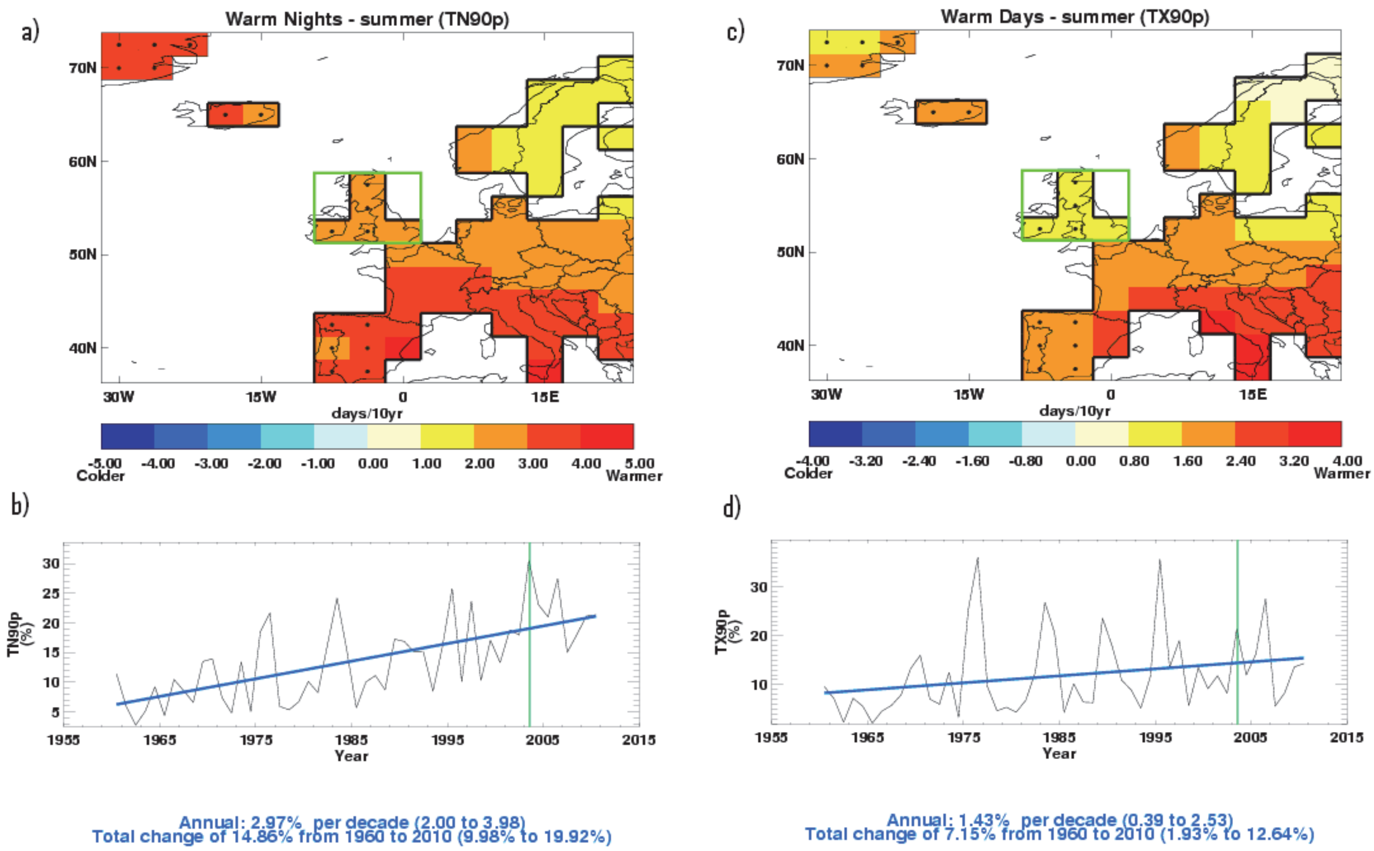


Figure 5. *The decadal change in warm nights (a,b) and warm days (c,d) for summer for the UK. The maps and time-series have been created in exactly the same way as Figure 3. The vertical lines show the date of the heat wave of 2003.*

Attribution of changes in likelihood of occurrence of seasonal mean temperatures

Today's climate covers a range of likely extremes. Recent research has shown that the temperature distribution of seasonal means would likely be different in the absence of anthropogenic emissions (Christidis et al., 2011). Here we discuss the seasonal means, within which the highlighted extreme temperature events occur, in the context of recent climate and the influence of anthropogenic emissions on that climate. The methods are fully described in the methodology section.

Summer 2003

The distributions of the summer mean regional temperature in recent years in the presence and absence of anthropogenic forcings are shown in Figure 6. Analyses with both models suggest that human influences on the climate have shifted the distribution to higher temperatures. Considering the average over the entire Northern European region, the 2003 summer is exceptionally hot, as it lies at the far end of the warm tail of the temperature distributions for the climate influenced by anthropogenic forcings (red distributions) and is the hottest since 1900 in the CRUTEM3 dataset. In the absence of human influences on the climate (green distributions), the season would be even more extreme. It should be noted that the attribution results shown here refer to temperature anomalies over the entire region and over an entire season, whereas the actual extreme event had a shorter duration and affected a smaller region.

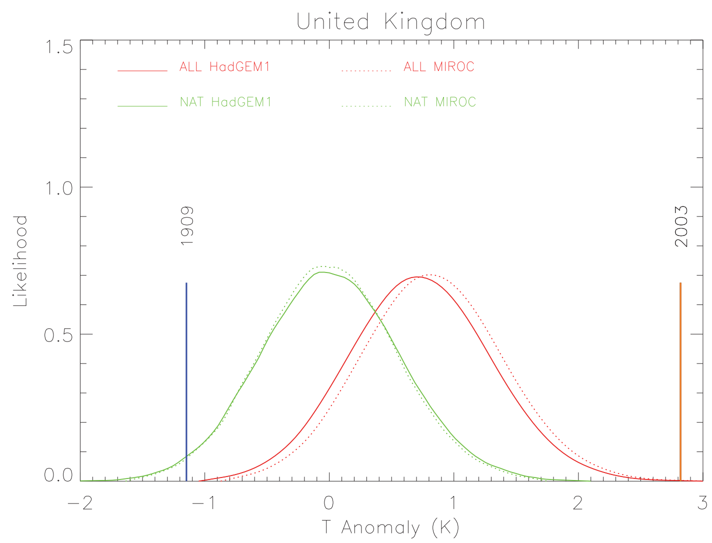


Figure 6. *Distributions of the June-July-August mean temperature anomalies (relative to 1961-1990) averaged over a Northern European region that encompasses the UK (10W-20E, 40-60N – as shown in Figure 1) including (red lines) and excluding (green lines) the influence of anthropogenic forcings. The distributions describe the seasonal mean temperatures expected in recent years (2000-2009) and are based on analyses with the HadGEM1 (solid lines) and MIROC (dotted lines) models. The vertical orange and blue lines correspond to the maximum and minimum anomaly in the CRUTEM3 dataset since 1900 respectively.*

Winter 2010/11

The distributions of the December-January-February (DJF) mean regional temperature in recent years in the presence and absence of anthropogenic forcings are shown in Figure 7. Analyses with both models suggest that human influences on the climate have shifted the distributions to higher temperatures. The winter of 2010/11 is cold, as shown in Figure 7, as it lies near the cold tail of the seasonal temperature distribution for the climate influenced by anthropogenic forcings (distributions plotted in red). It is considerably warmer than the winter of 1962/63, which is the coldest since 1900 in the CRUTEM3 dataset. In the absence of human influences (green distributions), the season lies near the central sector of the temperature distribution and would therefore be an average season. The attribution results shown here refer to temperature anomalies over the entire region and over an entire season, whereas an extreme event has a shorter duration and affects a smaller region.

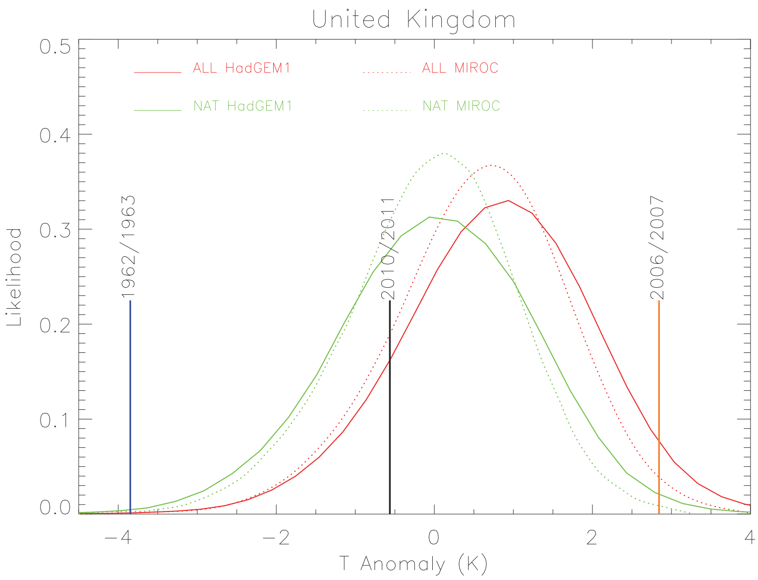


Figure 7. *Distributions of the December-January-February mean temperature anomalies (relative to 1961-1990) averaged over a Northern European region that encompasses the UK (10W-20E, 40-60N – as shown in Figure 1) including (red lines) and excluding (green lines) the influence of anthropogenic forcings. The distributions describe the seasonal mean temperatures expected in recent years (2000-2009) and are based on analyses with the HadGEM1 (solid lines) and MIROC (dotted lines) models. The vertical black line marks the observed anomaly in 2010/11 and the vertical orange and blue lines correspond to the maximum and minimum anomaly in the CRUTEM3 dataset since 1900 respectively.*

Precipitation extremes

Precipitation extremes, either excess or deficit, can be hazardous to human health, societal infrastructure, and livestock and agriculture. While seasonal fluctuations in precipitation are normal and indeed important for a number of societal sectors (e.g. tourism, farming etc.), flooding or drought can have serious negative impacts. These are complex phenomena and often the result of accumulated excesses or deficits or other compounding factors such as spring snow-melt, high tides/storm surges or changes in land use. This section below deals purely with precipitation amounts.

Table 2 shows selected extreme events since 2000 that are reported in WMO Statements on Status of the Global Climate and/or BAMS State of the Climate reports. The flooding of 2007 is highlighted below as an example of a recent precipitation extreme that affected the UK.

Year	Month	Event	Details	Source
2000	Sept-Dec	Flooding	Wet and stormy autumn caused severe flooding.	WMO (2001)
2004	Jan	Snow	Severe winter weather during the last week of January caused heavy accumulations of snow.	WMO (2005)
2004/5	Oct-Jun	Drought	Multi-month drought conditions affected much of Western Europe. From October 2004 to June 2005, rainfall was less than half the normal in areas of the UK.	WMO (2006)
2007	Jun-Jul	Flooding	Worst flooding in 60 years following the wettest May-Jul since records began in 1766.	WMO (2008)
2008	Jun-Aug	Wet	One of the top 10 wettest summers since records began in 1914 for the country.	WMO (2009)
2009	Nov	Wet	Wettest November since records began in 1914. Severe flooding to areas of the northern UK, with daily rainfall of more than 200 mm in Seathwaite.	WMO (2010)

***Table 2**. Selected extreme precipitation events reported in WMO Statements on Status of the Global Climate and/or BAMS State of the Climate reports since 2000.*

Recent extreme precipitation events

Flooding, June – July 2007

Excessive rainfall and flooding affected large areas of the United Kingdom during the summer, where the wettest May-July since records began in 1766 resulted in the worst flooding in 60 years (WMO, 2008). Some stations in northeast England reported totals exceeding 500% of the June average, and the south Midlands and Wales had 300%–400%

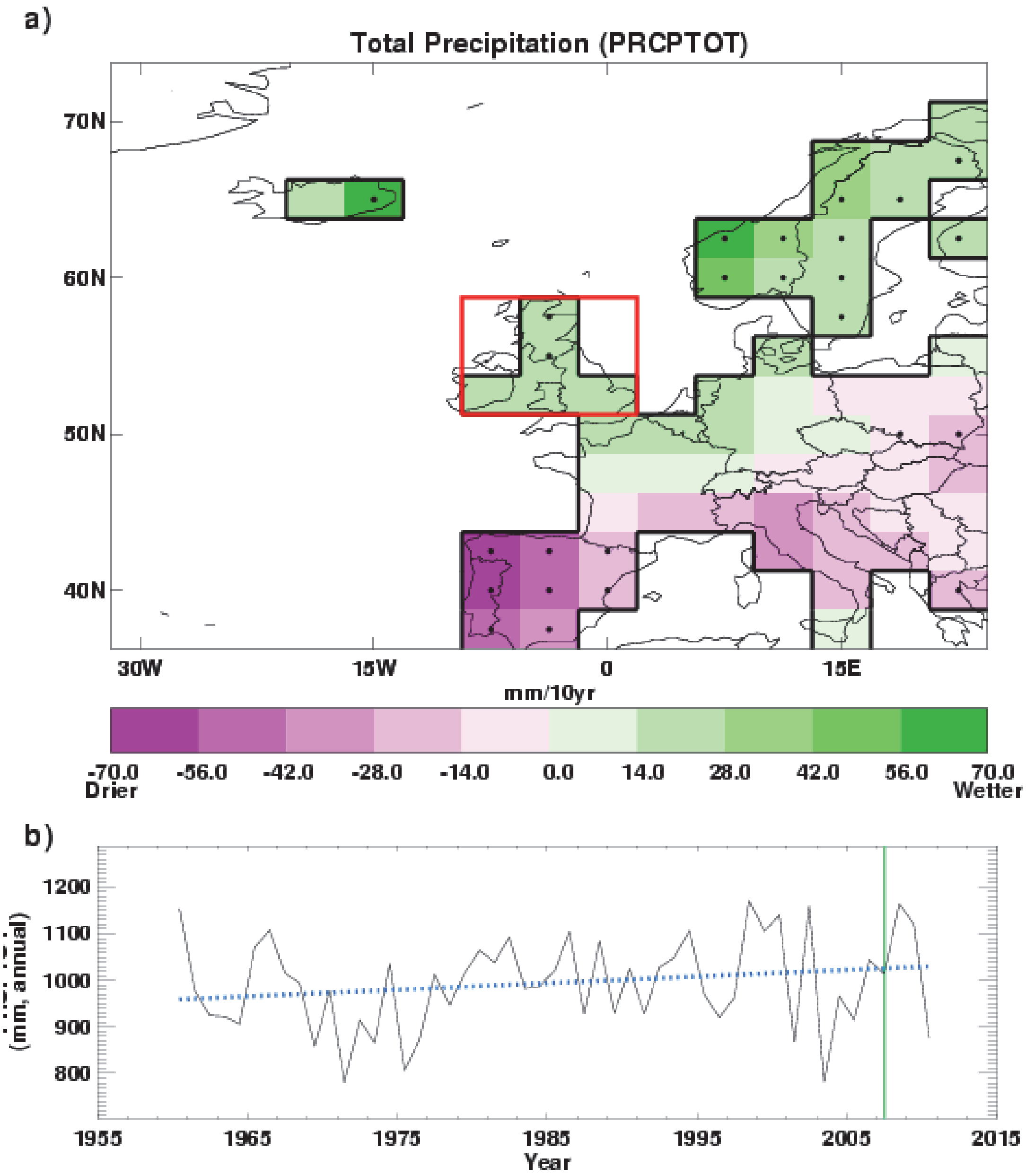
of the July average (Obregón et al., 2008a). The estimated average frequency of occurrence (return period) of these high totals is over 200 years (UK Met Office, 2011c).

In summer 2007, the jet stream was farther south than normal causing low pressure systems to be directed through central and southern areas of the United Kingdom (Obregón et al., 2008b). From 12-15th June there was a very unsettled spell of weather with slow moving bands of heavy rain/showers affecting Northern Ireland and northern England. This resulted in widespread flooding, affecting homes, businesses, and transport networks. There was further significant rainfall on 24-25th June, affecting northern England, north Wales and the Midlands, with Yorkshire and the Humber particularly wet on both days. This heavy and prolonged rainfall was caused by a slow moving area of low pressure and associated frontal system.

The extensive flooding across England and Wales killed nine people and caused more than US$ 6 billion in damages (WMO, 2008). Thousands of homes and businesses were flooded and disruption was caused to road and rail transport across northern and western England (UK Met Office, 2011c).

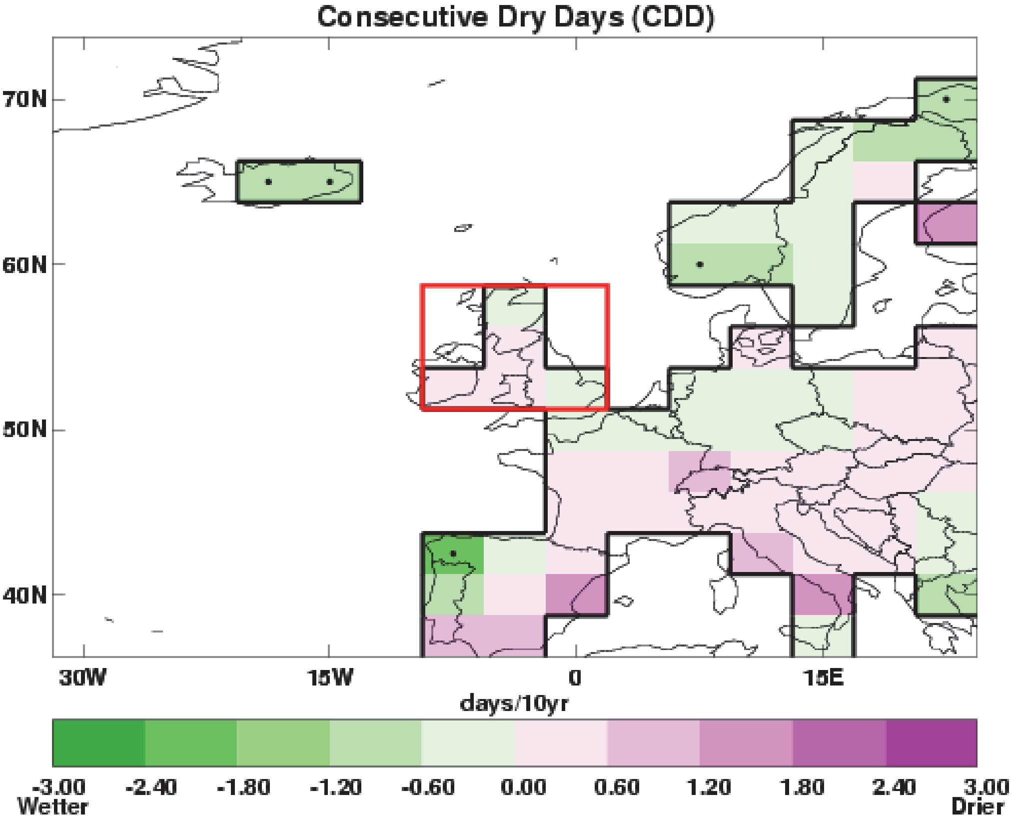
Analysis of long-term features in precipitation

ECA&D data (Klein Tank et al. 2002) have been used to update the HadEX extremes analysis for the UK from 1960 to 2010 for daily precipitation totals. Here we discuss changes in the annual total precipitation, and in the frequency of prolonged (greater than 6 days) wet and dry spells. The methods are fully described in the methodology annex.

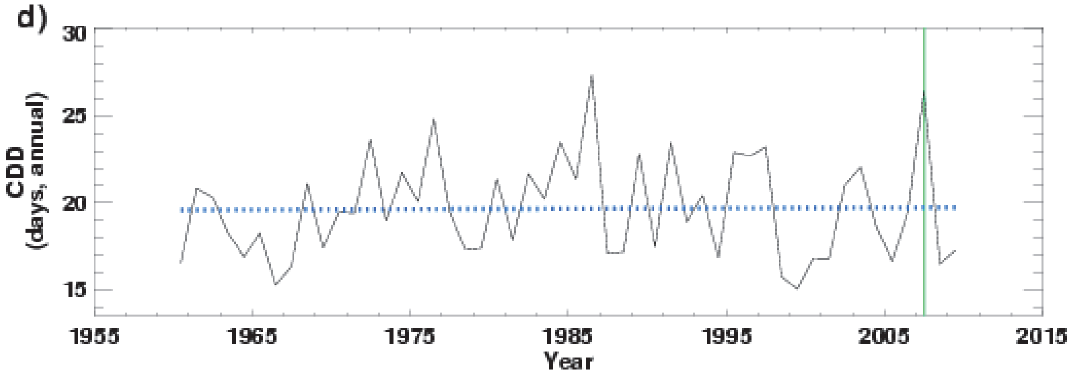


Annual: 14.21mm per decade (-6.72 to 37.01)
Total change of 71.07mm from 1960 to 2010 (-33.59mm to 185.04mm)

c)

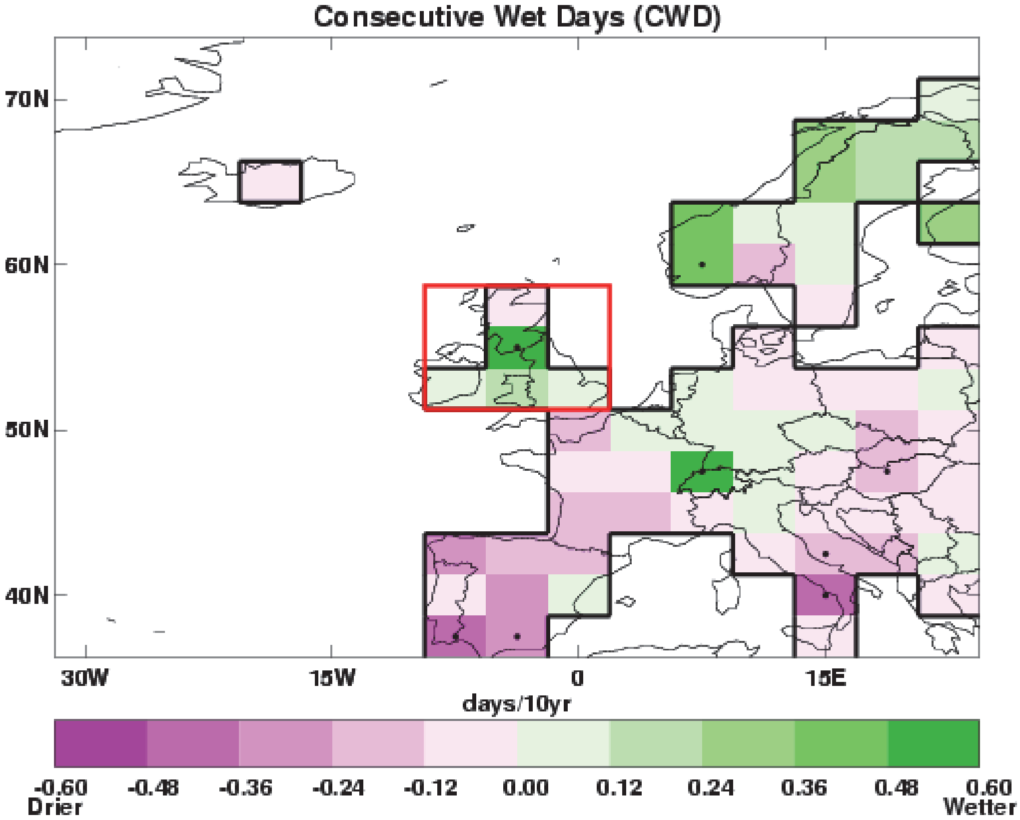


d)



Annual: 0.03days per decade (-0.46 to 0.73)
Total change of 0.12days from 1960 to 2009 (-1.85days to 2.90days)

e)



f)

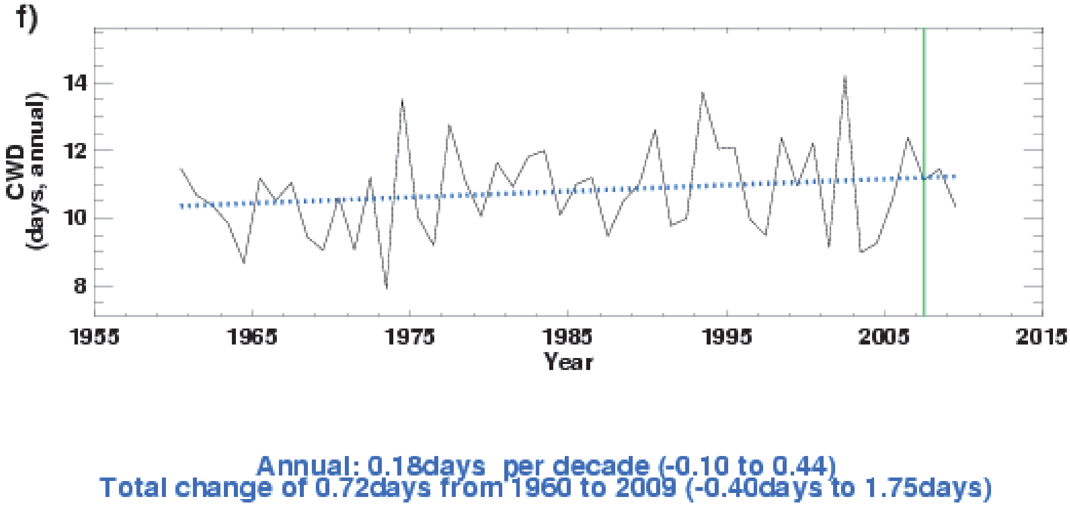


Figure 8. *The change in the annual total rainfall (a,b), the annual number of continuous dry days (c,d) and annual number of continuous wet days (e,f) over the period 1960-2010. The maps and timeseries have been created in exactly the same way as Figure 2. The vertical green lines show the date of the floods of 2007. Only annual regional averages are shown in (b,d,f). All the trends have lower confidence that they are different from zero, as their 5th to 95th percentile slopes are of different signs, and hence are marked with dotted lines.*

There is a uniform signal for increased rainfall over the UK; however in only two grid boxes is there high confidence that the trend is different from zero (Figure 8). For the other two indices there is a more mixed signal, with one box showing higher confidence of an increase in the number of wet days, but a neighbouring one showing a decrease. There is no clear signal at all from the number of dry days. The time-series do not show any strong trend, as is indicated by the maps. The floods of 2007 do not have a clear signal in the total precipitation and consecutive wet days plots, but there is actually a spike in the number of dry days. The 2007 floods were a localised event and so not well captured by these indices.

Storms

Storms can be very hazardous to all sectors of society. They can be small with localised impacts or spread across wide areas. There is no systematic observational analysis included for storms because, despite recent progress (Peterson et al. 2011; Cornes and Jones 2011), wind data are not yet adequate for worldwide robust analysis (see methodology annex). Further progress awaits studies of the more reliable barometric pressure data through the new 20th Century Reanalysis (Compo et al., 2011) and its planned successors.

Table 3 shows selected extreme events since 2000 that are reported in WMO Statements on Status of the Global Climate and/or BAMS State of the Climate reports. The UK is susceptible to storms from the Atlantic. These can be the remnants of extra tropical cyclones, or just intense low pressure systems in winter. The extra-tropical cyclone Kyrill is highlighted below as an example of a recent storm that affected the UK.

Year	Month	Event	Details	Source
2007	Jan	Storm	Winter storm *Kyrill* was a powerful extratropical storm with wind gusts up to 170 km/h affecting Northern Europe; nearly 50 lives lost.	WMO (2008)

Table 3. *Selected extreme storm events reported in WMO Statements on Status of the Global Climate and/or BAMS State of the Climate reports since 2000.*

Recent storm events

Extra-tropical Cyclone Kyrill, January 2007

On the 17th and 18th January a powerful storm system, *Kyrill*, affected much of northern Europe with torrential rains and winds gusting up to 170 km/h. At least 47 people were killed across northern Europe, and the storm caused disruptions in electricity supply that affected tens of thousands of people (WMO, 2008).

Winter storm “Kyrill” made landfall on British coasts on 17th January which experienced the strongest measured winds since 1990 (Obregón, 2008a). Strong winds became widespread with exceptional gusts on the 18th causing disruption as gust speeds reached 161 km/h at Capel Curig in Wales (UK Met Office, 2011b). In Ireland, a gust of 148 km/h was measured at Dublin Airport, the highest at the station since it opened in 1941 (Obregón, 2008a). Gusts of 124 km/h were recorded at Heathrow airport (UK Met Office, 2011b).

The BBC reported that the storm had resulted in the deaths of 9 people, as well as cancelled flights, rail speed restrictions and the closure of sections of motorway due to the high winds. Thousands of homes across the UK were left without power when the storm was at its peak (BBC, 2007).

Summary

The main features seen in observed climate over the UK from this analysis are:

- There has been warming over the UK since 1960 with greater warming in summer than winter.
- Since 1960 there has been a decreasing trend in the frequency of cool nights and cool days and an increasing trend in the frequency of warm nights and warm days.
- There has been a general increase in summer temperatures averaged over the country as a result of human influence on climate, making the occurrence of warm summer temperatures more frequent and cold summer temperatures less frequent.

Methodology annex

Recent, notable extremes

In order to identify what is meant by 'recent' events the authors have used the period since 1994, when WMO Status of the Global Climate statements were available to the authors. However, where possible, the most notable events during the last 10 years have been chosen as these are most widely reported in the media, remain closest to the forefront of the memory of the country affected, and provide an example likely to be most relevant to today's society. By 'notable' the authors mean any event which has had significant impact either in terms of cost to the economy, loss of life, or displacement and long term impact on the population. In most cases the events of largest impact on the population have been chosen, however this is not always the case.

Tables of recent, notable extreme events have been provided for each country. These have been compiled using data from the World Meteorological Organisation (WMO) Annual Statements on the Status of the Global Climate. This is a yearly report which includes contributions from all the member countries, and therefore represents a global overview of events that have had importance on a national scale. The report does not claim to capture all events of significance, and consistency across the years of records available is variable. However, this database provides a concise yet broad account of extreme events per country. This data is then supplemented with accounts from the monthly National Oceanic and Atmospheric Administration (NOAA) State of the Climate reports which outline global extreme events of meteorological significance.

We give detailed examples of heat, precipitation and storm extremes for each country where these have had significant impact. Where a country is primarily affected by precipitation or heat extremes this is where our focus has remained. An account of the impact on human life, property and the economy has been given, based largely on media reporting of events, and official reports from aid agencies, governments and meteorological organisations. Some data has also been acquired from the Centre for Research on Epidemiological Disasters (CRED) database on global extreme events. Although media reports are unlikely to be completely accurate, they do give an indication as to the perceived impact of an extreme event, and so are useful in highlighting the events which remain in the national psyche.

Our search for data has not been exhaustive given the number of countries and events included. Although there are a wide variety of sources available, for many events, an official account is not available. Therefore figures given are illustrative of the magnitude of impact only (references are included for further information on sources). It is also apparent that the reporting of extreme events varies widely by region, and we have, where possible, engaged with local scientists to better understand the impact of such events.

The aim of the narrative for each country is to provide a picture of the social and economic vulnerability to the current climate. Examples given may illustrate the impact that any given extreme event may have and the recovery of a country from such an event. This will be important when considering the current trends in climate extremes, and also when examining projected trends in climate over the next century.

Observational record

In this section we outline the data sources which were incorporated into the analysis, the quality control procedure used, and the choices made in the data presentation. As this report is global in scope, including 23 countries, it is important to maintain consistency of methodological approach across the board. For this reason, although detailed datasets of extreme temperatures, precipitation and storm events exist for various countries, it was not possible to obtain and incorporate such a varied mix of data within the timeframe of this project. Attempts were made to obtain regional daily temperature and precipitation data from known contacts within various countries with which to update existing global extremes databases. No analysis of changes in storminess is included as there is no robust historical analysis of global land surface winds or storminess currently available.

Analysis of seasonal mean temperature

Mean temperatures analysed are obtained from the CRUTEM3 global land-based surface-temperature data-product (Brohan et al. 2006), jointly created by the Met Office Hadley Centre and Climatic Research Unit at the University of East Anglia. CRUTEM3 comprises of more than 4000 weather station records from around the world. These have been averaged together to create 5° by 5° gridded fields with no interpolation over grid boxes that do not contain stations. Seasonal averages were calculated for each grid box for the 1960 to 2010 period and linear trends fitted using the median of pairwise slopes (Sen 1968; Lanzante 1996). This method finds the slopes for all possible pairs of points in the data, and takes their median. This is a robust estimator of the slope which is not sensitive to outlying points. High confidence is assigned to any trend value for which the 5^{th} to 95^{th} percentiles of the pairwise slopes are of the same sign as the trend value and thus inconsistent with a zero trend.

Analysis of temperature and precipitation extremes using indices

In order to study extremes of climate a number of indices have been created to highlight different aspects of severe weather. The set of indices used are those from the World Climate Research Programme (WCRP) Climate Variability and Predictability (CLIVAR) Expert Team on Climate Change Detection and Indices (ETCCDI). These 27 indices use daily rainfall and maximum and minimum temperature data to find the annual (and for a subset of the indices, monthly) values for, e.g., the 'warm' days where daily maximum temperature exceeds the 90^{th} percentile maximum temperature as defined over a 1961 to 1990 base period. For a full list of the indices we refer to the website of the ETCCDI (http://cccma.seos.uvic.ca/ETCCDI/index.shtml).

Index	Description	Shortname	Notes
Cool night frequency	Daily minimum temperatures lower than the 10th percentile daily minimum temperature using the base reference period 1961-1990	TN10p	---
Warm night frequency	Daily minimum temperatures higher than the 90th percentile daily minimum temperature using the base reference period 1961-1990	TN90p	---
Cool day frequency	Daily maximum temperatures lower than the 10th percentile daily maximum temperature using the base reference period 1961-1990	TX10p	---
Warm day frequency	Daily maximum temperatures higher than the 90th percentile daily maximum temperature using the base reference period 1961-1990	TX90p	---
Dry spell duration	Maximum duration of continuous days within a year with rainfall <1mm	CDD	Lower data coverage due to the requirement for a 'dry spell' to be at least 6 days long resulting in intermittent temporal coverage
Wet spell duration	Maximum duration of continuous days with rainfall >1mm for a given year	CWD	Lower data coverage due to the requirement for a 'wet spell' to be at least 6 days long resulting in intermittent temporal coverage
Total annual precipitation	Total rainfall per year	PRCPTOT	---

Table 4. *Description of ETCCDI indices used in this document.*

A previous global study of the change in these indices, containing data from 1951-2003 can be found in Alexander et al. 2006, (HadEX; see http://www.metoffice.gov.uk/hadobs/hadex/). In this work we aimed to update this analysis to the present day where possible, using the most recently available data. A subset of the indices is used here because they are most easily related to extreme climate events (Table 4).

Use of HadEX for analysis of extremes

The HadEX dataset comprises all 27 ETCCDI indices calculated from station data and then smoothed and gridded onto a 2.5° x 3.75° grid, chosen to match the output from the Hadley Centre suite of climate models. To update the dataset to the present day, indices are calculated from the individual station data using the RClimDex/FClimDex software; developed and maintained on behalf of the ETCCDI by the Climate Research Branch of the Meteorological Service of Canada. Given the timeframe of this project it was not possible to obtain sufficient station data to create updated HadEX indices to present day for a number of countries: Brazil; Egypt; Indonesia; Japan (precipitation only); South Africa; Saudi Arabia; Peru; Turkey; and Kenya. Indices from the original HadEX data-product are used here to show changes in extremes of temperature and precipitation from 1960 to 2003. In some cases the data end prior to 2003. Table 5 summarises the data used for each country. Below, we give a short summary of the methods used to create the HadEX dataset (for a full description see Alexander et al. 2006).

To account for the uneven spatial coverage when creating the HadEX dataset, the indices for each station were gridded, and a land-sea mask from the HadCM3 model applied. The interpolation method used in the gridding process uses a decorrelation length scale (DLS) to determine which stations can influence the value of a given grid box. This DLS is calculated from the e-folding distance of the individual station correlations. The DLS is calculated separately for five latitude bands, and then linearly interpolated between the bands. There is a noticeable difference in spatial coverage between the indices due to these differences in decorrelation length scales. This means that there will be some grid-box data where in fact there are no stations underlying it. Here we apply black borders to grid-boxes where at least 3 stations are present to denote greater confidence in representation of the wider grid-box area there. The land-sea mask enables the dataset to be used directly for model comparison with output from HadCM3. It does mean, however, that some coastal regions and islands over which one may expect to find a grid-box are in fact empty because they have been treated as sea

Data sources used for updates to the HadEX analysis of extremes

We use a number of different data sources to provide sufficient coverage to update as many countries as possible to present day. These are summarised in Table 5. In building the new datasets we have tried to use exactly the same methodology as was used to create the original HadEX to retain consistency with a product that was created through substantial international effort and widely used, but there are some differences, which are described in the next section.

Wherever new data have been used, the geographical distributions of the trends were compared to those obtained from HadEX, using the same grid size, time span and fitting method. If the pattern of the trends in the temperature or precipitation indices did not match that from HadEX, we used the HadEX data despite its generally shorter time span. Differences in the patterns of the trends in the indices can arise because the individual stations used to create the gridded results are different from those in HadEX, and the quality control procedures used are also very likely to be different. Countries where we decided to use HadEX data despite the existence of more recent data are Egypt and Turkey.

GHCND:
The Global Historical Climate Network Daily data has near-global coverage. However, to ensure consistency with the HadEX database, the GHCND stations were compared to those stations in HadEX. We selected those stations which are within 1500m of the stations used in the HadEX database and have a high correlation with the HadEX stations. We only took the precipitation data if its $r>0.9$ and the temperature data if one of its r-values >0.9. In addition, we required at least 5 years of data beyond 2000. These daily data were then converted to the indices using the *fclimdex* software.

ECA&D and SACA&D:
The European Climate Assessment and Dataset and the Southeast Asian Climate Assessment and Dataset data are pre-calculated indices comprising the core 27 indices from the ETCCDI as well as some extra ones. We kindly acknowledge the help of Albert Klein Tank, the KNMI[1] and the BMKG[2] for their assistance in obtaining these data.

Mexico:
The station data from Mexico has been kindly supplied by the SMN[3] and Jorge Vazquez. These daily data were then converted to the required indices using the *Fclimdex* software.

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[1] Koninklijk Nederlands Meteorologisch Instituut – The Royal Netherlands Meteorological Institute

[2] Badan Meteorologi, Klimatologi dan Geofisika – The Indonesian Meteorological, Climatological and Geophysical Agency

[3] Servicio Meteorológico Nacional de México – The Mexican National Meteorological Service

There are a total of 5298 Mexican stations in the database. In order to select those which have sufficiently long data records and are likely to be the most reliable ones we performed a cross correlation between all stations. We selected those which had at least 20 years of data post 1960 and have a correlation with at least one other station with an *r*-value >0.95. This resulted in 237 stations being selected for further processing and analysis.

Indian Gridded:

The India Meteorological Department provided daily gridded data (precipitation 1951-2007, temperature 1969-2009) on a 1° x 1° grid. These are the only gridded daily data in our analysis. In order to process these in as similar a way as possible the values for each grid were assumed to be analogous to a station located at the centre of the grid. We keep these data separate from the rest of the study, which is particularly important when calculating the decorrelation length scale, which is on the whole larger for these gridded data.

Country	**Region box** (red dashed boxes in Fig. 1 and on each map at beginning of chapter)	**Data source** (T = temperature, P = precipitation)	**Period of data coverage** (T = temperature, P = precipitation)	**Indices included** (see Table 4 for details)	**Temporal resolution available**	**Notes**
Argentina	73.125 to 54.375 ° W, 21.25 to 56.25 ° S	Matilde Rusticucci (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	annual	
Australia	114.375 to 155.625 ° E, 11.25 to 43.75 ° S	GHCND (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	Land-sea mask has been adapted to include Tasmania and the area around Brisbane
Bangladesh	88.125 to 91.875 ° E, 21.25 to 26.25 ° N	Indian Gridded data (T,P)	1960-2007 (P), 1970-2009 (T)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	Interpolated from Indian Gridded data
Brazil	73.125 to 31.875 ° W, 6.25 ° N to 33.75 ° S	HadEX (T,P)	1960-2000 (P) 2002 (T)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	annual	Spatial coverage is poor
China	73.125 to 133.125 ° E, 21.25 to 53.75 ° N	GHCND (T,P)	1960-1997 (P) 1960-2003 (T_{min}) 1960-2010 (T_{max})	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	Precipitation has very poor coverage beyond 1997 except in 2003-04, and no data at all in 2000-02, 2005-11
Egypt	24.375 to 35.625 ° E, 21.25 to 31.25 ° N	HadEX (T,P)	No data	TN10p, TN90p, TX10p, TX90p, PRCPTOT,	annual	There are no data for Egypt so all grid-box values have been interpolated from stations in Jordan, Israel, Libya and Sudan

France	5.625 ° W to 9.375 ° E, 41.25 to 51.25 ° N	ECA&D (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	
Germany	5.625 to 16.875 ° E, 46.25 to 56.25 ° N	ECA&D (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	
India	69.375 to 99.375 ° E, 6.25 to 36.25 ° N	Indian Gridded data (T,P)	1960-2003 (P), 1970-2009 (T)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	
Indonesia	95.625 to 140.625 ° E, 6.25 ° N to 11.25 ° S	HadEX (T,P)	1968-2003 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT,	annual	Spatial coverage is poor
Italy	5.625 to 16.875 ° E, 36.25 to 46.25 ° N	ECA&D (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	Land-sea mask has been adapted to improve coverage of Italy
Japan	129.375 to 144.375 ° E, 31.25 to 46.25 ° N	HadEX (P) GHCND (T)	1960-2003 (P) 1960-2000 (T_{min}) 1960-2010 (T_{max})	TN10p, TN90p, TX10p, TX90p, PRCPTOT,	monthly, seasonal and annual (T), annual (P)	
Kenya	31.875 to 43.125 ° E, 6.25 ° N to 6.25 ° S	HadEX (T,P)	1960-1999 (P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT	annual	There are no temperature data for Kenya and so grid-box values have been interpolated from neighbouring Uganda and the United Republic of Tanzania. Regional averages include grid-boxes from outside Kenya that enable continuation to 2003

Mexico	118.125 to 88.125 ° W, 13.75 to 33.75 ° N	Raw station data from the Servicio Meteorológico Nacional (SMN) (T,P)	1960-2009 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	237/5298 stations selected. Non uniform spatial coverage. Drop in T and P coverage in 2009.
Peru	84.735 to 65.625 ° W, 1.25 ° N to 18.75 ° S	HadEX (T,P)	1960-2002 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	annual	Intermittent coverage in TX90p, CDD and CWD
Russia	West Russia 28.125 to 106.875 ° E, 43.75 to 78.75 ° N, East Russia 103.125 to 189.375 ° E, 43.75 to 78.75 ° N	ECA&D (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	Country split for presentation purposes only.
Saudi Arabia	31.875 to 54.375 ° E, 16.25 to 33.75 ° N	HadEX (T,P)	1960-2000 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT	annual	Spatial coverage is poor
South Africa	13.125 to 35.625 ° W, 21.25 to 36.25 ° S	HadEX (T,P)	1960-2000 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	annual	---
Republic of Korea	125.625 to 129.375 ° E, 33.75 to 38.75 ° N	HadEX (T,P)	1960-2003 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD	annual	There are too few data points for CWD to calculate trends or regional timeseries

Spain	9.375 ^{o} W to 1.875 ^{o} E, 36.25 to 43.75 ^{o} N	ECA&D (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	
Turkey	24.375 to 46.875 ^{o} E, 36.25 to 43.75 ^{o} N	HadEX (T,P)	1960-2003 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	annual	Intermittent coverage in CWD and CDD with no regional average beyond 2000
United Kingdom	9.375 ^{o} W to 1.875 ^{o} E, 51.25 to 58.75 ^{o} N	ECA&D (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	
United States of America	125.625 to 65.625 ^{o} W, 23.75 to 48.75 ^{o} N	GHCND (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	

Table 5. *Summary of data used for each country*

Quality control and gridding procedure used for updates to the HadEX analysis of extremes

In order to perform some basic quality control checks on the index data, we used a two-step process on the indices. Firstly, internal checks were carried out, to remove cases where the 5 day rainfall value is less than the 1 day rainfall value, the minimum T_min is greater than the minimum T_max and the maximum T_min is greater than the maximum T_max. Although these are physically impossible, they could arise from transcription errors when creating the daily dataset, for example, a misplaced minus sign, an extra digit appearing in the record or a column transposition during digitisation. During these tests we also require that there are at least 20 years of data in the period of record for the index for that station, and that some data is found in each decade between 1961 and 1990, to allow a reasonable estimation of the climatology over that period.

Weather conditions are often similar over many tens of kilometres and the indices calculated in this work are even more coherent. The correlation coefficient between each station-pair combination in all the data obtained is calculated for each index (and month where appropriate), and plotted as a function of the separation. An exponential decay curve is fitted to the data, and the distance at which this curve has fallen by a factor 1/*e* is taken as the decorrelation length scale (DLS). A DLS is calculated for each dataset separately. For the GHCND, a separate DLS is calculated for each hemisphere. We do not force the fitted decay curve to show perfect correlation at zero distance, which is different to the method employed when creating HadEX. For some of the indices in some countries, no clear decay pattern was observed in some data sets or the decay was so slow that no value for the DLS could be determined. In these cases a default value of 200km was used.

We then perform external checks on the index data by comparing the value for each station with that of its neighbours. As the station values are correlated, it is therefore likely that if one station measures a high value for an index for a given month, its neighbours will also be measuring high. We exploit this coherence to find further bad values or stations as follows. Although raw precipitation data shows a high degree of localisation, using indices which have monthly or annual resolution improves the coherence across wider areas and so this neighbour checking technique is a valid method of finding anomalous stations.

We calculate a climatology for each station (and month if appropriate) using the mean value for each index over the period 1961-1990. The values for each station are then anomalised using this climatology by subtracting this mean value from the true values, so that it is clear if the station values are higher or lower than normal. This means that we do not need to take differences in elevation or topography into account when comparing neighbours, as we are not comparing actual values, but rather deviations from the mean value.

All stations which are within the DLS distance are investigated and their anomalised values noted. We then calculate the weighted median value from these stations to take into account the decay in the correlation with increasing distance. We use the median to reduce the sensitivity to outliers.

If the station value is greater than 7.5 median-absolute-deviations away from the weighted median value (this corresponds to about 5 standard deviations if the distribution is Gaussian, but is a robust measure of the spread of the distribution), then there is low confidence in the veracity of this value and so it is removed from the data.

To present the data, the individual stations are gridded on a 3.75° x 2.5° grid, matching the output from HadCM3. To determine the value of each grid box, the DLS is used to calculate which stations can reasonably contribute to the value. The value of each station is then weighted using the DLS to obtain a final grid box value. At least three stations need to have valid data and be near enough (within 1 DLS of the gridbox centre) to contribute in order for a value to be calculated for the grid point. As for the original HadEX, the HadCM3 land-sea mask is used. However, in three cases the mask has been adjusted as there are data over Tasmania, eastern Australia and Italy that would not be included otherwise (Figure 9).

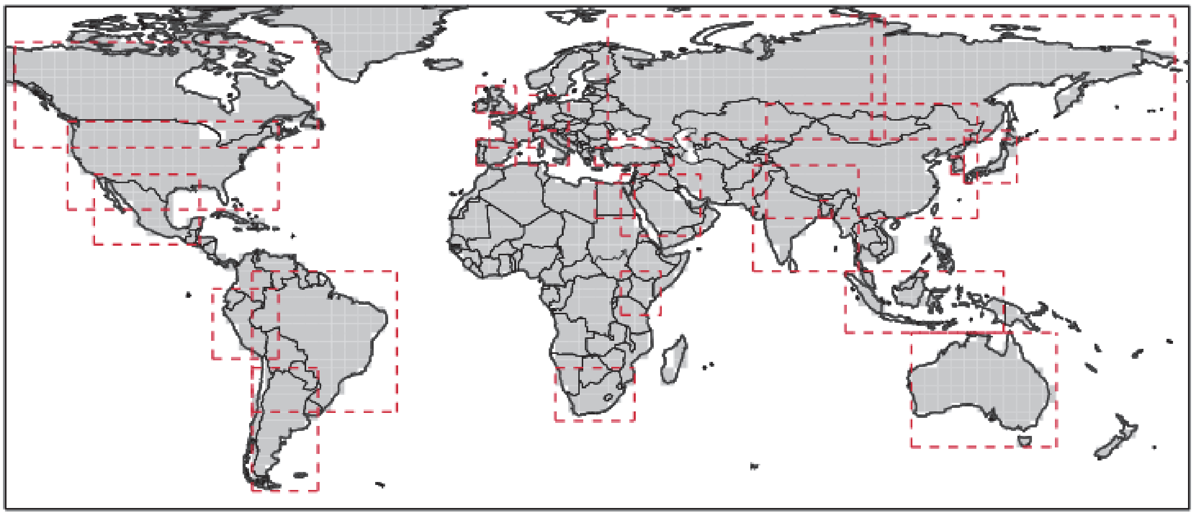


Figure 9. *Land-sea mask used for gridding the station data and regional areas allocated to each country as described in Table 5.*

Presentation of extremes of temperature and precipitation

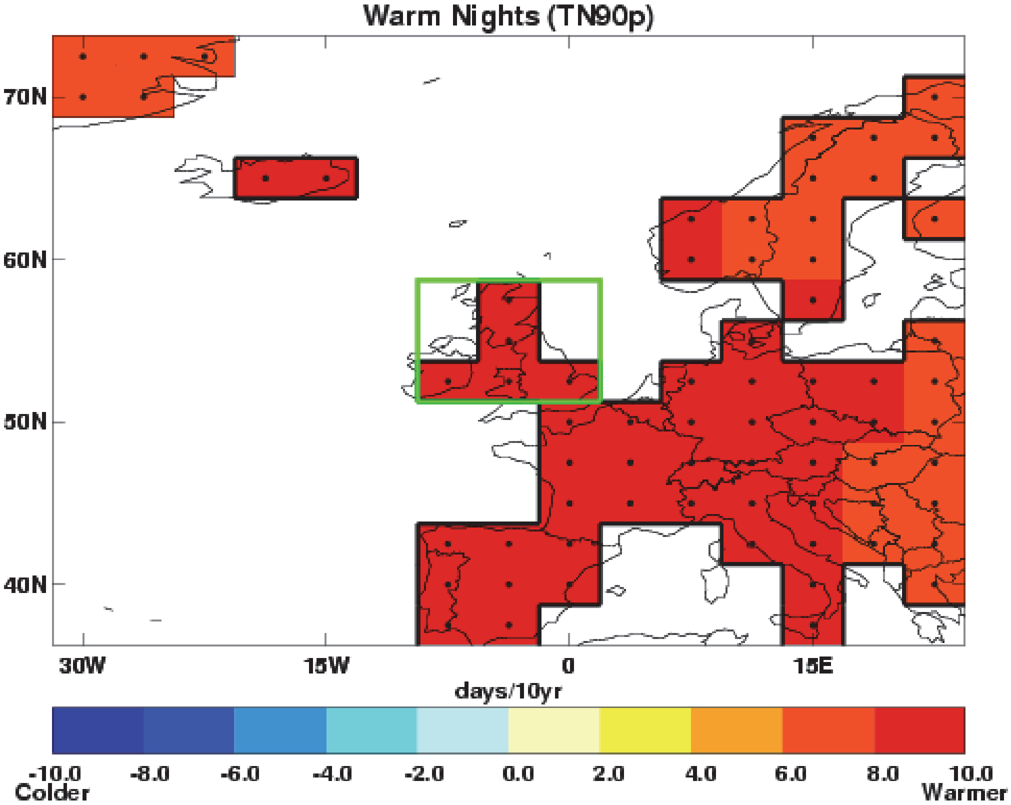
Indices are displayed as regional gridded maps of decadal trends and regional average time-series with decadal trends where appropriate. Trends are fitted using the median of pairwise slopes method (Sen 1968, Lanzante 1996). Trends are considered to be significantly different from a zero trend if the 5th to 95th percentiles of the pairwise slopes do not encompass zero. This is shown by a black dot in the centre of the grid-box or by a solid line on time-series plots. This infers that there is high confidence in the sign (positive or negative) of the sign. Confidence in the trend magnitude can be inferred by the spread of the 5th to 95th percentiles of the pairwise slopes which is given for the regional average decadal trends. Trends are only calculated when there are data present for at least 50% of years in the period of record and for the updated data (not HadEX) there must be at least one year in each decade.

Due to the practice of data-interpolation during the gridding stage (using the DLS) there are values for some grid boxes when no actually station lies within the grid box. There is more confidence in grid boxes for which there are underlying data. For this reason, we identify those grid boxes which contain at least 3 stations by a black contour line on the maps. The DLS differs with region, season and index which leads to large differences in the spatial coverage. The indices, by their nature of being largely threshold driven, can be intermittent over time which also effects spatial and temporal coverage (see Table 4).

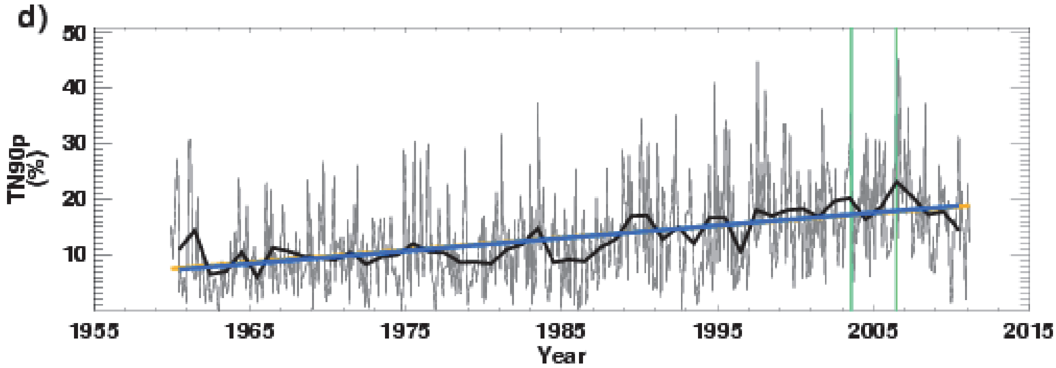
Each index (and each month for the indices for which there is monthly data) has a different DLS, and so the coverage between different indices and datasets can be different. The restrictions on having at least 20 years of data present for each input station, at least 50% of years in the period of record and at least one year in each decade for the trending calculation, combined with the DLS, can restrict the coverage to only those regions with a dense station network reporting reliably.

Each country has a rectangular region assigned as shown by the red dashed box on the map in Figure 1 and listed in Table 2, which is used for the creation of the regional average. This is sometimes identical to the attribution region shown in grey on the map in Figure 1. This region is again shown on the maps accompanying the time series of the regional averages as a reminder of the region and grid boxes used in the calculation. Regional averages are created by weighting grid box values by the cosine of their grid box centre latitude. To ensure consistency over time a regional average is only calculated when there are a sufficient number of grid boxes present. The full-period median number of grid-boxes present is calculated. For regions with a median of more than six grid-boxes there must be at least 80% of the median number of grid boxes present for any one year to calculate a regional average. For regions with six or fewer median grid boxes this is relaxed to 50%. These limitations ensure that a single station or grid box which has a longer period of record than its neighbours cannot skew the timeseries trend. So sometimes there may be grid-boxes present but no regional average time series. The trends for the regional averages are calculated in the same way as for the individual grid boxes, using the median of pairwise slopes method (Sen 1968, Lanzante 1996). Confidence in the trend is also determined if the 5^{th} to 95^{th} percentiles of the pairwise slopes are of the same sign and thus inconsistent with a zero trend. As well as the trend in quantity per decade, we also show the full change in the quantity from 1960 to 2010 that this fitted linear trend implies.

c)



d)



Monthly: 2.20% per decade (1.80 to 2.61)
Total change of 11.02% from 1960 to 2011 (9.00% to 13.06%)

Annual: 2.28% per decade (1.69 to 2.86)
Total change of 11.41% from 1960 to 2010 (8.43% to 14.28%)

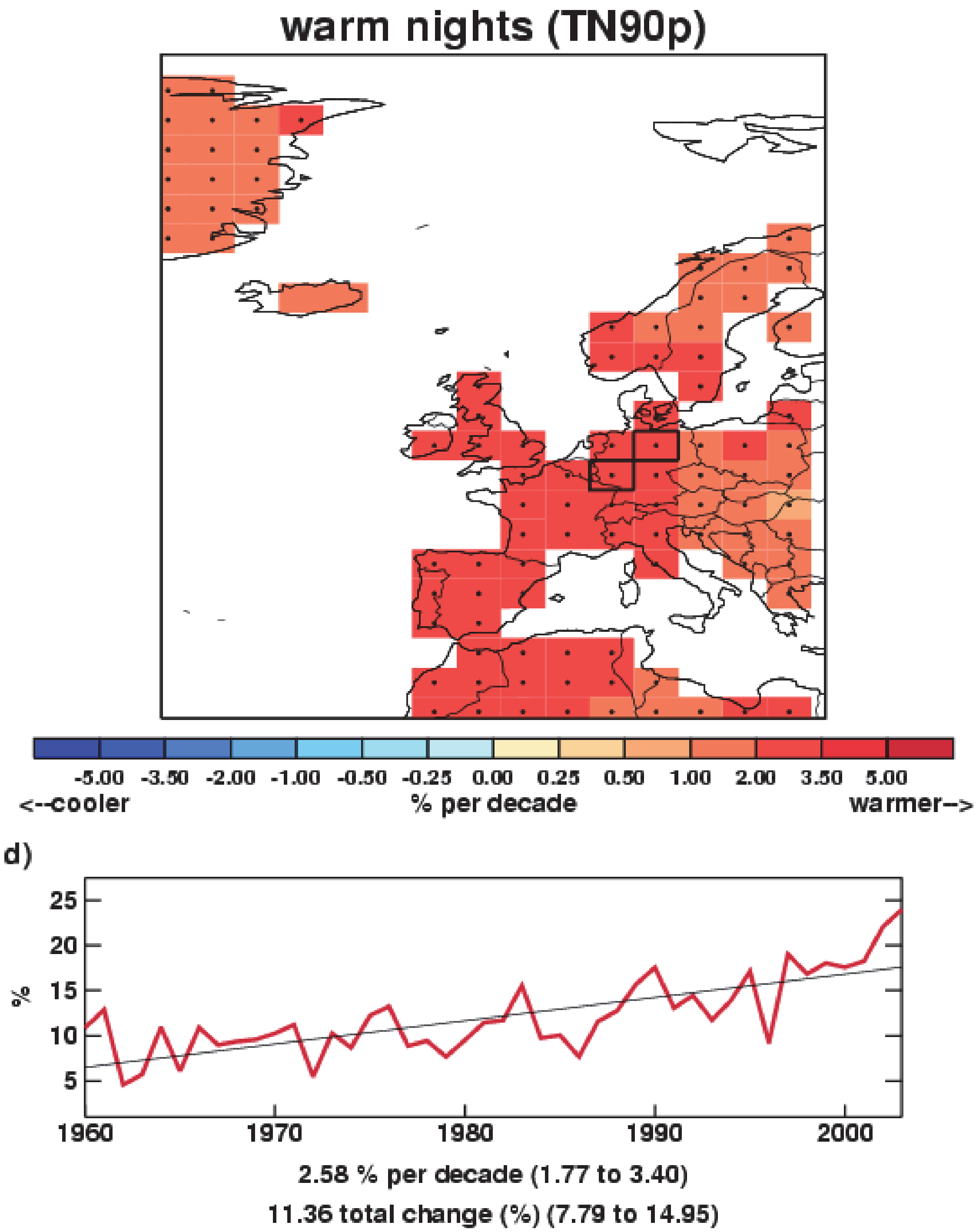


__Figure 10.__ Examples of the plots shown in the data section. Left: From ECA&D data between 1960-2010 for the number of warm nights, and Right: from HadEX data (1960-2003) for the total precipitation. A full explanation of the plots is given in the text below.

The results are presented in the form of a map and a time series for each country and index. The map shows the grid box decadal trend in the index over the period for which there are data. High confidence, as determined above, is shown by a black dot in the grid box centre. To show the variation over time, the values for each year (and month if available) are shown in a time series for a regional average. The values of the indices have been normalised to a base period of 1961-1990 (except the Indian gridded data which use a 1971 to 1990 period), both in HadEX and in the new data acquired for this project. Therefore, for example, the percentage of nights exceeding the 90th percentile for a temperature is 10% for that period.

There are two influences on whether a grid box contains a value or not – the land-sea mask, and the decorrelation length scale. The land-sea mask is shown in Figure 9. There are grid boxes which contain some land but are mostly sea and so are not considered. The decorrelation length scale sets the maximum distance a grid box can be from stations before no value is assigned to it. Grid boxes containing three or more stations are highlighted by a thick border. This indicates regions where the value shown is likely to be more representative of the grid box area mean as opposed to a single station location.

On the maps for the new data there is a box indicating which grid boxes have been extracted to calculate the area average for the time series. This box is the same as shown in Figure 1 at the beginning of each country's document. These selected grid boxes are combined using area (cosine) weighting to calculate the regional average (both annual [thick lines] and monthly [thin lines] where available). Monthly (orange) and annual (blue) trends are fitted to these time series using the method described above. The decadal trend and total change over the period where there are data are shown with 5th to 95th percentile confidence intervals in parentheses. High confidence, as determined above, is shown by a solid line as opposed to a dotted one. The green vertical lines on the time series show the dates of some of the notable events outlined in each section.

Attribution

Regional distributions of seasonal mean temperatures in the 2000s are computed with and without the effect of anthropogenic influences on the climate. The analysis considers temperatures averaged over the regions shown in Figure 11. These are also identified as grey boxes on the maps in Figure 1. The coordinates of the regions are given in Table 6. The methodology combines information from observations and model simulations using the approach originally introduced in Christidis et al., 2010 and later extended in Christidis et al., 2011, where more details can be found. The analysis requires spatial scales greater than about 2,500 km and for that reason the selected regions (Fig.11 and Table 6) are often larger than individual countries, or include several smaller countries in a single region (for example UK, Germany and France are grouped in one region).

Observations of land temperature come from the CRUTEM3 gridded dataset (Brohan et al., 2006) and model simulations from two coupled GCMs, namely the Hadley Centre HadGEM1 model (Martin et al., 2006) and version 3.2 of the MIROC model (K-1 Developers, 2004). The use of two GCMs helps investigate the sensitivity of the results to the model used in the analysis. Ensembles of model simulations from two types of experiments are used to partition the temperature response to external forcings between its anthropogenic and natural components. The first experiment (ALL) simulates the combined effect of natural and anthropogenic forcings on the climate system and the second (ANTHRO) includes anthropogenic forcings only. The difference of the two gives an estimate of the effect of the natural forcings (NAT). Estimates of the effect of internal climate variability are derived from long control simulations of the unforced climate. Distributions of the regional summer mean temperature are computed as follows:

a) A global optimal fingerprinting analysis (Allen and Tett, 1999; Allen and Stott, 2003) is first carried out that scales the global simulated patterns (fingerprints) of climate change attributed to different combinations of external forcings to best match them to the observations. The uncertainty in the scaling that originates from internal variability leads to samples of the scaled fingerprints, i.e. several realisations that are plausibly consistent with the observations. The 2000-2009 decade is then extracted from the scaled patterns and two samples of the decadal mean temperature averaged over the reference region are then computed with and without human influences, which provide the Probability Density Functions (PDFs) of the decadal mean temperature attributable to ALL and NAT forcings.

b) Model-derived estimates of noise are added to the distributions to take into account the uncertainty in the simulated fingerprints.

c) In the same way, additional noise from control model simulations is introduced to the distributions to represent the effect of internal variability in the annual values of the seasonal mean temperatures. The result is a pair of estimated distributions of the annual values of the seasonal mean temperature in the region with and without the effect of human activity on the climate. The temperatures throughout the analysis are expressed as anomalies relative to period 1961-1990.

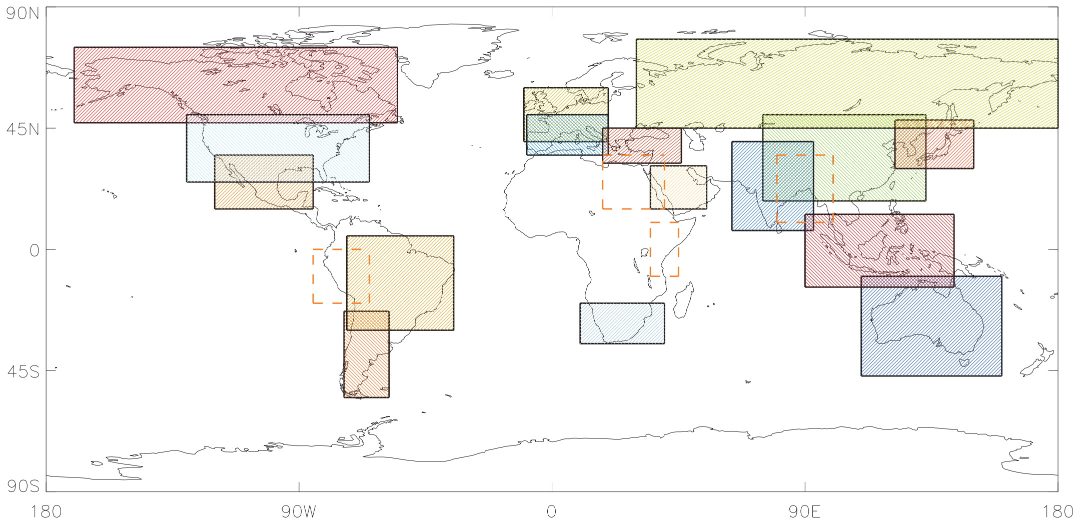


Figure 11. *The regions used in the attribution analysis. Regions marked with dashed orange boundaries correspond to non-G20 countries that were also included in the analysis*

Region	Region Coordinates
Argentina	74-58W, 55-23S
Australia	110-160E, 47-10S
Bangladesh	80-100E, 10-35N
Brazil	73-35W, 30S-5N
Canada-Alaska	170-55W, 47-75N
China	75-133E, 18-50N
Egypt	18-40E, 15-35N
France-Germany-UK	10W-20E, 40-60N
India	64-93E, 7-40N
Indonesia	90-143E, 14S-13N
Italy-Spain	9W-20E, 35-50N
Japan-Republic of Korea	122-150E, 30-48N
Kenya	35-45E, 10S-10N
Mexico	120-85W, 15-35N
Peru	85-65W, 20-0S
Russia	30-185E, 45-78N
Saudi Arabia	35-55E, 15-31N
South Africa	10-40E, 35-20S
Turkey	18-46E, 32-45N

Table 6. The coordinates of the regions used in the attribution analysis.

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Chapter 2 – Climate Change Projections

Introduction

Climate models are used to understand how the climate will evolve over time and typically represent the atmosphere, ocean, land surface, cryosphere, and biogeochemical processes, and solve the equations governing their evolution on a geographical grid covering the globe. Some processes are represented explicitly within climate models, large-scale circulations for instance, while others are represented by simplified parameterisations. The use of these parameterisations is sometimes due to processes taking place on scales smaller than the typical grid size of a climate model (a Global Climate Model (GCM) has a typical horizontal resolution of between 250 and 600km) or sometimes to the current limited understanding of these processes. Different climate modelling institutions use different plausible representations of the climate system, which is why climate projections for a single greenhouse gas emissions scenario differ between modelling institutes. This gives rise to “climate model structural uncertainty”.

In response to a proposed activity of the World Climate Research Programme's (WCRP's; http://www.wcrp-climate.org/) Working Group on Coupled Modelling (WGCM), the Program for Climate Model Diagnosis and Intercomparison (PCMDI; http://www-pcmdi.llnl.gov/) volunteered to collect model output contributed by leading climate modelling centres around the world. Climate model output from simulations of the past, present and future climate was collected by PCMDI mostly during the years 2005 and 2006, and this archived data constitutes phase 3 of the Coupled Model Intercomparison Project (CMIP3). In part, the WGCM organised this activity to enable those outside the major modelling centres to perform research of relevance to climate scientists preparing the IPCC Fourth Assessment Report (AR4). This unprecedented collection of recent model output is commonly known as the “CMIP3 multi-model dataset". The GCMs included in this dataset are referred to regularly throughout this review, although not exclusively.

The CMIP3 multi-model ensemble has been widely used in studies of regional climate change and associated impacts. Each of the constituent models was subject to extensive testing by the contributing institute, and the ensemble has the advantage of having been constructed from a large pool of alternative model components, therefore sampling alternative structural assumptions in how best to represent the physical climate system. Being assembled on an opportunity basis, however, the CMIP3 ensemble was not designed to represent model uncertainties in a systematic manner, so it does not, in isolation, support robust estimates of the risk of different levels of future climate change, especially at a regional level.

Since CMIP3, a new (CMIP5) generation of coupled ocean-atmosphere models has been developed, which is only just beginning to be available and is being used for new projections for the IPCC Fifth Assessment Report (AR5).

These newer models typically feature higher spatial resolution than their CMIP3 counterparts, including in some models a more realistic representation of stratosphere-troposphere interactions. The CMIP5 models also benefit from several years of development in their parameterisations of small scale processes, which, together with resolution increases, are expected to result in a general improvement in the accuracy of their simulations of historical climate, and in the credibility of their projections of future changes. The CMIP5 programme also includes a number of comprehensive Earth System Models (ESMs) which explicitly simulate the earth's carbon cycle and key aspects of atmospheric chemistry, and also contain more sophisticated representations of aerosols compared to CMIP3 models.

The CMIP3 results should be interpreted as a useful interim set of plausible outcomes. However, their neglect of uncertainties, for instance in carbon cycle feedbacks, implies that higher levels of warming outside the CMIP3 envelope cannot be ruled out. In future, CMIP5 coupled model and ESM projections can be expected to produce improved advice on future regional changes. In particular, ensembles of ESM projections will be needed to provide a more comprehensive survey of possible future changes and their relative likelihoods of occurrence. This is likely to require analysis of the CMIP5 multi-model ESM projections, augmented by larger ensembles of ESM simulations in which uncertainties in physical and biogeochemical feedback processes can be explored more systematically, for example via ensembles of model runs in which key aspects of the climate model are slightly adjusted. Note that such an exercise might lead to the specification of wider rather than narrower uncertainties compared to CMIP3 results, if the effects of representing a wider range of earth system processes outweigh the effects of refinements in the simulation of physical atmosphere-ocean processes already included in the CMIP3 models.

Climate projections

The Met Office Hadley Centre is currently producing perturbed parameter ensembles of a single model configuration known as HadCM3C, to explore uncertainties in physical and biogeochemical feedback processes. The results of this analysis will become available in the next year and will supplement the CMIP5 multi-model ESM projections, providing a more comprehensive set of data to help progress understanding of future climate change. However, many of the studies covered in the chapter on climate impacts have used CMIP3 model output. For this reason, and because it is still the most widely used set of projections available, the CMIP3 ensemble output for temperature and precipitation, for the A1B emission scenario, for the UK and the surrounding region is shown below.

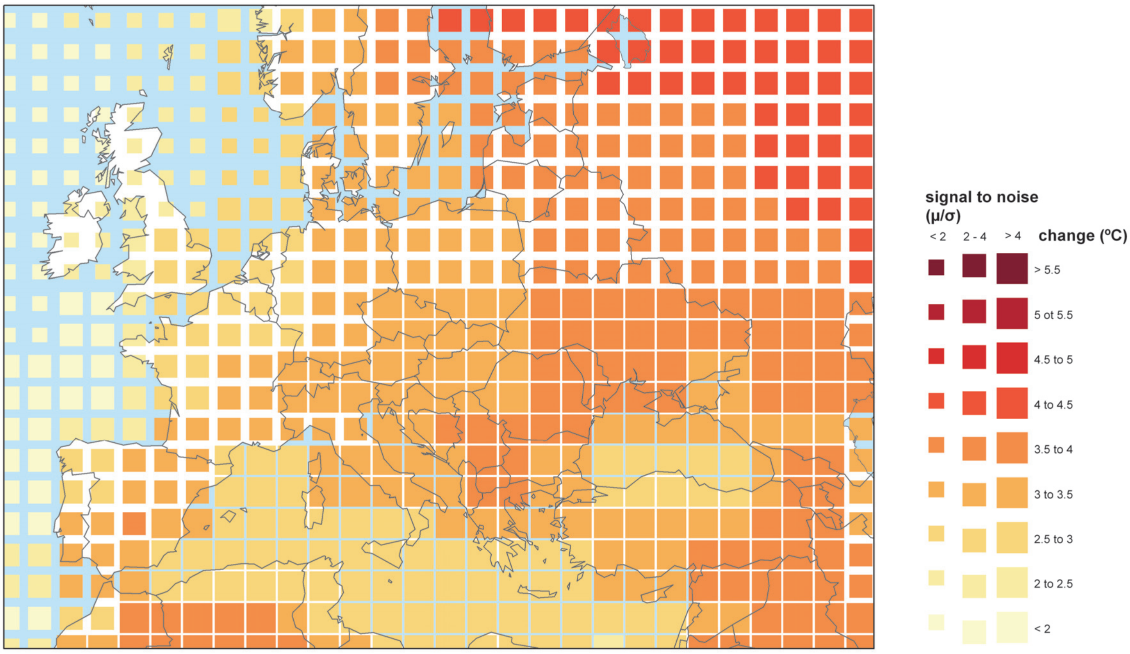

Figure 1*. Percentage change in average annual temperature by 2100 from 1960-1990 baseline climate, averaged over 21 CMIP3 models. The size of each pixel represents the level of agreement between models on the magnitude of the change.*

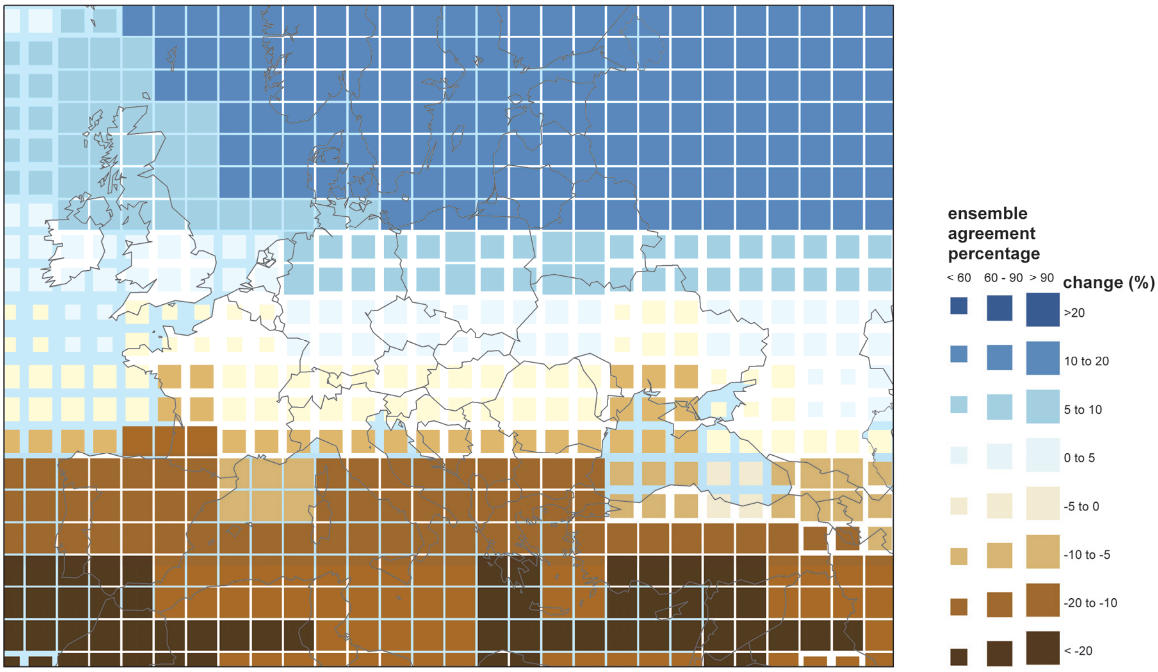

Figure 2. *Percentage change in average annual precipitation by 2100 from 1960-1990 baseline climate, averaged over 21 CMIP3 models. The size of each pixel represents the level of agreement between models on the sign of the change.*

Summary of temperature change in the UK

Figure 1 shows the percentage change in average annual temperature by 2100 from 1960-1990 baseline climate, averaged over 21 CMIP3 models. All of the models in the CMIP3 ensemble project increased temperatures in the future, but the size of each pixel indicates how well the models agree over the magnitude of the increase.

The UK is projected to experience temperature increases of up to around 3°C in the south and 2.5°C further north. The agreement between models is moderate in the south of the UK and low further north.

Summary of precipitation change in the UK

Figure 2 shows the percentage change in average annual precipitation by 2100 from 1960-1990 baseline climate, averaged over 21 CMIP3 models. Unlike for temperature, the models sometimes disagree over whether precipitation is increasing or decreasing over a region, so in this case the size of each pixel indicates the percentage of the models in the ensemble that agree on the sign of the change in precipitation.

Europe shows a strong contrast in projected precipitation changes, with large decreases in the south and large increases in the north. The UK falls towards the northern region with generally increasing precipitation, with projected increases of up to 10%, though some southern parts of the UK may experience decreases of up to 5%. There is generally good agreement between ensemble members over the north of UK, but moderate agreement further south, indicating uncertainty in the position of the transition zone between increasing and decreasing precipitation over Europe.

Chapter 3 – Climate Change Impact Projections

Introduction

Aims and approach

This chapter looks at research on a range of projected climate change impacts, with focus on results for the UK. It includes projections taken from the AVOID programme, for some of the impact sectors.

The aim of this work is to take a 'top down' approach to assessing global impacts studies, both from the literature and from new research undertaken by the AVOID programme. This project covers 23 countries, with summaries from global studies provided for each of these. This global approach allows some level of comparison between countries, whilst presenting information on a scale most meaningful to inform international policy.

The literature covered in this chapter focuses on research published since the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) and should be read in conjunction with IPCC AR4 WG1 and WG2 reports. For some sectors considered, an absence of research developments since the IPCC AR4, means earlier work is cited as this helps describe the current level of scientific understanding. This report focuses on assessing scientific research about climate change impacts within sectors; it does not present an integrated analysis of climate change adaptation policies.

Some national and sub-national scale literature is reported to a limited extent to provide some regional context.

Impact sectors considered and methods

This report reviews the evidence for the impact of climate change on a number of sectors, for the UK. The following sectors are considered in turn in this report:

- Crop yields
- Food security
- Water stress and drought
- Pluvial flooding and rainfall
- Fluvial flooding

- Tropical cyclones (where applicable)
- Coastal regions

Supporting literature

Literature searches were conducted for each sector with the Thomson Reuters Web of Science (WoS., 2011) and Google Scholar academic search engines respectively. Furthermore, climate change impact experts from each of the 23 countries reviewed were contacted. These experts were selected through a combination of government nomination and from experts known to the Met Office. They were asked to provide literature that they felt would be of relevance to this review. Where appropriate, such evidence has been included. A wide range of evidence was considered, including; research from international peer-reviewed journal papers; reports from governments, non-governmental organisations, and private businesses (e.g. reinsurance companies), and research papers published in national journals.

For each impact sector, results from assessments that include a global- or regional-scale perspective are considered separately from research that has been conducted at the national- or sub-national-scale. The consideration of global- and regional-scale studies facilitates a comparison of impacts across different countries, because such studies apply a consistent methodology for each country. While results from national- and sub-national-scale studies are not easily comparable between countries, they can provide a level of detail that is not always possible with larger-scale studies. However, the national- and sub-national scale literature included in this project does not represent a comprehensive coverage of regional-based research and cannot, and should not replace individual, detailed impacts studies in countries. For the UK, this includes the UK Climate Change Risk Assessment (CCRA). The review aims to present an up-to-date assessment of the impact of climate change on each of the sectors considered.

AVOID programme results

Much of the work in this report is drawn from modelling results and analyses coming out of the AVOID programme. The AVOID programme is a research consortium funded by DECC and Defra and led by the UK Met Office and also comprises the Walker Institute at the

University of Reading, the Tyndall Centre represented through the University of East Anglia, and the Grantham Institute for Climate Change at Imperial College. The expertise in the AVOID programme includes climate change research and modelling, climate change impacts in natural and human systems, socio-economic sciences, mitigation and technology. The unique expertise of the programme is in bringing these research areas together to produce integrated and policy-relevant results. The experts who work within the programme were also well suited to review the literature assessment part of this report. In this report the modelling of sea level rise impacts was carried out for the AVOID programme by the University of Southampton.

The AVOID programme uses the same emissions scenarios across the different impact sectors studied. These are a business as usual (IPCC SRES A1B) and an aggressive mitigation (the AVOID A1B-2016-5-L) scenario. Model output for both scenarios was taken from more than 20 GCMs and averaged for use in the impact models. The impact models are sector specific, and frequently employ further analytical techniques such as pattern scaling and downscaling in the crop yield models.

Data and analysis from AVOID programme research is provided for the following impact sectors:

- Crop yields
- Water stress and drought
- Fluvial flooding
- Coastal regions

Uncertainty in climate change impact assessment

There are many uncertainties in future projections of climate change and its impacts. Several of these are well-recognised, but some are not. One category of uncertainty arises because we don’t yet know how mankind will alter the climate in the future. For instance, uncertainties in future greenhouse gas emissions depends on the future socio-economic pathway, which, in turn, depends on factors such as population, economic growth, technology development, energy demand and methods of supply, and land use. The usual approach to dealing with this is to consider a range of possible future scenarios.

Another category of uncertainties relate to our incomplete understanding of the climate system, or an inability to adequately model some aspects of the system. This includes:

- Uncertainties in translating emissions of greenhouse gases into atmospheric concentrations and radiative forcing. Atmospheric CO_2 concentrations are currently rising at approximately 50% of the rate of anthropogenic emissions, with the remaining 50% being offset by a net uptake of CO_2 into the oceans and land biosphere. However, this rate of uptake itself probably depends on climate, and evidence suggests it may weaken under a warming climate, causing the CO_2 rise to be larger proportion of emissions. The extent of this feedback is highly uncertain, but it not considered in most studies. The 3rd Coupled Model Intercomparison Project (CMIP3), which provided the future climate projections for the IPCC 4th Assessment Report, used a single estimate of CO_2 concentration rise for each emissions scenario, so the CMIP3 projections (which were used in most studies presented here, including AVOID) do not account for this uncertainty.

- Uncertainty in climate response to the forcing by greenhouse gases and aerosols. One aspect of this is the response of global mean temperature ("climate sensitivity"), but a more relevant aspect for impacts studies is the response of regional climates, including temperature, precipitation and other meteorological variables. Different climate models can give very different results in some regions, while giving similar results in other regions. Confidence in regional projections requires more than just agreement between models: physical understanding of the relevant atmospheric, ocean and land surface processes is also important, to establish whether the models are likely to be realistic.

- Additional forcings of regional climate. Greenhouse gas changes are not the only anthropogenic driver of climate change; atmospheric aerosols and land cover change are also important, and unlike greenhouse gases, the strength of their influence varies significantly from place to place. The CMIP3 models used in most impacts studies generally account for aerosols but not land cover change.

- Uncertainty in impacts processes. The consequences of a given changes in weather or climatic conditions for biophysical impacts such as river flows, drought, flooding, crop yield or ecosystem distribution and functioning depend on many other processes which are often poorly-understood, especially at large scales. In particular, the extent to which different biophysical impacts interact with each other has been hardly studied, but may be crucial; for example, impacts of climate change on crop yield may depend not only on local climate changes affecting rain-fed crops, but also remote climate changes affecting river flows providing water for irrigation.

- Uncertainties in non-climate effects of some greenhouse gases. As well as being a greenhouse gas, CO_2 exerts physiological influences on plants, affecting photosynthesis and transpiration. Under higher CO_2 concentrations, and with no other limiting factors, photosynthesis can increase ,while the requirements of water for transpiration can decrease. However, while this has been extensively studied under experimental conditions, including in some cases in the free atmosphere, the extent to which the ongoing rise in ambient CO_2 affects crop yields and natural vegetation functioning remains uncertain and controversial. Many impacts projections assume CO_2 physiological effects to be significant, while others assume it to be non-existent. Studies of climate change impacts on crops and ecosystems should therefore be examined with care to establish which assumptions have been made.

In addition to these uncertainties, the climate varies significantly through natural processes from year-to-year and also decade-to-decade, and this variability can be significant in comparison to anthropogenic forcings on shorter timescales (the next few decades) particularly at regional scales. Whilst we can characterise the natural variability it will not be possible to give a precise forecast for a particular year decades into the future.

A further category of uncertainty in projections arises as a result of using different methods to correct for uncertainties and limitations in climate models. Despite being painstakingly developed in order to represent current climate as closely as possible, current climate models are nevertheless subject to systematic errors such as simulating too little or too much rainfall in some regions. In order to reduce the impact of these, '*bias correction*' techniques are often employed, in which the climate model as a source of information on the *change* in climate which is then applied to the observed present-day climate state (rather than using the model's own simulation of the present-day state). However, these bias-corrections typically introduce their own uncertainties and errors, and can lead to inconsistencies between the projected impacts and the driving climate change (such as river flows changing by an amount which is not matched by the original change in precipitation). Currently, this source of uncertainty is rarely considered

When climate change projections from climate models are applied to climate change impact models (e.g. a global hydrological model), the climate model structural uncertainty carries through to the impact estimates. Additional uncertainties include changes in future emissions and population, as well as parameterisations within the impact models (this is rarely considered). Figure 1 highlights the importance of considering climate model structural uncertainty in climate change impacts assessment. Figure 1 shows that for 2°C prescribed global-mean warming, the magnitude of, and sign of change in average annual runoff from present, simulated by an impacts model, can differ depending upon the GCM that provides the climate change projections that drive the impact model. This example also shows that the choice of impact model, in this case a global hydrological model (GHM) or catchment-scale hydrological model (CHM), can affect the magnitude of impact and sign of change from present (e.g. see IPSL CM4 and MPI ECHAM5 simulations for the Xiangxi). To this end, throughout this review, the number of climate models applied in each study reviewed, and the other sources of uncertainty (e.g. emissions scenarios) are noted. Very few studies consider the application of multiple impacts models and it is recommended that future studies address this.

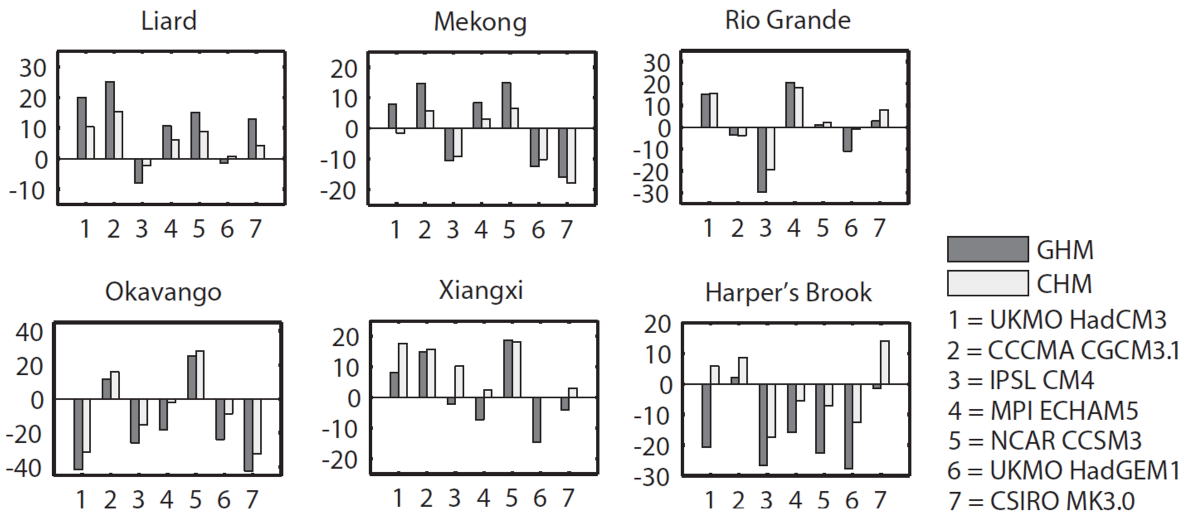

Figure 1. *Change in average annual runoff relative to present (vertical axis; %), when a global hydrological model (GHM) and a catchment-scale hydrological model (CHM) are driven with climate change projections from 7 GCMs (horizontal axis), under a 2°C prescribed global-mean warming scenario, for six river catchments. The figure is from Gosling et al. (2011).*

Uncertainties in the large scale climate relevant to the UK include the Atlantic Ocean Meridional Overturning Circulation (MOC) which transports large amounts of heat northwards in the Atlantic from the Equator. A key part of this is called the thermohaline circulation (THC). Disruption of the MOC could have a major impact on the Northern Hemisphere climate, including that of the UK, with likely detrimental impacts on human and animal systems. The IPCC AR4 concluded that "… it is very likely that the Atlantic Ocean Meridional Overturning Circulation could slow down during the course of the 21st century. A multi-model ensemble shows an average reduction of 25% with a broad range from virtually no change to a reduction of over 50% averaged over 2080 to 2099" (IPCC, 2007a).

Schneider et al. (2007) analysed simulations from several GCMs that were included in the CMIP3 multi-model dataset and found that projections of MOC change indicate it may weaken by 25-30% by the year 2100. Recent monitoring (Cunningham et al., 2007, Kanzow et al., 2007) has revealed large variability in the strength of the MOC on daily to seasonal timescales. This significant variability casts doubt on a previous report of decreases in MOC transport from several hydrographic sections (Bryden et al., 2005), although it does not explain the observed water mass changes below 3000m. Recent results based on radar altimeter and Argo data also suggest that there has been no slowdown, at least over the altimeter era (1993-present) (Willis, 2010). In contrast, two ocean state estimation studies (Balmaseda et al., 2007, Wunsch and Heimbach, 2006) indicated an MOC slow down. It has been suggested, based on model studies, that anthropogenic aerosols have slowed the weakening of the MOC and such weakening might only become significant several decades into the 21st century (Delworth and Dixon, 2006).

Regarding the possibility of MOC shutdown, a recent study presented by Swingedouw et al. (2007) with one climate model found that additional melt from Greenland could lead to complete AMOC shutdown in a CO_2 stabilisation experiment. However, a previous study with a different model (Ridley et al., 2005) found no effect from similar levels of meltwater input. Mikolajewicz et al. (2007) coupled an earth system model with atmospheric and ocean GCMs and observed a complete shutdown of the AMOC under a high emission scenario (SRES A2), but not before 2100. Moreover, Mikolajewicz et al. (2007) observed only a temporary weakening of the deep water formation in the North Atlantic by 2100 under a low emission scenario (B1).

Reversibility following AMOC shutdown is a key issue. Hofmann and Rahmstorf (2009) showed that hysteresis still occurs in a new low-diffusivity model. This is contrary to previous theoretical arguments that hysteresis is a product of diffusivity of the low-resolution simplified ocean models which are applied to perform the long-term simulations that are required to investigate this issue.

There is some new work on the impacts of AMOC weakening. Two studies (Kuhlbrodt et al., 2009, Vellinga and Wood, 2008) found SLR of several tens of cm along parts of the North Atlantic coast. The studies found that regional cooling could partially offset the greenhouse gas warming, and various other impacts may be substantial but hard to quantify such as change in tropical precipitation patterns and change in ocean currents leading to declining fish stocks and ecosystems (Schmittner, 2005).

In conclusion, large uncertainty remains in the probability of a complete MOC shutdown (Kriegler et al., 2009, Zickfeld et al., 2007). However, for the high temperature scenario considered by a recent expert elicitation exercise (centred on 4.5°C by 2100, 6.5°C by 2200) (Kriegler et al., 2009), the probability of complete shutdown was assessed to be at least 10% (according to several experts). Comparable results were found by the exercise reported by Zickfeld et al. (2007). To this end, it is thought unlikely that the AMOC could significantly weaken with 2°C global-mean warming.

Summary of findings for each sector

Crop yields

- Quantitative crop yield projections under climate change scenarios for the UK vary across studies due to the application of different models, assumptions and emissions scenarios.
- A definitive conclusion on the impact of climate change on crop yields in the UK cannot be drawn from the studies included here. There is some indication from global- and regional-scale studies for a difference in yield changes between the north and south of the UK. For instance, yield increases are projected for Northern Ireland and Scotland but declines projected in the South of England with climate change.
- National-scale studies included here note that the effects of heat stress during flowering on wheat variety crop yields in the UK should be quantified and implemented into crop models.
- Important knowledge gaps and key uncertainties include the quantification of yield increases due to CO_2 fertilisation, the quantification of yield reductions due to ozone damage and the extent to which crop diseases might affect crop yields with climate change.

Food security

- The UK is currently a country of extremely low undernourishment. Global-scale studies included here generally project that the UK is likely to remain food secure over the next 40 years, largely due to its high adaptive capacity associated with an ability to import food.
- Simulations from the AVOID programme project that population increases coupled with potential declines in crop yields by the 2080s could increase exposure to

undernourishment in the UK, and that structural adjustment will be instrumental in decreasing exposure.

- One study concluded that the national economy of the UK presents a very low vulnerability to climate change impacts on fisheries by the 2050s. Another projects that the 10-year averaged maximum catch potential from 2005 to 2055 could increase by 1% under SRES A1B in the UK.

Water stress and drought

- Global- and national-scale studies included here project that the vulnerability to water stress with climate change is mainly focussed in the south and south-east of the UK. On the whole, these regions are projected to experience an increase in the frequency of droughts and water stress with climate change.

- Recent simulations by the AVOID programme project that the UK could experience a moderate increase in water stress with climate change, although the median estimate the models suggested no increase in water stress with climate change for the UK by 2100.

Pluvial flooding and rainfall

- Post-IPCC AR4 research for precipitation extremes over the UK focus upon understanding and quantifying uncertainties, and detection and attribution studies.

- Rainfall extremes are generally projected to increase, particularly during winter.

- Changes during summer are more uncertain.

- New work is exploring connections between changes in extreme precipitation and anthropogenic climate change.

Fluvial flooding

- Several European-scale and national-scale assessments suggest an increase in flood risk with climate change in the UK.

- Simulations from the AVOID programme support this. For the UK as a whole, the projections show a much greater tendency for increasing flood risk, particularly later in the century and particularly in the A1B scenario.

- However, national-scale studies have also shown that the UK exhibits a high degree of spatial variability in the sensitivity of rivers to changes in climate, and projections of changes in flood hazard show large uncertainty, which is mainly due to climate modelling uncertainty. Further work is necessary to better account for the influence of natural variability and the uncertainties related to climate scenarios.

- This supports conclusions from the IPCC AR4 but now more regional detail across the UK is available.

Tropical cyclones

- The UK is not impacted by tropical cyclones.

Coastal regions

- Several global-scale and regional-scale assessments suggest that without adaptation, the UK could experience major impacts on coastal flooding from sea level rise (SLR).

- For example, one study shows that by the 2080s under a high SLR scenario and without adaptation, the average annual number of people flooded in the UK could be around 986,300; this is greatly reduced with adaptation (raising of flood dykes and the application of beach nourishment), to around 5,600.

- New work also demonstrates the potential benefits of climate change mitigation policy. For example, one study shows that aggressive mitigation could avoid an exposure of around 51,000 people to SLR in the UK, relative to un-mitigated climate change.

- These results add evidence to support the conclusions from the IPCC AR4.

Crop yields

Headline

Crop yield projections under climate change scenarios for the UK vary across studies due to the application of different models, assumptions and emissions scenarios. Some studies suggest a strong difference in yield changes between the north and south of the UK. For instance, yield increases are projected for Northern Ireland and Scotland but declines in the South of England, with climate change.

Results from the AVOID programme for UK indicate that the balance is much more towards areas of increased rather than decreased cropland suitability due to climate change. However, the area benefiting from climate change is projected to be smaller under A1B than the mitigation scenario by the end of the 21st century, so the initial beneficial effects of low-level climate change may remain if climate change remains low.

Supporting literature

Introduction

The impacts of climate change on crop productivity are highly uncertain due to the complexity of the processes involved. Most current studies are limited in their ability to capture the uncertainty in regional climate projections, and often omit potentially important aspects such as extreme events and changes in pests and diseases. Importantly, there is a lack of clarity on how climate change impacts on drought are best quantified from an agricultural perspective, with different metrics giving very different impressions of future risk. The dependence of some regional agriculture on remote rainfall, snowmelt and glaciers adds to the complexity - these factors are rarely taken into account, and most studies focus solely on the impacts of local climate change on rain-fed agriculture. However, irrigated agricultural land produces approximately 40-45 % of the world's food (Doll and Siebert 2002), and the water for irrigation is often extracted from rivers which can depend on climatic conditions far from the point of extraction. Hence, impacts of climate change on crop productivity often need to take account of remote as well as local climate changes. Indirect impacts via sea-level rise, storms and diseases have also not been quantified. Perhaps most seriously, there is high uncertainty in the extent to which the direct effects of CO_2 rise on plant physiology will interact with climate change in affecting productivity. Therefore, at present, the aggregate impacts of climate change on large-scale agricultural productivity cannot be reliably quantified (Gornall et al, 2010). This section summarises findings from a range of post IPCC AR4 assessments to inform and contextualise the analysis performed by AVOID programme for this project. The results from the AVOID work are discussed in the next section.

The FAO (2008) showed that wheat, sugar beet, barley and potatoes are the important food crops in the UK (see Table 1). Rapeseed is also important because of its economic value.

Harvested area (ha)		**Quantity (Metric ton)**		**Value ($1000)**	
Wheat	2080000	Wheat	17200000	Wheat	1660000
Barley	1030000	Sugar beet	7500000	Potatoes	819000
Rapeseed	598000	Barley	6140000	Rapeseed	495000
Oats	135000	Potatoes	5990000	Sugar beet	345000
Sugar beet	119000	Rapeseed	1970000	Barley	290000
Pulses (nes) [1]	99400	Oats	783000	Carrots and turnips	133000
Peas, green	35000	Carrots and turnips	719000	Strawberries	92500

Table 1. *The top 7 crops by harvested area, quantity and value according to the FAO (2008) in the UK. Crops that feature in all lists are shaded green; crops that feature in two top 7 lists are shaded amber. Data is from FAO (2008) and has been rounded down to three significant figures.*

A number of impact model studies looking at crop yield which include results for some of the main crops in the UK have been conducted. They apply a variety of methodological approaches, including using different climate model inputs and treatment of other factors that might affect yield, such as impact of increased CO_2 in the atmosphere on plant growth and adaption of agricultural practises to changing climate conditions. Some studies report projections for geographic or climatic areas larger than the UK alone and it is not always clear to what extent the crop yield projections are representative for the UK only in these cases. These different models, assumptions and emissions scenarios mean that there are a range of crop yield projections for the UK.

Important knowledge gaps and key uncertainties which are applicable to the UK as well as at the global-scale, include; the quantification of yield increases due to CO_2 fertilisation and yield reductions due to ozone damage (Ainsworth and McGrath, 2010, Iglesias et al., 2009), and the extent crop diseases could affect crop yields with climate change (Luck et al., 2011). The effects of heat stress during flowering on wheat variety crop yields in the UK should also be quantified and implemented into crop models. Most crop simulation models do not include the direct effect of extreme temperatures on crop development and growth, thus only changes in mean climate conditions are considered to affect crop yields for the studies included here.

Assessments that include a global or regional perspective

Recent Past

Crop yield changes could be due to a variety of factors, which might include, but not be confined to, a changing climate. In order to assess the impact of recent climate change (1980-2008) on wheat, maize, rice and soybean, Lobell et al. (2011) looked at how the overall yield trend in these crops changed in response to changes in climate over the period studied. The study was conducted at the global-scale but national estimates for the UK were also calculated. Lobell et all. (2011) divided the climate-induced yield trend by the overall yield trend for 1980–2008, to produce a simple metric of the importance of climate relative to all other factors. The ratio produced indicates the influence of climate on the productivity trend. So for example a value of –0.1 represents a 10% reduction in yield gain due to climate change, compared to the increase that could have been achieved without climate change, but with technology and other gains. This can also be expressed as 10 years of climate trend being equivalent to the loss of roughly 1 year of technology gains. For the UK, wheat yield was estimated to have been impacted negatively relative to what could have been achieved without climate trends (see Table 2).

Crop	Trend
Maize	n/a
Rice	n/a
Wheat	- 0.1 to -0.2
Soybean	n/a

Table 2. *The estimated net impact of climate trends for 1980-2008 on crop yields in the UK. Climate-induced yield trend divided by overall yield trend. 'n/a' infers zero or insignificant crop production or unavailability of data. Data is from Lobell et al. (2011).*

Climate change studies

Recent studies have applied climate projections from Global Climate Models (GCMs) to crop yield models to assess the global-scale impact of climate change on crop yields (Iglesias and Rosenzweig, 2009, Moriondo et al., 2010, Olesen et al., 2007). Most of these studies include impact estimates at the national-scale for the UK which are presented in this section. The process of CO_2 fertilisation of some crops is usually included in most climate impact studies of yields. However, other gases can influence crop yield and are not always included in impacts models. An example of this is ozone (O_3) and so a study which attempts to quantify the potential impact on crop yield of changes in ozone in the atmosphere is also included (Avnery et al. 2011). In addition to these studies, the AVOID programme analysed the patterns of climate change for 21 GCMs, to establish an index of 'climate suitability' of agricultural land. Climate suitability is not directly equivalent to crop yields, but is a means of looking at a standard metric across all the countries including in this project, and of assessing the level of agreement on variables that affect crop production, between all 21 GCMs.

Iglesias and Rosenzweig (2009) repeated an earlier study presented by Parry et al. (2004) by applying climate projections from the HadCM3 GCM (instead of HadCM2, which was applied by Parry et al. (2004)), under seven SRES emissions scenarios and for three future time periods. This study used a globally consistent crop simulation methodologies and climate change scenarios, and weighted the model site results by their contribution to regional and national, and rain-fed and irrigated production. The study also applied a quantitative estimation of physiological CO_2 effects on crop yields and considered the affect of adaptation by assessing the country or regional potential for reaching optimal crop yield. The results from the study for the UK are presented in Table 3 and Table 4. Wheat yields were projected to increase steadily above baseline (1970-2000) levels with climate change for each time horizon, and under all emissions scenarios. However, under the emissions scenario associated with greatest warming; A1FI, a slight decrease in yields was projected between 2050 and 2080, but total yield was still above baseline levels.

Scenario	Year	Wheat
A1FI	2020	4.19
	2050	9.28
	2080	7.48
A2a	2020	5.67
	2050	9.20
	2080	13.14
A2b	2020	3.49
	2050	8.92
	2080	13.15
A2c	2020	3.34
	2050	9.07
	2080	13.51
B1a	2020	1.61
	2050	5.28
	2080	6.86
B2a	2020	3.66
	2050	5.13
	2080	7.24
B2b	2020	3.16
	2050	5.50
	2080	8.85

***Table 3.** Wheat yield changes (%) in the UK relative to baseline scenario (1970-2000) for different emission scenarios and future time periods. Some emissions scenarios were run in an ensemble simulation (e.g. A2a, A2b, A2c). Data is from Iglesias and Rosenzweig (2009).*

	Wheat	
	Up	**Down**
Baseline to 2020	7	0
Baseline to 2050	7	0
Baseline to 2080	7	0
2020 to 2050	7	0
2050 to 2080	6	1

***Table 4**. The number of emission scenarios that predict yield gains ("Up") or yield losses ("Down") for wheat in the UK between two points in time. Data is from Iglesias and Rosenzweig (2009).*

Moriondo et al. (2010) simulated relative changes in crop yield for sunflower, soybean, spring wheat and durum wheat for a global mean warming of 2°C warmer than present climate change scenario with A2 socioeconomics. The study accounted for changes in extreme events such as droughts and the CO_2 fertiliser effect. Moriondo et al. (2010) compared the effectiveness of various adaptation options relative to no adaptation. No quantitative information on impacts is available from the study but estimates can be made whether, on average, a relative yield loss or a yield gain was projected for a given crop, adaptation method and country (see Table 5). For the UK, the results presented by Moriondo et al. (2010) imply that for the 2030-2060 time horizon and even without adaptation, on average, climate change is associated with yield increases for soybean, sunflower and spring wheat. Applying longer cycle varieties and/or irrigation could even enhance these increases in yield.

	No adaptation[1]	Advanced sowing	Delayed sowing	Shorter cycle varieties	Longer cycle varieties	Irrigation
Sunflower	+	+ -	-	-	+	+
Soybean	+	+	-	-	+	+
Spring wheat	+	+ -	-	-	+	+
Durum wheat	n/a	n/a	n/a	n/a	n/a	n/a

[1] Yield changes with respect to the present period, not considering adaptation methods

***Table 5**. Relative change in yield of four crops in a +2 °C world under SRES A2 socioeconomics for the UK. The relative change is calculated with respect to the same +2°C scenario without adaptation (left column). "+" = relative yield gain, "-" = relative yield loss, "+ -" = high spatial variability and uncertainty over sign of average yield change, "n/a" = crop is not grown. After Moriondo et al. (2010).*

Olesen et al. (2007) addressed the issue of uncertainty in projecting impacts of climate change on agriculture. They projected rain-fed winter wheat yield across the European domain using nine different RCMs with HadAM3H as the bounding GCM, under SRES A2 emissions. For over 90% of the cropping area of the UK, all RCMs simulated an increase of wheat yields.

Elsewhere, several recent studies have assessed the impact of climate change on a global-scale or regional-scale and include impact estimates for Northern Europe as a whole (Ciscar et al., 2009, Iglesias et al., 2009, Tatsumi et al., 2011). Whilst these studies provide a useful indicator of crop yields under climate change for the larger *region*, it should be noted that the crop yields presented in such cases are not definitive *national* estimates. This is because the yields are averaged over the entire region, which includes other countries as well as the UK.

Tatsumi et al. (2011) applied an improved version of the GAEZ crop model (iGAEZ) to simulate crop yields on a global scale for wheat, potato, cassava, soybean, rice, sweet potato, maize, green beans. The impact of global warming on crop yields from the 1990s to 2090s was assessed by projecting five GCM outputs under the SRES A1B scenario and comparing the results for crop yields as calculated using the iGAEZ model for the period of 1990-1999. The results for Northern Europe, the regional grouping which included the UK, are displayed in Table 6 and suggest, in contrast to most other studies, a decline in yield for most crops including wheat.

Wheat	Potato	Cassava	Soybean	Rice	Sweet potato	Maize	Green beans
-16.37	-5.83	-	0.91	-	-	-	-5.81

Table 6. *Average change in yield (%), during 1990s-2090s in Northern Europe. Data is from Tatsumi et al. (2011).*

The PESETA project estimated the impacts of climate change on crop yields for different regions in the EU (Ciscar et al., 2009, Iglesias et al., 2009). Climate scenarios were created for the 2070-2100 time horizon using a combination of two GCMs and SRES emissions scenarios (A2 and B2). Crop yield simulations (winter wheat, spring wheat, rice, grassland, maize and soybeans) were then conducted using the DSSAT suite of crop models. The results for the “British Isles” region, which is comprised of the UK and Ireland, are displayed in Table 7. As mentioned previously, it should be noted that the projected yield changes may vary widely within a geographic region. British Isles average is not fully representative for the UK. Nevertheless, the PESETA project includes useful maps that show projected changes in crop yield for each emissions scenario, from which impacts for the UK can be inferred (see Figure 2). These show that the projected crop yield change for the UK is spatially heterogeneous across all emissions scenarios; e.g. the north of the UK is generally associated with yield increases with climate change, whereas the south is associated with yield decreases.

2011-2040	**2071-2100**			
A2 ECHAM4	A2 HadAM3h	B2 HadAM3h	A2 ECHAM4	B2 ECHAM4
+20	−11	−9	+19	+15

Table 7. *Projected crop yield changes (%), compared to 1961-1990 period for the “British Isles” region, which is comprised of the UK and Ireland. Data is from Ciscar et al. (2009).*

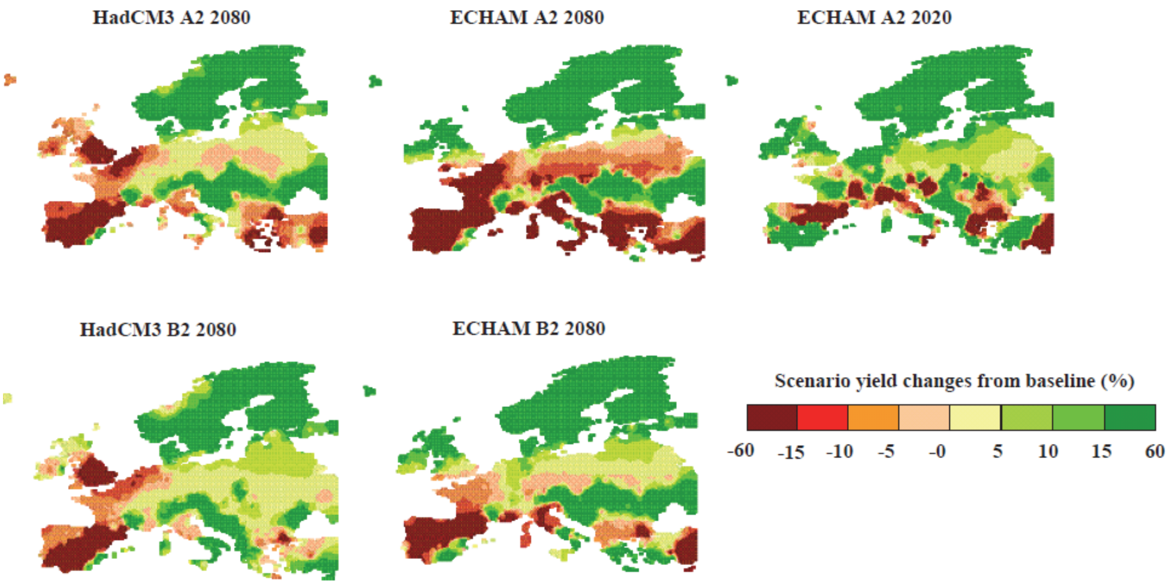

__Figure 2.__ Crop yield changes under the HadCM3/HIRHAM A2 and B2 scenarios for the period 2071 - 2100 and for the ECHAM4/RCA3 A2 and B2 scenarios for the period 2011 – 2040 compared to baseline. The figure is from (Iglesias et al., 2009), p.31.

In addition to the studies looking at the effect of changes in climate and CO_2 concentrations on crop yield, Avnery et al. (2011) investigated the effects of ozone surface exposure on crop yield losses for soybeans, maize and wheat under the SRES A2 and B1 scenarios respectively. Two metrics of ozone exposure were investigated; seasonal daytime (08:00-19:59) mean O_3 ("M12") and accumulated O_3 above a threshold of 40 ppbv ("AOT40"). The effect of the ozone exposure was considered in isolation from climate and other changes. The results for the UK are presented in Table 8.

	A2		B1	
	M12	AOT40	M12	AOT40
Soybeans	-	-	-	-
Maize	-	-	-	-
Wheat	0-2	4-6	0-2	2-4

__Table 8.__ National relative crop yield losses (%) for 2030 under A2 and B1 emission scenarios according to the M12 (seasonal daytime (08:00–19:59) mean) and AOT40 (accumulated O_3 above a threshold of 40 ppbv) metrics of O_3 exposure. Data is from Avnery et al. (2011).

National-scale or sub-national scale assessments

In this section we present results from recent studies that have looked at ongoing trends in crop yields, or have produced national or sub-national scale projections of future crop yields in the UK.

Recent past

Jaggard et al. (2007) assessed the impact of historical climate trends on sugarbeet yields for the UK. The authors analysed weather and sugarbeet yield data for the 1976-2004 time horizon. They found that changes in the weather during the growing season, including those that allow earlier sowing, are sufficiently large to account for about 66% of all the sugarbeet yield improvement measured in the national variety trials since 1976. In absolute terms, annual yield gains attributable to climate change were estimated at 0.139 t/ha.

Climate change studies

Semenov (2009) simulated yield increases for an early and late flowering winter wheat variety due to the CO_2 fertilisation effect if yield losses due to heat stress around flowering and drought stress were ignored. Yield losses due to drought stress could become less frequent because wheat could mature earlier in a warmer climate and avoid severe summer drought. However, the probability of heat stress around flowering is estimated to increase significantly, which might result in considerable yield losses. Semenov (2009) concludes that breeding strategies for the future climate might need to focus on wheat varieties tolerant to high temperature rather than to drought.

Ferrara et al. (2010) linked a newly developed and calibrated micro-meteorological model for hilly terrain and plains in the country of Bedfordshire, to a crop growth simulation model to quantify how durum wheat production in hilly terrain and on plains respectively could be affected by climate change. Under baseline (1961-1990) climate, wheat yield reduction was significantly related to a function of slope and elevation index, which was associated with increased crop failure in drier elevated areas but not in wet years. For the 2080s, under both the SRES A2 and B2 emissions scenarios, Ferrara et al. (2010) simulated increased crop yields relative to baseline. For hilly terrain, crop yields increased by 27% (A2) and 23% (B2), relative to baseline. For the plains, crop yields increased by 28% (A2) and 22% (B2), relative to baseline.

AVOID programme results

To further quantify the impact of climate change on crops, the AVOID programme simulated the effect of climate change on the suitability of land for crop cultivation for all countries reviewed in this literature assessment based upon the patterns of climate change from 21 GCMs (Warren et al., 2010). This ensures a consistent methodological approach across all countries and takes consideration of climate modelling uncertainties.

Methodology

The effect of climate change on the suitability of land for crop cultivation is characterised here by an index which defines the percentage of cropland in a region with 1) a decrease in suitability or 2) an increase in suitability. A threshold change of 5% is applied here to characterise decrease or increase in suitability. The crop suitability index is calculated at a spatial resolution of 0.5°x0.5°, and is based on climate and soil properties (Ramankutty et al., 2002). The baseline crop suitability index, against which the future changes are measured, is representative conditions circa 2000. The key features of the climate for the crop suitability index are temperature and the availability of water for plants, and changes in these were derived from climate model projections of future changes in temperature and precipitation, with some further calculations then being used to estimate actual and potential evapotranspiration as an indicator of water availability. It should be noted that changes in atmospheric CO_2 concentrations can decrease evapotranspiration by increasing the efficiency of water use by plants (Ramankutty et al., 2002), but that aspect of the index was not included in the analysis here. Increased CO_2 can also increase photosynthesis and improve yield to a small extent, but again these effects are not included. Exclusion of these effects may lead to an overestimate of decreases in suitability.

The index here is calculated only for grid cells which contain cropland circa 2000, as defined in the global crop extent data set described by Ramankutty et al. (2008) which was derived from satellite measurements. It is assumed that crop extent does not change over time. The crop suitability index varies significantly for current croplands across the world (Ramankutty et al., 2002), with the suitability being low in some current cropland areas according to this index. Therefore, while climate change clearly has the potential to decrease suitability for cultivation if temperature and precipitation regimes become less favourable, there is also scope for climate change to increase suitability in some existing cropland areas if conditions become more favourable in areas where the suitability index is not at its maximum value of 1. It should be noted that some areas which are not currently croplands may already be suitable for cultivation or may become suitable as a result of future climate change, and may become used a croplands in the future either as part of climate change adaptation or changes in land use arising for other reasons. Such areas are not included in this analysis.

Results

Crop suitability was estimated under the pattern of climate change from 21 GCMs with two emissions scenarios; 1) SRES A1B and 2) an aggressive mitigation scenario where emissions follow A1B up to 2016 but then decline at a rate of 5% per year thereafter to a low emissions floor (denoted A1B-2016-5-L). The application of 21 GCMs is an attempt to quantify the uncertainty due to climate modelling, although it is acknowledged that only one crop suitability impacts model is applied. Simulations were performed for the years 2030, 2050, 2080 and 2100. The results for the UK are presented in Figure 3.

Under all the climate projections, a large proportion of existing cropland areas in the UK become more suitable for cultivation, while some existing cropland areas become less suitable under the projections of a few models. The areas of increased and decreased suitability differ somewhat according to the climate model used, but some common trends can be discerned.

In 2030, under both the A1B and mitigation scenarios, the model projections imply an improvement in suitability for cultivation over 90%-95% of current UK croplands. This situation remains similar throughout the 21st century under the mitigation scenario, with a small increase in the difference between models resulting in increased suitability being projected over 93%-98% of current croplands by 2100. However, under the A1B scenario, the uncertainty becomes larger over time and a greater proportion of the models project smaller areas (as low as 60%) experiencing improved suitability by 2100.

Most model projections do not imply any area of UK croplands to become less suitable for cultivation according to the metric used here, under either scenario. The only exceptions are 4 projections (of the full set of 21) which imply declining suitability over up to 10% and 20% of current croplands by 2080 and 2100 respectively, under the A1B scenario only. These models indicated no change under the mitigation scenario.

So, for the UK, the balance is much more towards areas of increased rather than decreased cropland suitability due to climate change. However, the area benefiting from climate change is projected to be smaller under A1B than the mitigation scenario by the end of the 21st century, so the initial beneficial effects of low-level climate change may remain if climate change remains low.

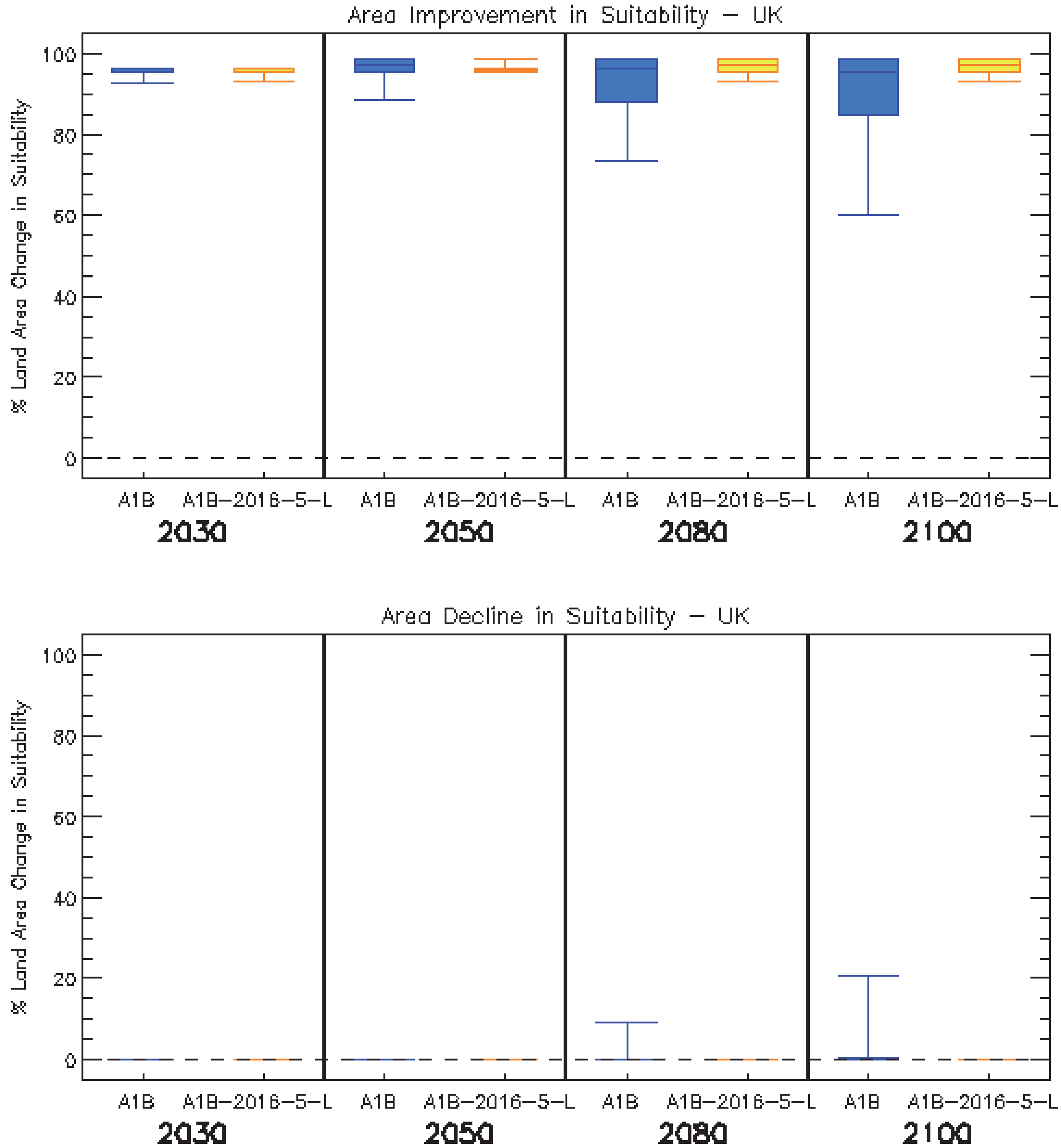

Figure 3. *Box and whisker plots for the impact of climate change on increased crop suitability (top panel) and decreased crop suitability (bottom panel) for the UK, from 21 GCMs under two emissions scenarios (A1B and A1B-2016-5-L), for four time horizons. The plots show the 25th, 50th, and 75th percentiles (represented by the boxes), and the maximum and minimum values (shown by the extent of the whiskers).*

Food security

Headline

Several recent global-scale assessments suggest that the UK could remain food-secure under climate change scenarios, largely due to its high adaptive capacity associated with an ability to import food. This adds detail to knowledge reported in the IPCC AR4. New understanding relative to the IPCC AR4, shows that the UK presents a very low vulnerability to climate change impacts on fisheries.

Supporting literature

Introduction

Food security is a concept that encompasses more than just crop production, but is a complex interaction between food availability and socio-economic, policy and health factors that influence access to food, utilisation and stability of food supplies. In 1998 the World Food Summit defined food security as existing 'when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs, and their food preferences are met for an active and healthy life'. As such this section cannot be a comprehensive analysis of all the factors that are important in determining food security, but does attempt to assess a selection of the available literature on how climate change, combined with projections of global and regional population and policy responses, may influence food security.

With regards to food security the UK is presently a country of very low concern, relative to other countries across the globe. According to FAO statistics (FAO, 2010) the UK has an extremely low level of undernourishment (less than 5% of the population). Moreover, a number of global studies point towards a generally optimistic and positive outlook for the impact of climate change on food security in the UK, largely due to its high adaptive capacity associated with an ability to import food (Falkenmark et al., 2009, Wu et al., 2011) and/or to make food production related-structural adjustments (Arnell et al., 2010).

Assessments that include a global or regional perspective

Climate change studies

Several recent studies have analysed food security under climate change across the globe. Wu et al. (2011) simulated crop yields with the GIS-based Environmental Policy Integrated Climate (EPIC) model. This was combined with crop areas simulated by a crop choice decision model to calculate total food production and per capita food availability across the globe, which was used to represent the status of food availability and stability. The study focussed on the SRES A1 scenario and applied climate change simulations for the 2000s (1991–2000) and 2020s (2011–2020). The climate simulations were performed by MIROC (Model for Interdisciplinary Research on Climate) version 3.2., which means the effects of climate model uncertainty were not considered. Downscaled population and GDP data from the International Institute for Applied Systems Analysis (IIASA) were applied in the simulations. Wu et al. (2011) concluded that the UK is not likely to face severe food insecurity in the next 20 years.

Moreover, the UK might be able to improve their food security situation due to either an increase in per capita food availability or an increase in the capacity to import food between 2000 and 2020. Falkenmark et al. (2009) present a global analysis of food security under climate change scenarios that considered the importance of water availability for ensuring global food security. The study presents an analysis of water constraints and opportunities for global food production on current croplands and assesses five main factors:

1) how far improved land and water management might go towards achieving global food security,

2) the water deficits that would remain in regions currently experiencing water scarcity and which are aiming at food self-sufficiency,

3) how the water deficits above may be met by importing food,

4) the cropland expansion required in low income countries without the needed purchasing power for such imports, and

5) the proportion of that expansion pressure which will remain unresolved due to potential lack of accessible land.

Similar to the study presented by Wu et al. (2011), there is no major treatment of modelling uncertainty; simulations were generated by only the LPJml dynamic global vegetation and water balance model (Gerten et al. 2004) with population growth and climate change under the SRES A2 emission scenario. Falkenmark et al. (2009) summarise the impacts of future improvements (or lack thereof) in water productivity for each country across the globe and show that this generates either a deficit or a surplus of water in relation to food water requirements in each country. These can be met either by trade or by horizontal expansion (by converting other terrestrial ecosystems to crop land). The study estimated that in 2050 around one third of the world's population will live in each of three regions: those that export food, those that import food, and those that have to expand their croplands at the expense of other ecosystems because they do not have enough purchasing power to import their food. The simulations demonstrated that the UK was a food importing country in 2050.

Similarly, Arnell et al. (2010) demonstrate how important adaptation measures could be for the UK, if major food security issues are to be avoided under climate change. The study considered the impacts of global climate change and mitigation policy on food security for eleven countries. The study applied climate change patterns from the HadCM3 GCM and explored food security under two emissions scenarios; a business as usual scenario (SRES A1B) and four mitigations scenarios where emissions peak in 2030 and subsequently reduce at 2% per year to a high emissions floor (referred to as 2030-2-H) or 5% per year to a low emissions floor (2030-5-L), or where they peak in 2016 and subsequently reduce at 2% per year to a high emissions floor (referred to as 2016-2-H) or 5% per year to a low emissions floor (2016-5-L). The study also considered a series of structural adjustments that could be made in the future to adapt to food security issues, including that 1) if there is a shortfall of any per-capita food availability due to crop yield and/or population changes, then original (baseline) food amounts are made up by reducing or removing export amounts; and 2) if, after the above adjustments, there is still a shortfall, then the amount of crops going to animal feed is reduced or removed to try to make up to the original (baseline) food amounts. The model simulations presented by Arnell et al. (2010) characterise the numbers of people *exposed to undernourishment* in the absence of increased crop production and imports, not actual numbers of undernourished people. The results are presented in Figure 4. Arnell et al. (2010) showed that the UK population is projected to increase by 24% by 2050 and to continue to rise until 2080. This, combined with decreases in crop yields of up to 25% by 2080, presents the possibility of a substantial increase in exposure to undernourishment. Without structural adjustments, under scenario A1B, 70% of the UK population could be exposed by 2080. However, this is substantially smaller under the mitigation scenarios; under the 2016-2-H and 2016-5-L scenarios in 2080, the proportion of the UK population exposed to undernourishment is around 27% and 29% respectively. Importantly, Arnell et al. (2010) show that if structural adjustments are incorporated into the simulations, then only 1% of the UK population is exposed to undernourishment in 2100.

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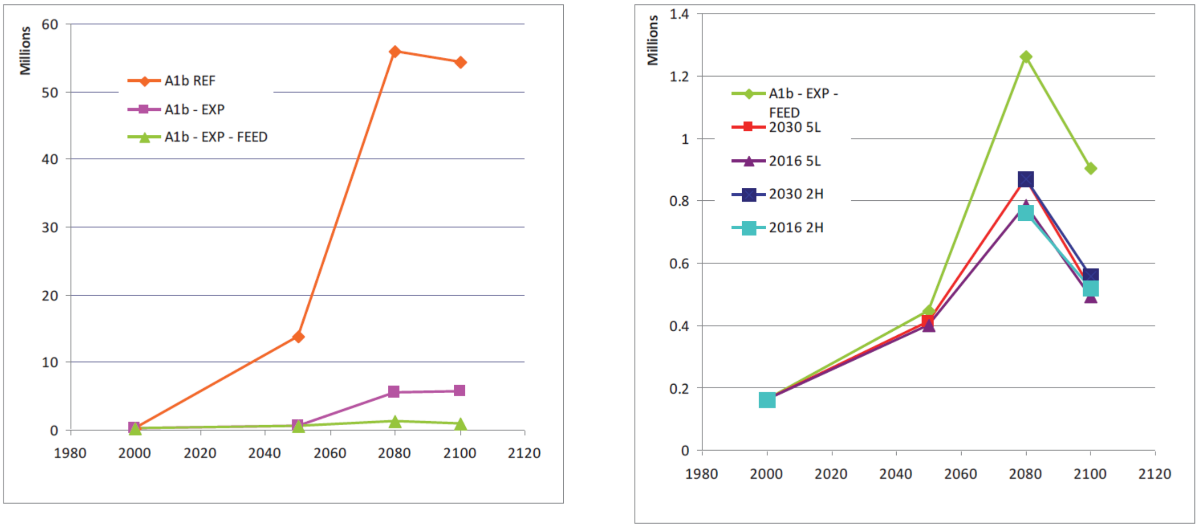

Figure 4. *Total projected population exposed to undernourishment in the UK. The left panel shows total exposure under the A1B emissions scenario ("A1b REF"), plus the A1B scenario with exports reduced or removed ("A1b–EXP") and the A1B scenario with exports removed and allocation to feed reduced or removed ("A1b–EXP–FEED"). The right panel shows the total exposure under the A1b–EXP–FEED and three mitigation scenarios. The figure is from Arnell et al. (2010).*

It is important to note that up until recently, projections of climate change impacts on global food supply have tended to focus solely on production from terrestrial biomes, with the large contribution of animal protein from marine capture fisheries often ignored. However, recent studies that are applicable to the UK have addressed this knowledge gap (Allison et al., 2009, Cheung et al., 2010). In addition to the direct affects of climate change, changes in the acidity of the oceans, due to increases in CO_2 levels, could also have an impact of marine ecosystems, which could also affect fish stocks. However, this relationship is complex and not well understood, and studies today have not been able to begin to quantify the impact of ocean acidification on fish stocks.

Allison et al. (2009) present a global analysis that compares the vulnerability of 132 national economies to potential climate change impacts on their capture fisheries. The study considered a country's vulnerability to be a function of the combined effect of projected climate change, the relative importance of fisheries to national economies and diets, and the national societal capacity to adapt to potential impacts and opportunities. Climate change projections from a single GCM under two emissions scenarios (SRES A1FI and B2) were used in the analysis. Allison et al. (2009) concluded that the national economy of the UK presented a very low vulnerability to climate change impacts on fisheries, in similarity with much of western Europe (see Figure 5). It should be noted, however, that results from studies that have applied only a single climate model or climate change scenario should be interpreted with caution. This is because they do not consider other possible climate change scenarios which could result in a different impact outcome, in terms of magnitude and in some cases sign of change.

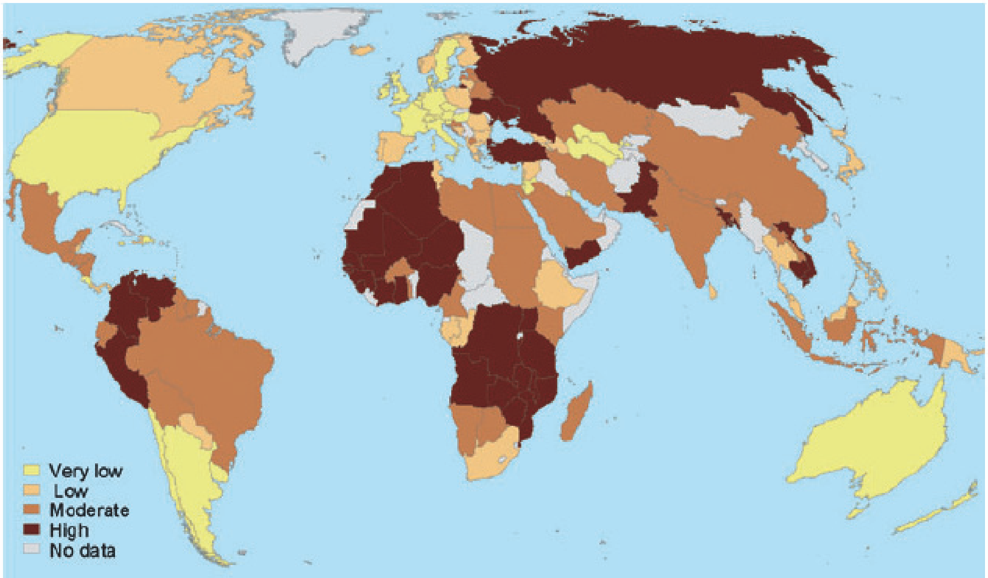

Figure 5. *Vulnerability of national economies to potential climate change impacts on fisheries under SRES B2 (Allison et al., 2009). Colours represent quartiles with dark brown for the upper quartile (highest index value), yellow for the lowest quartile, and grey where no data were available.*

Cheung et al. (2010) also consider marine capture fisheries at the global scale for several countries and the results confirm the optimistic projections presented by Allison et al. (2009). The study projected changes in global catch potential for 1066 species of exploited marine fish and invertebrates from 2005 to 2055 under climate change scenarios. Cheung et al. (2010) found that climate change may lead to large-scale redistribution of global catch potential, with an average of 30–70% increase in high-latitude regions and a decline of up to 40% in the tropics. The simulations were based climate simulations from a single GCM (GFDL CM2.1) under a SRES A1B emissions scenario (CO_2 concentration at 720ppm in 2100) and a stable-2000 level scenario (CO_2 concentration maintains at year 2000 level of 365 ppm). The limitations of applying a single climate model have been noted previously. The projected change in the 10-year averaged maximum catch potential between 2005-2055 was, for the UK, around a 1% increase under both scenarios, based upon 121 exploited species included in the analysis. Figure 6 demonstrates how this compares with projected changes for other countries across the globe.

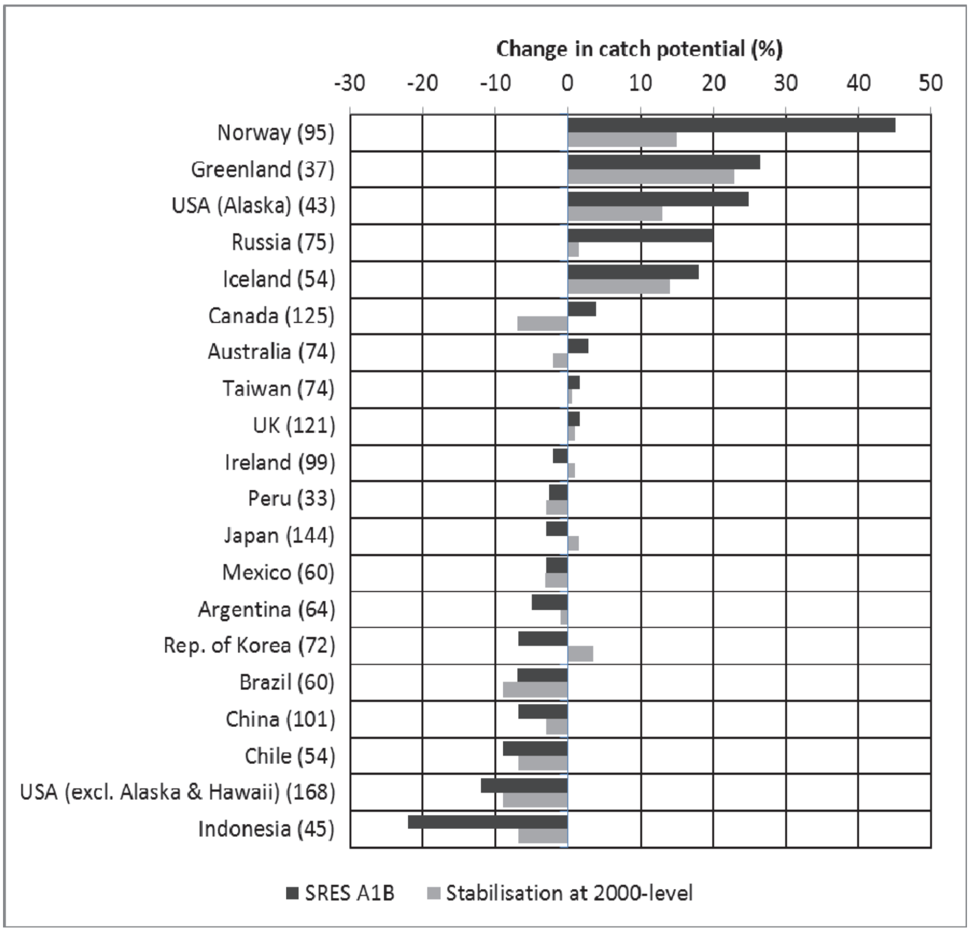

Figure 6. *Projected changes in the 10-year averaged maximum catch potential from 2005 to 2055. The numbers in parentheses represent the numbers of exploited species included in the analysis. Adapted from Cheung et al. (2010).*

National-scale or sub-national scale assessments

Literature searches yielded no results for national-scale or sub-national scale studies for this impact sector.

Water stress and drought

Headline

Vulnerability to water stress is currently focussed in the south and south-east of the UK. These regions are projected to experience an increase in the frequency of droughts and water stress with climate change. However, the rest of the UK may be relatively unaffected by changes in water availability with climate change.

Results from the AVOID programme show that the UK could experience a moderate increase in water stress with climate change, although the median estimate from 21 climate models suggested no increase in water stress with climate change for the UK as a whole.

Supporting literature

Introduction

For the purposes of this report droughts are considered to be extreme events at the lower bound of climate variability; episodes of prolonged absence or marked deficiency of precipitation. Water stress is considered as the situation where water stores and fluxes (e.g. groundwater and river discharge) are not replenished at a sufficient rate to adequately meet water demand and consumption.

A number of impact model studies looking at water stress and drought for the present (recent past) and future (climate change scenario) have been conducted. These studies are conducted at global or national scale and include the application of global water 'availability' or 'stress' models driven by one or more climate change scenario from one or more GCM. The approaches variously include other factors and assumptions that might affect water availability, such as the impact of changing demographics and infrastructure investment, etc. These different models (hydrological and climate), assumptions and emissions scenarios mean that there are a range of water stress projections for the UK. This section summarises findings from these studies to inform and contextualise the analysis performed by the AVOID programme for this project. The results from the AVOID work and discussed in the next section.

Important knowledge gaps and key uncertainties which are applicable to the UK as well as at the global-scale, include; the appropriate coupling of surface water and groundwater in hydrological models, including the recharge process, improved soil moisture and evaporation dynamics, inclusion of water quality, inclusion of water management (Wood et al. 2011) and further refinement of the down-scaling methodologies used for the climate driving variables (Harding et al. 2011).

Assessments that include a global or regional perspective

Recent Past

Recent research presented by Vörösmarty et al. (2010) describes the calculation of an '*Adjusted Human Water Security Threat'* (HWS) indicator. The indicator is a function of the cumulative impacts of 23 biophysical and chemical drivers simulated globally across 46,517 grid cells representing 99.2 million km^2. With a digital terrain model at its base, the calculations in each of the grid boxes of this model take account of the multiple pressures on the environment, and the way these combine with each other, as water flows in river basins. The level of investment in water infrastructure is also considered. This infrastructure measure (the *investment benefits factor*) is based on actual existing built infrastructure, rather than on the financial value of investments made in the water sector, which is a very unreliable and incomplete dataset. The analysis described by Vörösmarty et al. (2010) represents the current state-of-the-art in applied policy-focussed water resource assessment. In this measure of water security, the method reveals those areas where this is lacking, which is a representation of human water stress. One drawback of this method is that no analysis is provided in places where there is 'no appreciable flow', where rivers do not flow, or only do so for such short periods that they cannot be reliably measured. This method also does not address places where water supplies depend wholly on groundwater or desalination, being piped in, or based on wastewater reuse. It is based on what is known from all verified peer reviewed sources about surface water resources as generated by natural ecosystem processes and modified by river and other hydraulic infrastructure (Vörösmarty et al., 2010).

Here, the present day HWS is mapped for the UK. The model applied operates at 50km resolution, so, larger countries appear to have smoother coverage than smaller countries, but all are mapped and calculated on the same scale, with the same data and model, and thus comparisons between places are legitimate. It is important to note that this analysis is a comparative one, where each place is assessed *relative* to the rest of the globe. In this way, this presents a realistic comparison of conditions across the globe. As a result of this, however, some places may seem to be less stressed than may be originally considered.

One example is Australia, which is noted for its droughts and long dry spells, and while there are some densely populated cities in that country where water stress is a real issue, for most of the country, *relative to the rest of the world*, the measure suggests water stress (as measured by HWS defined by Vörösmarty et al. (2010)), is not a serious problem.

Figure 7 presents the results of this analysis for the UK. The UK is unusual as a small country in that its level of water security ranges from very high to very low. The highest level of threat is in the south east, while areas of the south, the Midlands, and southern Scotland are shown to have moderate threat.

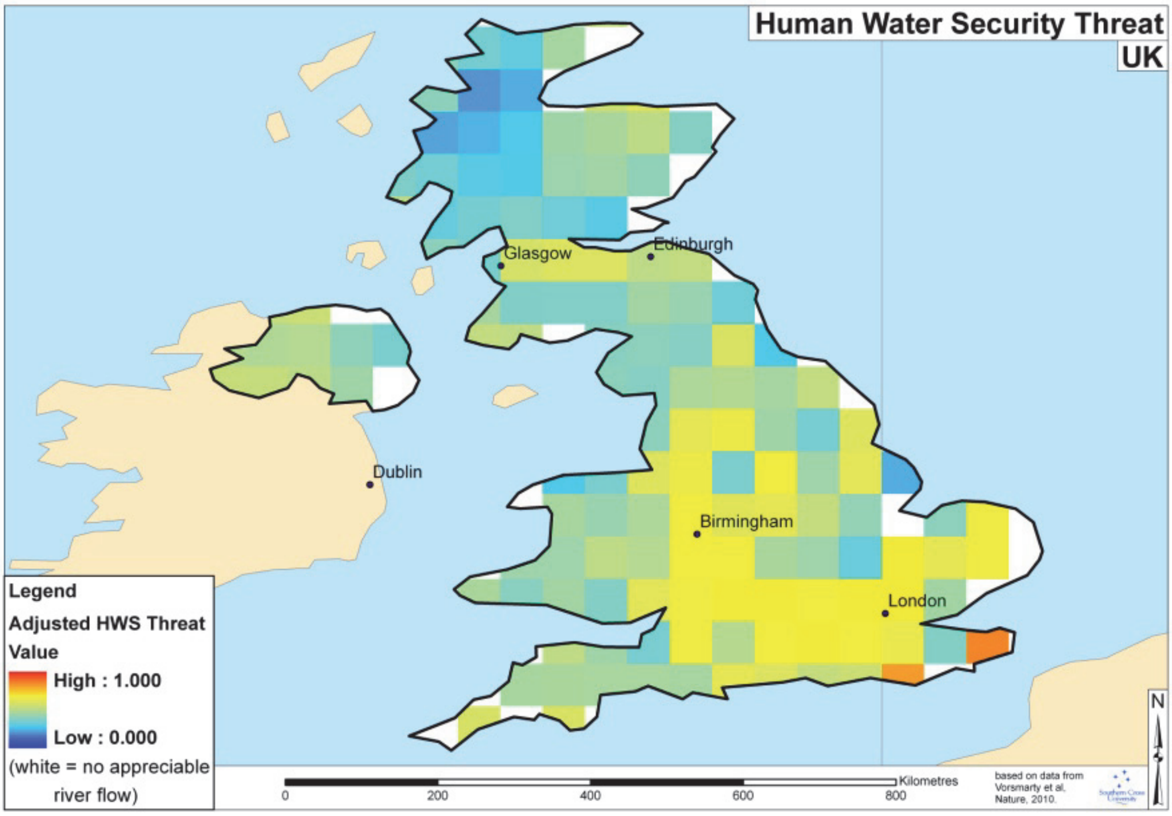

Figure 7. *Present Adjusted Human Water Security Threat (HWS) for the UK, calculated following the method described by Vörösmarty et al. (2010).*

Smakhtin et al. (2004) present a first attempt to estimate the volume of water required for the maintenance of freshwater-dependent ecosystems at the global scale. This total environmental water requirement (EWR) consists of ecologically relevant low-flow and high-flow components. The authors argue that the relationship between water availability, total use and the EWR may be described by the water stress indicator (WSI). If WSI exceeds 1.0, the basin is classified as “environmentally water scarce”. In such a basin, the discharge has already been reduced by total withdrawals to such levels that the amount of water left in the basin is less than EWR. Smaller index values indicate progressively lower water resources exploitation and lower risk of “environmental water scarcity.” Basins where WSI is greater than 0.6 but less than 1.0 are arbitrarily defined as heavily exploited or “environmentally water stressed” and basins where WSI is greater than 0.3 but less than 0.6 are defined as moderately exploited. In these basins, 0-40% and 40-70% of the utilizable water respectively is still available before water withdrawals come in conflict with the EWR. Environmentally “safe” basins are defined as those where WSI is less than 0.3. The global distribution of WSI for the 1961-1990 time horizon is shown in Figure 8. For the UK, the results show moderate to high water stress the south east of the country.

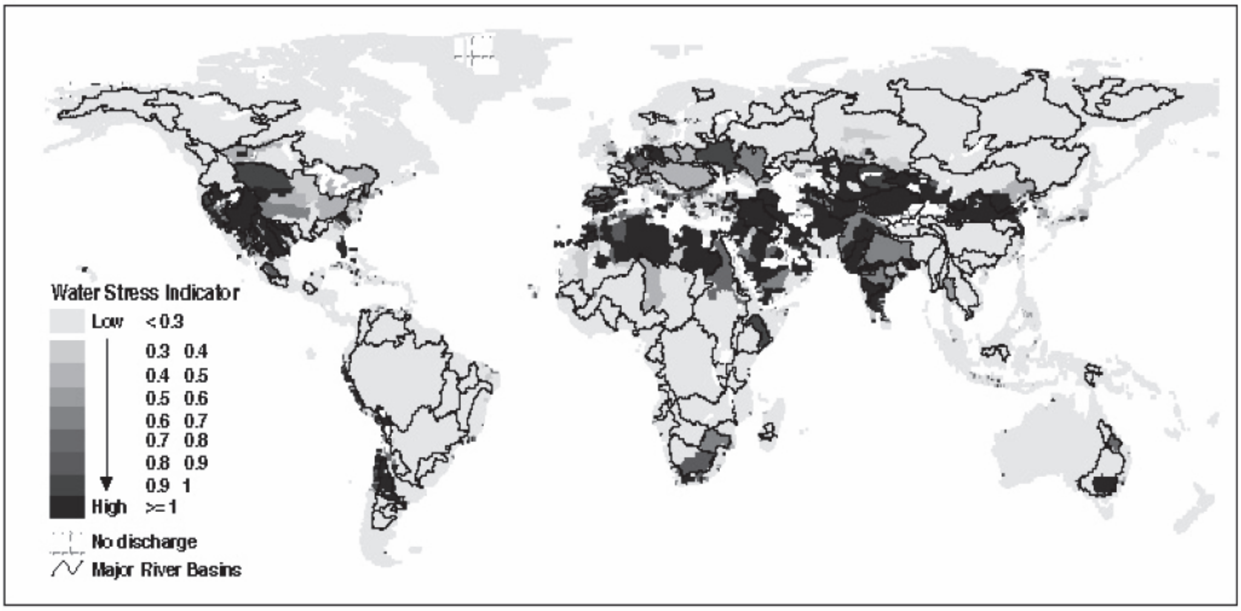

Figure 8. *A map of the major river basins across the globe and the water stress indicator (WSI) for the 1961-1990 time horizon. The figure is from Smakhtin et al. (2004).*

Climate Change Studies

The IPCC AR4 (2007a) noted that annual precipitation is very likely to increase in most of northern Europe. The sign of changes in summer vary between climate models, but most models simulate decreased precipitation over this region. It was also noted that in northern Europe, the CMIP3 multi-model dataset GCMs disagree on whether summer soil moisture might increase or decrease, due to the competition between increased precipitation on one hand, and earlier snowmelt and increased evaporation on the other.

Rockstrom et al.(2009) applied the LPJml vegetation and water balance model (Gerten et al. 2004) to assess green-blue water (irrigation and infiltrated water) availability and requirements. The authors applied observed climate data from the CRU TS2.1 gridded dataset for a present-day simulation, and climate change projections from the HadCM2 GCM under the SRES A2 scenario to represent the climate change scenario for the year 2050. The study assumed that if water availability was less than 1,300m^3/capita/year, then the country was considered to present insufficient water for food self-sufficiency. The simulations presented by Rockstrom et al.(2009) should not be considered as definitive, however, because the study only applied one climate model, which means climate modelling uncertainty was overlooked. The results from the two simulations are presented in Figure 9. Rockstrom et al. (2009) found that globally in 2050 and under the SRES A2 scenario, around 59% of the world's population could be exposed to "blue water shortage" (i.e. irrigation water shortage), and 36% exposed to "green water shortages" (i.e. infiltrated rain shortage). For the UK, Rockstrom et al. (2009) found that blue-green water availability was well above the 1,300m^3/capita/year threshold at present and under future climate change. This indicates that at a national level, the UK's water resource requirements should be met by 2050. It should be noted, however, that results from studies that have applied only a single climate model or climate change scenario should be interpreted with caution.

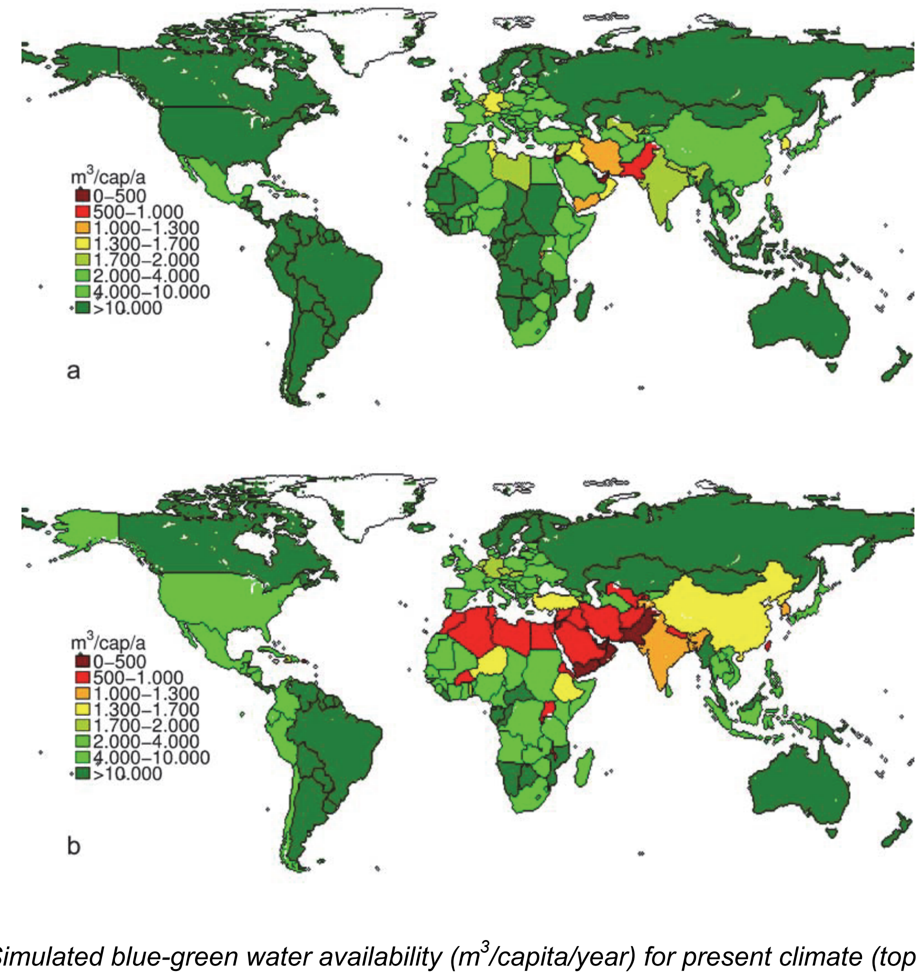

Figure 9. *Simulated blue-green water availability (m^3/capita/year) for present climate (top panel) and including both demographic and climate change under the SRES A2 scenario in 2050 (bottom panel). The study assumed that if water availability was less than 1,300m^3/capita/year, then the country was considered to present insufficient water for food self-sufficiency. The figure is from Rockstrom et al. (2009).*

Doll (2009) presents updated estimates of the impact of climate change on groundwater resources by applying a new version of the WaterGAP hydrological model. The study accounted for the number of people affected by changes in groundwater resources under climate change relative to present (1961-1990). To this end, the study provides an assessment of the vulnerability of humans to decreases in available groundwater resources (GWR). This indicator was termed the “Vulnerability Index” (VI), defined as; VI = -% change GWR * Sensitivity Index (SI). The SI component was a function of three more specific sensitivity indicators that include an indicator of water scarcity (calculated from the ratio between consumptive water use to low flows), an indicator for the dependence upon groundwater supplies, and an indicator for the adaptive capacity of the human system. Doll (2009) applied climate projections from two GCMs (ECHAM4 and HadCM3) to WaterGAP, for two scenarios (SRES A2 and B2), for the 2050s. Figure 10 presents each of these four simulations respectively. There is variation across scenarios and GCMs. For the UK, simulations with HadCM3 showed only a small GWR reduction for much of the UK, so the vulnerability to water stress is negligible. However, under the ECHAM4 model, significant GWR reduction is predicted in the south of the UK associated with a VI in the range of 10-30, but this is still relatively low when compared with other European countries.

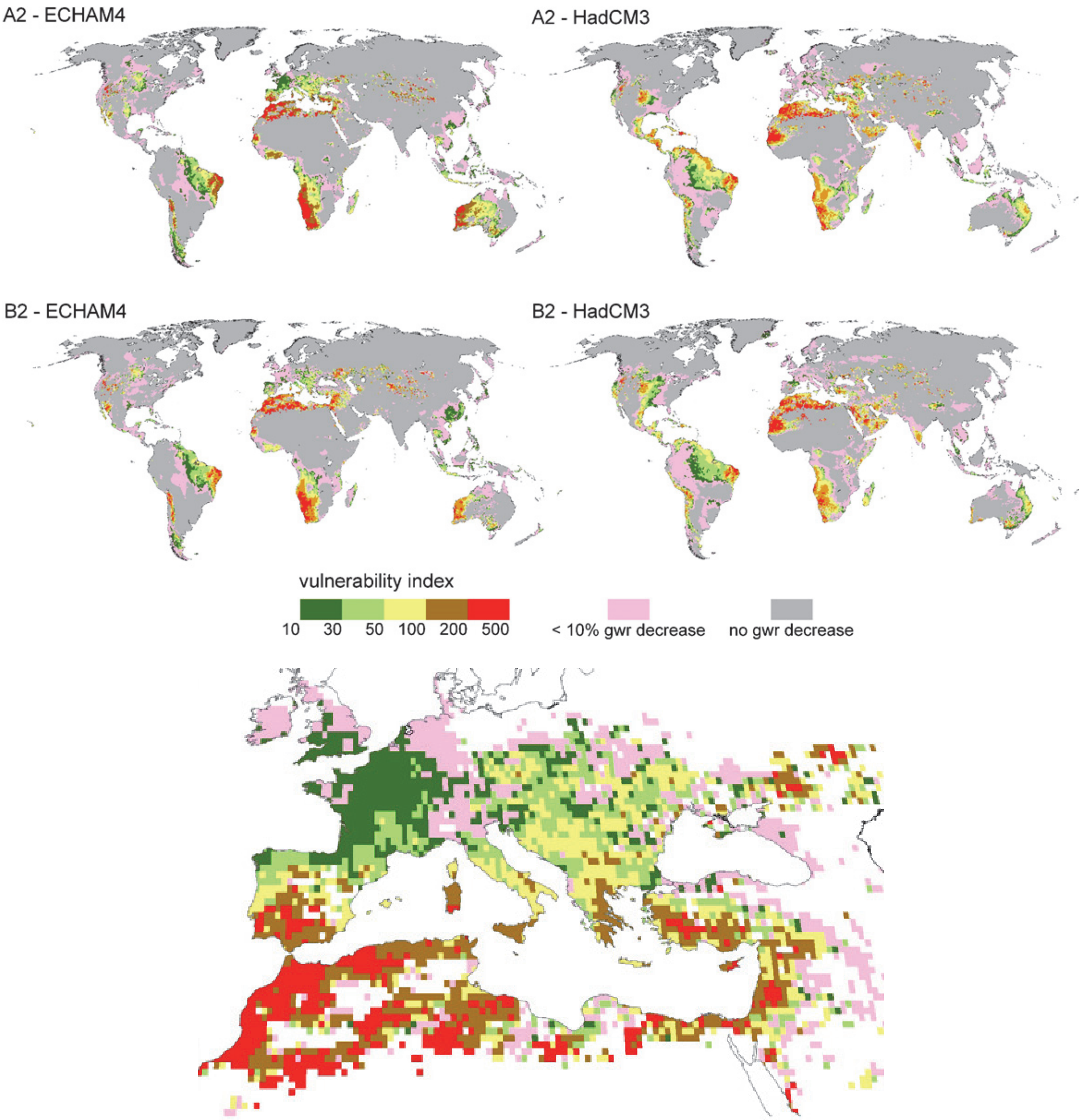

Figure 10. *Vulnerability index (VI) showing human vulnerability to climate change induced decreases of renewable groundwater resources (GWR) by the 2050s under two emissions scenarios for two GCMs. VI is only defined for areas with a GWR decrease of at least 10% relative to present (1961-1990). Also shown is VI for the Mediterranean region with ECHAM4 under A2 emissions. The figure is from Doll (2009).*

Lehner et al. (2006) assessed the impact of climate change on European drought risk. The authors accounted for future human water use and assessed future flood and drought frequencies by applying the WaterGAP hydrological model, driven by climate projections from the HadCM3 and ECHAM4 GCMs, under a 1%/year CO_2 increase emissions scenario. The simulations are presented in Figure 11 and Figure 12. The results reflect the general consensus from other studies that southern and south-eastern Europe could experience increased drought frequencies, leading to water stress. This in part due to increased water use but the impacts are much more pronounced and wide spread when climate change is factored in (Lehner et al., 2006). Long term projections indicate those drought events expected to occur once every 100 years could become much more frequent, to around every 40 years in the most extreme areas, including much of the Mediterranean. For the UK, both GCMs simulated that the current 100-year drought could be expected to occur more frequently with climate change, and more so with the ECHAM4 GCM. Moreover, the results show that the 100-year drought could become more intense with climate change, increasing in intensity by over 25% from present magnitude in the south of the UK.

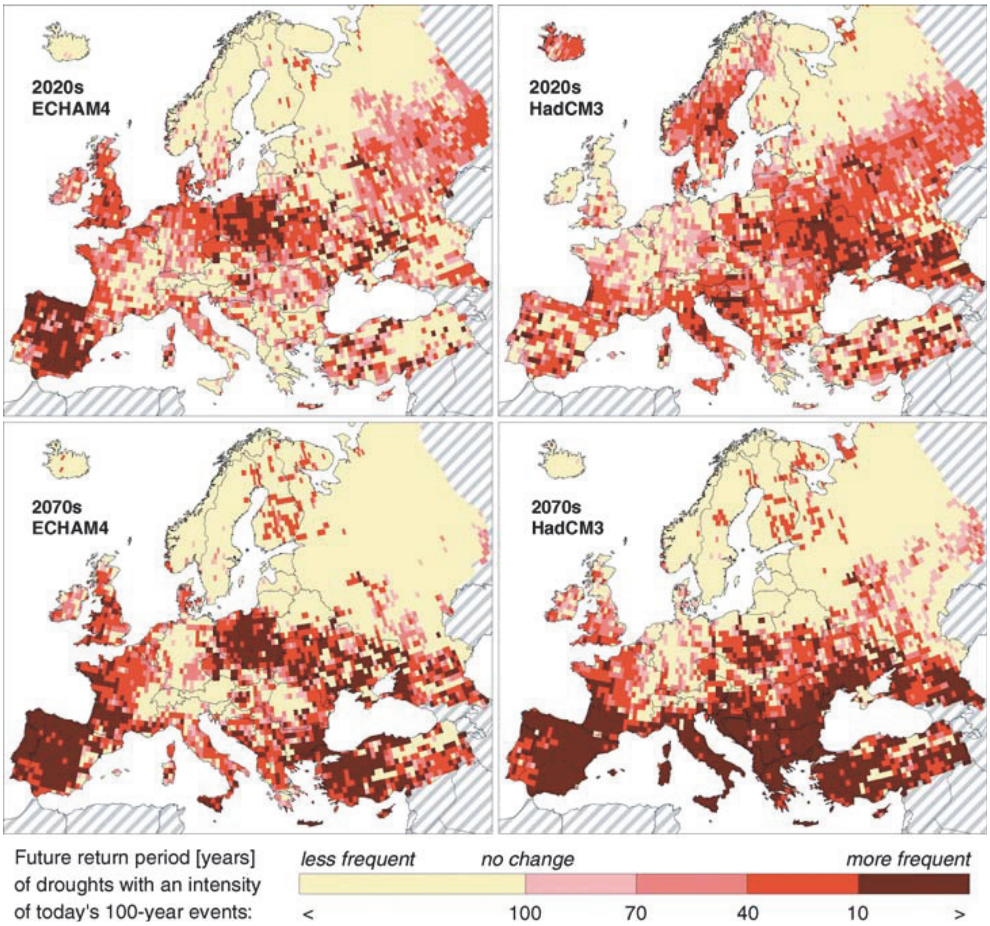

Figure 11. *Change in recurrence of 100-year droughts, based on comparisons between today's climate and water use (1961–1990) and simulations for the 2020s and 2070s (ECHAM4 and HadCM3 GCMs), under a 1%/year CO_2 increase emissions scenario. The figure is from Lehner et al. (2006).*

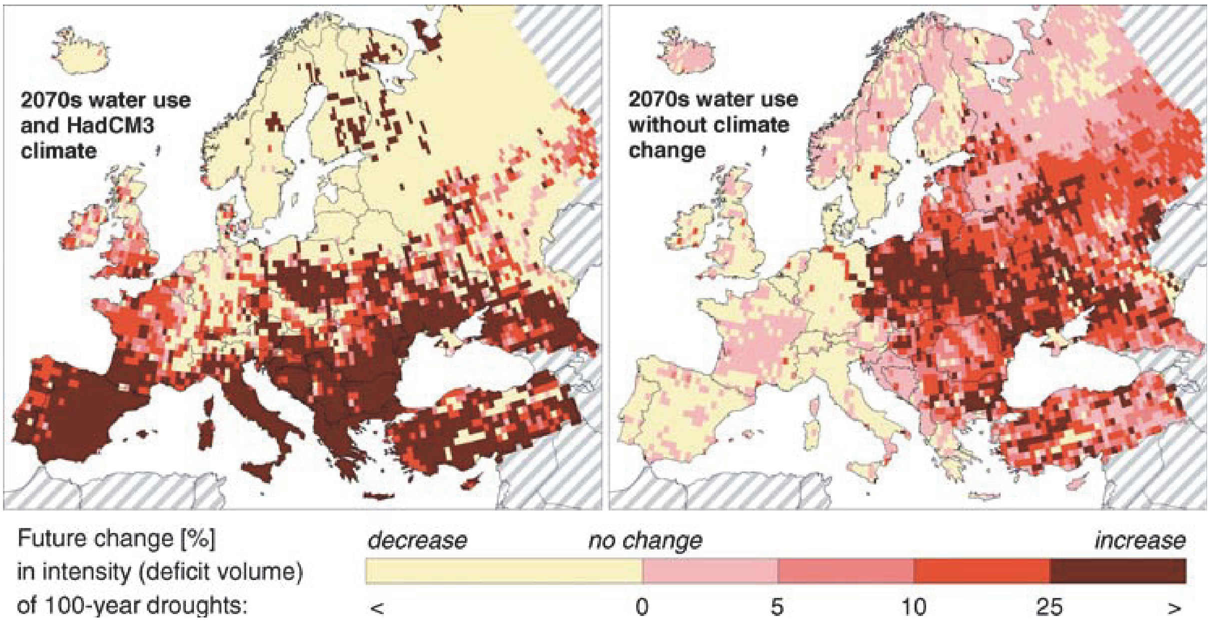

Figure 12. *Change in intensity of 100-year droughts, based on comparison between today's climate and water use (1961–1990) and simulations for the 2070s (left map: HadCM3 GCM; right map: only water use scenario, no climate change), under a 1%/year CO_2 increase emissions scenario.*

National-scale or sub-national scale assessments

The simulations of more frequent droughts with climate change for the UK, presented by Lehner et al. (2006), are supported by findings from national-scale studies. The UKCP09 assessment conducted by Murphy et al. (2009) found that precipitation over most of the UK is likely to decrease during the summer with climate change, with the largest decreases in the south of England. Furthermore, Burke et al. (2010) showed that ensemble RCM projections under increased greenhouse gas scenarios showed an overall increase in drought occurrence, but the spread was considerable. This corresponds with the large uncertainties found by Blenkinsop and Fowler (2007) and Vidal and Wade (2009). In those papers, the authors projected an increase in short duration droughts over the UK. Burke et al. (2010) clearly highlight the high sensitivity of future UK drought projection to climate modelling uncertainty and that the present state of climate science does not provide a well defined picture of future drought changes for adaptation planning. The likelihood of a drought such as that of 1976 occurring at the end of the 21st century ranges from the same as the historic frequency to more frequently than once every 10 years, depending on the RCM ensemble member and drought metric considered.

Charlton and Arnell (2011) present an assessment of loss in deployable output of water companies as a result of climate change and population growth. An overall loss equivalent to 3% by 2035 is feasible with most of the impacts estimated to be realised in southern England. Such substantial reductions in the availability of supply necessitate adaptation measures, particularly in those areas most affected. Moreover, research presented by Henriques et al. (2008) suggests that climate change could drive increased irrigation requirements in the south-east and north-west of England. Such demand might not be met in the south-east under baseline socio-economic standing. Future water availability under economically focused futures could have to be moderated. The authors argue that future demand, restricted by environmental policies, could lead to reductions in the supply available.

The potential impacts of the UKCIP02 ‘high-emissions’ scenario were assessed on groundwater recharge in Great Britain by Herrerea-Pantoja et al. (2008). By the end of the century variable decreases between 7% and 40% were found across the locations considered, leading to increased stress on local and regional groundwater supplies that are already under pressure to maintain both human and ecosystem needs. This is largely supportive of the results presented by Doll (2009).

AVOID Programme Results

To further quantify the impact of climate change on water stress and the inherent uncertainties, the AVOID programme calculated water stress indices for all countries reviewed in this literature assessment based upon the patterns of climate change from 21 GCMs (Warren et al., 2010), following the method described by Gosling et al. (2010) and Arnell (2004). This ensures a consistent methodological approach across all countries and takes consideration of climate modelling uncertainties.

Methodology

The indicator of the effect of climate change on exposure to water resources stress has two components. The first is the number of people within a region with an *increase in exposure to stress*, calculated as the sum of 1) people living in water-stressed watersheds with a significant reduction in runoff due to climate change and 2) people living in watersheds which become water-stressed due to a reduction in runoff. The second is the number of people within a region with a *decrease in exposure to stress*, calculated as the sum of 1) people living in water-stressed watersheds with a significant increase in runoff due to climate change and 2) people living in watersheds which cease to be water-stressed due to an increase in runoff. It is not appropriate to calculate the net effect of “increase in exposure” and “decrease in exposure”, because the consequences of the two are not equivalent. A water-stressed watershed has an average annual runoff less than 1000m^3/capita/year, a widely used indicator of water scarcity. This indicator may underestimate water stress in watersheds where per capita withdrawals are high, such as in watersheds with large withdrawals for irrigation.

Average annual runoff (30-year mean) is simulated at a spatial resolution of 0.5x0.5^{o} using a global hydrological model, MacPDM (Gosling and Arnell, 2011), and summed to the watershed scale. Climate change has a “significant” effect on average annual runoff when the change from the baseline is greater than the estimated standard deviation of 30-year mean annual runoff: this varies between 5 and 10%, with higher values in drier areas.

The pattern of climate change from 21 GCMs was applied to MacPDM, under two emissions scenarios; 1) SRES A1B and 2) an aggressive mitigation scenario where emissions follow A1B up to 2016 but then decline at a rate of 5% per year thereafter to a low emissions floor (denoted A1B-2016-5-L). Both scenarios assume that population changes through the 21st century following the SRES A1 scenario as implemented in IMAGE 2.3 (van Vuuren et al., 2007). The application of 21 GCMs is an attempt to quantify the uncertainty due to climate modelling, although it is acknowledged that only one impacts model is applied (MacPDM). Simulations were performed for the years 2030, 2050, 2080 and 2100. Following Warren et al. (2010), changes in the population affected by increasing or decreasing water stress represent the additional percentage of population affected due to climate change, not the absolute change in the percentage of the affected population relative to present day.

Results

The results for the UK are presented in Figure 13. They show only a single model indicates a proportion of the population experiencing a decrease in water stress by 2100. The other 20 models show none of the population experiencing a decrease in water stress. More models indicate that a proportion of the population will experience an increase in water stress by 2100 under both the A1B and the aggressive mitigation emission scenarios.

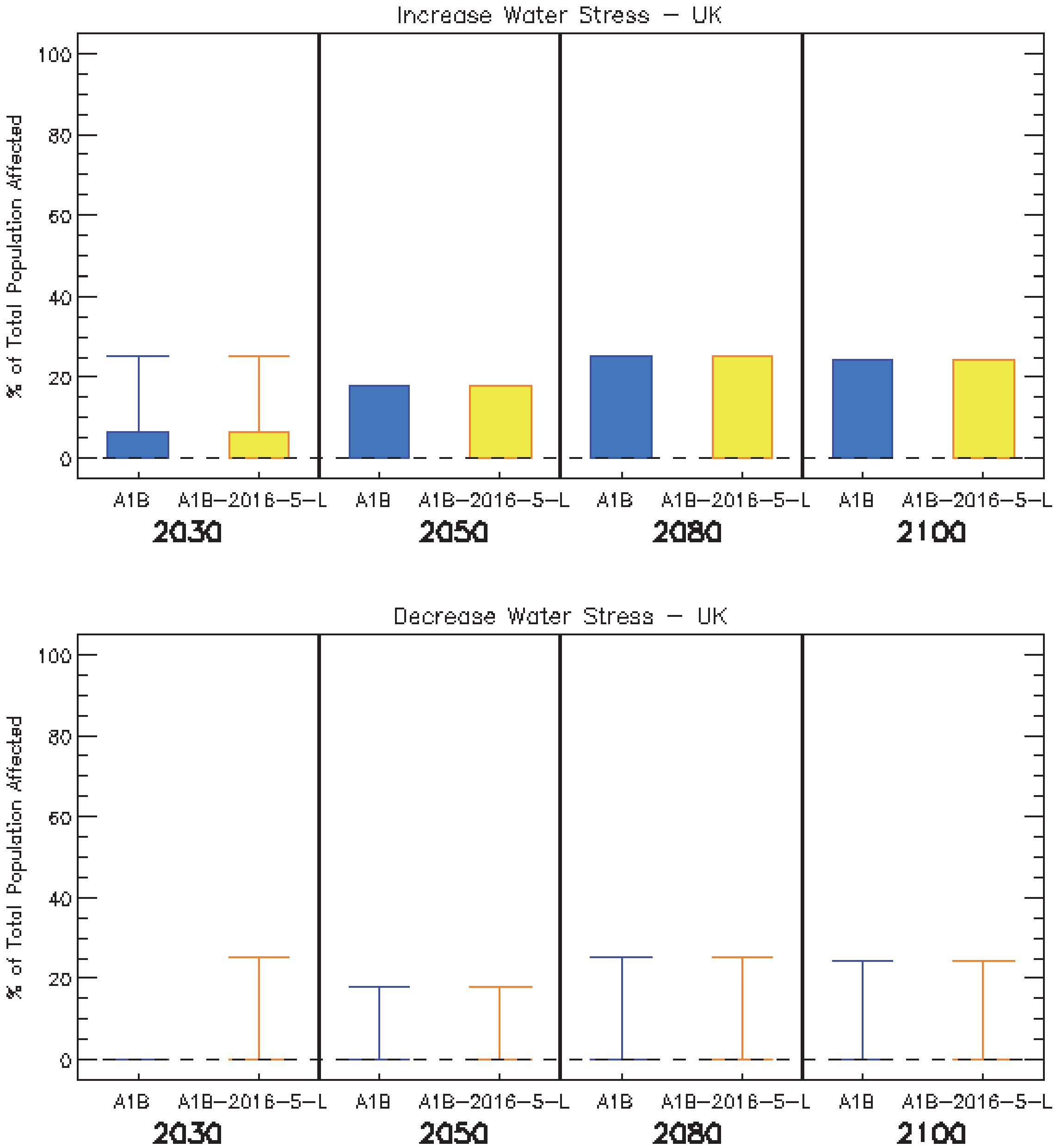

Figure 13. *Box and whisker plots for the impact of climate change on increased water stress (top panel) and decreased water stress (bottom panel) in the UK, from 21 GCMs under two emissions scenarios (A1B and A1B-2016-5-L), for four time horizons. The plots show the 25th, 50th, and 75th percentiles (represented by the boxes), and the maximum and minimum values (shown by the extent of the whiskers).*

Pluvial flooding and rainfall

Headline

Post-IPCC AR4 research for precipitation extremes over the UK focus upon understanding and quantifying uncertainties, and detection and attribution studies. Extremes are generally projected to increase, particularly during winter. Changes during summer are more uncertain. Connections are being made between changes in extreme precipitation and anthropogenic climate change.

Supporting literature

Introduction

Pluvial flooding can be defined as flooding derived directly from heavy rainfall, which results in overland flow if it is either not able to soak into the ground or exceeds the capacity of artificial drainage systems. This is in contrast to fluvial flooding, which involves flow in rivers either exceeding the capacity of the river channel or breaking through the river banks, and so inundating the floodplain. Pluvial flooding can occur far from river channels, and is usually caused by high intensity, short-duration rainfall events, although it can be caused by lower intensity, longer-duration events, or sometimes by snowmelt. Changes in mean annual or seasonal rainfall are unlikely to be good indicators of change in pluvial flooding; changes in extreme rainfall are of much greater significance. However, even increases in daily rainfall extremes will not necessarily result in increases in pluvial flooding, as this is likely to be dependent on the sub-daily distribution of the rainfall as well as local factors such as soil type, antecedent soil moisture, land cover (especially urbanisation), capacity and maintenance of artificial drainage systems etc. It should be noted that both pluvial and fluvial flooding can potentially result from the same rainfall event.

Assessments that include a global or regional perspective

Climate change studies

The IPCC AR4 (2007a) noted that annual precipitation is very likely to increase in most of northern Europe, and daily precipitation extremes are likely to increase under the A1B emissions scenario during the 21st century. However, although the IPCC noted that the simulated responses between models are qualitatively consistent, significant uncertainties remain particularly on the magnitude and geographical details of precipitation change. The substantial natural variability of European climate is also a major uncertainty, particular with respect to near-term climate projections (IPCC, 2007a). Annual precipitation changes by the end of the 21st century under A1B range between 0% and 16% in Northern Europe (IPCC, 2007a). The largest increases are simulated during winter. The sign of changes in summer vary between models, but most models simulate decreased precipitation over this region (IPCC, 2007a). Precipitation extremes during winter are also very likely to increase in both magnitude and frequency (IPCC, 2007a).

A global-scale assessment presented by Bates et al. (2008) found that for Europe, using various emissions scenarios from the ECHAM4 and HadCM3 GCMs, in the 2020s, there could be an increased risk of winter floods in northern Europe, and increased risk of flash floods over the whole of Europe. The risk of snowmelt flooding was found to shift from spring to winter (Bates et al., 2008).

Similarly, a European-scale assessment presented by Beniston et al. (2007) found heavy winter precipitation increases in northern Europe with climate change. These changes were weaker with the B2 emissions scenario than with the A2 scenario. Model choices had greater effects on the magnitude (RCM) and pattern (GCM) of response than the choice of emissions scenario. Analysing projections under the A2 and B2 scenarios from an ensemble of four RCMs, Beniston et al. (2007) found that changes in maximum 5-day rainfall simulated under the B2 scenario were smaller than those simulated under the A2 scenario in two cases, and similar in the two other cases. However, there were no systematic differences in projected increases in maximum 1-day rainfall between the scenarios, though the increases were positive and up to about 40% relative to present.

National-scale or sub-national scale assessments

Climate change studies

Fowler and Ekström's (2009) analysis of output from 13 RCMs identified projected increases in extreme precipitation for the UK in winter, spring and autumn, with climate change. There was considerable uncertainty about the magnitude of change due to climate model uncertainty. In summer, the authors reported least confidence in climate model projections because reproduction of observed precipitation extremes by RCMs is poor. Similarly, Fowler and Wilby (2010) found that changes in summer flash flood risk with climate change for the UK are highly uncertain due to differences across RCMs (see Figure 14). In terms of detecting an anthropogenic influence, Fowler and Wilby (2010) found that the earliest detection times were for 10-day winter precipitation totals within a 10-year return period in south-west England. The authors conclude that formal detection may be possible within a decade from now if climate model projections are realised.

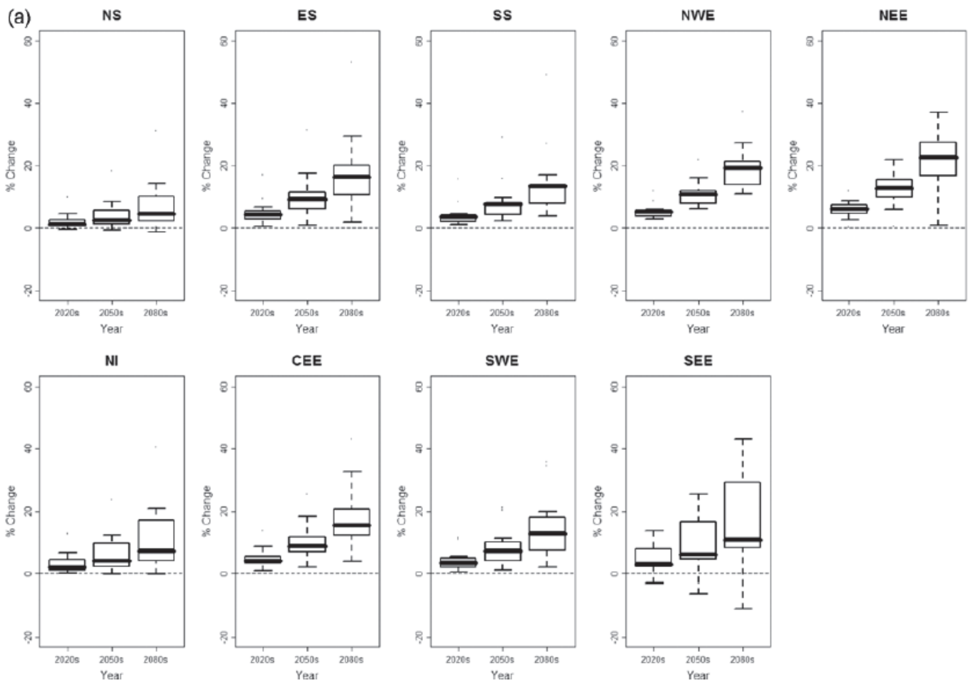

Figure 14. *Box and whisker plots showing the mean and uncertainty in percentage changes to precipitation by the 2020s, 2050s and 2080s for the UK, projected by the European Union PRUDENCE climate model ensemble for 1 day winter precipitation totals with 10 year return period (a) and 10 day winter precipitation totals with 10 year return period (b). Panels are for regions; North Scotland (NS), East Scotland (ES), South Scotland (SS), Northern Ireland (NI), Northwest England (NWE), Northeast England (NEE), Central and Eastern England (CEE), Southeast England (SEE), and Southwest England (SWE). The figure is from Fowler and Wilby (2010).*

The most comprehensive study of UK climate projections has been the UKCP09 Report, conducted by Murphy et al. (2009), which applied a probabilistic approach to regional climate modelling. The change in the 99th percentile of daily precipitation in each season is approximately equivalent to the change in the wettest day in the season (see Figure 15). For the 2080s, in winter, the central estimate is for increases in precipitation on the wettest day of up to 30% in a few areas of southern England, with a reduction to near zero change in northern Scotland. For the 2080s, in summer, the central estimate shows reductions in wettest day precipitation over southern and eastern England, but increases of up to 10% in other areas of the UK.

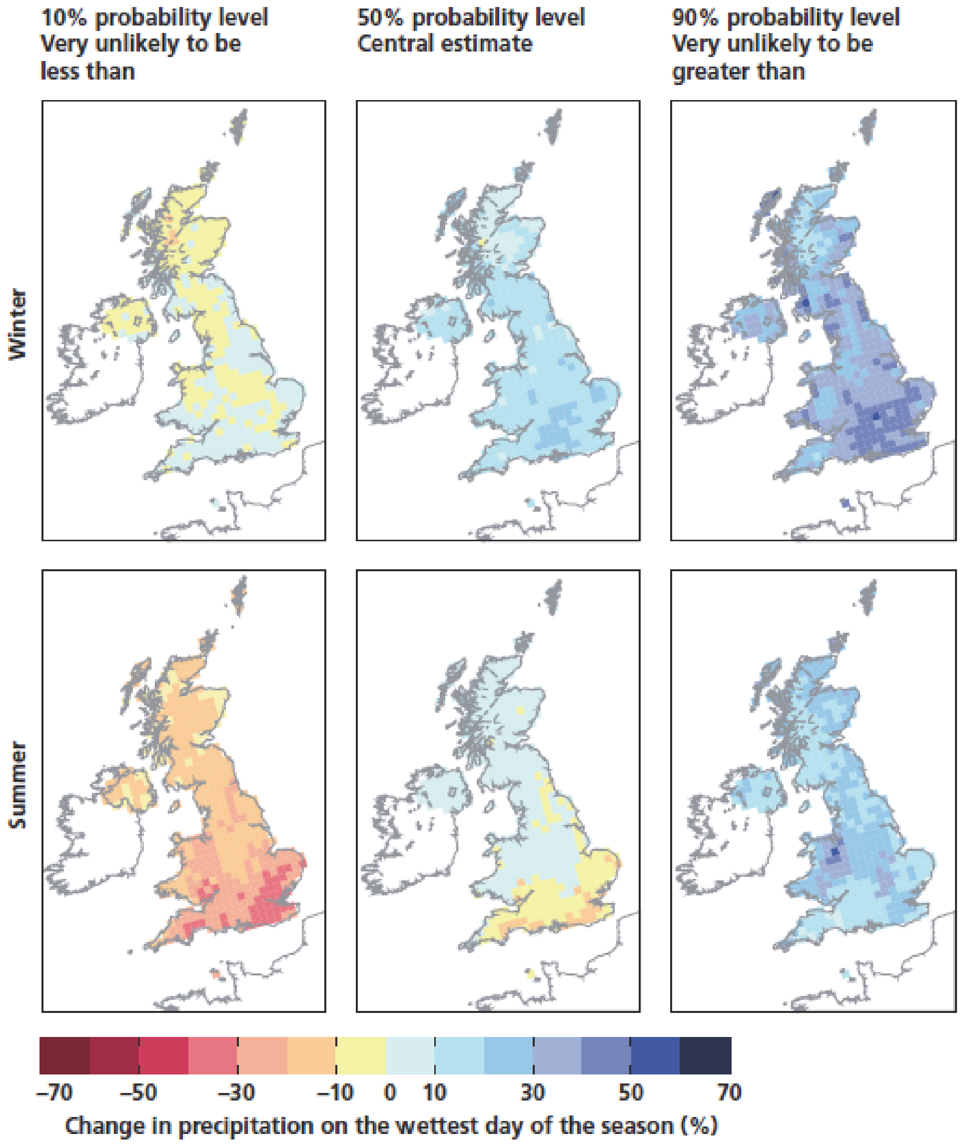

Figure 15. *Changes to precipitation on the wettest day of the winter (top) and of the summer (bottom) at the 10, 50, and 90% probability levels for the 2080s under a medium emissions scenario. The figure is from Murphy et al. (2009).*

Fluvial flooding

Headline

Several European-scale and national-scale assessments suggest an increase in flood risk with climate change in the UK. Simulations from the AVOID programme, based on climate projections from 21 GCMs, support this. For the UK as a whole, the projections show a much greater tendency for increasing flood risk, particularly later in the century and particularly in the A1B scenario. However, national studies have also shown that the UK exhibits a high degree of spatial variability in the sensitivity of rivers to changes in climate, and projections of changes in flood hazard show large uncertainty, which is mainly due to climate modelling uncertainty. Further work is necessary to better account for the influence of natural variability and the uncertainties related to climate scenarios.

Supporting literature

Introduction

This section summarises findings from a number of post IPCC AR4 assessments on river flooding in the UK to inform and contextualise the analysis performed by the AVOID programme for this project. The results from the AVOID work are discussed in the next section.

Fluvial flooding involves flow in rivers either exceeding the capacity of the river channel or breaking through the river banks, and so inundating the floodplain. A complex set of processes is involved in the translation of precipitation into runoff and subsequently river flow (routing of runoff along river channels). Some of the factors involved are; the partitioning of precipitation into rainfall and snowfall, soil type, antecedent soil moisture, infiltration, land cover, evaporation and plant transpiration, topography, groundwater storage. Determining whether a given river flow exceeds the channel capacity, and where any excess flow will go, is also not straightforward, and is complicated by the presence of artificial river embankments and other man-made structures for example. Hydrological models attempt to simplify and conceptualise these factors and processes, to allow the simulation of runoff and/or river flow under different conditions. However, the results from global-scale hydrological modelling need to be interpreted with caution, especially for smaller regions, due to the necessarily coarse resolution of such modelling and the assumptions and simplifications this entails (e.g. a 0.5^{o} grid corresponds to landscape features spatially averaged to around 50-55km for mid- to low-latitudes). Such results provide a consistent, high-level picture, but will not show any finer resolution detail or variability. Smaller-scale or catchment-scale hydrological modelling can allow for more local factors affecting the hydrology, but will also involve further sources of uncertainty, such as in the downscaling of global climate model data to the necessary scale for the hydrological models. Furthermore, the application of different hydrological models and analysis techniques often makes it difficult to compare results for different catchments.

Assessments that include a global or regional perspective

Climate change studies

Dankers and Feyen (2008) applied a very high resolution (~12 km) RCM for the end of the century (2071-2100) under the A2 emissions scenario, to force a flood forecasting model, at the European-scale. The authors found increases in extreme discharge levels in most of the main rivers in England. The increase in the 100-year flood level was found particularly in winter, while in summer and autumn it mostly showed decreases in magnitude. In some rivers the return period of the current (1961-1990) 100-year flood level decreased to less than 50 years, suggesting a doubling of the probability of occurrence. A decrease in return period was also found in rivers in Scotland even though in this region there was little change in the magnitude of the 100-year return level.

In a follow-up study using an ensemble of two RCMs, each driven with boundary conditions from two different GCMs and for two different emission scenarios (A2 and B2), Dankers and Feyen (2009) found that the projected increase in flood discharges was consistent in most rivers in England. Most model experiments either projected increases in the 100-year flow level or otherwise little change, but no significant decreases. On average the increases were slightly stronger under the A2 scenario than with the B2 scenario. In the Thames River, one model simulation showed small increases at lower return levels (below 20 year) and a slight decrease at more extreme discharge levels. All other experiments projected increases across all return levels of up to 30%, with one model simulation showing increases above 50% at all return levels. Similar to other studies, Dankers and Feyen (2009) found that some of these changes in simulated flood hazard may partly be attributed to large, decadal-scale variability in the simulated climate, although this effect seemed smaller in three of the main English rivers (Severn, Thames and Great Ouse) than in other major European river basins.

Further work is necessary to better account for the influence of natural variability and the uncertainties related to the climate scenarios.

National-scale or sub-national scale assessments

Recent past

Pall et al. (2011) investigated whether it was possible to attribute a specific flooding event (the Autumn 2000 England and Wales floods) to anthropogenic influences. They found that the floods were substantially more likely to occur when including the effect of climate change due to emissions in the past century. A follow-up study by Kay et al. (2011), looking at 8 catchments in two areas of England severely affected by flooding in Autumn/Winter 2000, showed that the size of the effect depended on the catchment. They also showed that it was important to include snow processes in the modelling, as the warmer temperatures of the industrial climate have reduced the likelihood of snowmelt-induced floods.

Climate change studies

Kay and Jones (in press) suggest a projected increase in flood risk with climate change across much of the UK, particularly in East Anglia and the Upper Thames. Negative trends in flood risk, present in a small number of places, were not significant. These changes, which were derived over the period 1950-2099 under the A1B emissions scenario, are however unlikely to occur linearly over the coming century, partly because of natural variability, but possibly also due to the non-linear response of hydrological systems (Kay and Jones, in press). The implication is that changes in flood frequency, whether caused by long-term climate change or medium-term natural variability, may potentially happen in a relatively short time span.

Other national-scale studies provide broadly similar results. In an earlier study using only a single RCM for the 2071-2100 time horizon under the A2 emissions scenario, Kay et al. (2006) found an increase in flood peaks, in some cases more than a 50% increase, in the 50-year return level, in the north and west of the country. At the same time they found a decrease in flood peaks for a number of catchments in the south and east of England, despite an increase in extreme rainfall. It was thought that higher soil moisture deficits in summer and autumn caused the decrease in peak flows (Kay et al., 2006). It should be noted, however, that results from studies that have applied only a single climate model or climate change scenario should be interpreted with caution. This is because they do not consider other possible climate change scenarios which could result in a different impact outcome, in terms of magnitude and in some cases sign of change.

A widespread increase in peak flow in catchments in England and Wales was also found by Bell et al. (2007) and Bell et al. (2009) under the same climate scenario (A2), although the results were affected by the occurrence of one or two extreme rainfall events in the timeseries. The maps of changes in future peak flows presented by Bell et al. (2009) suggest a high degree of spatial variability in the sensitivity of UK rivers to changes in climate, with changes ranging from –60% to +100%. Most of the projected large increases were located in Scotland and Northern England while in South East England and the Midlands there was more spatial variability. These regions have lower relief and spatially more variable soils and geology and include areas where groundwater is a significant component of river flow. It should be noted that Bell et al. (2009) used only one climate model simulation and one emissions scenario.

Kay et al. (2009) investigated the uncertainties introduced into climate change flood projections by emissions scenarios, GCMs, downscaling techniques (including dynamical downscaling through regional climate models (RCMs)), hydrological models, and internal variability of the climate system, for the UK. They found the largest source of uncertainty by far was the GCM structure, but this was due to the extremely large increases in winter rainfall simulated by one of the five GCMs they applied. Even when this model was omitted, they found that uncertainties associated with climate modelling were larger than uncertainties related to emissions or hydrological modelling. This supports the findings of other work in this area (Gosling et al., 2011, Todd et al., 2011).

AVOID programme results

To quantify the impact of climate change on fluvial flooding and the inherent uncertainties, the AVOID programme calculated an indicator of flood risk for all countries reviewed in this literature assessment based upon the patterns of climate change from 21 GCMs (Warren et al., 2010). This ensures a consistent methodological approach across all countries and takes consideration of climate modelling uncertainties.

Methodology

The effect of climate change on fluvial flooding is shown here using an indicator representing the percentage change in average annual flood risk within a country, calculated by assuming a standardised relationship between flood magnitude and loss. The indicator is based on the estimated present-day (1961-1990) and future flood frequency curve, derived from the time series of runoff simulated at a spatial resolution of 0.5°x0.5° using a global hydrological model, MacPDM (Gosling and Arnell, 2011). The flood frequency curve was combined with a generic flood magnitude–damage curve to estimate the average annual flood damage in each grid cell. This was then multiplied by grid cell population and summed across a region, producing in effect a population-weighted average annual damage. Flood damage is thus assumed to be proportional to population in each grid cell, not the value of exposed assets, and the proportion of people exposed to flood is assumed to be constant across each grid cell (Warren et al., 2010).

The national values are calculated across major floodplains, based on the UN PREVIEW Global Risk Data Platform (preview.grid.unep.ch). This database contains gridded estimates, at a spatial resolution of 30 arc-seconds (0.00833°x0.00833°), of the estimated frequency of flooding. From this database the proportion of each 0.5°x0.5° grid cell defined as floodplain was determined, along with the numbers of people living in each 0.5°x0.5° grid cell in flood-prone areas. The floodplain data set does not include “small” floodplains, so underestimates actual exposure to flooding. The pattern of climate change from 21 GCMs was applied to MacPDM, under two emissions scenarios; 1) SRES A1B and 2) an aggressive mitigation scenario where emissions follow A1B up to 2016 but then decline at a rate of 5% per year thereafter to a low emissions floor (denoted A1B-2016-5-L). Both scenarios assume that population changes through the 21st century following the SRES A1 scenario as implemented in IMAGE 2.3 (van Vuuren et al., 2007). The application of 21 GCMs is an attempt to quantify the uncertainty due to climate modelling, although it is acknowledged that only one impacts model is applied (MacPDM). Simulations were performed for the years 2030, 2050, 2080 and 2100. The result represents the change in flood risk due to climate change, not the change in flood risk relative to present day (Warren et al., 2010).

Results

The results for the UK are presented in Figure 16. By the 2030s, the models project a range of changes in mean fluvial flooding risk over the UK as a whole in both scenarios, with some models projecting decreases and others increases. However, the balance is much more towards increased flood risk, with nearly three quarters of the models projecting an increase. The largest decrease projected for the 2030s is −20%, while the largest increase is +70%. The mean across all projections is approximately a 4% increase in flood risk.

By 2100 the balance shifts even more towards increased flood risk in both scenarios, and the difference in projections from the different models also becomes greater. Both these aspects of the results are more pronounced for the A1B scenario than the mitigation scenario. Under the mitigation scenario, some models still project a lower flood risk (down to

−20%), but more than three quarters of the models project an increase. The mean of all projections is a 10% increase, but the upper projection is approximately +120%. Under the A1B scenario, a large majority of the models project an higher flood risk, although a few still project a decrease (down to a minimum change of −20%). The largest projected increase is over 360%, with the mean of all projections being an increase in the average annual flood risk of approximately +70%.

So for the UK as a whole, the models show a much greater tendency for increasing flood risk, particularly later in the century and particularly in the A1B scenario. Differences between the model projections are also greater later in the century and particularly for A1B.

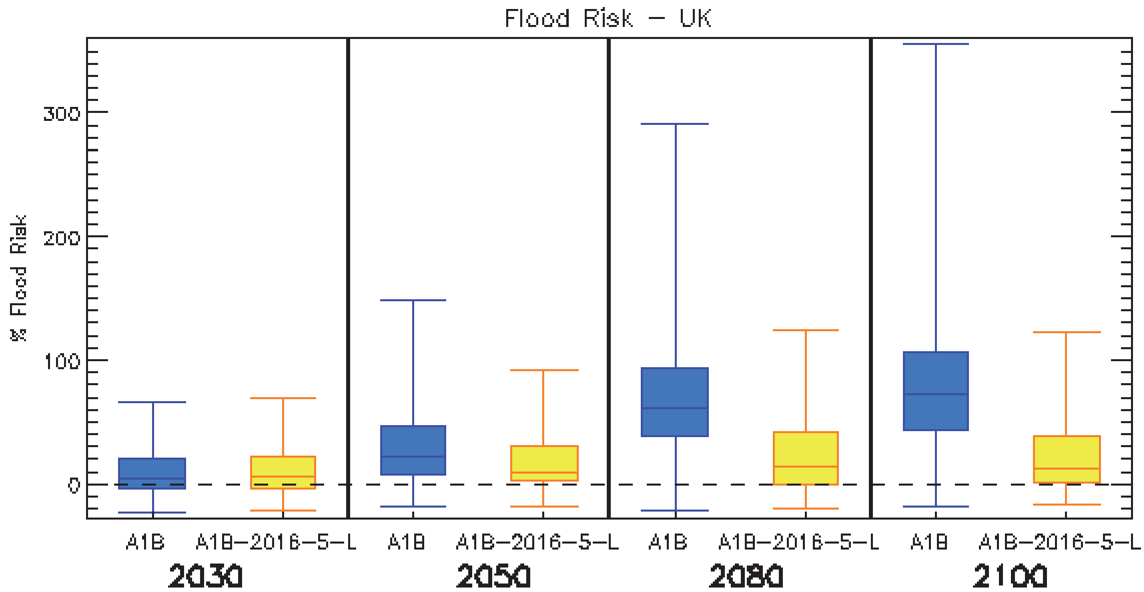

Figure 16. *Box and whisker plots for the percentage change in average annual flood risk within the UK, from 21 GCMs under two emissions scenarios (A1B and A1B-2016-5-L), for four time horizons. The plots show the 25th, 50th, and 75th percentiles (represented by the boxes), and the maximum and minimum values (shown by the extent of the whiskers).*

Tropical cyclones

This country is not impacted by tropical cyclones.

Coastal regions

Headline

Several global-scale and regional-scale assessments suggest that without adaptation, the UK could experience major impacts on coastal flooding from sea level rise (SLR). For example, one study shows that by the 2080s under a high SLR scenario and without adaptation, the average annual number of people flooded in the UK could be around 986,300; this is greatly reduced with adaptation (raising of flood dykes and the application of beach nourishment), to around 5,600. New work also demonstrates the potential benefits of climate change mitigation policy. For example, one study shows that aggressive mitigation could avoid an exposure of around 51,000 people to SLR in the UK, relative to un-mitigated climate change.

Assessments that include a global or regional perspective

The UK is highly vulnerable to SLR with climate change (European Commission, 2009, Hanson et al., 2010, Richards and Nicholls, 2009). The IPCC AR4 concluded that at the time, understanding was too limited to provide a best estimate or an upper bound for global SLR in the twenty-first century (IPCC, 2007b). However, a range of SLR, excluding accelerated ice loss effects was published, ranging from 0.19m to 0.59m by the 2090s (relative to 1980-2000), for a range of scenarios (SRES A1FI to B1). The IPCC AR4 also provided an illustrative estimate of an additional SLR term of up to 17cm from acceleration of ice sheet outlet glaciers and ice streams, but did not suggest this is the upper value that could occur. Although there are published projections of SLR in excess of IPCC AR4 values (Nicholls et al., 2011), many of these typically use semi-empirical methods that suffer from limited physical validity and further research is required to produce a more robust estimate. Linking sea level rise projections to temperature must also be done with caution because of the different response times of these two climate variables to a given radiative forcing change.

Nicholls and Lowe (2004) previously showed that mitigation alone would not avoid all of the impacts due to rising sea levels, adaptation would likely be needed too. Recent work by van Vuuren et al. (2011) estimated that, for a world where global mean near surface temperatures reach around 2°C by 2100, global mean SLR could be 0.49m above present levels by the end of the century. Their sea level rise estimate for a world with global mean temperatures reaching 4°C by 2100 was 0.71m, suggesting around 40% of the future increase in sea level to the end of the 21st century could be avoided by mitigation. A qualitatively similar conclusion was reached in a study by Pardaens et al. (2011), which examined climate change projections from two GCMs. They found that around a third of global-mean SLR over the 21st century could potentially be avoided by a mitigation scenario under which global-mean surface air temperature is near-stabilised at around 2°C relative to pre-industrial times. Under their baseline business-as-usual scenario the projected increase in temperature over the 21st century is around 4°C, and the sea level rise range is 0.29-0.51m (by 2090-2099 relative to 1980-1999; 5% to 95% uncertainties arising from treatment of land-based ice melt and following the methodology used by the IPCC AR4). Under the mitigation scenario, global mean SLR in this study is projected to be 0.17-0.34m.

The IPCC 4th assessment (IPCCa) followed Nicholls and Lowe (2004) for estimates of the numbers of people affected by coastal flooding due to sea level rise. Nicholls and Lowe (2004) projected for the North and West Europe region that an additional 100 thousand people per year could be flooded due to sea level rise by the 2080s relative to the 1990s for the SRES A2 Scenario (note this region also includes other countries, such as The Netherlands and Norway). However, it is important to note that this calculation assumed that protection standards increased as GDP increased, although there is no additional adaptation for sea level rise. More recently, Nicholls et al. (2011) also examined the potential impacts of sea level rise in a scenario that gave around 4°C of warming by 2100. Readings from Figure 3 from Nicholls et al. (2011) for the North and West Europe region suggest that less than an approximate 1 million additional people could be flooded for a 0.5 m SLR (assuming no additional protection). Nicholls et al. (2011) also looked at the consequence of a 2m SLR by 2100, however as we consider this rate of SLR to have a low probability we don't report these figures here.

The European Commission (2009) assessed the vulnerability of several European countries to SLR. The study showed that 10-15% of UK's coastline is comprised of 10km long stretches that are below 5m elevation and that 3009km (16%) is subject to erosion. The study also calculated that 69% of GDP is located within 50km of the coast and that 78% of the country's population live within this zone. This makes the UK one of the most vulnerable

European countries to SLR and this is confirmed by a number of recent global and large-scale regional assessments, which suggest that without adaptation, the UK could experience major impacts on coastal flooding from SLR (Hanson et al., 2010, Richards and Nicholls, 2009).

Recent results from the PESETA (Projection of Economic impacts of climate change in Sectors of the European Union based on boTtom-up Analysis) project have afforded consistent quantitative projections of the impact of SLR for several European countries (Richards and Nicholls, 2009). These are advantageous because previous European assessments have tended to be more qualitative in nature (Nicholls, 2000). Results from (Richards and Nicholls, 2009) show that while Europe is potentially highly threatened by SLR, adaptation (in the form of the two protection options considered) can greatly reduce these impacts to levels which appear manageable. The adaptation methods and costs assessed were the raising of flood dykes and the application of beach nourishment. Richards and Nicholls (2009) show that there are almost immediate benefits of adaptation, and the analysis suggests that widespread adaptation to SLR across Europe could be prudent. The assessment considered SLR projections from two GCMs, ECHAM4 and HadCM3. For each of these, SLR estimates for low, medium and high climate sensitivities were applied, and under the A2 and B2 emissions scenarios. To further quantify uncertainty, the upper and lower estimates of global SLR from the IPCC TAR (IPCC, 2001) were also applied. The estimates of global SLR considered by Richards and Nicholls (2009) are summarised in Table 9. Given that the IPCC Third Assessment Report (TAR) estimates of SLR encompass the full range of uncertainty that Richards and Nicholls (2009) considered, impacts for the IPCC TAR low and high scenarios are presented in Table 10. The results show that by the 2080s under the high SLR scenario and without adaptation, the average annual number of people flooded in the UK is around 986,300. This is greatly reduced with adaptation, to around 5,600. Under the low SLR scenario, 6,800 people are flooded annually without adaptation and 4,300 are flooded with adaptation. The results highlight the importance of climate sensitivity in determining the impacts as well as demonstrating clear potential benefits of adaptive measures, which by the 2080s can almost completely remove any incremental climate change effect. Moreover, the results presented by Richards and Nicholls (2009) highlight the UK’s high vulnerability to SLR and emphases that impacts could be large in the absence of adaptation.

GCM	ECHAM4		HadCM3		IPCC TAR
SRES scenario	**A2**	**B2**	**A2**	**B2**	**A2/B2**
Climate sensitivity					
Low	*29.2*	*22.6*	*25.3*	*19.4*	*9*
Medium	*43.8*	*36.7*	*40.8*	*34.1*	
High	*58.5*	*50.8*	*56.4*	*48.8*	*88*

Table 9. *Global SLR (cm) for low, medium and high climate sensitivities at 2100, for the A2 and B2 SRES scenarios, that were applied by Richards and Nicholls (2009).*

Country	Indicator	Baseline (1995)	**IPCC** A2 2020s **Low SLR**		**IPCC** A2 2020s **High SLR**		**IPCC** A2 2080s **Low SLR**		**IPCC** A2 2080s **High SLR**	
			No adaptation	**With adaptation**	**No adaptation**	**With adaptation**	**No adaptation**	**With adaptation**	**No adaptation**	**With adaptation**
France	Total damage costs (millions €/year)	253.2	362.7	228.8	434.9	291.7	673.3	220.9	3359.8	456.6
	Land loss (submergence) (km^2/year)	0	0.2	0.2	0.6	0.6	0.2	0.2	130.8	1.6
	Migration due to land loss (1000s of people/year)	0	0	0	0	0	0	0	19.5	0
	Net loss of wetland area (km^2/year)	12.4	300.7	300.7	688.7	688.7	950.9	950.9	1963.8	1963.8
	People actually flooded (1000s/year)	1.96	2.4	2.0	2.9	2.1	3.0	1.8	463.7	2.5
	Salinity intrusion costs (millions €/year)	135.85	145.3	145.3	153.5	153.5	199.9	199.9	268.7	268.7
Germany	Total damage costs (millions €/year)	428.1	473.7	398.9	590.3	448.3	782.2	344.6	2607.6	686.9
	Land loss (submergence) (km^2/year)	0	0	0	0	0	0	0	178.1	0
	Migration due to land loss (1000s of people/year)	0	0	0	0	0	0	0	14.3	0.1
	Net loss of wetland area (km^2/year)	0.3	146.4	146.4	418.3	418.3	673.2	673.2	1938.5	1938.5
	People actually flooded (1000s/year)	2.23	2.6	2.3	3.7	2.5	4.4	2.1	293.3	2.9
	Salinity intrusion costs (millions €/year)	274.78	240.8	240.8	251.2	251.2	343.3	343.3	431.4	431.4
Italy	Total damage costs (millions	8.5	18.5	6.6	271.9	7.1	444.2	9.6	8044.2	17.0

	€/year)									
	Land loss (submergence) (km^2/year)	0	0	0	0	0	0	0	188.5	0.1
	Migration due to land loss (1000s of people/year)	0	0	0	0	0	0	0	55.2	0
	Net loss of wetland area (km^2/year)	9.6	78.2	78.2	155.5	155.5	221.8	221.8	393.7	393.7
	People actually flooded (1000s/year)	1.49	1.9	1.5	3.1	1.6	3.3	1.5	512.9	2.3
	Salinity intrusion costs (millions €/year)	5.84	6.4	6.4	6.7	6.7	9.2	9.2	11.9	11.9
Spain	Total damage costs (millions €/year)	15.3	23.6	9.4	55.6	14.5	75.6	3.9	749.7	32.0
	Land loss (submergence) (km^2/year)	0	0	0	0	0	0	0	38.3	0.1
	Migration due to land loss (1000s of people/year)	0	0	0	0	0	0	0	7.0	0
	Net loss of wetland area (km^2/year)	0.2	64.4	64.4	174.3	174.3	242.5	242.5	659.8	659.8
	People actually flooded (1000s/year)	0.73	0.9	0.7	1.3	0.8	1.1	0.7	321.8	1.1
	Salinity intrusion costs (millions €/year)	0.92	1.0	1.0	1.0	1.0	1.4	1.4	1.8	1.8
UK	Total damage costs (millions €/year)	189.5	414.2	50.1	743.5	136.4	1087.0	6.3	10062.6	155.1
	Land loss (submergence) (km^2/year)	0	0	0	0	0	0	0	239.3	0
	Migration due to land loss (1000s of people/year)	0	0	0	0	0	0	0	73.6	0
	Net loss of wetland area (km^2/year)	8.5	175.1	175.1	522.6	522.6	789.4	789.4	1690.2	1690.2
	People actually flooded (1000s/year)	4.85	5.7	4.4	6.1	4.9	6.8	4.3	986.3	5.6
	Salinity intrusion costs (millions €/year)	2.32	2.5	2.5	2.8	2.8	3.6	3.6	5.7	5.7

***Table 10**. Estimates of the impact of SLR with the low and high estimates of SLR from the IPCC TAR in the 2020s and 2080s, and assuming no adaptation or adaptation. Baseline impacts (1995) are also presented. Data is from Richards and Nicholls (2009).*

Hanson et al. (2010) present a global-scale analysis of the impact of SLR on coasts and include national-scale estimates for the UK. The study investigated population exposure to global SLR, natural and human subsidence/uplift, and more intense storms and higher storm surges, for 136 port cities across the globe. Future city populations were calculated using global population and economic projections, based on the SRES A1 scenario up to 2030. The study accounted for uncertainty on future urbanization rates, but estimates of population exposure were only presented for a rapid urbanisation scenario, which involved the direct extrapolation of population from 2030 to 2080. All scenarios assumed that new inhabitants of cities in the future will have the same relative exposure to flood risk as current inhabitants. The study is similar to a later study presented by Hanson et al. (2011) except here, different climate change scenarios were considered, and published estimates of exposure are available for more countries, including the UK. Future water levels were generated from temperature and thermal expansion data related to greenhouse gas emissions with SRES A1B (un-mitigated climate change) and under a mitigation scenario where emissions peak in 2016 and decrease subsequently at 5% per year to a low emissions floor (2016-5-L). Table 11 shows the aspects of SLR that were considered for various scenarios and Table 12 displays regional population exposure for each scenario in the 2030s, 2050s and 2070s. The results show that the UK is around the midpoint of all countries considered by this review, in terms of the magnitude of impact SLR could have on the national population (Table 12).

Scenario		**Water levels**				
		Climate			**Subsidence**	
Code	**Description**	**More intense storms**	**Sea-level change**	**Higher storm surges**	**Natural**	**Anthropogenic**
FNC	Future city	V	x	x	x	x
FRSLC	Future City Sea-Level Change	V	V	x	V	x
FCC	Future City Climate Change	V	V	V	V	x
FAC	Future City All Changes	V	V	V	V	V

Table 11. *Summary of the aspects of SLR considered by Hanson et al. (2010). 'V' denotes that the aspect was considered in the scenario and 'x' that it was not.*

Rapid urbanisation projection																	
2030						2050						2070					
Country	Ports	Water level projection				Country	Ports	Water level projection				Country	Ports	Water level projection			
		FAC	FCC	FRSLC	FNC			FAC	FCC	FRSLC	FNC			FAC	FCC	FRSLC	FNC
CHINA	15	17,100	15,500	15,400	14,600	**CHINA**	15	23,000	19,700	18,700	17,400	**CHINA**	15	27,700	22,600	20,800	18,600
INDIA	6	11,600	10,800	10,300	9,970	**INDIA**	6	16,400	14,600	13,600	12,500	**INDIA**	6	20,600	17,900	15,600	13,900
US	17	8,990	8,960	8,830	8,460	**US**	17	11,300	11,200	10,800	9,970	**US**	17	12,800	12,700	12,100	10,700
JAPAN	6	5,260	4,610	4,430	4,390	**JAPAN**	6	6,440	5,280	5,000	4,760	**JAPAN**	6	7,800	5,970	5,580	5,070
INDONESIA	4	1,420	1,200	1,200	1,170	**INDONESIA**	4	2,110	1,610	1,610	1,500	**INDONESIA**	4	2,680	1,830	1,830	1,530
BRAZIL	10	833	833	833	802	**BRAZIL**	10	929	929	929	879	**BRAZIL**	10	940	940	940	864
UK	2	497	497	478	459	**UK**	2	609	609	564	521	**UK**	2	716	716	640	569
CANADA	2	459	433	422	405	**CANADA**	2	549	512	486	457	**CANADA**	2	614	585	545	489
REP. OF KOREA	3	344	344	331	441	**REP. OF KOREA**	3	361	361	341	318	**REP. OF KOREA**	3	377	377	325	303
GERMANY	1	257	257	253	248	**GERMANY**	1	287	287	273	269	**GERMANY**	1	309	309	290	280
RUSSIA	1	177	177	177	177	**RUSSIA**	1	202	202	173	173	**RUSSIA**	1	226	226	197	169
AUSTRALIA	5	162	162	157	157	**AUSTRALIA**	5	197	197	191	181	**AUSTRALIA**	5	196	196	186	175
SAUDI ARABIA	1	24	24	24	22	**SAUDI ARABIA**	1	33	33	33	27	**SAUDI ARABIA**	1	38	38	38	29
SOUTH AFRICA	2	30	30	30	29	**SOUTH AFRICA**	2	28	28	28	27	**SOUTH AFRICA**	2	30	30	30	27
FRANCE	1	15	15	15	15	**FRANCE**	1	19	19	19	17	**FRANCE**	1	23	23	23	18
ITALY	1	2	2	2	2	**ITALY**	1	4	4	4	3	**ITALY**	1	6	6	6	4
MEXICO	0	0	0	0	0	**MEXICO**	0	0	0	0	0	**MEXICO**	0	0	0	0	0

Table 12. *National estimates of population exposure (1,000s) for each water level projection (ranked according to exposure with the FAC (Future City All Changes) scenario) under a rapid urbanisation projection for the 2030s, 2050s and 2070s. Estimates for present day exposure and in the absence of climate change (for 2070 only) for comparison are presented in Table 13. Data is from Hanson et al. (2010) and has been rounded down to three significant figures.*

The effect of climate change is observed by comparing the projections in Table 12 with the estimates for exposure in the absence of climate change that are presented in Table 13. At present, 414,000 people are exposed to SLR in the UK. By the 2070s in the absence of climate change 569,000 are exposed. With climate change in the 2070s under the A1B and FAC (Future City All Changes) scenarios, 716,000 people are exposed, which equates to an incremental climate change impact of 147,000 people that is well within the range estimated by Richards and Nicholls (2009) in the PESETA project. Hanson et al. (2010) also demonstrated that an aggressive mitigation scenario could avoid an exposure of around 51,000 people in the UK, relative to un-mitigated climate change (see Table 13).

Country	Ports	Population exposure				Exposure avoided
		Current	2070. Rapid urbanisation, FAC water level scenario			
			No climate change	A1B un-mitigated	Mitigated (2016-5-L)	
CHINA	15	8,740	18,600	27,700	26,500	1,140
UNITED STATES	17	6,680	10,700	12,800	12,300	505
RUSSIA	1	189	169	226	197	28
JAPAN	6	3,680	5,070	7,800	7,290	515
SOUTH AFRICA	2	24	27	30	29	0
INDIA	6	5,540	13,900	20,600	18,900	1,670
BRAZIL	10	555	864	940	926	14
MEXICO	0	0	0	0	0	0
CANADA	2	308	489	614	599	15
AUSTRALIA	5	99	175	196	190	6
INDONESIA	4	602	1,530	2,680	2,520	156
REP. OF KOREA	3	294	303	377	343	34
UK	2	414	569	716	665	51
FRANCE	1	13	18	23	20	2
ITALY	1	2	4	6	6	0
GERMANY	1	261	280	309	295	15
SAUDI ARABIA	1	15	29	38	35	3

***Table 13**. Exposed population (1,000s) in present (current), and in the 2070s in the absence of climate change (no climate change), with unmitigated climate change (A1B un-mitigated), and mitigated climate change (mitigated 2016-5-L), under the rapid urbanisation and FAC (Future City All Changes) water level scenarios. The final column shows the potential avoided exposure, as a result of mitigation. Data is from Hanson et al. (2010) and has been rounded down to three significant figures.*

To further quantify the impact of SLR and some of the inherent uncertainties, the DIVA model was used to calculate the number of people flooded per year for global mean sea level increases (Brown et al., 2011). The DIVA model (DINAS-COAST, 2006) is an integrated model of coastal systems that combines scenarios of water level changes with socio-economic information, such as increases in population. The study uses two climate scenarios; 1) the SRES A1B scenario and 2) a mitigation scenario, RCP2.6. In both cases an SRES A1B population scenario was used. The results are shown in Table 14.

	A1B		**RCP**	
	Low	**High**	**Low**	**High**
Additional people flooded (1000s)	11.87	162.61	5.83	49.57
Loss of wetlands area (% of country's total wetland)	29.99%	46.77%	25.23%	46.06%

Table 14. *Number of additional people flooded (1000s), and percentage of total wetlands lost by the 2080s under the high and low SRES A1B and mitigation (RCP 2.6) scenarios (Brown et al., 2011).*

National-scale or sub-national scale assessments

The UK is highly vulnerable to SLR with climate change (European Commission, 2009, Hanson et al., 2010, Richards and Nicholls, 2009). The methods applied in the Thames Estuary 2100 study (Howard et al. 2008) and the Marine and coastal projections of UK Climate Projections 2009 (Lowe et al., 2009) concluded that increases in sea level during the 21st century up to 2m cannot be ruled out. However, there is evidence to suggest that increases significantly above 1m have a low probability of occurring (Lowe and Gregory, 2010, Pfeffer et al., 2008).

Mokrech et al. (2008) explored the impact of low (0.14-0.18m in 2050) and high (0.54m in 2050) SLR on the numbers of people affected by coastal flooding in North-West (NW) UK and East Anglia, under 1 in 10 year and 1 in 75 year flood events. Simulations were performed that excluded the implementation of future adaptation measures (dike upgrades) and that included them. The results are presented in Table 15, which illustrates that adaptation measures can significantly reduce – by over half – the magnitude of the impact of SLR in the UK. For example, with high SLR for NW UK in 2050, over 192,000 people could be affected if no adaptation measures are implemented but with adaptation, fewer than 20,000 people are affected. This demonstration of the significance of adaptation within the UK for avoiding major impacts of SLR, is largely supportive of the conclusions from global-scale assessments that have considered national-scale impact estimates for the UK (Hanson et al., 2010, Richards and Nicholls, 2009). However, stakeholder elicitation exercises suggest the potential for policy paralysis in response to what is a highly uncertain phenomena (the magnitude of SLR), when extreme cases of SLR are considered for the UK (Lonsdale et al., 2008)

Region and with or without adaptation	Scenario	Magnitude of flood event					
		1 in 10 year event			1 in 75 year event		
		Area at risk of flooding (ha)	Damage (£ million)	People affected	Area at risk of flooding (ha)	Damage (£ million)	People affected
East Anglia	**Baseline**	**76,900**	**527**	**48,000**	**140,000**	**1,080**	**77,800**
East Anglia (without adaptation)	Low SLR	89,000	2,170	51,500	295,000	7,260	132,000
	High SLR	95,600	2,300	54,000	297,000	8,600	160,000
East Anglia (with adaptation)	Low SLR	38,800	1,190	25,300	135,000	4,060	75,500
	High SLR	46,700	1,410	30,200	141,000	4,280	79,600
NW	**Baseline**	**10,000**	**53**	**4,290**	**81,600**	**1,730**	**122,000**
NW (without adaptation)	Low SLR	10,000	118	3,910	103,000	6,250	182,000
	High SLR	10,000	118	3,910	109,000	6,600	192,000
NW (with adaptation)	Low SLR	9,300	55	1,880	21,200	687	19,100
	High SLR	9,300	55	1,880	21,400	687	19,100

Table 15. *The impacts of SLR (low and high scenarios) on the area at risk of flooding, damage costs and number of people affected from two types of flood magnitude event (1 in 10 year and 1 in 75 year). Simulations assumed adaptation and no adaptation cases. Data is from Mokrech et al. (2008) and has been rounded down to three significant figures.*

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