Too hot, too cold, too wet, too dry: Drivers and impacts of seasonal weather in the UK

Synopsis report CS01
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Contents

Executive summary

The UK has seen a run of seasonal weather over recent years that has had impacts and led to disruption across the country. The question for climate science is whether this seasonal weather is only part of the natural variability we expect, or if there is any connection to our changing climate? Also, what can we say about how the UK's extremes of weather may be affected in the future by climate change?

This paper investigates these questions by focussing on seasons that are too hot, too cold, too wet or too dry – drawing on recent examples both in the UK and an example of an overseas event that had impacts on the UK. The main conclusions are:

Too Hot

- Heat waves in large parts of Europe, Asia and Australia are *likely* to have increased since 1950.
- Climate change has at least doubled the risk of a heat wave exceeding the temperatures experienced in the European heat wave of 2003.
- Observations of temperature across Europe over the last ten years since 2003 suggest that we are continuing along a track where, by the 2040s, more than half of summers are projected to be warmer than that seen in 2003 if emissions of greenhouse gases continue on their current rising path.

Too Cold

- As temperatures in the UK warm overall, the frequency of particularly cold seasons is expected to reduce on average.
- The strong year to year fluctuations in our winter climate, associated with natural variations, will continue. New analysis suggests that we should plan to be resilient to very cold winters, such as 2010/11.
- The role of reducing Arctic sea ice on the jet stream and UK winter climate remains an area of scientific debate, with no consensus on how it might exert influence.

Too Wet

- UK rainfall shows large year to year variability, making trends hard to detect.
- There is an increasing body of evidence that extreme daily rainfall rates around the world are becoming more intense, and that the rate of increase is consistent with what is expected from fundamental physics. There is no evidence to counter the

basic premise that a warmer world will lead to more intense daily and hourly heavy rain events.

- There is evidence to suggest that the character of UK rainfall has changed, with days of very heavy rain becoming more frequent. What in the 1960s and 1970s might have been a 1 in 125 day event is now more likely a 1 in 85 day event.
- Five of the last seven summers in the UK have been wetter than average, and prior to that there was a run of drier than average summers. This variation is thought to be part of a natural cycle of the climate system called the Atlantic Multidecadal Oscillation. Recent research suggests that emissions of small particles of pollution (aerosols) influence this natural cycle.

Too Dry

- While connections can be made between climate change and dry seasons in some parts of the world, there is currently no clear evidence of such a link to recent dry periods in the UK, such as those seen in 2010-2012 or the summer of 2006.
- Some climate impacts on the UK are experienced through economic and trade links to other nations that experience unusual seasonal weather. For example, the risk of the temperatures experienced during the heat wave and drought in Texas in 2011 was increased by human influence, and the impacts of this drought in the UK were reported to have been felt through higher food prices.

So what do we conclude from this analysis? When viewed over long-term averages, the UK is expected to see more milder wetter winters and more hotter drier summers in the future. The role of human influence on our climate is already detectable on summertime heat waves and on the character of rainfall. But the UK has seasonal weather that also varies hugely from year to year due to natural processes. New analysis suggests that we should also plan to be resilient to wet summers and to cold winters through this century.

While the role of human influence on temperature extremes can be detected, more research is urgently needed to deliver robust detection of changes in storminess and daily/hourly rain rates. The attribution of these changes to anthropogenic global warming requires climate models of sufficient resolution to capture storms and their associated rainfall. Such models are now becoming available and should be deployed as soon as possible to provide a solid evidence base for future investments in flood and coastal defences.

Table 1: Selected UK hazardous events 2003 - 2013 and future projections of change in temperature and precipitation out to 2100

	Event	Have humans changed the odds of occurrence?	Projections of future UK change	Confidence in Projection
Too Hot	Summer 2003	**Yes** - Increased	A continued rise in the UK's annual average temperature and daily average maximum temperature across all seasons are to be expected in future.	* * * *
	Autumn 2011	**Yes** - Increased		
Too Cold	Winter 2010/11	**Yes** - **Decreased**	As the atmosphere warms the frequency of cold winters and cool spring seasons is likely to decrease, but this does not mean such severe cold seasons will not occur in the future, especially in the near-term where natural variations in the climate are much larger than the influence of the long term warming trend.	* * *
	Spring 2013	Too early to say		
Too Wet	Winter 2013/14	Too early to say	When viewed over long-term averages, the frequency of wetter winters and drier summers is projected to increase over time. This does not mean that a very dry winter or very wet summer will not happen. Natural variability looks likely to continue to give the UK wet summers, and the role of the AMO in giving runs of wetter than average summers. As yet, there is no definitive answer on the possible contribution of climate change to the recent storminess, rainfall amounts and the consequent flooding. More research is urgently needed to deliver robust detection of changes in storminess and daily/hourly rain rates.	* *
	Summer 2012	Too early to say		
Too Dry	Dry 2010/12	Too early to say	The frequency of extremely dry summers in the UK is projected to increase over time. Further research and climate model development is required however, as confidence is limited by the relatively coarse resolution of climate models. New, higher resolution models coming on line now should be exploited as soon as possible to better determine the changing incidence of dry extremes.	* *
	Summer 2006	Too early to say		

Confidence rating: Scientific confidence is given a star rating from 1 to 5 stars, with more stars indicating higher confidence.
This is a subjective measure based on an expert opinion of the science. Factors influencing this opinion include agreement between climate models, maturity of research and consensus for robust studies over the UK region.

1. Introduction

The UK has just experienced an exceptionally wet winter. Overall England and Wales have just experienced their wettest January and winter season (December to February) since records began in 1766. Southern England was particularly wet with some areas receiving two to three times their normal winter rainfall. The jet stream locked into a persistent pattern across the Atlantic bringing a succession of rainstorms which saturated the soil early in the winter and then led to widespread flooding, as described in a previous Met Office/CEH report[1]. The effects of the heavy rains and the flooding were widespread: power was cut in some areas, homes were flooded and the transport network was severely disrupted.

The winter of 2013/14 is the latest in a run of seasonal weather that has had large impacts on the UK and across Europe over recent years, for example the cold winter of 2010/11, the wet summer of 2012 and the cold spring of 2013. Each of these seasons had substantial economic and social impacts in the UK. There has been public and media interest in the role of climate variability and climate change in these events, with concern as to how often such conditions should be expected in the future. To help inform this debate, this synopsis paper analyses examples of seasonal weather that had an impact in the UK, to elucidate the meteorological factors behind them. So, what can we say about seasons that are too hot, too cold, too wet or too dry? The first aim of this paper is to examine the question of the role of *natural climate variability* in extreme seasonal weather.

In September 2013 Working Group I (WGI) of the Intergovernmental Panel on Climate Change published its 5th Assessment Report (AR5). Two of the primary questions addressed by the report were: Is the world warming and, if it is, is it due to human activities? AR5 concluded that (i) warming is unequivocal and (ii) it is *extremely likely*[2] that human influence has been the dominant cause of the observed warming since the mid-20th century. The evidence to support these conclusions came from analysis of the climate across the world. But what does this human influence on climate mean for the UK? And what are the likely impacts of any climate change in the UK? Since it is through extreme seasonal weather that we feel the impacts of climate and climate change, it is natural to ask these questions particularly of the recent run of seasons. So the second purpose of this paper is to address the question as to the role of *climate change* in extreme seasons.

[1] Met Office and CEH; Feb 2014; 'The Recent Storms and Floods in the UK', Met Office, Exeter.
[2] IPCC use calibrated language where *extremely likely* means a result has greater than 95% confidence.

Both key questions are addressed by analysing trends in UK weather and by analysing specific UK seasons that exemplify too hot, too cold and too wet conditions. In our globally connected world, the weather abroad can also have impacts on the UK, and so we also use an example of an overseas season to exemplify too dry.

2. Too Hot?

2.1 What has been observed?

Global view: The world has warmed by about 0.85°C since 1880, with much of that warming having occurred since the middle of the 20th Century[3] at a rate of approximately 0.12°C per decade since 1951[4]. The land surface temperature has risen more than the ocean surface temperature and the polar regions have warmed more than the equatorial regions for physical reasons that are largely understood. The 5th Assessment Report of the IPCC WGI concluded that it is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid-20th century. Heat waves in large parts of Europe, Asia and Australia are *likely* to have increased since 1950[4]. Finally, observations show that there has been a continued increase of hot extremes even during the last 10-15 years[5], when there has been a slowdown in the warming of the global mean temperature[6].

UK view: The UK has seen warming occur faster than the global average: at 0.23°C per decade in winter and 0.28°C per decade in summer since 1960[7]. Results from Brown et al (2008)[8] show that the extreme values of the maximum daily temperature and minimum daily temperature in the UK have risen by just over 1°C since the 1950s, and there is a suggestion that the warmest daily temperature extremes are rising faster in summer, whereas the coolest daily temperature extremes are rising faster in winter.

[3] Source: HadCRUT4; MLOST dataset, National Climatic Data Center at NOAA; Goddard Institute for Space Studies at NASA.
[4] Hartmann, D.L., et al., 2013: Observations: Atmosphere and Surface. In: Climate Change 2013: The Physical Science Basis. *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
[5] Seneviratne, S.I, M. Donat, B. Mueller, and L.V. Alexander, 2014: 'No pause in the increase of hot temperature extremes', *Nature Climate Change*, **4**, 161-163.
[6] Met Office; 2013: Three papers on the recent pause in warming: Paper 1: 'Observing changes in the climate system', Paper 2: 'Recent pause in global warming', Paper 3: 'Implications for projections', Met Office, Exeter.
[7] Source: CRUTEM3 data, methodology as cited in Met Office et al., 2011: 'Climate: Observations, Projections and Impacts, UK report', Met Office, Exeter, UK.
[8] Brown, S.J., J. Caeser and C.A.T. Ferro, 2008: 'Global changes in extreme daily temperature since 1950', *J. Geophys. Res.,* **113**, D05101 and Christidis, N., et al., 2005: 'Detection of changes in temperature extremes during the second half of the 20th century', *Geophys. Res. Lett.,* **32**, L20716

2.2 The hot summer of 2003

The summer of 2003 was the hottest for 500 years across parts of Europe[9]. The highest temperatures associated with the heat wave were centred over central and southern Europe (figure 2.1a). The heat wave also extended to the UK: in July 2003 the UK recorded its highest ever temperature of 38.5°C and experienced runs of days where the maximum temperature consistently exceeded 32°C (figure 2.1b).

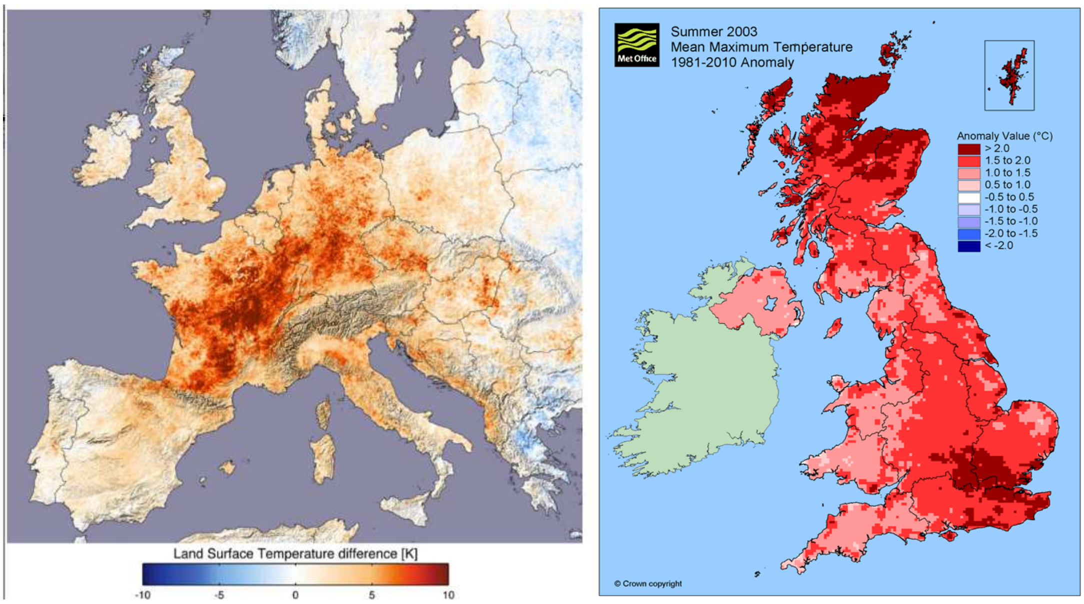


Figure 2.1: Surface temperature patterns during the exceptionally hot summer of 2003. (a) Difference in surface temperature from the average, showing the centre of the heat wave over central and southern Europe. (Source: NASA). (b) Difference in surface temperature from the average (over 1981-2010) in the UK, showing the particular warming in South-East England. (Source: Met Office, NCIC).

Overall in England there were 2,091 (17%) excess deaths in the first two weeks of August 2003. Worst affected were those over the age of 75[10]. The high temperatures were also reported to have caused disruption to transport networks. Speed restrictions were imposed on the UK rail network when air temperatures reached 30°C to prevent the tracks from buckling.

There is evidence from climate models to suggest that summer 2003 is part of a broadening of the range of temperatures experienced in Europe as a result of climate change: the hot events are getting hotter faster than the cold events are warming[11]. This

[9] Trigo, R.M., et al., 2005: 'How exceptional was the early August 2003 heatwave in France?' *Geophys. Res. Letts.*, **32 (10)**

[10] Johnson, H., et al., 2005: 'The impact of the 2003 heat wave on mortality and hospital admissions in England', Health Statistics Quarterly, **25,** 6-12

[11] Schar, C., et al., 2004: 'The role of increasing temperature variability in European summer heatwaves', *Nature*, **427**, 332-336

can be understood through an important physical mechanism that contributes to the amplification of heat wave events more generally. There was little rainfall during spring 2003 so that by summer there was little moisture in the soil. During summer a persistent anticyclone sat over central Europe, giving clear skies and so high solar heating, which then heated the ground. Whilst the ground remained moist, part of the heat absorbed by the ground evaporated moisture, and only the remainder warmed the air. Early in the event the soil dried out, and so all the heat absorbed by the ground then warmed the air. It is estimated that this process of the soil drying out doubled the temperature increase associated with the heat wave[12]. Notice in figure 2.1a how the heat wave produced much more modest increases in temperature in arid Spain (when compared to average temperatures), where the ground there is already dry. A transition from wet soils to dry soils is therefore an important and general mechanism for local amplification of global warming, particularly in summertime heat waves[13].

Stott et al (2004)[14] assessed the change in the probability of temperatures experienced in summer 2003 occurring as a result of greenhouse gas emissions. Simulations were performed with a climate model with pre-industrial levels of greenhouse gases, and simulations were performed with the same climate model with the measured emissions of greenhouse gases since the industrial revolution. The two sets of simulations were then used to establish the effects of the greenhouse gases on the occurrence of temperatures over Europe experienced in summer 2003. They concluded that past human influence more than doubled the risk of European mean summer temperatures as hot as 2003. Furthermore, projections with the same climate model indicated that the probability of European mean summer temperatures exceeding those of 2003 increases rapidly under an A2 emissions scenario. The simulations indicate that by the 2040s more than half of summers in Europe will be warmer than 2003, and by the end of this century 2003 would be classed as a cold summer relative to the new climate.

So how have these predictions fared in the 10 years since they were made? Figure 2.2 shows the results of Stott et al (2004) updated with the most recent measurements of European temperature and with the most recent simulations from the CMIP5 model archive. Firstly, figure 2.2 shows that the measured temperatures (black lines) are above the range of model results obtained with pre-industrial levels of greenhouse gases (blue

[12] Fischer et al., 2007: ‘Soil Moisture–Atmosphere Interactions during the 2003 European Summer Heat Wave’, *J. Clim,* **20,** 5081-5099

[13] Vidale, P.L., et al., 2007: ‘European summer climate variability in a heterogeneous multi-model ensemble’, *Clim. Change*, **81**: 209-232

[14] Stott, P.A., et al., 2004: ‘Human contribution to the European heatwave of 2003’, *Nature,* **432,** 610-614

lines), which supports the finding of Stott et al (2004) that there is a human influence on European summer temperatures. Secondly, the measured temperatures for this European region have continued to rise, and in the upper half of the CMIP5 range of projections based on greenhouse gas concentrations consistent with high fossil fuel burning (RCP 8.5). And this is during a period when there has been a pause in the global mean temperature rise (discussed in a series of three Met Office papers[6]). So we seem to continue on the trajectory described by Stott et al (2004): the evidence suggests that by the 2040s more than half the summers in Europe will be warmer than 2003 and by the end of this century, 2003 would be classed as a cold summer relative to the new climate.

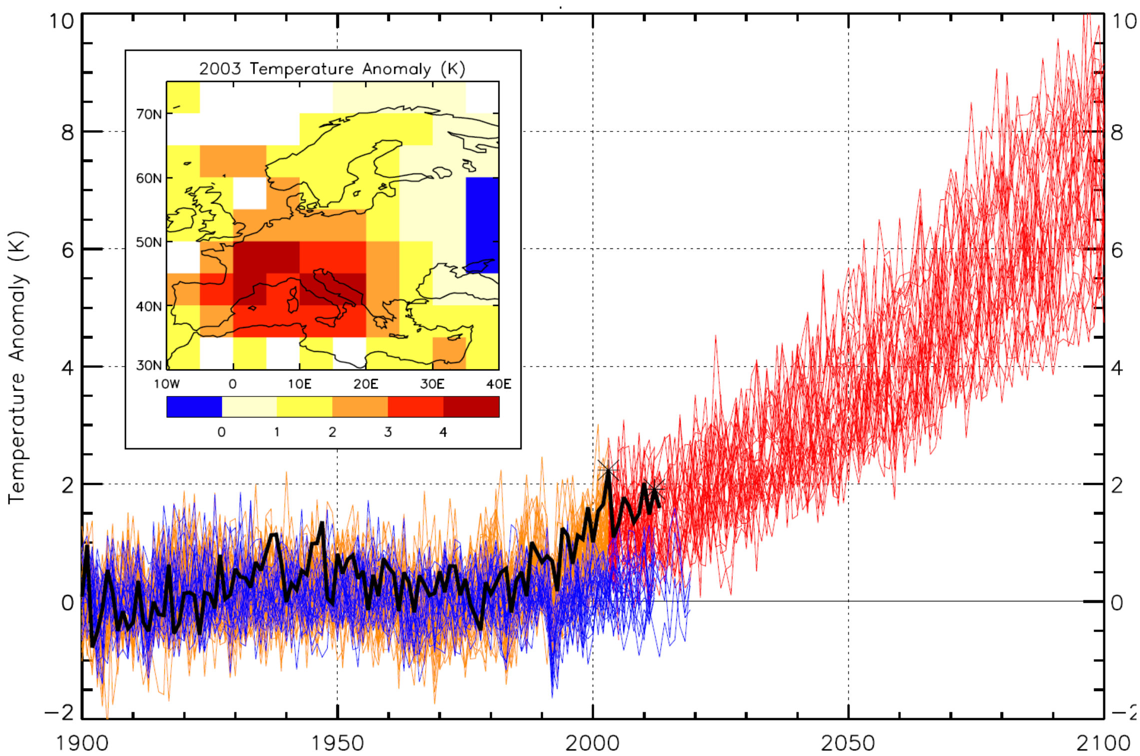


Figure 2.2: Variation of summer (JJA) temperatures over Europe, relative to the pre-industrial period (1880-1919). Black line: observed temperatures, notice the high value during 2003, and in years since then. Blue lines: results from climate model simulations with pre-industrial concentrations of greenhouse gases. Orange/red lines: results from climate model simulations, that include emissions of greenhouse gases; from 1900 to 2003 assessed from observations (orange); and out to 2100 according to RCP 8.5 (red). The inset shows the area used here to calculate European temperatures, overlaid with observed temperature differences (in Kelvin) during summer 2003, relative to the 1961-1990 JJA average (Source: Met Office; observations from CRUTEM4, Met Office/UEA).

2.3 How are hot events projected to change in future?

We expect a continuation of the observed increase in the UK's annual mean

temperature. The central estimate from the UKCP09 projections suggests that, under a medium emissions scenario (A1B), the UK's annual mean temperature will rise by up to 3.5°C (with a range of 2.2°C - 5.1°C) in the south and 2.8°C (with a range of 1.7°C - 4.2°C) in Scotland by the 2080s compared to the 1961-1990 average. Figure 2.3 shows that under the A1B emissions scenario, the central estimate for the change in average daily maximum temperatures in the south is 5°C (with a range of 2.2°C – 9.5°C) by the 2080s[15].

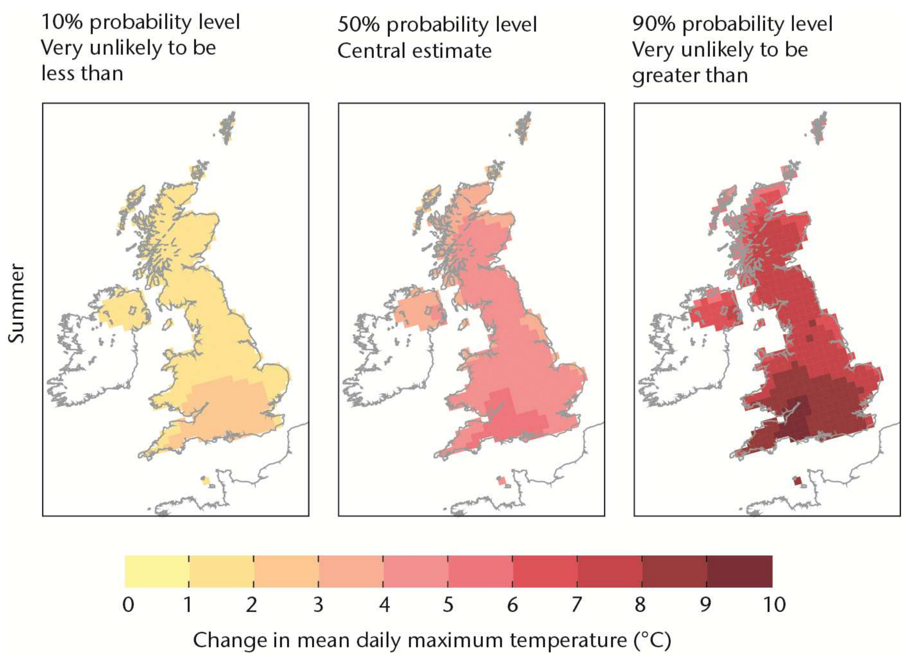


Figure 2.3: 10, 50 and 90% probability levels of changes to mean daily maximum temperature (ºC) in summer, by the 2080s, under the Medium (A1B) emissions scenario.

The intensity of heat waves in Europe is projected to increase in the future, through the mechanism of soil drying described in section 2.2 above, by between 1.4°C and 7.5°C for a rise in global mean temperature of 2°C. Uncertainties remain in the magnitude of the increased intensity because of sensitivity to the modelling of the physics associated with vegetation and drying of the soil[16].

[15] Murphy, J.M. et al., 2008: 'UK Climate Projections Science Report: Climate change projections', Met Office Hadley Centre, Exeter.
[16] Clark, R.T., et al., 2010: Do global warming targets limit heatwave risk? *Geophys. Res. Lett.,* **37,** L17703 and Clark, R.T. and S. Brown, 2013: 'Influences of Circulation and Climate Change on European Summer Heat Extremes', *J. Clim*., **26**, 9621-9632

3. Too Cold?

3.1 What has been observed?

Global view: From observational records, IPCC AR5 WGI concluded that it is *very likely* that there are now fewer cold days and nights. There is very high confidence that snow cover extent in the Northern Hemisphere has decreased, by a mean of 1.6% per decade for March and April over 1967 to 2012[17].

UK view: When viewed in terms of long-term averages there are many indicators of warming in the UK. For example, Met Office data shows that wintertime temperature has seen a long-term warming of 0.23°C per decade since 1960 (slightly lower than the 0.28°C per decade in summer)[18]. Also, since 1961 the number of days of air frost in each year in the UK has fallen across the country, by up to 50 days in parts of Wales, Scotland and North West England.[19]

3.2 The cold winter of 2010/11

Severe winter weather affected the UK in winter 2010/11. Figure 3.1 shows that December 2010 was the coldest December for at least 100 years, based on its mean temperature. Across much of the country temperatures regularly fell to between -10°C and -20°C overnight and many places saw temperatures struggling to get above freezing by day. Figure 3.2 shows a map of the mean daily temperature for December, which shows that average temperatures remained below 0˚C for most parts of the country during the month as a whole.

[17] Vaughan, D.G., et al., 2013: Observations: Cryosphere. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
[18] Source: CRUTEM3 data, methodology as cited in Met Office et al., 2011: 'Climate: Observations, Projections and Impacts, UK report', Met Office Hadley Centre, Exeter, UK.
[19] Jenkins, G.J., Perry, M.C., and Prior, M.J., 2008: 'The climate of the United Kingdom and recent trends.' Met Office Hadley Centre, Exeter, UK.

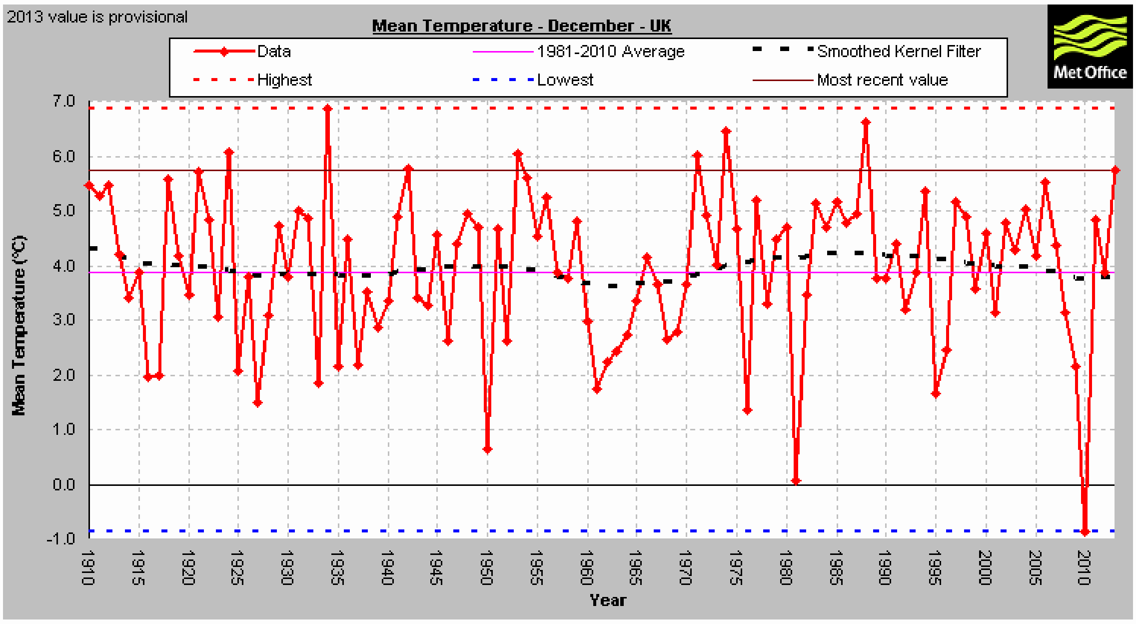


Figure 3.1: Time series of average temperatures (in °C) during December across the UK, 1910-2013. The cold Decembers of 1950, 1991 and 2010 are clearly visible, with December 2010 the coldest based on this measure, with an average temperature below zero.

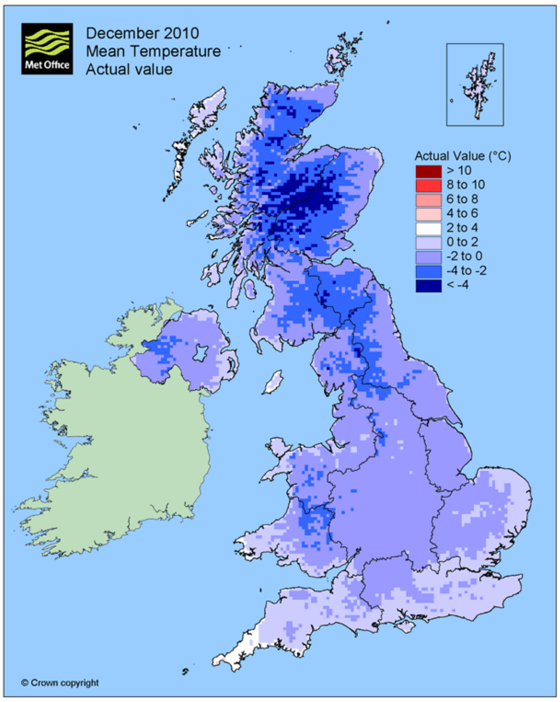


Figure 3.2: Map of the mean daily temperature for December, which shows that temperatures on average remained below 0°C for most parts of the country during the month as a whole.

The freezing conditions caused widespread impacts throughout the UK with the emergency services, local authorities, utilities and transport networks all under pressure. Most significantly for transport was the closure of Heathrow airport for two days. Over the course of the winter thousands of motorists were stranded due to heavy snowfall, and rail services were disrupted. The House of Commons Transport Committee reported

that the travel disruption cost the UK economy £280m per day[20]. As the severe cold came in the run up to Christmas, the UK retail industry was badly affected, with sales at times reportedly down 20 - 30% on the previous year[21]. Overall the severe winter weather was reported as reducing the UK's GDP by 0.5%[20] with some experts speculating it had delayed the UK's economic recovery[22].

The most important pattern of fluctuation of winter weather in Europe affects the jet stream, which steers weather systems over the North Atlantic. The pattern is known as the North Atlantic Oscillation (NAO), which is measured by the NAO index (figure 3.3). When the NAO index is positive, the jet stream is shifted north and positioned over the UK, with a south-west to north-east orientation and the UK experiences mild, wet and windy weather. When the NAO index is negative, the jet stream is shifted south, with a more east to west orientation and the UK experiences cold and dry weather[23].

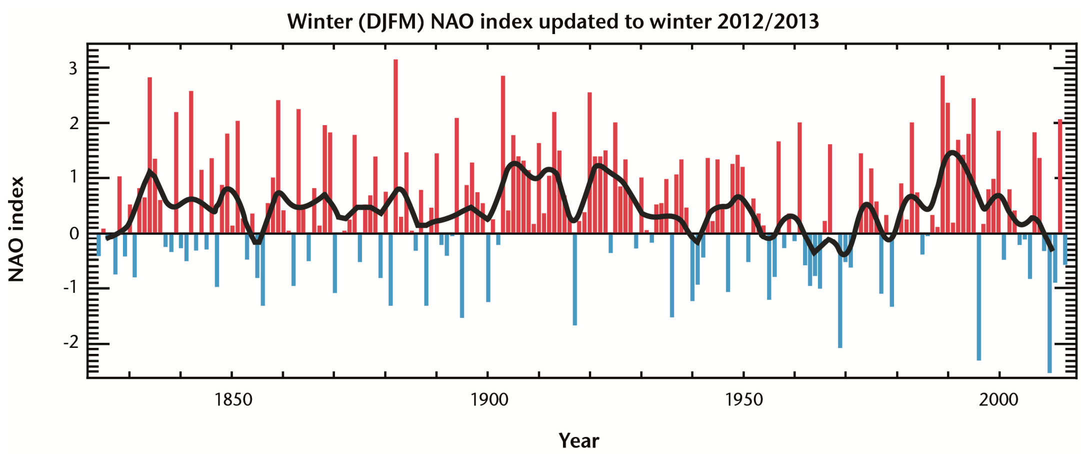


Figure 3.3: Time series of the NAO index in winter (December to March average). Positive values (red) indicate a positive NAO phase and more westerly flow over the UK indicating warmer, wetter weather; negative values (blue) indicate a negative phase and more easterly flow over the UK with colder, clearer weather. The black line is the data smoothed to indicate the decadal variability of the NAO. *Source CRU, UEA.*

The NAO varies due to a range of natural processes in the climate system, including inherent chaos and systematic forcing from the oceans, the stratosphere and from variations in solar heating. As shown in figure 3.3, the winter of 2009/10 had the lowest NAO index on record and saw a persistent shift in the position of the jet stream. In this

[20] House of Commons Transport Committee, 2011: 'Keeping the UK moving: the impact on transport of the winter weather in December 2010', Volume 1, London
[21] Brown, J., 2010: "Economy feels chill as UK grinds to a halt", London: Independent.co.uk., accessed 14th March 2014
[22] Wallop, H., 2010: "UK snow: bad weather costing economy £1bn a day". London: Telegraph.co.uk., accessed 14th March 2014
[23] Hurrell, J.W., 1995: Decadal trends in the North Atlantic Oscillation: Regional Temperatures and Precipitation, *Science,* **269**, 676-679

case the external forcing from the Pacific Ocean, the stratosphere and a reduction in solar output conspired together[24]. The winter of 2009/10 then produced cold surface waters in the Atlantic, which played a role in producing the very cold temperatures during the winter of 2010/11, which is the focus here[25]. The role of climate change in changing the nature of these drivers, for example by changing the sea-surface temperature variations, or altering the ocean currents, is an active area of research in climate science.

One candidate for a role of climate change on the NAO is the influence of the long-term loss of Arctic sea ice on European climate, which has led to a high profile debate in climate science[26]. Some research suggests that the ice loss could predispose the winter and spring atmospheric circulation over the North Atlantic and Europe to negative NAO regimes, and hence cold winters. As yet there is no consensus, however, on the role of Arctic sea ice: the relationship at present is based on correlation, and there is currently no robustly established physical mechanism to explain how retreating Arctic sea ice might exert influence on the jet stream[27].

3.3 How are extreme cold events projected to change in future?

The UKCP09 projections give scenarios for changes to the long-term average UK climate. Winter climate in the UK is projected to continue to warm, by an amount that depends on the levels of greenhouse gases and other pollutants emitted into the atmosphere. As shown in figure 3.4, the UKCP09 projections suggest a central estimate of change in the average daily temperature in winter of between 2°C and 3°C (with a range between 0.8°C - 4.8°C) across most of the country under a medium emissions scenario, with slightly larger changes in the south east and slightly smaller changes in the north west of the country.

[24] Fereday, D. R., et al., 2012: 'Seasonal forecasts of northern hemisphere winter 2009/10', *Environ. Res. Lett., 7*
[25] Maidens, A., et al., 2014: 'The Influence of Surface Forcings on Prediction of the North Atlantic Oscillation Regime of Winter 2010/11', *Monthly Weather Rev.* **141**
[26] Screen, J., et al., 2013: 'The atmospheric response to three decades of observed Arctic sea ice loss', *J. Climate*, **26**, 1230–1248.
[27] 'Wallace, J.M., et al, 2014 :'Global warming and winter weather', *Science*, **343** (6172) pp. 729-730

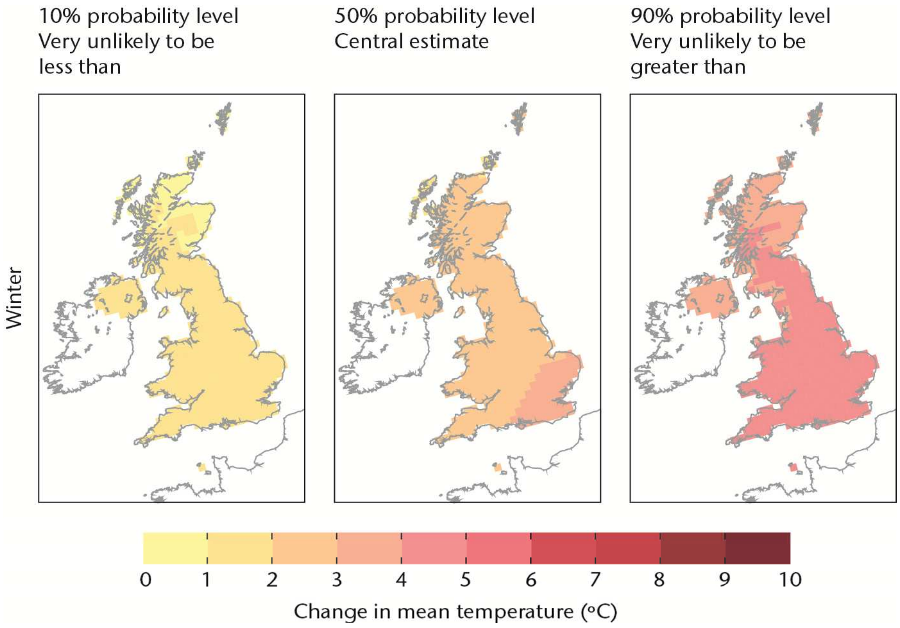


Figure 3.4: 10, 50 and 90% probability levels of changes to the average daily mean temperature (ºC) of the winter by the 2080s, under the Medium (A1B) emissions scenario.

This general trend is expected to decrease the long-term average likelihood of cold winters. However as shown in figure 3.1, there is a substantial natural variability in wintertime temperatures. So whilst when averaged over 30 years winters are expected to warm, very cold individual winters cannot be ruled out. Current research at the Met Office Hadley Centre is analysing the projections used to construct UKCP09 to examine the changing frequencies of different types of UK seasonal weather. Early results suggest that cold winters like 2010/11 are still expected to occur, although with diminishing frequency, interspersed between the warmer wetter winters, to the end of the century[28]. So we should not expect climate change to be expressed as gradual warming of our climate. Rather we should plan for a broader range of climatic conditions: we shall need to remain prepared for the cold winters, but also prepare for the hotter summers.

[28] Sexton, D.M.H. & G. Harris; 2014: ‘The importance of including variability in climate change projections used for adaptation’, in prep.

4. Too Wet?

4.1 What has been observed?

Global view: The accumulation of rainfall over a month or a season is the product of two factors, the number of rainstorms and the amount of rain that falls in each rainstorm. The climate plays distinct roles in these two factors. The number of rainstorms is strongly influenced by the atmospheric circulation and its natural variability, so for example in a positive NAO winter the UK tends to experience more rainstorms. The amount of rain that falls in each storm is expected to change in a warming world. As the atmosphere warms, the air can hold more moisture, at an increase of 6-7% per degree of warming (the Clausius-Clapeyron relation). This increase in moisture is expected to lead, on average, to increased rainfall within rainstorms.

It is difficult to detect trends in rainfall, because the number of storms and the amount of rain in individual storms both vary so much from year to year. Nevertheless, in the Northern hemisphere mid-latitudes (which encompass the UK), where the long-term observations are densest, there is a robust trend of increasing precipitation[4]. Attribution of precipitation trends suggest evidence of human influence at latitudes similar to that of the UK[29].

In thunderstorms with very heavy rainfall, the additional moisture in the air could provide additional latent heat that leads to a stronger thunderstorm and a stronger increase in rainfall. There is evidence from hourly rainfall data from the Netherlands that the amount of rain that falls in very heavy rainstorms increases with temperature at a rate of about double the Clausius-Clapeyron, which supports this idea[30].

UK view: The longest-running UK series of observed rainfall is the England and Wales precipitation record, which catalogues monthly rainfall accumulations since January 1766. The record shows very large year to year and decade to decade variations in rainfall (see below), which makes trends hard to detect. There are suggestions,

[29] Zhang et al., 2007: ‘Detection of human influence on twentieth-century precipitation trends’, *Nature,* 448, 461-465
[30] Lenderink and Van Meijgaard 2008: ‘Increase in hourly precipitation extremes beyond expectations from temperature changes’, *Nature Geosci,* **1**, 511–514. doi:10.1038/ngeo262

however, that the character of daily UK precipitation has changed over the last 50 years. There is evidence that heavy rainfall events may have become more frequent over time[31]: What in the 1960s and 1970s might have been a 1 in 125 day event is now more likely a 1 in 85 day event (see figure 4.1).

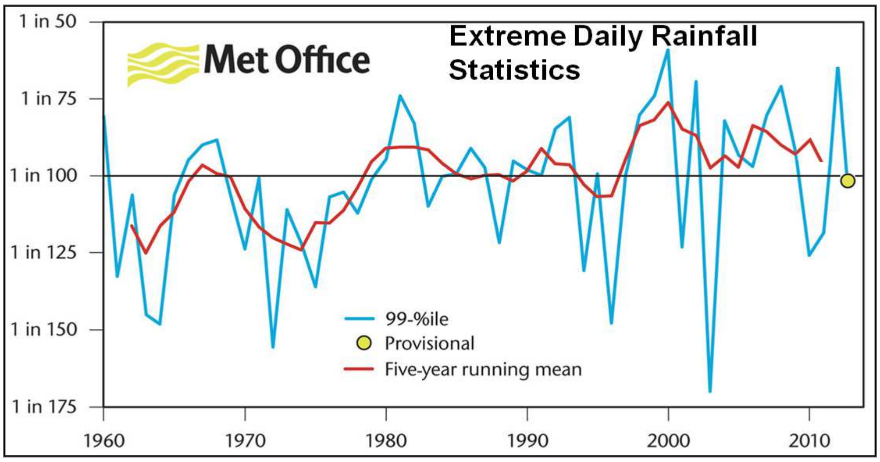


Figure 4.1: Time series showing an increased frequency of occurrence of 'heavy rainfall' events (defined here to be what climate averages tell us should be roughly 1 in 100 day heavy rainfall events in each year). The yellow dot shows the provisional 99th percentile for 2013.

4.2 The wet summer of 2012

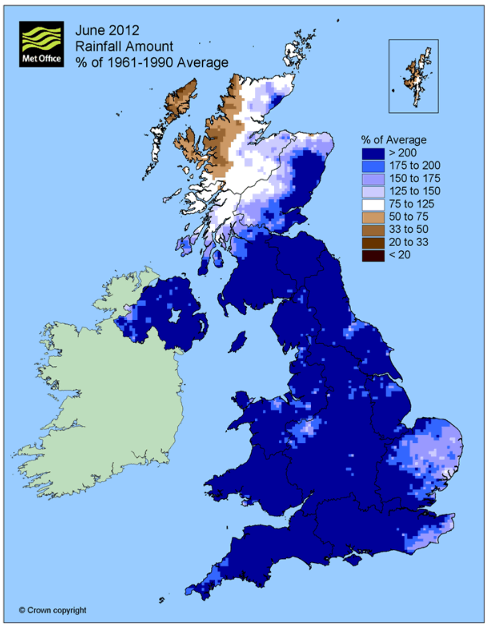
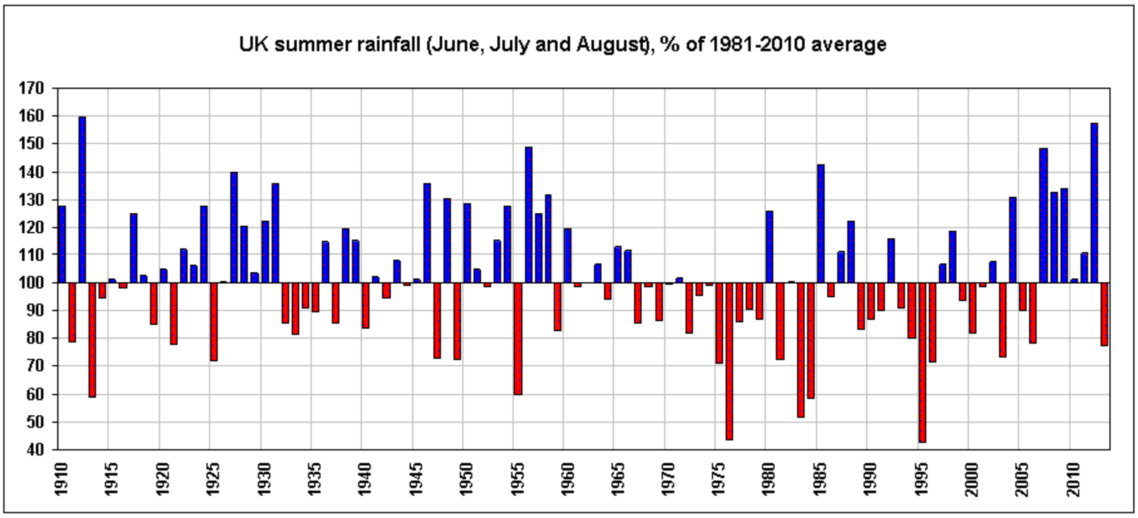


Figure 4.2: UK rainfall accumulation during June 2012 expressed as a percentage of the 1961-1990 average. The dark blue indicates rainfall 200% (i.e. a factor of two) above the average.

A previous Met Office/CEH report has discussed in detail the wet winter of 2013/14 and

[31] Jones et al., 2013: 'An assessment of changes in seasonal and annual extreme rainfall in the UK between 1961 and 2009', *Int. J. Clim,* **33**, 1178-1194 and Maraun et al., 2008: 'United Kingdom daily precipitation intensity: improved early data, error estimates and an update from 2000 to 2006'. *Int. J. Clim* **28,** 833-842

the resulting flooding[1]. And so we discuss here the summer of 2012, which was the wettest summer in the UK since 1912, with much of the UK seeing more than double the average rainfall during June (see figure 4.2).



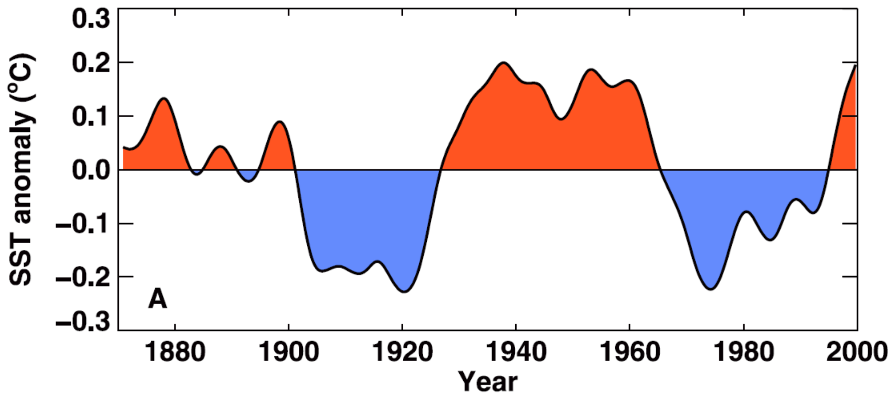


Figure 4.3: Multidecadal variation in the UK summer rainfall and the index of the Atlantic Multidecadal Oscillation. (a) Variation in the UK summer rainfall: time series of rainfall accumulation during UK summers from 1910 to 2013. Rainfall is expressed as a percentage of the average from 1981-2010. Source: Met Office (NCIC). (b) AMO index derived from de-trended area-weighted mean North Atlantic SST anomalies by using a Chebyshev filter with a half-power period of 13.3 years. Source: Knight et al., 2005. SST data are from the HadISST data set: Rayner et al., 2003[32].

Figure 4.3a shows 2012 summer rainfall in historical context. Rainfall is expressed as a percentage of the average from 1981-2010. The figure shows that five out of the last seven UK summers have seen above average rainfall: summers of 2007, 2008, 2009, 2011, 2012 were wetter than average; summer 2010 was average; and summer 2013 was below average. Between the early 1970s and mid 1990s the UK experienced a greater number of drier summers and prior to that from the mid 1930s until the late

[32] Knight, J. T., et al., 2005: 'A signature of persistent natural thermohaline circulation cycles in observed climate', *Geophys. Res. Lett.*, **32**, L20708, doi:10.1029/2005GL024233 and Rayner, N. A., et al., 2003: 'Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century', *J. Geophys. Res.,* **108**(D14), 4407, doi:10.1029/2002JD002670.

1960s the UK experienced a greater number of wet summers. A body of evidence is accumulating that suggests that long-term variations in sea surface temperatures (SST) in the Atlantic Ocean are playing an important role in driving this pattern of UK summer rainfall.

Figure 4.3b shows an index derived from sea surface temperatures in the North Atlantic. The temperatures vary through periods of warmer and colder phases. This variation is known as the Atlantic Multidecadal Oscillation (AMO), which varies on cycles of a few decades: the temperatures were cold during the early part of the 20th century and during the 1970s through to the 1990s, and the temperatures were warm during the 1930s to the early 1960s, and have been warm since the mid 1990s.

When we compare figures 4.3a and 4.3b we see a striking relation between the warm phases of the AMO and a greater tendency for wetter summers in the UK, and the cold phases of the AMO and a greater tendency for drier summers in the UK[33]. The pattern of rainfall variation extends beyond the UK, and when we experience wetter summers in the UK the Mediterranean region experiences drier summers[34].

Analysis of observations and model simulations suggest that warm sea surface temperatures, particularly in the northern part of the Atlantic Ocean[33], during warm phases of the AMO are associated with a shift in the jet stream, and therefore also the number of rain-bearing weather systems, onto the UK. This pattern matched the pattern seen in summer 2012 and many of the other years since 2007.

There is evidence linking these swings in the AMO index to the "meridional overturning" or "thermohaline" circulation of the Atlantic. Reconstructed estimates of this circulation suggest it intensified in the 1990s[33]. These variations in the AMO are thought to be consistent with a natural mode of climate variability, and an important topic for climate science research is to determine the physical mechanisms behind the shifts in the AMO and the degree to which they are predictable. The new generation of models that have been developed at the Met Office Hadley Centre are designed to investigate these questions. Critical observations such as from the NERC-funded "RAPID" array[35] in the

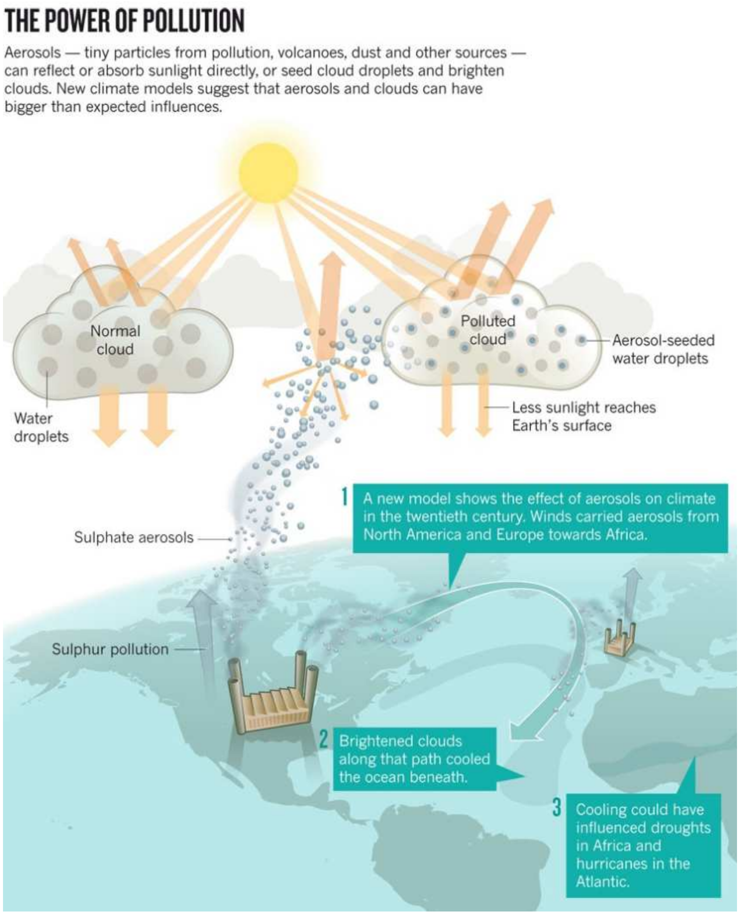
[33] Knight, J. T., et al., 2005: A signature of persistent natural thermohaline circulation cycles in observed climate, Geophys. Res. Lett., 32, L20708, doi:10.1029/2005GL024233 and Sutton, R and B. Dong, 2012: Atlantic Ocean influence on a shift in European climate in the 1990s', *Nature Geosci,* **5**, 788-792

[34] Bladé, I., et al., 2011: 'Observed and simulated impacts of the summer NAO in Europe: implications for projected drying in the Mediterranean region', *Clim Dynam*, **39**, 3-4. DOI:10.1007/s00382-011-1195-x

[35] National Environmental Research Cooncil : RAPID project homepage, accessed March 12th 2014

North Atlantic should help us to understand better the role of Atlantic Ocean circulation in climate, but it is a challenging problem and advances may take some years.

A second important question is whether human influence on climate is affecting this natural mode of variability. Recent modelling at the Met Office Hadley Centre[36] suggests that human emissions of aerosols (small particles of pollution associated with industrial processes, such as burning fossil fuels) can influence the phase of the AMO (see figure 4.4). Aerosols can brighten clouds and so reduce the sunlight reaching the ocean surface. When the aerosol influence decreases this brightening effect decreases, leading to a greater amount of shortwave radiation reaching the planet's surface and warming the North Atlantic. This variation in aerosol was shown by Met Office research to correlate with changes in the phase of the AMO. The strength of this physical effect, and so also the strength of aerosols on UK summer rainfall, is uncertain and a topic of active research.



[36] Booth, B., et al 2012: 'Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability', *Nature*, **484**, 228-232

Figure 4.4: Schematic of the potential influence of human emitted aerosols on sea surface temperatures in the Atlantic[37]. Source: *Nature*

4.3 How are rainfall events projected to change in future?

The overall trend given in UKCP09 is for winters to become wetter and summers drier. But, just as with cold winters, this does not mean that a very wet summer or very dry winter will not occur at all, only that their likelihood is expected to fall over time. Further analysis of the UKCP09 projections is being conducted at the Met Office Hadley Centre to see better what they can tell us about the changing likelihood of future wet and dry extremes.

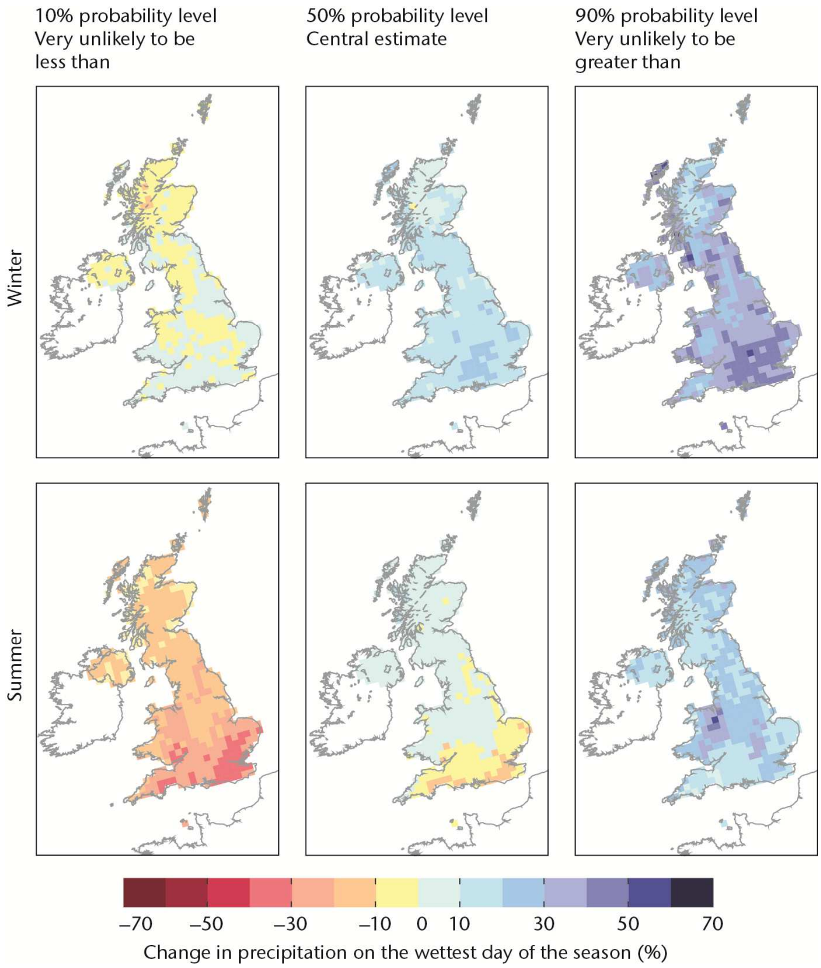


Figure 4.5: Changes to precipitation on the wettest day of the winter (top) and of the summer (bottom) at the 10, 50 and 90% probability levels, for the 2080s under the Medium (A1B) emissions scenario.[38]

[37] Tollefson, J., 2012: 'Climate Forecasting: A break in the clouds'. Nature, **485**, 7397
[38] Murphy, J.M. et al., 2008: 'UK Climate Projections Science Report: Climate change projections', Met Office Hadley Centre, Exeter. The change in the 'wettest day' is calculated from the change in the 99th percentile of daily precipitation in a season.

As shown in figure 4.5, under the medium (A1B) emissions scenario, the wettest days in winter are projected to become wetter on average. There is no clear signal for how the wettest days in summer may change. Projecting changes in summer rainfall is more complicated than for winter. Firstly, long-term fluctuations associated with the AMO contribute to the variability. Secondly, much summer rainfall in the UK comes from convective rainfall systems, whereas winter rainfall comes more from larger, frontal weather systems. Current research at the Met Office Hadley Centre is investigating the changes to winter and summer rainfall with a new regional climate model that represents the convective rainfall systems more faithfully. This new model should assess better the effects of rainfall from thunderstorms increasing faster than the Clausius-Clapeyron relation (discussed in section 4.1), which will provide more robust estimates of future rainfall change in the UK.

5. Too Dry?

5.1 What has been observed?

Global view: The amount of water at the ground and in the soil changes because of precipitation, which tends to moisten the ground, and evaporation, which tends to dry the ground. As discussed in section 4.1, rainfall is expected to increase in a warming world. But evaporation is also expected to increase in a warming world, because evaporation drives the air humidity towards its saturated value, and the saturation value increases with temperature (again according to the Clausius-Clapeyron relation). The ground and soil tend to dry out when evaporation exceeds precipitation. So the effect of climate change on the tendency to dry the surface and the soil and cause drought is a delicate balance between the increase in rainfall and the increase in evaporation. IPCC AR5 WGI assigned 'low confidence' to whether a global trend in drought is being seen, due to lack of agreement in the literature arising from different metrics of drought.

UK view: There are many droughts in the UK's historic record. However, the key characteristics of *duration*, *area extent* and *intensity*, which play a strong role in their impact, vary. Some droughts occurred over one or two winter seasons, whereas others were most intense during the summer, coinciding with heat waves. The 1975-76 drought was the most significant for at least the last 150 years in the UK, and is usually regarded as a benchmark against which all other droughts are compared. Forest fires in Southern England destroyed trees and millions of pounds worth of crops were reported to have been lost to the drought. Widespread water rationing took place, with public standpipes in some areas[39].

5.2 The Texas heat wave and drought of 2011

The Government Office for Science report on 'International Dimensions of Climate Change' found that 'the consequences for the UK of climate change occurring in other parts of the world could be as important as climate change directly affecting these shores'. So here we take an example of a drought overseas that had a significant impact on the global economy and consequently the prices on UK supermarket shelves.

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[39] BBC, 2009; Features: The drought of 1976, accessed March 10th 2014

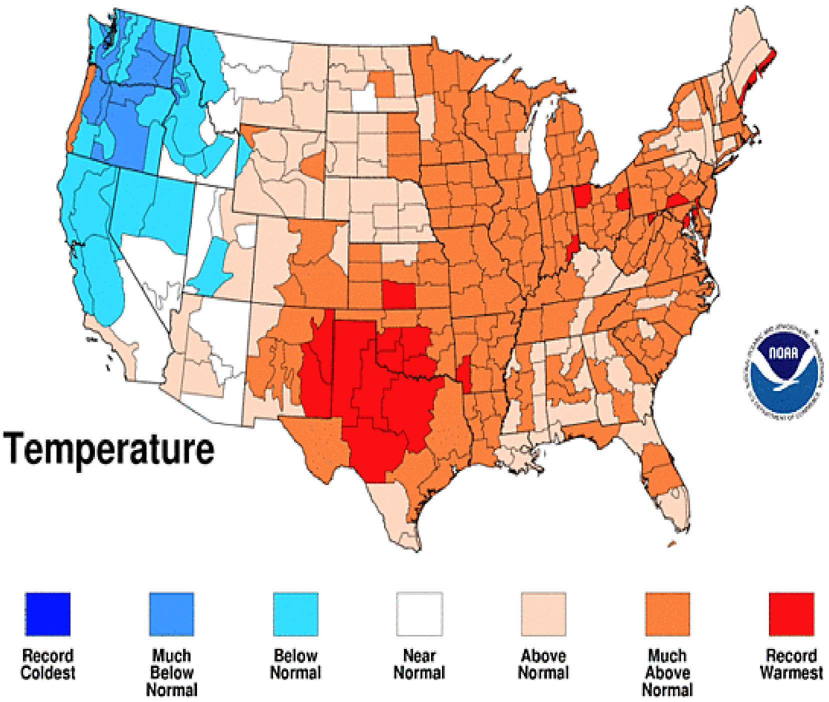

Figure 5.1: Map classifying temperatures across the U.S.A into above and below normal categories during the Texas heat wave of July 2011. *Source: NOAA*

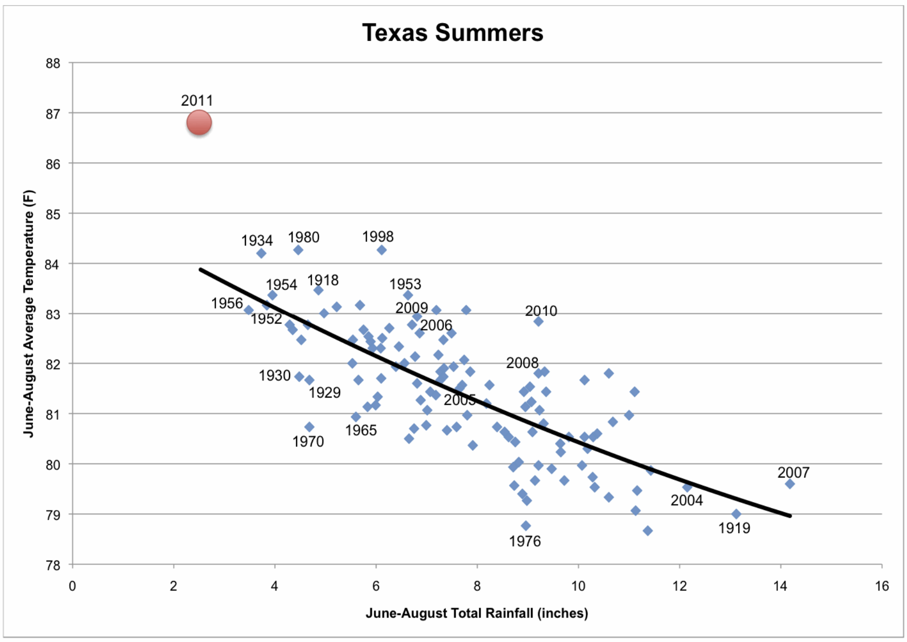

Figure 5.2: Relationship between rainfall and temperature during summers in Texas. The summer of 2011 stands well outside the trend of other years, because the low rainfall and high temperatures caused soils to dry out and temperatures to rise dramatically.

As shown in figure 5.1, the state of Texas experienced an extraordinary heat wave and drought in 2011, with the spring and summer both the hottest and driest in the 116-year record. The record temperatures were driven in part by the remote consequences of the La Niña phase of ENSO. A transition from moist to dry soils was probably also important: figure 5.2 shows the relationship between precipitation (which moistens the soil) and temperature. Most years lie on a trend, with higher temperatures for lower precipitation. 2011 stands alone, and the soil drying mechanism discussed in section 2.2 was probably an important factor. For most of years other than 2011 the soil probably retained some moisture, which kept temperatures lower. During 2011 the soil totally dried out, giving the drought, which then meant all of the available energy went into heating the air, adding substantially to an already hot event.

An attribution study found that human emissions of greenhouse gases increased the odds of such high temperatures in the mid-US during a La Niña year[40]. A one in 100 year temperature event in the 1960s during a La Niña year has become a one in five- or six- year event during a La Niña year for the Texas region today. This study did not attempt to quantify the effect of climate change on ENSO and hence the results are conditioned on La Niña year.

The impacts of the drought were severe, both at a local level and on the national and global economy. On average, Texas reportedly produces 55% of U.S. cotton. 50% of the crop was reported as lost to the 2011 drought[41]. As the majority of U.S cotton is exported to mills overseas for textiles and clothing, the diminished supply caused costs of cotton-fabric goods to surge[42]. In February, before the worst of the drought hit, herders were already selling cattle feed much earlier than normal, as there was little grass for the cattle to eat. The United States Department of Agriculture was reported as stating that retail-beef prices were 9.4% higher in February 2011 than at the same time a year earlier[43]. In 2011 the global food price index rose by nearly 42 points compared to 2010.[44] Global weather patterns and events like the Texas drought of 2011, might have contributed to this rise. Events like that of the 2011 Texas drought show how anthropogenic climate change could be increasing the risk of economic cost in the UK,

[40] Peterson, T. C., P. A. Stott and S. Herring, 2012: 'Explaining Extreme Events of 2011 from a Climate Perspective', Bull. Amer. Meteor. Soc., **93**, 1041–1067
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[43] McFerron, W. and E. Campbell, 2011: 'Worst Texas Drought in 44 Years Damaging Wheat Crop, Reducing Cattle Herds', Bloomberg News, accessed March 13th 2014
[44] Source: FAO

even when the country is not affected by extreme weather itself.

6. Conclusions

So what can we say about the role of climate change on seasonal weather in the UK? The UK has seasonal weather that varies hugely from year to year due to natural processes. Nevertheless, human influence has been detected in the hot temperatures experienced in Europe during the summer of 2003, and there are signs that the character of rainfall has shifted in the last 50 years with slightly more heavy rainfall events, consistent with a warmer atmosphere holding more water. Other seasons, such as the cold winter of 2010/11 and the wet summer of 2012, appear to be associated with natural fluctuations in the UK's varied climate. So although the overall trend for the UK is for winters to become milder and wetter, we shall still need to plan for cold winters like the one we experienced in 2010/11. And, although the trend for the UK is for summers to be hotter and drier, we shall still need to plan for wet summers like 2012.

While the role of human influence on temperature extremes can be detected, more research is urgently needed to deliver robust detection of changes in storminess and daily/hourly rain rates. The attribution of these changes to anthropogenic global warming requires climate models of sufficient resolution to capture storms and their associated rainfall. Work is underway at the Met Office Hadley Centre to deliver robust detection of changes in storminess and daily/hourly rainfall rates and to project how extreme rainfall rates are expected to change in the UK in the future.

Current research is also investigating the role of human influence in shifting the otherwise natural variability of the climate. For example, in the case of the summer 2012 the role of aerosols (small particles of pollution) in shifting the natural fluctuation is being investigated.

These topics are substantial scientific challenges but new observing systems and higher resolution computational models of the climate system coming online now are providing new insights that promise progress and the continuing improvement of UK adaptation advice.

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Table 2: Details of notable seasons 2003 - 2013 and their key impacts

Event	Contributing factors	Key Impacts
Autumn 2011 *Second warmest November since records began in 1659*	Research ongoing into improving the understanding and representation of summertime dynamics in climate models. **Likelihood of occurrence increased by climate change:** Warm November UK temperatures are now about 60 times more likely than in the 1960s[1].	**Tourism:** The warm autumn was reported to have increased visitor numbers at UK attractions and numbers of holiday makers around parts of the UK[2]. **Retail:** Negative effects were reported for UK clothing retail, as sales for winter clothing decreased compared to the average for the time of year[3].
Summer 2003 *Record-setting heat wave that affected large parts of Europe. UK affects were greatest in the south east*	Research ongoing into the role of the summer NAO on the incidence of heat waves. Focus is on improving predictability of such events on a decadal scale by improved understanding and representation of the Atlantic Multi-decadal Oscillation (AMO), strongly suspected to influence European summer rainfall, in climate models. **Likelihood of occurrence increased by climate change:** Human influence has very likely at least doubled the probability of European summer temperatures as hot as those in 2003[4].	**Health**: Excess UK deaths of ~2000,[5] 30% of the total occurred in London[6]. The heat wave was associated with a short-term increase in emergency hospital admissions[7]. Heat wave plan for England created. **Transport**: Speed restrictions imposed on UK railways to prevent track buckling. Cost of road repairs in Oxfordshire alone as a consequence of roads buckling reportedly estimated at £3.6 million[8].

Event	Contributing factors	Key Impacts
Spring 2013 *Cold and snowy start to Spring, with the second coldest March in the UK record since 1910*	March 2013 was associated with a negative phase of the NAO which leads to the prevalence of easterly winds and cold conditions over the UK. A number of potential drivers may predispose the climate system to negative NAO states in early spring; weather in the tropics, the Stratosphere, conditions in the North Atlantic and the state of the Arctic[9]. Whilst the cold March 2013 weather was remarkable when set in the context of increasingly mild springs over the last few decades, it was not unprecedented or outside the expected natural variability of our climate. More work is needed to determine the exact roles of these modes of natural variability and the influence of long-term decline in Arctic sea ice extent on spring weather.	**Energy**: Thousands of people were reportedly left without power in Scotland[10] and parts of Devon and Cornwall which saw significant flooding. **Agriculture**: The timing of the snow was particularly difficult for the livestock sector as it coincided with the lambing season. According to the NFU 64,000 more animals died on farms in England, Scotland and Wales between January and April 2013 than during the same period in 2012[11].
Winter 2010/11 *Most widespread and prolonged cold and snowy spell since winter 81/82. December 2010 coldest in over 100 years[12]*	Met Office research shows that cool sea surface temperatures in the Atlantic helped to drive low temperatures over the UK[13]. **Likelihood of occurrence decreased by climate change:** cold December temperatures like 2010 are about half as likely now as they were in the 1960s[14].	**Transport**: Disruption to transport alone cost the UK economy £280 million per day[15]. **Retail**: As the severe cold came in the run up to Christmas, the UK retail industry was badly affected, with sales at times reportedly down 20 - 30% on the previous year[16].

Event	Contributing factors	Key Impacts
Winter 2013/14 *Wettest winter in England and Wales for at least 248 years*	Met Office research[17] shows that the storms were part of a global pattern, with major perturbations to the Pacific jet stream driven in part by rainfall patterns in Indonesia and the topical west pacific. The North Atlantic jet was unusually strong, which can be linked to exceptional wind patterns in the stratosphere with a very intense polar vortex. As yet, there is no definitive answer on the possible contribution of climate change to the winter 2013/14 storminess or rainfall amounts. Nevertheless, there is an increasing body of evidence that extreme daily rainfall rates are becoming more intense, and that the rate of increase is consistent with what is expected from fundamental physics. There is no evidence to counter the basic premise that a warmer world will lead to more intense daily and hourly heavy rain events.	**Insurance:** Loss prevention experts reported that the cost of clear-up could cost insurers £1 billion by April 2014[18]. **Transport:** Damage to the railway in Devon caused the main line between Devon and Cornwall to close. The cost of the closure to the regional economy is yet to be determined but likely to be substantial. **Energy:** The Energy Networks Association was reported stating that in the second week of February 2014 alone 900,000 people experienced power cuts[19].
Summer 2012 *Wettest summer since 1912 for UK overall*	The months April and June were each the wettest on record in the England and Wales precipitation series from 1766, while for the UK overall summer 2012 (June, July, August) was the wettest since 1912. There is evidence that the warm phase of the AMO favours wetter summers and autumns over the UK[20]. It should be noted though that the AMO is only one factor in determining conditions. More work needs to be done to see exactly how the AMO links to summer rainfall and how we can predict its influence on future seasons. Higher resolution models, coming on line now, and sufficient computing capacity, are needed to capture and model the changing frequency of such conditions.	**Business**: Floods in 2012 cost businesses in England up to £200 million (£84 million in property damage). Indirect impacts – such as lost working days - was estimated to have cost the local economy up to £33 million[21]. **Infrastructure**: Overall 7,950 properties were flooded in 2012, and the floods estimated to have cost the UK economy close to £600 million[22]. Over 230 homes were flooded in Devon over one weekend in Summer 2012. Overwhelming of the sewage works by the sheer volume of water also created a significant health risk.

Event	Contributing factors	Key Impacts
Dry 2010-2012 *Two drier than average winters and dry springs culminated in drought for large swathes of the UK in 2012*	A number of factors likely acted together to predispose the climate system to a negative NAO state in the springs of 2011 and 2012; La Nina forcing from the Pacific, solar variability and stratospheric influences[19] Work led by the Met Office suggests that early breakdown of the polar vortex during the transition from winter to summer circulation may pre-dispose the Euro-Atlantic sector to negative NAO patterns in April and therefore anticyclonic and dry conditions[23]. Neither the development nor the severity of the drought was exceptional compared with historical events. As yet, there is no evidence that this drought wasn't part of the natural variability of the climate system.	Spring 2011 was the warmest in 100 years and April 2011 was the warmest on record. **Ecosystem:** Both spring 2011 and 2012 saw forest and moorland fires across many parts of the country due to the parched ground[24]. **Water:** In Spring 2011 areas of East Anglia were declared in drought, with other parts of the country in a 'near drought' state. By 2012, 20 million UK homes were subject to hosepipe bans[25]. Low farm reservoirs also affected the ability to grow crops. **Retail:** it was reported that sales figures for March showed a surprise rise of 0.2%, which analysts attributed to the prolonged dry weather[26].
Summer 2006 *Heat wave and drought that saw the hottest July temperature on record over much of the UK*	As the largest impact of summer 2006 was drought, it is classified here however, 2006 also saw a significant heat wave, sharing similarities with that experienced in summer 2003. More work is needed to determine the role and drivers of the NAO that lead to hot, dry conditions. Questions are particularly around whether, through its influence on winter rainfall, the winter NAO can predispose Europe to hot and dry summers. More investigation is needed to determine whether an increase in interannual temperature variability in response to greenhouse gases may be one mechanism for the occurrence of European summer heat waves.	**Water:** Demand rose, while levels continued to fall. Severn Trent Water was reported saying consumption in its area had rose by 200 million litres per day - the equivalent of supplying 800,000 extra people[27]. The first drought order in 11 years was granted, banning the non-essential use of water in the south east[28]. **Transport:** It was reported that gritters were being used to protect road surfaces as the asphalt began to melt. Heat caused railway lines to buckle in the Midlands, stopping service. Speed restrictions were put in place on the West Coast Main Line. **Workplace:** Unions were reported calling for a change in the law to create a maximum working temperature[29].

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Errata

Executive Summary
'There is evidence to suggest that the character of UK rainfall is changing'
This has been corrected to: 'There is evidence to suggest that the character of UK rainfall has changed'

'The role of human influence on our climate is already detectable on summertime heat waves and on the character of UK rainfall'
This has been corrected to: 'The role of human influence on our climate is already detectable on summertime heat waves and on the character of rainfall'

Section 2.2
'The simulations indicate that by the 2040s more than half of summers in Southern Europe will be warmer than 2003'
This has been corrected to: 'The simulations indicate that by the 2040s more than half of summers in Europe will be warmer than 2003'
And
'...the evidence suggests that by the 2040s more than half the summers in Southern Europe will be warmer than 2003…
This has been corrected to: '…the evidence suggests that by the 2040s more than half the summers in Europe will be warmer than 2003'

Reference 28
Sexton, D.M.H. & G. Harris; 2014: 'More informative climate projections through the use of shorter averaging periods', in prep.
This has been corrected to: Sexton, D.M.H. & G. Harris; 2014: 'The importance of including variability in climate change projections used for adaptation', in prep.

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