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Trends in the weather and climate of the UK:

Evidence from observations

21st June 2013

Executive Summary

Introduction:

This report has been prepared by the Walker Institute at the University of Reading to assess whether recent UK weather patterns fit with known trends of increased temperature, precipitation, and extreme weather events affecting the UK climate and what they may indicate looking forward for the next three to five years. We explain at a high level the mechanisms supporting these trends and also offer an initial view whether they are in line with predictions of long term man made climate change and how they are also partly attributable to other short to medium term (decadal) trends representative of natural climate variability (such as variations in position of the North Atlantic jet stream).

Additionally we comment of the findings of recent research looking at the linkages between known meteorological features affecting the UK climate and assess whether they can be attributed to man-made climate change.

Key message:

In summary, it is clear that the UK has become wetter over the past decade and rainfall events have become more intense. We find these changes to be driven both by natural year-to-year (and decade-to-decade) climate variability and long term (centennial) anthropogenic greenhouse gas emissions. The recent decade in the UK has included some of the most extreme weather on record and at this stage there is little evidence to suggest such a pattern will be broken in the near term. We summarise the recent data statistics and trends later in the paper, and it is clear that we are currently in a period of increased weather volatility and this pattern is likely to persist for the remainder of 2013 and for some time beyond. Increased local variability in weather patterns can be expected to be observed both geographically across the UK and in terms of seasonal variations with increases both in absolute terms (eg higher average UK rainfall) and in individual peak events (eg record temperature, rainfall events etc.). In summary we see the short term (three to five year) outlook as follows: *

		Spring	**Summer**	**Autumn**	**Winter**
Rainfall	**Mean**	Normal	Normal*** (see note)	Normal to wet	Wet
	Extreme	Enhanced	Enhanced	Enhanced	Enhanced
Wind	**Mean**	Normal**	Normal**	Normal**	Normal**
	Extreme	Normal**	Normal**	Normal**	Normal**
Temperature	**Mean**	Normal to warm	Normal to warm	Normal to warm	Normal to warm
	Minimum	Small increase	Small increase	Small increase	Small increase
	Maximum	Small increase	Small increase	Small increase	Small increase

* Expected conditions relative to1971-2000. Major assumptions: (1) No major shifts in North Atlantic sea surface temperature (see Section 2.1.3 &2.1.4 for details). (2) No major changes in aerosol (e.g. from a volcanic eruption) or greenhouse gas concentrations. (3) Constant solar output.

** Normal, however significant year to year volatility can be expected in response to the North Atlantic Oscillation (see Section 3.4 for details).

*** Long term trends (30 to 100 years) indicate a shift to drier summers. However, the influence of the North Atlantic Ocean at decadal scales (10 to 20 years) has tended to favour wetter than average summers in recent years (see Section 2.1.3 for details). The net effect is neutral but volatility can be expected c.f. 2006 (worst groundwater drought in SE England since 1976, hottest summer in 234 year record) and 2012 (wettest summer in 100 years).

Key findings:

Rainfall:

- Thermodynamic arguments suggest that in a warmer world, as expected from greenhouse gas emissions, contributions to precipitation from extreme (heavy) rainfall events will increase. This is supported by observations. All regions of the UK have experienced an increase over the past forty five years in the contribution to winter rainfall from heavy precipitation events.

- Recent wet summers and unseasonal weather patterns in the UK and Northern Europe are partially attributable to unusually warm sea surface temperatures in the North Atlantic, leading to an anomalous position of the jet stream. The observed long term pattern of variation in sea surface temperature known as the Atlantic Multidecadal Oscillation (AMO) can cause these climatic conditions to remain in place for many years or decades. It is expected that a reversion to drier summers in the UK will take place at some stage in line with longer term climate change predictions but it is not known with certainty when this will occur. The AMO is covered in more detail in Section 2.1.3, 2.1.4 and in the attached Annex: Atlantic Multi-decadal Climate Variability..

- Analysis of recent weather statistics highlights these underlying trends and the evidence of increased variability:
    - Four out of five of the wettest years on record for the UK have occurred since the year 2000.
    - The months of April and June 2012 were the wettest in the history of the England and Wales rainfall series from 1766.
    - Summer 2012 (June, July, August) was the wettest since 1912.
    - 2013 was the coldest spring in over 50 years.
    - However, in the context of the climatic drivers, these conditions can be considered to be closer to normal than exceptional for the current decade.

Windstorms:

- Storminess over the UK is related to changes in the North Atlantic Oscillation (NAO) (see Section 3.4). The NAO is an atmospheric phenomenon and can switch phase quickly, thus year to year and decade to decade volatility can be expected.

- However climate data shows severe windstorms (with gusts > 60 mph) around the UK have become more frequent in the past few decades and significantly above levels seen throughout most of the last century, although not above that seen in the 1920s.

Temperatures:

- Summer maximum temperatures have increased by 1 to 2^{o}C and winter minimum temperatures have increased by approximately 1^{o}C over the period 1961-2006.

- The number of frost days has reduced from 50-90 days per year (depending on region) to 30-70 days per year for the same regions over the period 1961-2006.

- Higher temperatures are expected as a consequence of greenhouse gas emissions. The natural decadal and multi-decadal cycles described above that are modulating precipitation and windstorms are currently working to supress temperatures. Current climate predictions suggest that these cycles will reverse at which point increases both in average temperature and temperature extremes can be expected to become commonplace in the UK (See Section 4).The timeframe for reversal to occur remains uncertain, however, reversal by 2020 is feasible (Keenlyside, Latif et al. 2008).

Contents

1 Introduction

In this report we address the subject of meteorological hazards and likely patterns of climate variables and extreme events for the UK. We address the following key questions:

- What are the major trends in UK weather patterns?
- What are the underlying drivers behind these changes?
- What is the likely outlook for the next three to five years?

The report is structured by meteorological hazard: Precipitation, windstorms, and temperature. However, it should be noted that these are not independent (e.g. wind will often occur with rain, drought with high temperatures etc.). The analysis of trends in such 'combined perils' is beyond the scope of the present work.

In assessing the likely impact of climate change on weather in the UK, it is useful to consider meteorological risk in the wider context of natural hazards. The environment of the UK, whilst generally benign, exhibits a range of disruptive behaviours. Notably, floods, droughts, wind storms, tornados, heatwaves, cold snaps, earthquakes, and epidemics of disease. The majority of these are directly attributable to the weather.

This can be seen from Figure 1-A which illustrates the relative frequency of natural catastrophes in the UK by type since 1850. Floods events are the most common and occur with almost twice the frequency as droughts or wind storms. Extremes of temperature lead to occasional impacts, however, the risk of disruption based on historical data is low. Non-meteorological hazards pose an even lower risk.

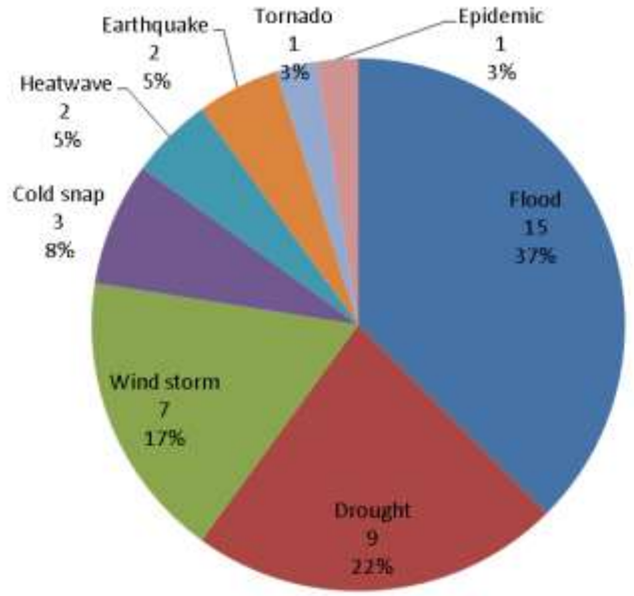

Figure 1-A Notable UK natural catastrophes by type, number and percentage from 1850 to 2012. [Source data from (Marsh, Cole et al. 2007; Wikipedia 2013)]

However, the summary statistics of Figure 1-A conceal large variations in the rates at which the events occur and their timing.

Figure 1-B provides a timeline of UK natural catastrophes by type and year from 1850 to 2012. Particularly striking is the apparent clustering of flood events over recent years: nine out of the fifteen recorded major floods have occurred since 1998. Such is the level of concern that the UK Met Office recently convened a workshop of experts to discuss the recent run of unusual seasons (Met Office 2013a).

The prevalence of major windstorms also appears to have increased in recent decades. Finally, although the numbers are small, there is some indication of a shift in temperatures from cold to warm extremes.

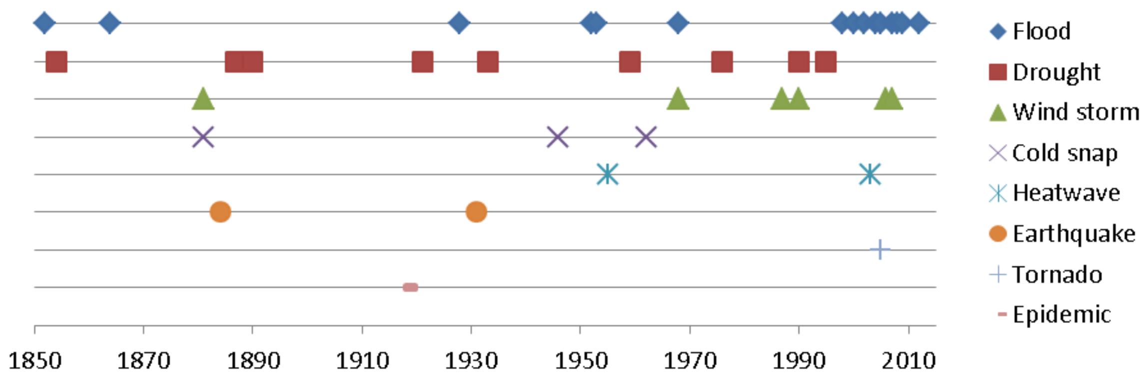

Figure 1-B UK natural catastrophes by type by year from 1850 to 2012. [Source data from (Marsh, Cole et al. 2007; Wikipedia 2013]

These summary statistics are in line with known climatic trends and this report looks in more detail at these major meteorological hazards and likely drivers. The following terminology is used throughout the report:

Climate
Climate is typically defined as the average weather (or more rigorously a statistical description of the average in terms of the mean and variability) over a period of time, usually thirty years. These quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.

Weather
Weather refers to the state of the atmosphere at a particular moment in time with regard to temperature, cloudiness, rainfall, wind, and other meteorological conditions.

Trend
The relatively constant movement of a climate variable (e.g. mean annual rainfall) throughout a period of time. The period may be short-term or long-term, depending upon whether the trend itself is short-term or long-term. A distinction will be made between short-term ‘decadal scale’ trends of the order of a few tens of years and longer-term ‘anthropogenic or human induced climate change’ which implies trends of the order of a century or more.

Variability
The erratic movement of a climate variable throughout a period of time.

Spatial and temporal scales

The UK climate varies on a large range of spatial and temporal scales. Spatial scales range from local (less than 1,000 km^2) through country wide (250,000 km^2). Temporal scales range from daily to seasonal to annual to centennial.

2 Hydrological extremes

2.1 Precipitation

2.1.1 Rain, hail and snow

Precipitation in the UK can fall either as liquid water or frozen in the form of hail or snow. All forms can lead to significant disruption. The main focus of this report is on rainfall leading to flooding but the possibility of increased snowfall should not be discounted.

(a) Variations in space

The complex terrain of the UK means that precipitation exhibits considerable geographical variability. This is illustrated in Figure 2-A which is a map of the average annual rainfall expected of the UK based upon measurements from 1971 to 2000.

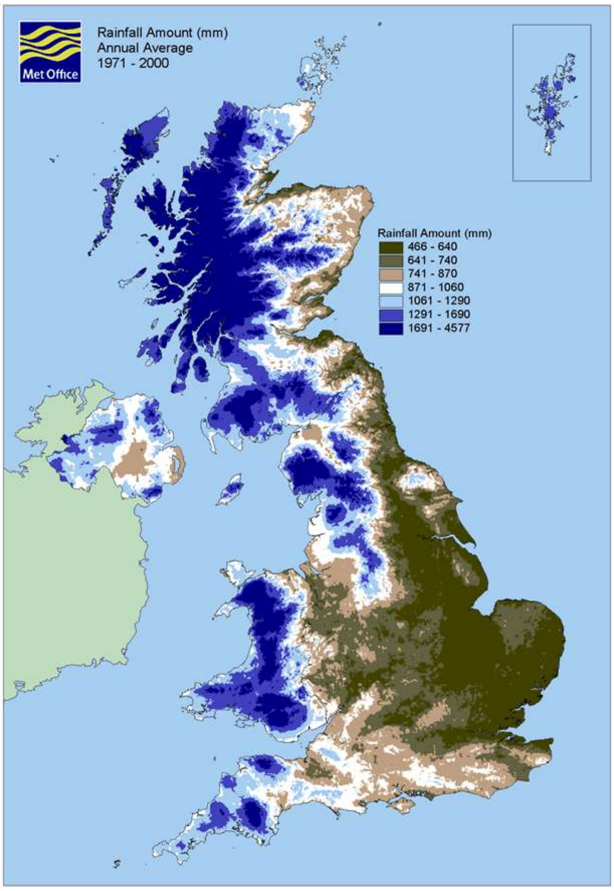

Figure 2-A Map of average UK annual rainfall based upon measurements from 1971 to 2000. [Source: Met Office, Crown Copyright]

These strong regional variations mean that it is difficult to compute meaningful summary statistics for the UK as a whole. This is important since naïvely averaging across large regions of the UK (e.g. the summer panel of Figure 2-C) may cause regions of positive and negative trend to cancel out and thus lead to a false sense of security with regard to weather variability.

Individual years and seasons will show variability by region, and as discussed in this report we expect such variability to increase and become more extreme due to both long term climate change and nearer term decadal factors.

(b) Variations in time

Precipitation over the UK also exhibits considerable temporal variations. This is illustrated by Figure 2-B which is a time series plot of annual England and Wales Precipitation (EWP). The EWP series is based on weighted averages of daily observations from a network of stations in five regions. It is the longest instrumental series of this kind in the world.

Decadal scale variability complicates the assessment of long term trends since the length of period used to assess the trend will greatly affect the result. This can be seen from the different slopes of the green, orange and red lines in Figure 2-B which show linear trends computed using different time periods.

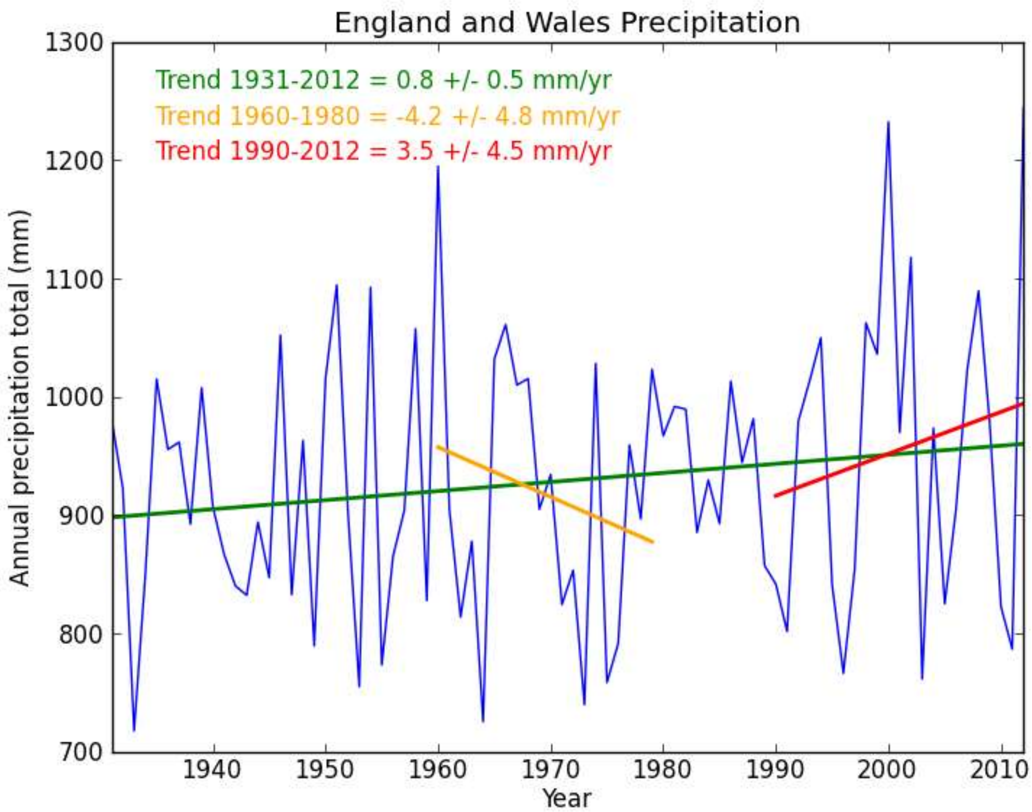

Figure 2-B Time series of annual England and Wales Precipitation (EWP). The blue line represents the annual total precipitation for each year from 1931-2012. The green, orange and red lines show linear trends computed using different time periods. [Source: Ben Lloyd-Hughes, University of Reading]

These show a clear long term trend of increased precipitation from 1931-2012 and another upturn in averages over recent years from 1990-2012. We examine the details and possible reasons underpinning these ‘long’ and ‘short’ term trends in more detail in Sections 2.1.2 to 2.1.4 below.

2.1.2 Long term trends 1961-2006

Spatio-temporal complications aside, the UK Department for Environment, Food and Rural Affairs (DEFRA) performed a comprehensive review of observed trends in UK weather as part of the UK Climate Projections (UKCP09) program. Based on data for 1961-2006, it can be stated with a reasonable degree of confidence that:

- All regions of the UK have experienced an increase over the past 45 years in the contribution to winter rainfall from heavy precipitation events; in summer all regions except north east England and north Scotland show decreases.

- There has been an increase in average annual precipitation in all regions of the UK between 1961 and 2006. It is difficult to confirm with high confidence the level of statistical significance given the large degree of natural variation over the period. However the trend can be seen to be statistically significant in Scotland where an increase of around 20% has been observed, and likewise the increase in average winter rainfall is also statistically significant in northern England and Scotland where increases of 30–65% have been experienced.

The geographical and seasonal distributions of trends in the total precipitation and the number of rainy days in the UK are presented below in Figure 2-C and Figure 2-D respectively. Seasonal data for spring and autumn have been omitted for the purposes of this report as the trends are not clear.

The illustrations are taken from the UKCP09 report '*The climate of the UK and recent trends (UKCP 2009)*'. UKCP09 contains historical observations (20th/21st century data on temperature, precipitation, storminess, sea surface temperatures and sea level), climate change projections (for temperature, precipitation, air pressure, cloud and humidity) as well as marine and coastal projections (for sea level rise, storm surge, sea surface and sub-surface temperature, salinity, currents, and waves). UKCP09 captures a detailed understanding of how the climate system operates, how it might change in the future, and also allows for a measure of the uncertainty in future climate projections to be included. Tabulated climate data values supplied by the Met Office which detail each individual UK reporting region can also be found in the report.

The UKCP09 analysis does not include very recent data (post 2006) but the relatively long baseline (from 1961) means that the long term observed trends are robust and likely to be relatively insensitive to the addition of new data. Hence the report substantiates a long term trend (1931-2012) for widespread increased winter and annual UK rainfall as indicated in Figure 2-B. However the analysis does not pick up the more recent rising trend observed in later data periods (1990-2012). As discussed in Sections 2.1.3 to 2.1.4 current research indicates a possible connection between this decadal trend and warming of the North Atlantic Ocean which may also be having a substantial effect on the UK climate by driving a period of increased summer rainfall, a pattern which may prevail for a period of years or decades.

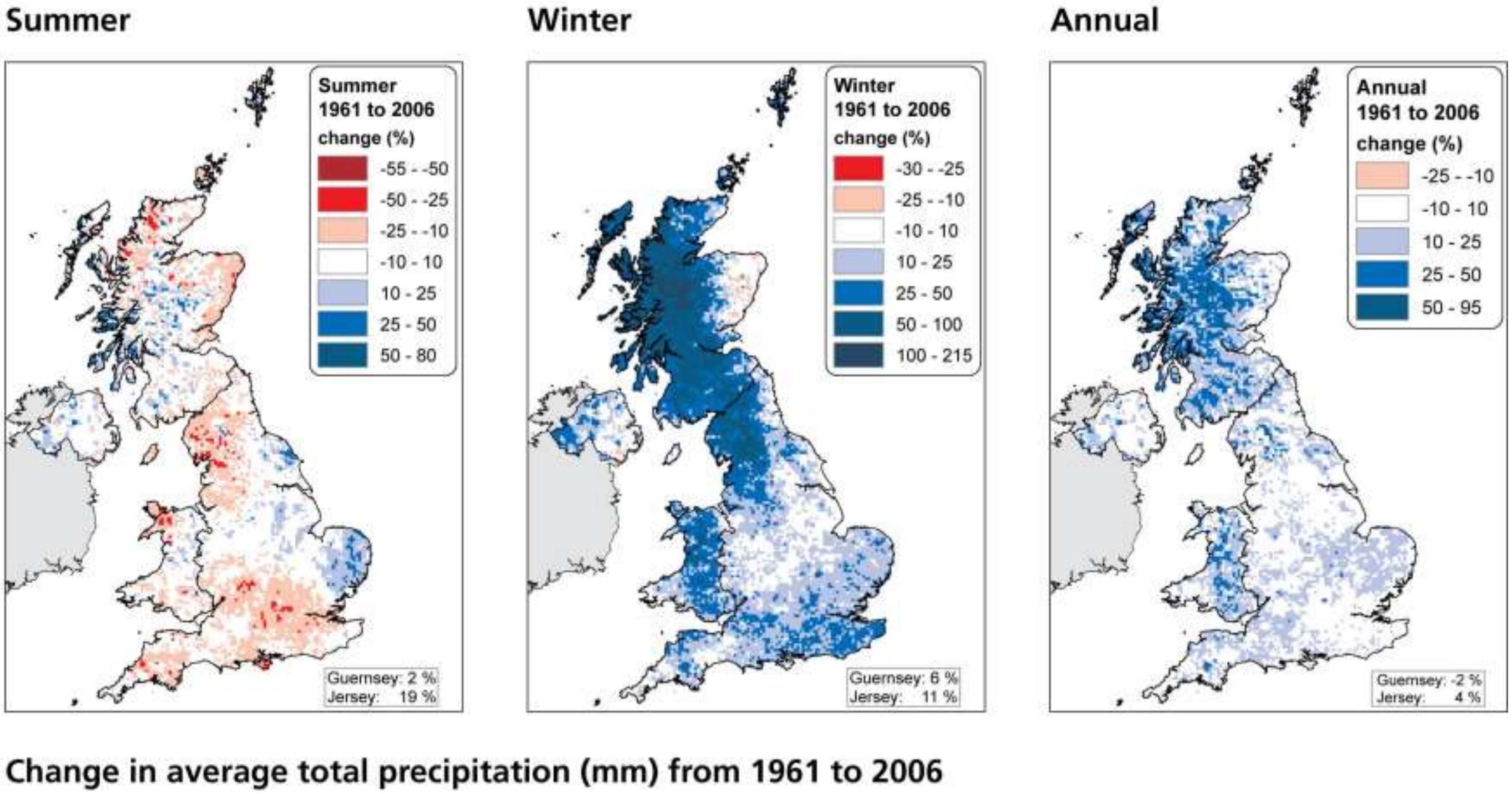

Figure 2-C Percentage change in total precipitation relative to the1961-2006 average for a) summer, b) winter, and c) annual. [Source: UKCP09].

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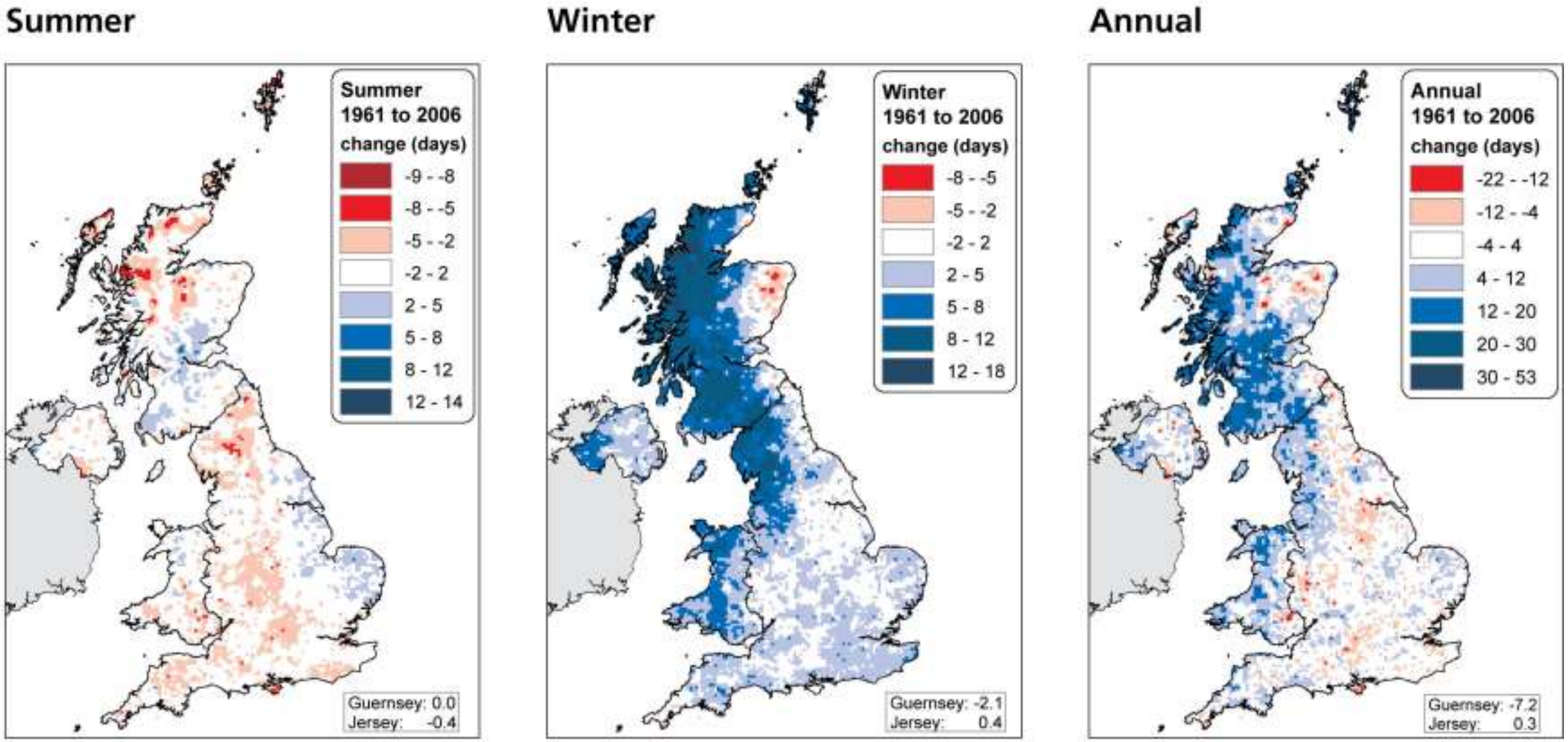
UK CLIMATE PROJECTIONS



Change in average number of days of rain ≥ 1 mm (days) from 1961 to 2006

Figure 2-D Percentage change in the number of days with rain ≥ 1mm relative to the1961-2006 average for a) summer, b) winter, and c) annual. [Source: UKCP09].

Of particular interest in the climate observations are trends in the contributions to the rainfall total made by 'extreme' events. Figure 2-E shows the trend in extreme precipitation as measured by the 99th percentile of a trailed thirty year sample of daily England and Wales Precipitation series (EWP) values. Each sample consists of the non-zero (> 0.1 mm) daily rainfall totals within a 30 year window. Inclusion of 2012 data (the last point in the graph) does not result in a large jump in the estimate of the 99th percentile (i.e. P_{99} for the period 1/1/1983-31/12/2012 is almost the same as P_{99} for the period 1/1/1982-31/12/2011. Thus, in the context of recent extremes in the last thirty years, 2012 can be viewed as fitting the emerging trend of higher extreme rainfall events.

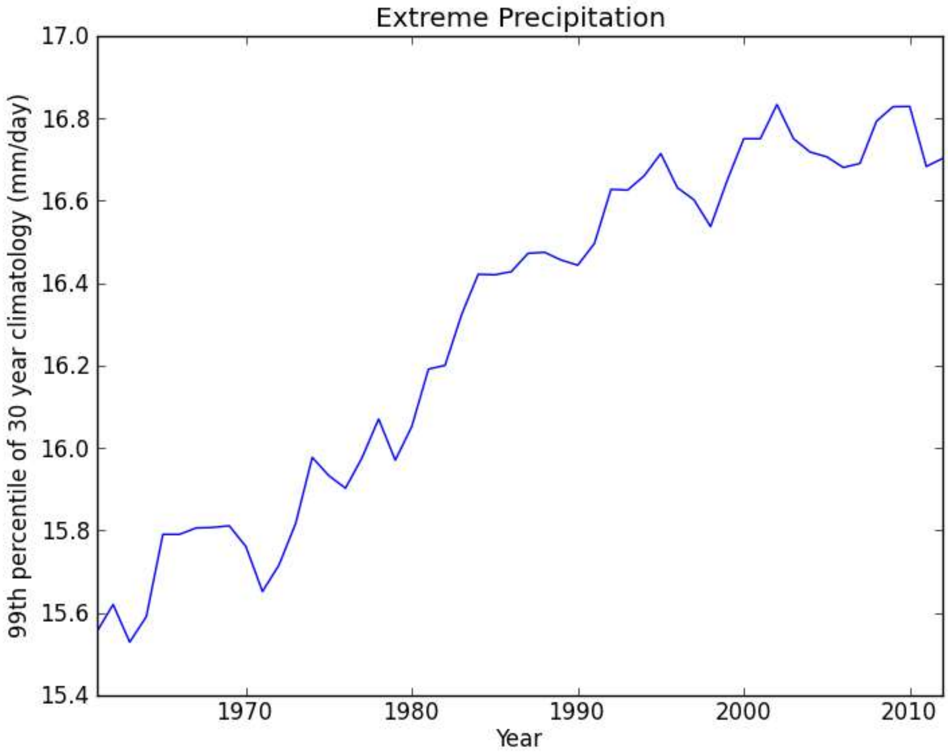


Figure 2-E Trend in extreme precipitation as measured by the 99th percentile of the England and Wales Precipitation series (EWP) of a trailed 30 year sample of daily values (conditional on it having rained at least 0.1 mm) 1961-2012.[Source Ben Lloyd-Hughes, University of Reading]

Further information on rainfall extremes is displayed in Figure 2-F which shows changes from 1961-2006 in the contribution from heavy precipitation to winter and summer precipitation in the nine Met Office climatological regions of the UK (Maraun, Osborn et al. 2008). A change of 5% in the contribution of heavy events (evident in most regions during winter) implies a change from a contribution of, say, 7.5% in the 1960s to a contribution of, say, 12.5% in the recent decade. It can be seen that all regions have seen an increase in the contribution in winter, albeit marginally in Northern Ireland and northwest England. In summer, all regions show decreases except north east England, which has a positive trend, and north Scotland which has little change. The detailed trends are aligned with overall increases in UK rainfall as absolute levels are substantially higher in winter and in geographic regions such as Scotland.

The data illustrates that the trends of increasing precipitation and variability in seasonal weather patterns are likely to impact differentially and in unpredictable ways in different regions of the UK.

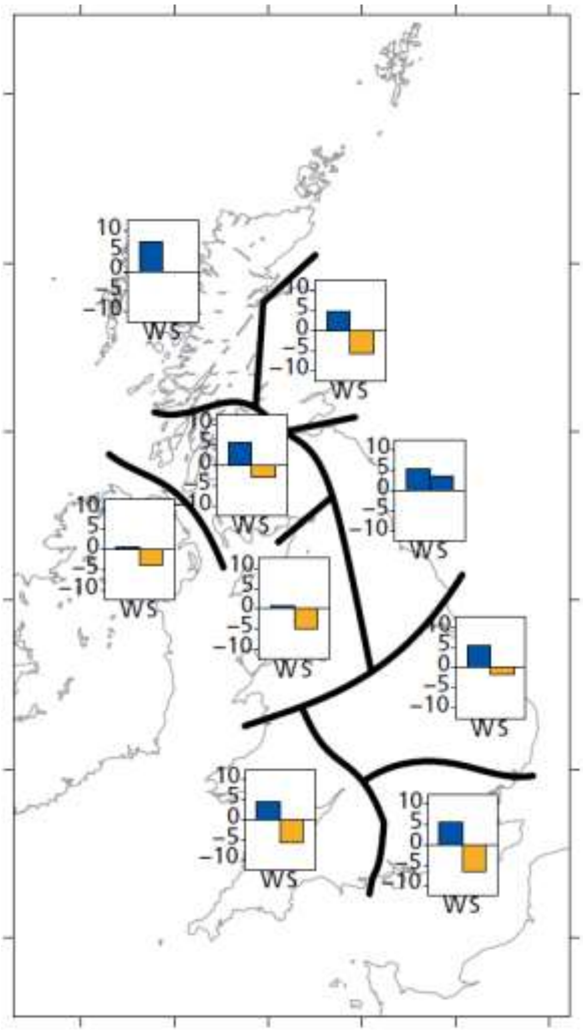


Figure 2-F Trends over the period 1961-2006 in the contribution (%) made by heavy precipitation events to total winter (left-hand bars labelled “W”) and summer (right-hand bars labelled “S”) precipitation. For clarity, positive trends are shown in blue, negative in orange. [Source: UKCP09, Tim Osborn, CRU, UEA]

Further detailed information on the climatologically expected return levels for 1-day accumulations can be found in the UKCP09 *Extremes Atlas* (UKCP 2009).

In addition preliminary research from the Met Office (Met Office 2013b) also suggests we may have seen a change in the nature of the rain we get with 'extreme' daily rainfall becoming more frequent. Their analysis of 1 in 100 day rainfall events since 1960 indicates these 'extreme' days of rainfall may have become more frequent over time.

In summary, trends in the long term average (1961-2006) indicate that summer rainfall is decreasing, winters are becoming wetter, and bouts of heavy rain are becoming more frequent throughout the year. The physical drivers for this long term trend and other factors driving UK climate in recent decades are considered further in the Sections 2.1.3 to 2.1.4 below.

2.1.3 Short term (Decadal) trends over the last 10 years

Official Met Office statistics show that four out of five of the wettest years on record (since 1931) have occurred since 2000:

1. 2000 1337.3 mm
2. 2012 1330.7 mm
3. 1954 1309.1 mm
4. 2008 1295.0 mm
5. 2002 1283.7 mm

(Met Office 2013b)

This fits within a long term trend where extreme precipitation is increasing (see Figure 2-E and Figure 2-F) and where average levels of annual precipitation in the UK are also increasing (see Figure2-B). However, close inspection of Figure 2-B suggests an accelerating trend over the last two decades.

In terms of the atmospheric circulation, the primary mechanism driving much of the recent wet weather (e.g. 2012) in the UK and particularly increased summer rainfall, can be attributed to the position of a phenomenon known as the jet stream. The jet stream has typically resided to the north of the UK in summer, directing areas of low pressure and bad weather further north. However changes in position of the jet stream can dramatically alter the weather in the UK. For example, in summer 2012, the jet stream shifted further south, bringing wet and windy weather to the south of the country.

This is illustrated in Figure 2-G below which shows the typical position of the summer jet stream (a) and the anomalously southern position seen in 2012 (b).

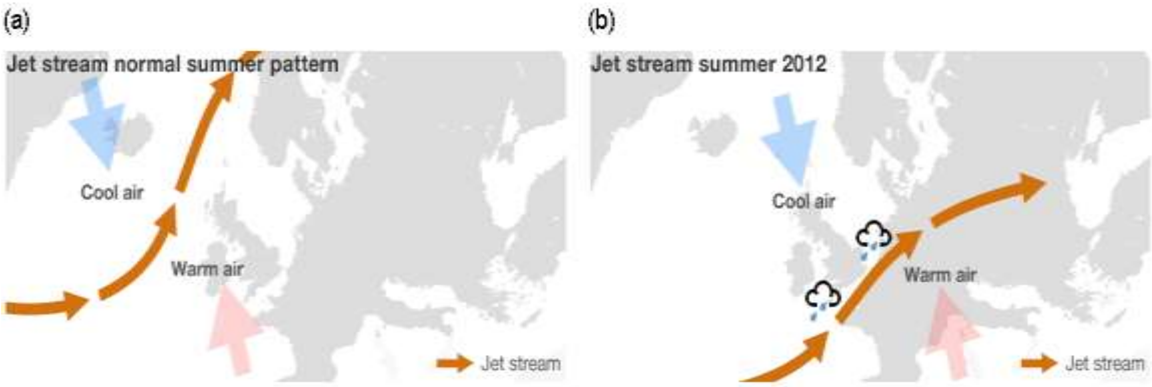


Figure 2-G The North Atlantic jet stream: (a) Average summer position, (b) position during summer 2012. [Source: BBC, 2013]

In general, the jet stream can be expected to meander north and south of the UK with the prevailing weather type changing every few days or so. In fact, it is precisely this variability that contributes to the typically ‘changeable’ weather experienced in the UK. However, for much of summer 2012 the circulation became ‘locked’ onto the southerly path. This blocking pattern is now being observed more frequently (Davini, Cagnazzo et al. 2012) and recent research indicates a possible driver being the current temperature of the North Atlantic (which is attributed to an ocean phenomenon known as the Atlantic Multi-decadal Oscillation (AMO)). This is covered further in below and in the Annex: Atlantic Multi-decadal Climate Variability.

2.1.4 Detection and attribution

The above discussion on detected trends in precipitation indicates a complex situation of signals which vary across time and space. Without an understanding of the factors driving these trends they are an unreliable indicator of future expectation. Thus, beyond detection, if we wish to use observed trends as a guide to the future, it is critical that we seek drivers and mechanisms to attribute these changes to. Of particular interest is the role of anthropogenic greenhouse gas emissions as a driver for long-term change. This is an on-going and substantial area of research.

(a) Attribution of long term trends to anthropogenic global warming

The UK Met Office has recently set up an initiative which aims to attribute unusual or extreme weather and climate-related events to anthropogenic climate change. They aim to achieve this through:

> *'… the development of carefully calibrated physically-based assessments of observed weather and climate-related events, we can identify any changed risk of such events attributable to particular factors.*
> *Research is under way, coordinated as part of the international Attribution of Climate-related Events (ACE) initiative, to develop the science needed to better respond to the demand for timely, objective, and authoritative explanations of extreme events.'*

Under this program, using a set of four detailed computer climate models (Pall, Aina et al. 2011) simulated the weather in Autumn 2000, both as it was, and as it might have been had there been no greenhouse gas emissions since the beginning of the 20th century. The findings of the study emphasized the importance of human induced (i.e. long-term) climate change as a driver for flooding:

> *'Using publicly volunteered distributed computing we generate several thousand seasonal-forecast-resolution climate model simulations of autumn 2000 weather, both under realistic conditions, and under conditions as they might have been had these greenhouse gas emissions and the resulting large-scale warming never occurred. Results are fed into a precipitation-runoff model that is used to simulate severe daily river runoff events in England and Wales (proxy indicators of flood events). The precise magnitude of the anthropogenic contribution remains uncertain, but in nine out of ten cases our model results indicate that twentieth-century anthropogenic greenhouse gas emissions increased the risk of floods occurring in England and Wales in autumn 2000 by more than 20%, and in two out of three cases by more than 90%.'*

This indicated a very strong explanatory linkage between the mechanisms underpinning the climate model and the climatic conditions leading to the floods of 2000. On-going research at the Met Office and in other government and academic bodies will continue to assess the extent to which individual events such as recent flood events can be attributed to man-made climate change but it will remain a significant and resource intensive modelling task. However the macroscopic understanding of how greenhouse gas emissions are linked to climate change is now very clear on a global (and regional basis) as demonstrated by exercises such as UKCP09. It is the attribution of single events which is more problematic given the natural wide statistical variation which is possible in climate systems.

(b) Attribution of short term (decadal) trends to changes in the North Atlantic Ocean

In addition to the well understood mechanisms which are driving long term man made climate change there are other large scale features of atmospheric and ocean systems which play a significant part in regional weather systems. In this respect the Atlantic Ocean has been suggested as an important driver of variability in European climate on decadal timescales (Schlesinger and Ramankutty 1994), but the importance of this influence in recent decades has been unclear, partly because of difficulties in separating the influence of the Atlantic Ocean from other contributions, for example, from the tropical Pacific Ocean and the stratosphere.

During the 1990s the North Atlantic shifted to a warm state similar to that experienced during the 1930s, 40s and 50s, and this warm state has persisted to the present day. The swings in the temperature of the North Atlantic are additional to a long term (century timescale) warming trend that is mainly due to increasing concentrations of greenhouse gases in the atmosphere. It is likely that the swings in the temperature of the North Atlantic have also been affected by human activities - both greenhouse gas emissions and other forms of pollution. Understanding how important these factors have been is a subject of active research.

Sutton and Dong (2012) analyse four data sets derived from observations to show that, since the 1990s, there has been a substantial shift in European climate towards a pattern characterized by anomalously wet summers in northern Europe, and hot, dry, summers in southern Europe (the research is summarised in the Annex to this paper). These changes in climate have coincided with a substantial warming of the North Atlantic Ocean, towards a state last seen in the 1950s. The patterns of European climate change since the 1990s are consistent with earlier changes attributed to the influence of the North Atlantic Ocean, and provide compelling evidence that the Atlantic Ocean is the key driver. (Sutton and Dong 2012) conclude that:

> *'Our results suggest that the recent pattern of anomalies in European climate will persist as long as the North Atlantic Ocean remains anomalously warm.'*

Research on this topic is on going by Professor Rowan Sutton at the University of Reading and indicates that for the time being the pattern is stable, but can change. At present, it is not known how long the prevailing conditions may persist. Whilst the present conditions could remain in place for decades, however when a change occurs it can happen over a period of two to three years. Professor Sutton comments (Guardian 2012):

> *'… we are not sure of the timing, which is what every one wants to know – but we are working on this now.'*

Further details on this research are provided in the attached Annex: Atlantic Multi-decadal Climate Variability.

2.2 Outlook for the next three to five years

The relative contributions to the wet weather of 'natural' decadal scale versus anthropogenic climate change will not be known until attribution studies such as those discussed in Section 2.1.4 have been completed. However, recent trends suggest that the near term (decadal) wetting influence of the North Atlantic on summer conditions is compensating for the average drying tendencies of long-term human induced climate change and further enhancing the long term trends in extreme precipitation. The combined impacts of these factors is summarised in the matrix below:

	Spring	Summer	Autumn	Winter
Mean	Normal	Normal (see note)	Normal to wet	Wet
Extreme	Enhanced	Enhanced	Enhanced	Enhanced

Note: Long term trends (30 to 100 years) indicate a shift to drier summers. However, the influence of the North Atlantic Ocean at decal scales (10 to 20 years) has tended to favour wetter than average summers in recent years. The net effect is neutral but volatility can be expected c.f. 2006 (worst groundwater drought in SE England since 1976, hottest summer in 234 year record) and 2012 (wettest summer in 100 years).

3 Windstorms

3.1 Introduction

This section of the report explains the major meteorological drivers, effects and trends for windstorms in the UK.

3.2 Extra-tropical cyclones

Damaging winds in the UK are usually the result of extra-tropical cyclones. These form as cyclonic windstorms associated with areas of low atmospheric pressure that track across the North Atlantic Ocean towards western Europe. Extra-tropical cyclones can form at any time of the year but they are most common in the winter months. Deep low pressure areas are relatively common over the North Atlantic, sometimes starting as nor'easters off the New England coast, and frequently track past the north coasts of the British Isles and into the Norwegian Sea. However, when they veer south they can affect almost any part of the UK.

3.3 Storm surge

Extra-tropical cyclones can also lead to significant coastal flooding from storm surge. The most damaging example in the UK was the ‘North Sea flood’ of 1953, which killed a total of over 2,000 people in the UK and the Netherlands.
A storm surge is an offshore rise of water associated with a low pressure weather system, typically tropical cyclones and strong extra-tropical cyclones. Storm surges are caused primarily by high winds pushing on the ocean's surface. The wind causes the water to pile up higher than the ordinary sea level. Low pressure at the centre of a weather system also has a small secondary effect, as can the bathymetry of the body of water. It is this combined effect of low pressure and persistent wind over a shallow water body which is the most common cause of storm surge flooding problems. For most practical purposes real quantity of interest is the rise of water associated with the storm, plus tide, wave run-up, and freshwater flooding. This is sometimes referred to as the ‘storm tide’ and is shown graphically in Figure 3-A.

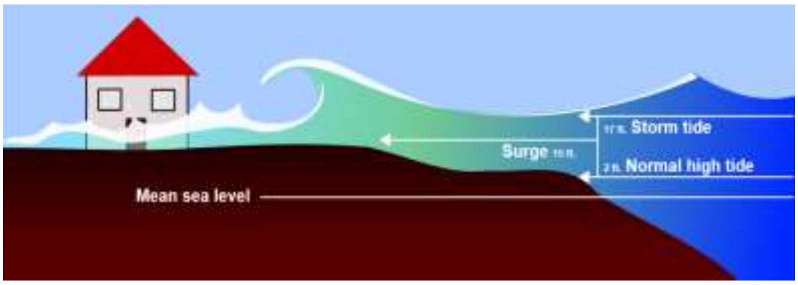


Figure 3-A Schematic illustration of the combined effects of storm surge and high tide. [Source: Emmanuel Boutet]

Obviously, sea level rise is an important factor when assessing the risk of storm related coastal flooding.

3.4 Trends in storminess

Trends in severe wind storms around the UK, are difficult to identify, due to low numbers of such storms, their decadal variability, and by the unreliability and lack of representativity of direct wind speed observations. However, it can be stated that (UKCP 2009):

> *'Severe windstorms around the UK have become more frequent in the past few decades, although not above that seen in the 1920s.'*

Trends in storminess can be seen in Figure 3-B which shows the total number of severe storms per decade over the UK and Ireland during the half year period October to March, from the 1920s to the 1990s. The variations can largely be described by changes in the large scale pressure distribution known as the North Atlantic Oscillation (NAO) (Wallace and Gutzler 1981).

Work by (Gillett, Zwiers et al. 2003) has shown that man-made factors have had a detectable influence on sea-level pressure distributions (and hence atmospheric circulation patterns) over the second half of the 20th century. However, clear evidence that links recent increases in storminess over the UK to man-made climate change is not yet available (UKCP 2009).

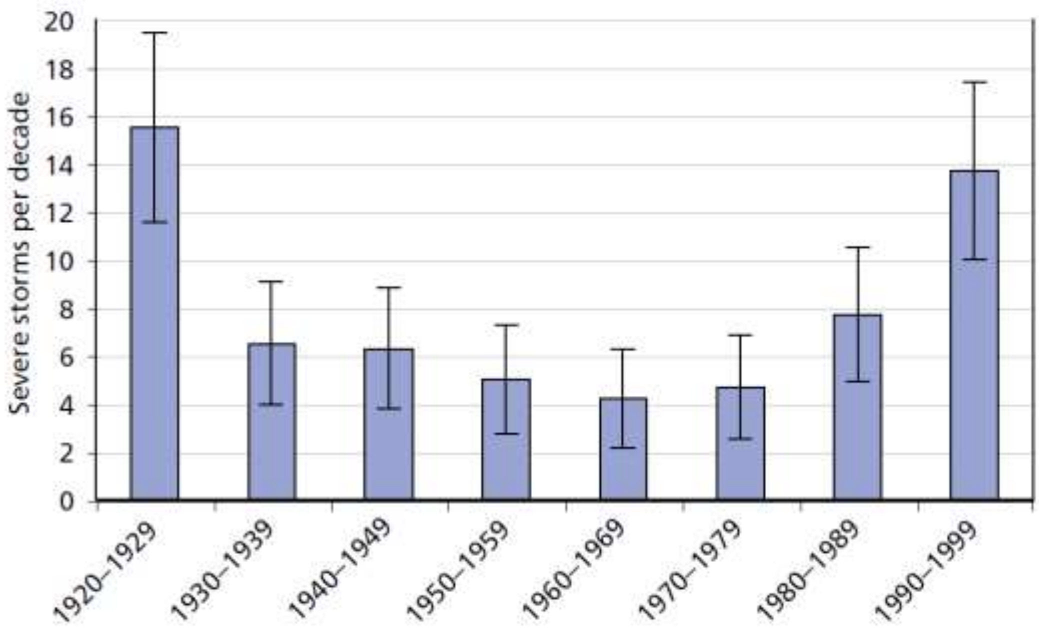


Figure 3-BThe total number of severe storms per decade over the UK and Ireland during the half year period October to March, from the 1920s to the 1990s. Error bars show ± one standard deviation. [Source: Rob Allan, Met Office Hadley Centre]

The two stormiest periods in *Figure 3-B*, in the 1920s and 1990s, coincide with decades of sustained positive NAO index, whereas the least stormy decade, the 1960s, is a time when the NAO index was most negative. The NAO shows significant decadal scale variability similar to that discussed above with reference to precipitation. Figure 3-C shows variations in the NAO from 1950 to date.

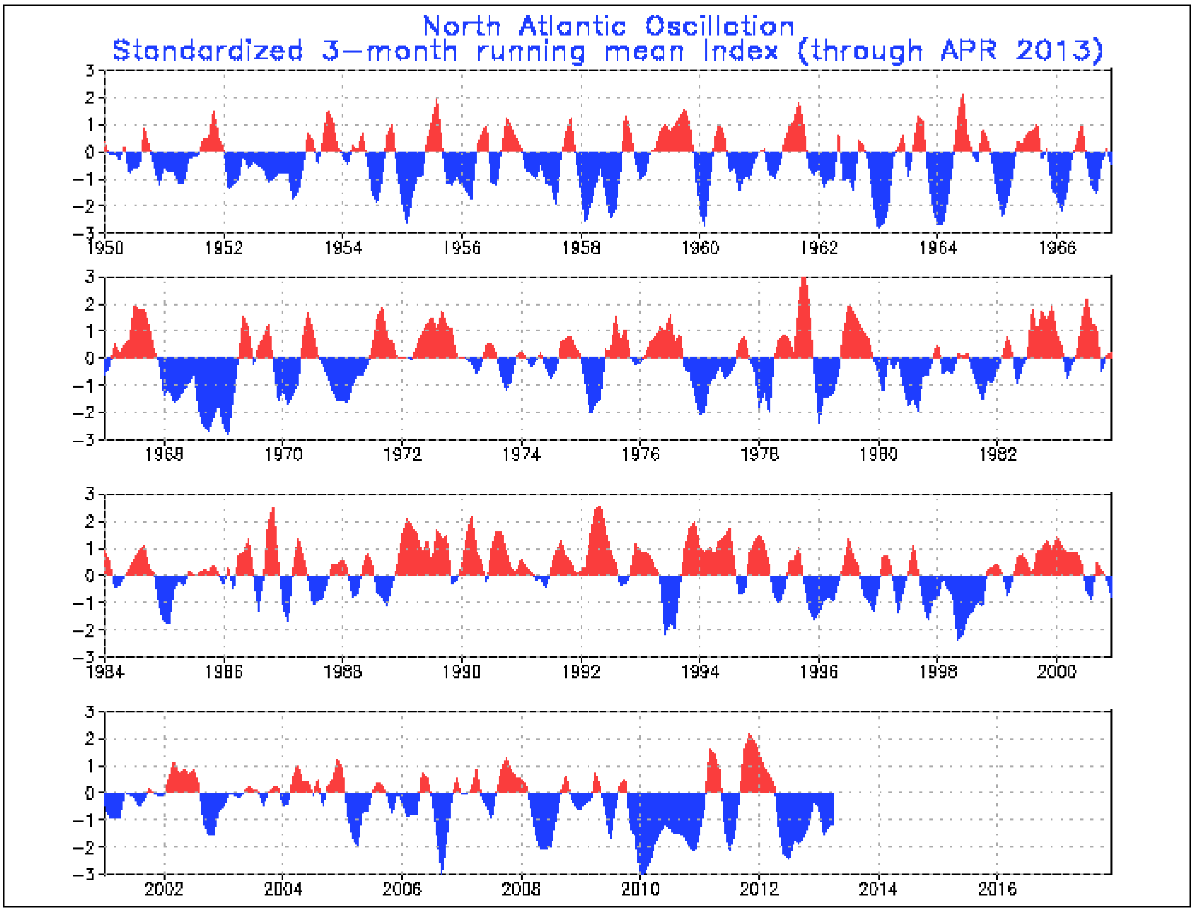


Figure 3-C North Atlantic Oscillation. [Source: US Climate Prediction Center]

3.5 Outlook for the next 3 to 5 years

In recent years (since 2000) the NAO has been in a mostly negative phase and thus storm activity has tended to be supressed. However, unlike the ocean temperatures in the north Atlantic which typically take years to switch sign, the NAO is an atmospheric phenomenon and can switch phase quickly. Given the fact that we appear to be mid-way through a negative phase, it seems likely that a positive NAO will be seen at some time in the next few years. Thus, on average, conditions can be expected to be neutral in line with the absence of a clear long term trend. However, year to year volatility may be expected.

4 Temperature

4.1 Introduction

This section of the report examines temperature trends in the UK. Variations in temperature are the key factor driving other climatic effects such as precipitation, and windstorms.

4.2 Average temperature

The UK is fortunate in having the longest continuous temperature record in existence (Manley 1974). The Central England Temperature (CET) monthly series runs from 1772 to date and is currently computed from five observing stations, namely: Rothamsted (Hertfordshire), Pershore (Worcestershire) and Stonyhurst (Lancashire). CET is illustrated in Figure 4-A below which shows a general trend toward warmer conditions.

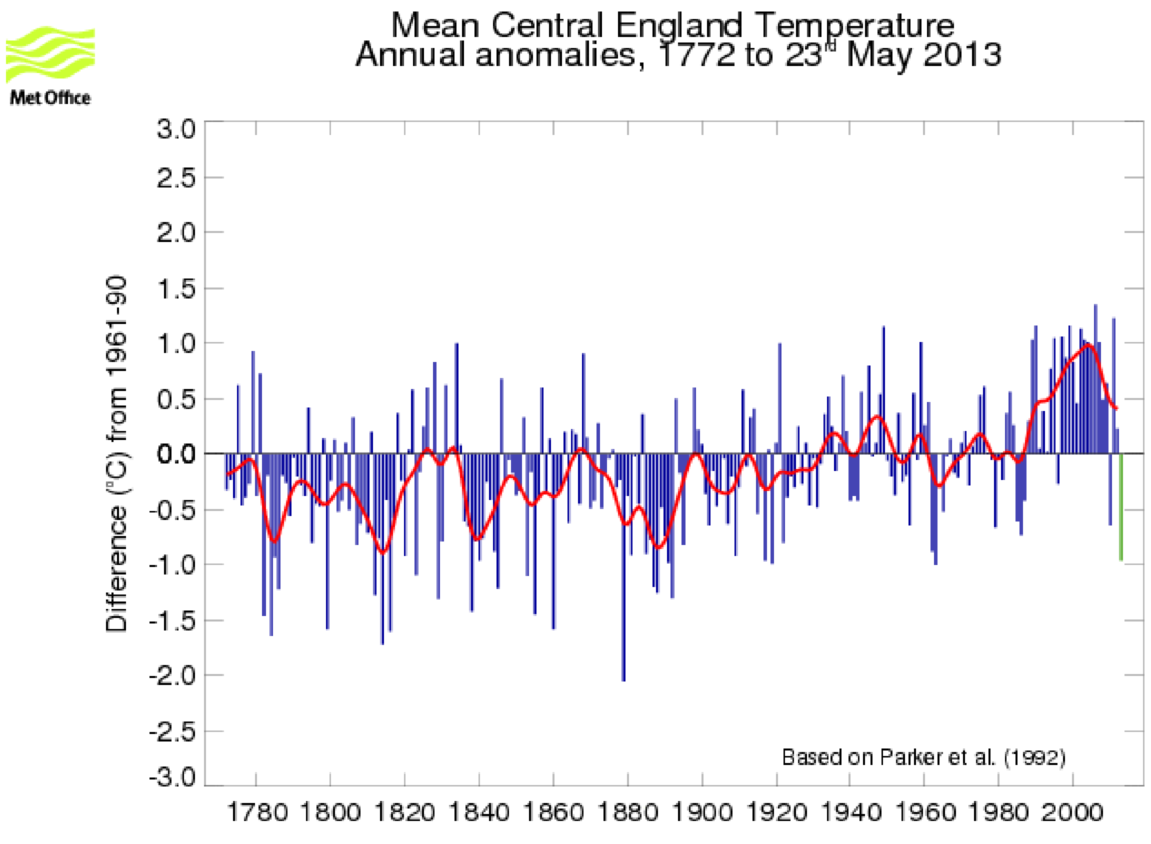


Figure 4-A Changes in CET annual values (blue bars) from 1772 to date relative to the average over the 1961-90 baseline period (about 9.5 ºC). The green line indicates provisional data for 2013. The red line emphasises decadal variations. [Source: Met Office Hadley Centre]

4.3 Trends in extreme temperatures

Changes in mean annual temperatures are relevant to operational heating and cooling costs, however, extremes of temperature are typically more relevant to business continuity. What follows are maps of trend in maximum temperatures (Figure 4-B), minimum temperatures (Figure 4-C) and the number of frost days (Figure 4-D) 1961-2006 from UKCP 2009. The unanimous picture is a shift toward warmer conditions in all regions in all seasons.

4.4 Outlook for the next 3 to 5 years

Trends in UK temperatures are dominated by the long-term effects of climate change. However, these effects are modulated by the decadal influences of the temperature of the North Atlantic Ocean (Section 2.1.4) and the North Atlantic Oscillation (Section 3.4). The net result over recent years has been a reduction in the warming trend (as seen in the latter years of Figure 4-A) however this has not been enough to entirely cancel the general warming. Thus, the long term outlook remains a shift toward increased temperatures and a reduction in the number of frost days. However, it should be cautioned that a reversion toward cooler ocean temperatures in the North Atlantic could push the jet stream north in summer at which point extremely warm temperatures can be expected.

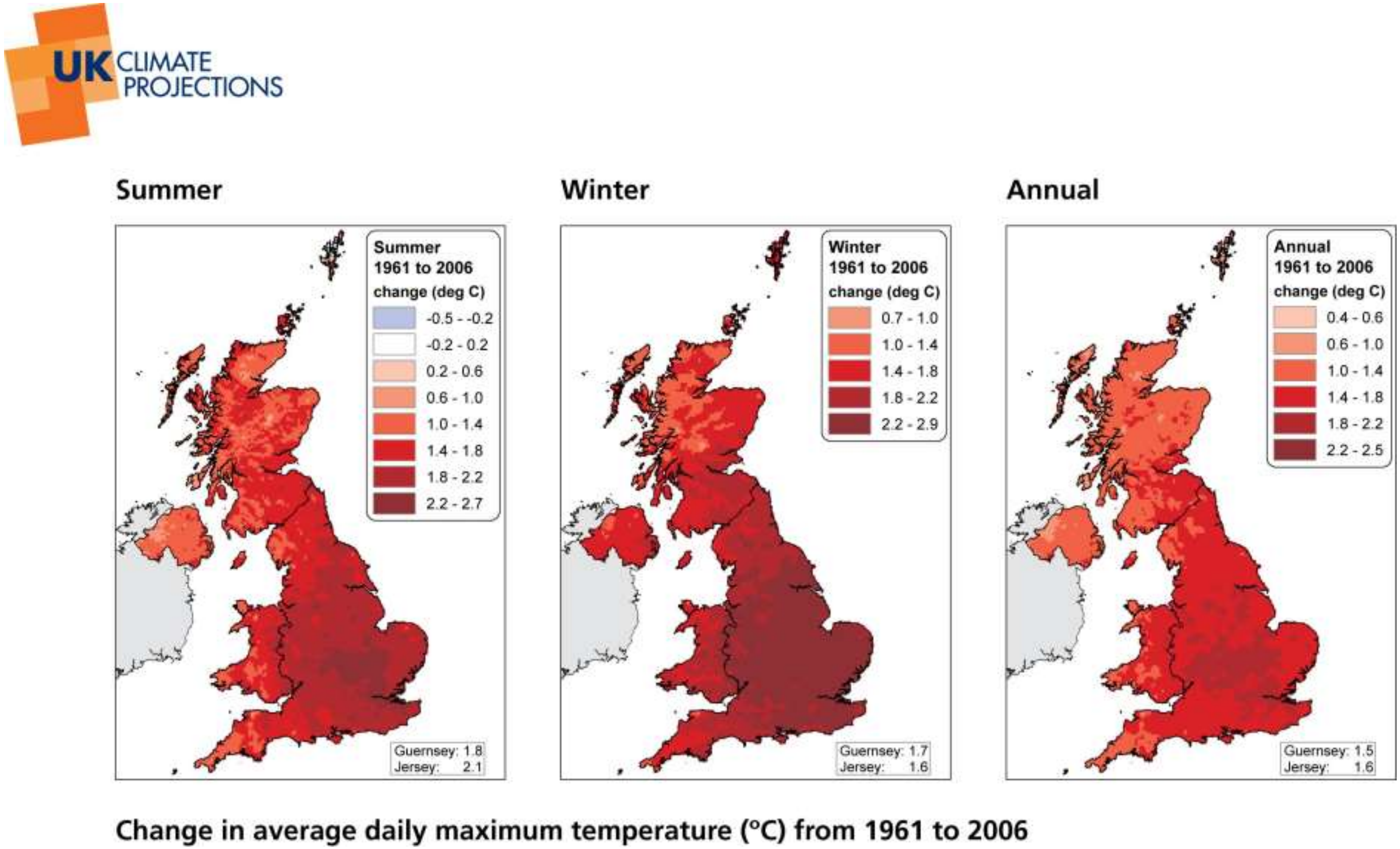


Figure 4-B Trends in maximum daily temperatures 1961 to 2006. [Source: UKCP09]

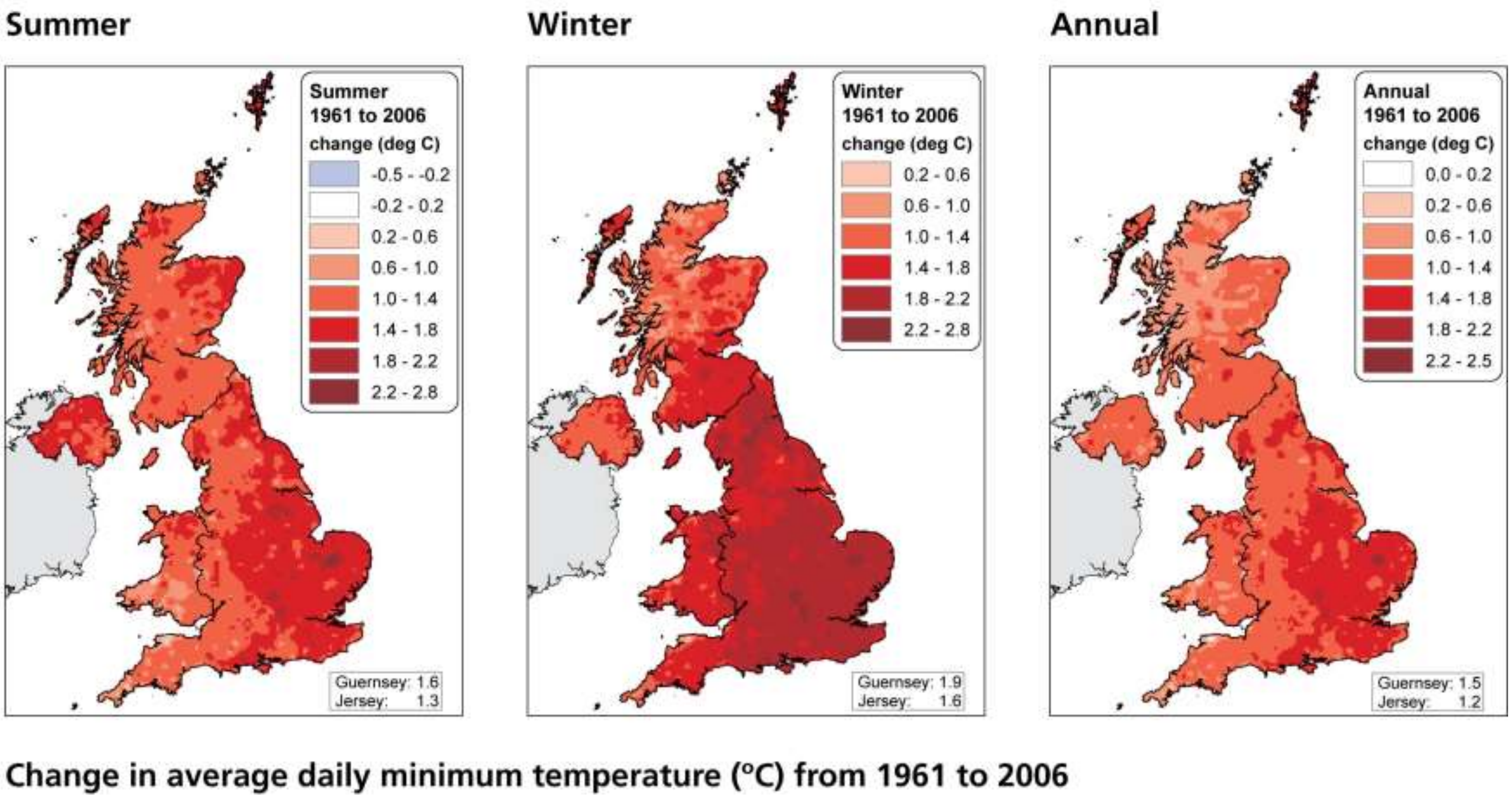


Figure 4-C Trends in minimum daily temperatures 1961 to 2006. [Source: UKCP09]

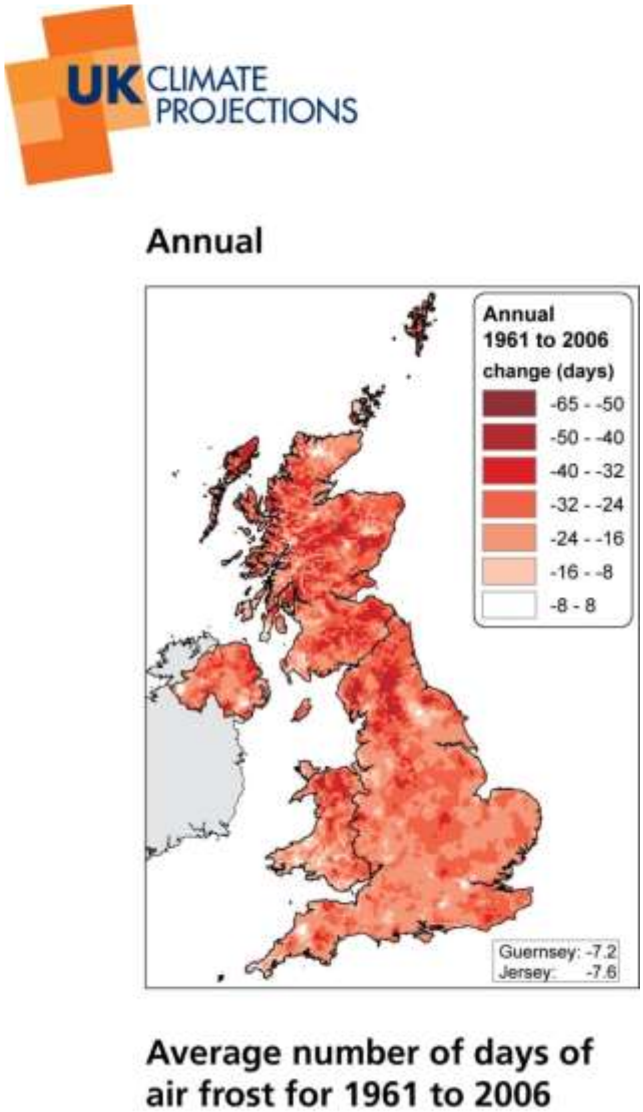


Figure 4-D Trends in the number of frost days 1961 to 2006. [Source: UKCP09]

5 Concluding remarks

Our analysis of recent trends in the UK weather and climate reveal a complicated picture of temporal (seasonal, decadal and centennial) and geographical variability across the various parameters considered.

Two dominant factors have emerged, namely the long-term influence of anthropogenic (man-made) climate change and the near-term influence of the North Atlantic Ocean.

In recent years the net effects of these drivers has been to enhance precipitation (particularly heavy summertime rain) and moderate (if not eliminate) increases in temperature. The long term trends driven by man-made climate change such as increased average and extreme precipitation can be expected to continue long into this century and beyond. Additionally these factors will have a strong influence on UK weather patterns over the coming decade but the near term view will also be strongly influenced by decadal trends identified in this report such as the AMO.

Such climatic drivers may remain in place for years or decades. However, the oscillatory nature of the ocean influence does imply a reversion is inevitable at some point. It is likely that the swings in the temperature of the North Atlantic will also have been affected by human activities - both greenhouse gas emissions and other forms of pollution. Understanding how important these factors have been is a subject of active research and will undoubtedly form part of future attribution studies.

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Annex: Atlantic Multi-decadal Climate Variability

Introduction

Many elements of the Atlantic climate system exhibit variations on a multidecadal time scale. The first analyses (Schlesinger and Ramankutty 1994; Kushnir 1994) were based on sea surface temperature (SST) and indicated variability on a time scale of 50–70 years. When a 10 year running mean of North Atlantic SST anomalies is constructed, the Atlantic is found to have been coldest around 1920 and 1980, and relatively warm around 1950 as well as over the last decade (Enfield et al. 2001; Sutton and Hodson 2005). Although only a few cycles can be identified from the instrumental SST record, the variability is often referred to as the Atlantic multidecadal oscillation (AMO; Kerr 2000).

However, the details of this variability, in particular the dominant patterns and time scales, are confusing from both an observational as well as a theoretical point of view. After analysing results from observational datasets and a 500 year simulation of an Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) climate model, Frankcombe et al. (2010) propose that two dominant time scales (20–30 and 50–70 year) of multidecadal variability in the North Atlantic. The 20–30 year variability is characterized by the westward propagation of subsurface temperature anomalies. The hypothesis is that the 20–30 year variability is caused by internal variability of the Atlantic Meridional Overturning Circulation (AMOC) while the 50–70 year variability is related to atmospheric forcing over the Atlantic Ocean and exchange processes between the Atlantic and Arctic Oceans.

Dynamics

An understanding of the dynamics that control the multidecadal variability is important for several reasons. There are strong indications that summer temperatures in western Europe and precipitation variations, in particular in the continental United States, are related to the AMO (Enfield et al. 2001; Sutton and Hodson 2005). Second, multidecadal variations may contribute to changes in global mean surface temperature and hence may alternately mask and enhance temperature and precipitation changes due to increasing levels of greenhouse gases (Zhang et al. 2007). Third, if there are preferred patterns of multidecadal variability, then these may play a significant role in climate predictability on these time scales (Griffies and Bryan 1997; Keenlyside et al. 2008). Finally, understanding this variability is an important component of any general theory of climate variability and climate change.

Water from the North Atlantic enters the Arctic Ocean through Fram Strait and the Barents Sea. The return flow of water from the Arctic occurs mainly via the East Greenland Current. This exchange forms an oceanic connection between the climates of the Arctic and the North Atlantic. Century-long records of sea ice extent in the Arctic display multidecadal variability (Venegas and Mysak 2000), which has been referred to as the low-frequency oscillation (LFO; Polyakov and Johnson 2000). This variability is strongest in the Kara Sea and decays toward the Canada Basin (Polyakov et al. 2003a). There are also multidecadal variations in sea ice transport through Fram Strait associated with the sea ice extent variability (Vinje et al. 2002).

The other connection between the North Atlantic and Arctic climates occurs through the atmosphere. The dominant atmospheric winter variability is the pattern of the North Atlantic Oscillation (NAO), with its Arctic extension, the Northern Annular Mode (NAM; Thompson and Wallace 2001). Although it cannot be demonstrated that the NAO has any significant preferential frequency, the Atlantic westerlies were relatively weak in the period between 1940 and 1970, and relatively strong from 1980 to the present. NAO variations impose a relatively well-known tripolar SST anomaly on the North Atlantic Ocean on seasonal to interannual time scales (Eden and Jung 2001; Alvarez-Garcia et al. 2008), while the low-frequency response of the ocean to the NAO is more of a basin-wide single-sign pattern (Visbeck et al. 2003).

Impacts

During the 1990s, there was a substantial shift in European climate towards a pattern characterized by anomalously wet summers in northern Europe, and hot, dry, summers in southern Europe, with related shifts in spring and autumn. Sutton and Dong (2012) show that these changes in climate coincided with a substantial warming of the North Atlantic Ocean, towards a state last seen in the 1950s. The patterns of European climate change in the 1990s are consistent with earlier changes attributed to the influence of the North Atlantic Ocean and provide compelling evidence that the Atlantic Ocean was the key driver. These results suggest that the recent pattern of anomalies in European climate will persist as long as the North Atlantic Ocean remains anomalously warm.

During the 1990s the North Atlantic returned to a warm state similar to the warm state of ~ 1931–1960. Recent evidence suggests that this 1990s warming was largely caused by an acceleration of the AMOC and associated northward ocean heat transport, in response to the persistent positive phase of the winter NAO in the 1980s and early 1990s. Since the 1990s the warm conditions have persisted. The pattern of North Atlantic SST anomalies for the recent warm period (1996–2010) is very similar to that for the previous warm period (1931–1960). The similarity between the two periods in the pattern of North Atlantic SST anomalies suggests that similar mechanisms may have been responsible for the transitions, and that similar climate impacts may have been excited.

To assess the climate impacts Sutton and Dong (2012) examine the anomalous patterns of surface air temperature (SAT), precipitation and sea level pressure (SLP) for the two warm periods, relative to the intervening cool period (~ 1964–1993). As it is particularly difficult to separate in winter the ocean's influence on the atmosphere from the atmosphere's influence on the ocean, they focus on spring, summer and autumn. The patterns of SAT anomalies over Europe for the two warm periods are very similar. In all three seasons, warm anomalies are found, but there is seasonal variation. In spring, significant warm anomalies are limited to western Europe, with the largest anomalies (>0.8 °C) over continental western Europe. In summer, warm anomalies extend much further east into central and eastern Europe and the largest anomalies (>1.0 °C) are found in the southern regions bordering the Mediterranean Sea. In autumn, in contrast, warm anomalies are limited to northern Europe, and the largest anomalies (>1.0 °C) are found over Scandinavia.

The similarity between the two warm periods can also be seen in the seasonal evolution of Central England Temperature (CET) and European SAT. In both periods both indices are anomalously warm from March to September (and also in November). These results are consistent with the seasonal mean correlations between the AMO and CET reported previously, and suggest that a warm state of the North Atlantic favours a mild spring (especially April), summer and autumn, in England and across Europe.

The patterns of precipitation anomalies are, not unexpectedly, noisier than those for SAT but there is again a high degree of consistency between the two warm periods, especially in summer. In spring, dry anomalies are found over the UK and France, and wet anomalies over Iberia, but the patterns are quite noisy, especially further east. In summer, however, there is a very clear banded pattern of wet anomalies extending across northern and central Europe (with a small region of dry anomalies along the west coast of Norway) and dry anomalies across southern Europe, reaching from Portugal to Turkey. Anomalies are 5–20% of the local seasonal mean rainfall. In autumn, dry anomalies (up to 20% of the seasonal mean value) are found over Scandinavia, and wet anomalies of similar magnitude are found over the UK and southeastern Europe in both periods. Anomalies over Iberia differ in sign between the two periods.

A warm state of the North Atlantic Ocean could cause warm anomalies in SAT over Europe without any significant effects on atmospheric circulation (by advection over land of air warmed by the ocean). However, the coherent and consistent patterns of precipitation anomalies suggest changes in atmospheric circulation. In spring, there is an anomalous ridge (high SLP) over central Europe, sandwiched between two anomalous troughs (low SLP) over the northeast Atlantic Ocean and northeastern Europe. It is likely that this ridge is linked to the low (dry) precipitation anomalies seen over the UK and France in this season. The implied anomalous southerly flow over western Europe may also contribute to the warm SAT anomalies. In summer, the pattern of SLP anomalies over North Africa, the northeast Atlantic and western Europe is again consistent between the two periods. The anomalous trough centred over western Europe is consistent with the band of high (wet) precipitation anomalies that stretches eastward from the UK through central and northern Europe. This pattern of anomalies is very similar to the summer NAO (Folland et al. 2009). In autumn, a dipolar pattern of SLP anomalies is located over Europe with an anomalous ridge over Scandinavia and northeastern Europe, and an anomalous trough over southern Europe, the Mediterranean Sea and North Africa. This pattern is again consistent with the pattern of precipitation anomalies (dry over Scandinavia and northeastern Europe and wet over central and southern Europe).

The consistency between the two warm North Atlantic periods in the patterns of anomalies in SAT, precipitation and SLP is strong circumstantial evidence that the North Atlantic Ocean was an important driver of these decadal changes in European climate. This hypothesis is supported by the correlations on decadal timescales between the AMO and indices of seasonal mean SAT, SLP and precipitation variability. Substantial further evidence for summer in particular is provided by the consistency between the observed pattern of anomalies, and patterns obtained in climate model simulations in which the Atlantic Ocean is unambiguously the driver responsible. Indeed, the pattern of anomalies shown for the recent warm period is entirely consistent with the prediction of Sutton and Hodson (2005) of 'increased [relative to 1961–1990] summer precipitation and temperatures in western Europe'. Put together, the evidence is compelling that the North Atlantic Ocean was indeed the driver of the shift in European summer climate that took place in the 1990s.

The anomalies found in the climate model simulations of Knight et al. (2006) for spring and autumn show some differences from those we have identified in the observations. The patterns of SLP anomalies are similar to Sutton and Dong (2012) over the North Atlantic (particularly for spring), but they differ over Europe. As expected, these differences in circulation anomalies are associated with different precipitation anomalies: in autumn, for example, the model simulations of Knight et al. (2006) show increased precipitation in northern Europe and decreased precipitation in southern Europe, whereas Sutton and Dong (2012) find approximately the opposite pattern. Sutton and Dong (2012) suggest that these differences may be caused by biases in the climate model used in Knight et al. (2006) Testing this hypothesis with other climate models is an important area for future work. An alternative hypothesis is that other factors, not included in the simulations of Knight et al. (2006), are important in spring and autumn; however, to account for the results, any such factors must vary in phase with the AMO.

Outlook

The results of Sutton and Dong (2012) provide evidence that the Atlantic Ocean is a key driver of decadal variability in the climate of Europe and other regions. They also suggest that the recent pattern of wet summers in northern Europe and hot, dry summers in southern Europe (and the related patterns of warm, dry, springs in northwestern Europe, warm dry autumns in Scandinavia, and wet autumns in southeastern Europe) may be expected to continue as long as the present warm phase of the AMO persists. However, it is uncertain how long this will be. This uncertainty reflects gaps in the understanding of the factors that drive the AMO. The evidence that the AMOC played an important role in the transition to a warm phase during the 1990s (Robson et al., 2012) suggests that the behaviour of the AMOC is likely to be one important factor for the future of the AMO. Some decline in the AMOC, favouring a return to the cool phase of the AMO, seems likely. Such a decline could arise as a response to the observed decline in the winter NAO index (Eden and Jung, 2001) following its peak in the early 1990s, or in response to recent and future surface warming (which acts to inhibit deep water formation in the subpolar North Atlantic). An interesting possibility is that the transition to a cool phase of the AMO—or part of such a transition—might occur rapidly, as seems to have occurred during the last transition from a warm to a cool phase (Thompson et al., 2010). Were this to happen, the results Sutton and Dong (2012) suggest that the consequences would include a rapid change in European climate, albeit one of uncertain magnitude.

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