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Temperature: Headlines

	What has happened	What could happen
Temperature *(more info)*	★★★ High Confidence Temperature has been increasing in Scotland in all seasons. The most rapid increase has been since 1980 and the last decade is the warmest on record.	★★★ High Confidence Average daily-mean, daily-minimum and daily-maximum temperatures will increase across Scotland, in all seasons. ★★☆ Medium Confidence The greatest change will be in summer.
Frost *(more info)*	★★★ High Confidence There has been a reduction in the number of days with frost in Scotland.	★★★ High Confidence It is expected that a typical winter will become milder, with an increase in daily minimum temperatures, implying reduced occurrence of frost. `Cold' winters will still occur, but will become rarer or less cold in the future.
Heatwaves *(more info)*	★★☆ Medium Confidence Identifying trends in heatwave occurrence is difficult due to high variability. There is some evidence of an increase in summer heatwave days since 1960.	★★☆ Medium Confidence As average temperatures increase, it is to be expected that what is considered a heatwave or extremely hot summer under present day conditions will occur more frequently in future. However changes in temperature variability would further affect heat waves. There is little evidence on this, or on specific measures of heat waves or hot summers, for Scotland.
Growing Season *(more info)*	★★★ High Confidence All regions have seen an increase of more than five weeks in the length of the growing season since 1961. The increase in the length of the growing season is part of a clear trend in all regions.	★★★ High Confidence The projected increase in spring and autumn temperatures will see the growing season continue to lengthen in the future

Temperature: Technical report

Contents

Overview 2
What has happened? 2
Global Context 2
Scotland 3
What might happen? 7
Global context 7
Scotland 7
Research Gaps 11
Data 11
References 12

Overview

This document reviews what is known about past and projected change in temperature and selected temperature indices in Scotland. Evidence is drawn from UKCP09, from the trend analysis conducted for Sniffer (2014) (the Climate Trends Handbook, cited throughout this document as CTH14), and from a limited number of journal articles which address temperature in Scotland or the wider UK.

Variability in temperature

Temperatures at any scale (from national to global, for example) vary naturally on all timescales, as well as gradually changing under the influence of larger changes. Particularly relevant to this document, there is variability from year to year ('interannual variability') and decade to decade. Different types of variability and the processes important for variability of climate in Scotland are discussed in more detail in an earlier ClimateXChange report. Changes in sea level pressure over the North Atlantic, quantified by the North Atlantic Oscillation (NAO) have a particularly large impact on winter temperatures in Scotland, with negative NAO winters tending to be cold, and positive NAO winters tending to be warm.

What has happened?

Global Context

Time series of global mean surface temperature show that temperature has increased since the mid-19th century (1850 or 1880, depending on data source; IPCC AR5 2013). The increase in temperature between 1880 and 2012 was 0.85°C, based on the average linear trend from three independent datasets (IPCC AR5, 2013). Further detail on the global context can be found in the IPCC (Intergovernmental Panel on Climate Change) fifth assessment report (AR5) "Summary for Policy Makers", and summaries thereof (e.g. Holmes, 2015).

The UKCP09 climate trends report (Jenkins et al, 2009) also gave global information, based on the IPCC fourth assessment report. However, IPCC AR5 contains newer information. First, it used data extended to 2010 to give updated values for the observed change in global mean temperature. It was also able, due to new scientific studies, to state with greater confidence (*extremely likely*, meaning at least 95% probability rather than *very likely*, meaning at least 90% probability) that human activity was responsible for more than half the observed global temperature rise in the more recent period. The core messages regarding temperature are unchanged between the reports.

It has been shown (e.g. IPCC AR5) using detection and attribution methodologies that the temperature increase since 1950 is consistent with human activity, in particular the increased concentrations of greenhouse gases in the atmosphere. The temperature increase is not consistent with only natural forcings, specifically volcanic eruptions and solar output variability. In addition to these forced changes, global mean temperature varies over time due to naturally occurring variability which is internal to the climate system. This includes the El Nino Southern Oscillation (ENSO).

2015 (the most recent complete year at the time of writing) was the hottest year on record in terms of global mean temperature, in three separate datasets which give temperatures back to 1850 or 1880 (WMO, 2016a). 2016 to date (to October) has been the hottest such period on record (NOAA, 2016); and 2016 is very likely to be hotter than 2015 and so the hottest year on record (WMO, 2016b). These two years are particularly warm due to a strong El Nino event superimposed on the ongoing warming trend. Other changes in the climate system associated with warming were also observed to continue in 2015 (extensive analysis can be found in 'State of the Climate in 2015', Blunden and Arndt, 2016)

Scotland

Sources of information and limitations

The Sniffer "Scotland's Climate Trends Handbook 2014" (hereafter CTH14) forms a major source of information for this document. This online resource quantifies trends in a number of variables both at grid box (5km x 5km) and regional ('East', 'West' and 'North'; see Figure 1) scale based on gridded data (Perry and Hollis, 2005). The time period covered by the CTH14 analysis varies between variables, beginning either in 1914 or 1961 and extending to sometime in the 21st century; therefore the reported periods in the current document vary somewhat between variables.

For each variable, extensive statements were made comparing seasons and regions, the key messages from which are referred to here. This provides a valuable resource for trends across the United Kingdom. However, care should be taken over the following points:-

Data quality. The quality of gridded data is limited by the spatial coverage of the underlying measurements, which are sparse for example in the Western Highlands. Although additional information is used in interpolation, for example the observed relationship that it is colder at higher altitude, the sparsity of underlying data remains a limitation.
Limitations of linear trends. Linear trends, while a useful summary of data, are affected by the end points (i.e., if a trend is calculated over a short period beginning in a particularly cold year, it may be exaggerated; if it is calculated over a period beginning in a warm year, it may be underestimated). CTH14 states statistical significance; the trends are significant if the probability that the calculated trend would be observed in a time series with no `real' trend is under 5%. However it does not give quantitative uncertainties on the estimated linear trend.
Interpreting regional and seasonal patterns. CTH14 trends are calculated for each gridpoint, region and season. The significance of difference between trends is not calculated, and as mentioned above uncertainties in trends are not calculated. Differences in trends should therefore not be over-interpreted. For example, for Scotland-mean temperature, the estimated change based on a linear

trend, for the 1961-2011 period, is 1.3°C (summer) and 1.0°C (autumn) (CTH14). It does not necessarily follow that it is valid to say 'the trend is greater in summer', as the estimates may be statistically indistinguishable.

These latter two limitations are raised here to guide the reader in understanding why greater emphasis is not placed on seasonal and regional differences in the present document.

Evidence from an extended temperature time series for Scotland (Jones and Lister, 2004, extended in Jenkins et al, 2009), and other results from the literature, are also reported in this document. These publications typically cover the period up to 2011 or earlier. Therefore cited trend values are not up to date. Notes on the five year period 2011-2016 are added in the present report based on regularly updated Met Office time series.

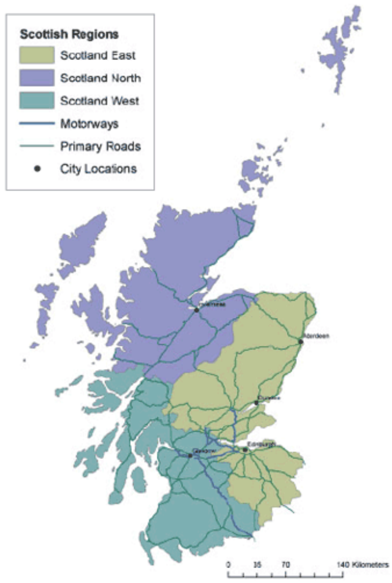

Figure 1. Scottish sub regions used in analysis in Scottish Climate Trends Handbook (CTH14). Graphic from *http://www.environment.scotland.gov.uk/climate_trends_handbook/index.html*

Mean Temperature

Linear trends derived from 5km UK gridded data (CTH14) suggest a statistically significant[1] warming of 0.7˚C over the period 1914-2011, and a greater warming of 1.3 ˚C for 1961-2011. Trends for the three sub-regions (Figure 1) differ by up to 0.2˚C from these national trends, but the analysis did not assess whether these differences are significant. The fact that the warming is greater for the shorter period demonstrates the nonlinearity of warming; generally, there was warming in the first part of the 20th century to the 1940s, followed by a period of relative cooling, and then a period of rapid warming since the 1980s and in particular during the 1990s (Figure 2). In addition to these variations on long timescales, there is significant year-to-year variability in Scottish-mean, annual-mean temperatures; the annual mean temperature of consecutive years may differ by well over 1˚C (e.g. Figure 2.)

[1] As can be seen from time series of weather data, such as in Figure 2, they display high year-to-year variability. When assessing whether this is superimposed on an underlying trend, assessment of statistical significance determines how likely it is that the calculated trend might be observed by chance and is therefore a measure of uncertainty, in some sense.

Three key results from CTH14 regarding seasonal and regional variation are as follows:-

- Statistically significant warming was observed in all seasons for both the shorter and longer periods.
- The non-significant warming in winter is as large as the significant warming in autumn and reflects the higher natural variability of temperature in the winter season.
- There is considerable seasonal and regional variation in trends, with the largest trends found in spring in southern Scotland.

Jones and Lister (2004) use the average of five representative meteorological observation stations from the Scottish mainland (Auchincruive, Eskdalemuir, Braemar, Wick, and Leuchars) to produce a timeseries of Scottish mainland temperature. The part of this dataset which is viewed to be high quality begins in the 1860s. In this dataset, the warming of annual mean temperature based on a linear trend over the period 1861-2000 is calculated to be 0.69 ˚C. For an equivalent dataset for

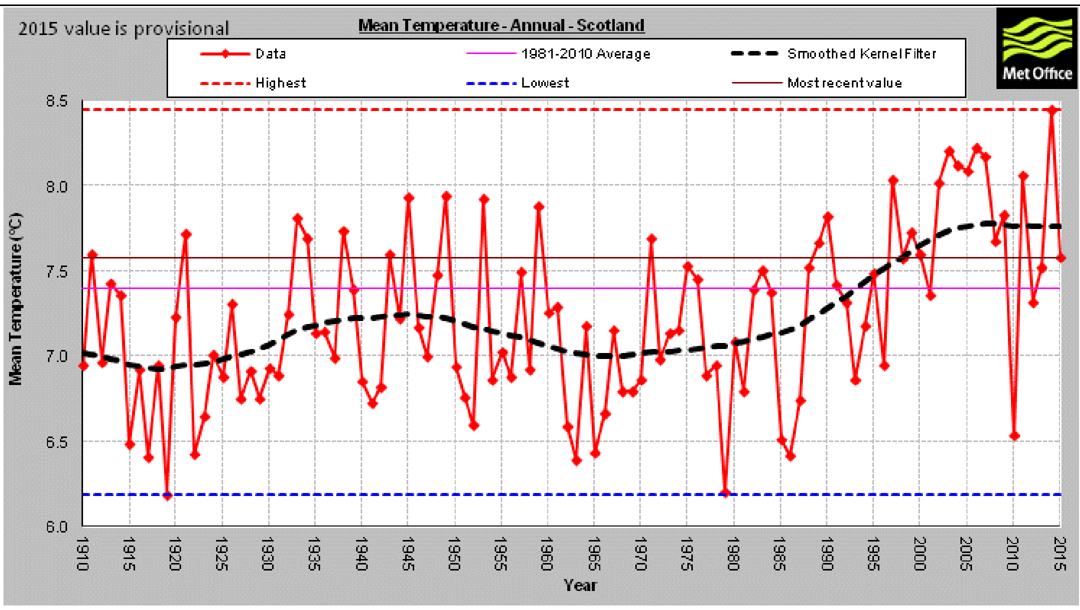

Figure 2 Mean Annual Temperature, Scotland, 1910 to 2015. (copyright Met Office). Available at http://www.metoffice.gov.uk/climate/uk/summaries/actualmonthly

Scottish islands, a warming of 0.64 ˚C was found (also based on a linear trend for 1861-2000).

Since 2010, four of five years (2012 is the exception) have had an annual mean temperature lying above the 1981-2010 average (approximately 7.4 ˚C; Figure 2), indicative of continued warming. 2014 was the hottest year on record in Scotland (Figure 2) and much of the UK. The Central England Temperature (CET; Parker et al 1992) monthly temperature dataset is a longer record than is available for Scotland, and is highly correlated with the Scotland mainland series (Jones and Lister, 2004). In CET, 2014 was the warmest year on record (i.e. since 1659; Met Office, 2015).

In contrast, the *coldest* years on record in Scotland occurred in the 19th century (Jones and Lister, 2004).

Mean Daily Maximum and Minimum Temperature

Meteorological observations typically record the minimum and maximum temperature recorded on each day. These may be more relevant for impacts (for example, implying frost incidence, or heat stress) than the daily-mean.

It is mentioned above, and shown in Figure 2, that mean temperatures display periods of warming or cooling lasting for a few decades ('multidecadal variability'). These same patterns are evident in the time series of maximum and minimum daily temperature. The following paragraphs give summaries based on linear trends.

Scotland-average daily maximum temperatures warmed by 0.8 ˚C in the period 1914—2011 and by 1.4 ˚C in the shorter period 1960—2011, a similar trend to that found in daily average temperatures. Over the longer period, summer and winter trends are non-significant; spring, autumn and annual trends are significant. Over the shorter period all trends are significant.

Scotland-average daily maximum temperatures warmed by 0.7 ˚C in the period 1914—2011 and by 1.1 ˚C in the shorter period 1960—2011, a similar trend to that found in daily average temperatures. Over the longer period, winter trends are non-significant and are approximately zero, and furthermore the annual trend is not significant in the North Scotland region. Over the shorter period, trends are significant except for in winter, but winter regional trends are positive (a warming of approximately 0.7 ˚C). Some gridboxes near Inverness have negative trends in winter daily minimum temperatures, and this region is well observed.

Temperature extremes (hottest day, heat waves, cold spells etc)

Of particular interest for many impacts of weather and climate are extreme periods; for example heat waves and cold spells. CTH14 analysed the duration of

- Summer heat waves, defined as a period of at least six days during summer where "the maximum temperature each day is more than the 1961 to 1990 average temperatures for those days by at least 3˚C."
- Winter cold spells, defined as a period of at least six days where "the minimum temperature each day is at least 3 ºC lower than the 1961 to 1990 average temperature for those days".

These metrics, analysed for the period 1961-2003, display a significant reduction in the length of winter cold spells, and an insignificant increase in the length of summer heat waves. (Intensity of the spells, i.e. exactly how hot or cold they were, was not analysed). The increase in summer heat wave duration occurs largely due to increases in the 1960s and early 1970s. Many years have no heat waves or, particularly in recent years, cold spells, so calculating trends is potentially problematic. A strong case could be make for extending the analysis to the present, and analysing other indices for heat waves and cold spells. For example approaches could include using a more recent climatology or an impact-driven threshold, including analysis of intensity, or analysing extremes in other seasons.

Frost

Two types of frost are covered by the gridded climatologies and trend calculations discussed above:-

- **Air frost** occurs when the daily minimum temperature at 1 m above the ground is below 0˚C
- **Ground frost** occurs when the daily minimum grass temperature is below 0˚C

Ground frosts are directly impact-relevant in terms of their impact on crops or risks to infrastructure. Ground frosts are also more common than air frost. In the period 1961-2010, the Scottish-average annual number of air frosts ranged between 36 and 96 while the annual number of ground frosts ranged between 91 and 153.

The incidence of frost decreased in the period 1961-2010. Reductions in ground frosts appear to have been slightly larger than reductions in air frosts.

Growing Season Length

Growing season length is a useful index for agriculture, defined as the number of days between the start and end of the growing season. It was used for example in CTH14 where the start of the growing season was defined as "the fifth day in a row from 1 January which has an average daily temperature of 5ºC or greater" and the end was defined as "the fifth day in a row from 1 July with an average temperature of 5ºC or less". The Scottish mean growing season length in the period 1961—1990 was approximately 245 days (~8 months) (CTH14) although the growing season is shorter in colder regions such as the highlands. One limitation of the definition is that cold spells in early Spring after an initial warm period would not prevent the growing season being defined as having started.

Linear trends as calculated in CTH14 show that the average growing season length in Scotland increased by approximately 5 and a half weeks (38.3 days) between 1960 and 2003 (statistically significant increase). Increases were larger (in some locations, increases of over two months) in many coastal areas, the Shetlands and the Hebrides, but negligible or even slightly negative in some regions of the highlands and the west.

What might happen?

Global context

The IPCC Fifth Assessment report Summary for Policy Makers (IPCC, 2013) gave various conclusions based on four different emissions scenarios for the period 2010-2100, known as representative concentration pathways (RCPs). The RCPs are RCP2.6 (weakest, largely assumes negative emissionsat some point in the 21st century and is inconsistent with emissions since 2010), RCP4.5, RCP6.0, and RCP8.5. IPCC (2013) concluded that:-

- "Global surface temperature change for the end of the 21st century is *likely* [>66% probability] to exceed 1.5°C relative to 1850 to 1900 for all RCP scenarios except RCP2.6.
    - It is *likely* to exceed 2°C for RCP6.0 and RCP8.5, and *more likely than not [>50% probability]* to exceed 2°C for RCP4.5. Warming will continue beyond 2100 under all RCP scenarios except RCP2.6.
    - Warming will continue to exhibit interannual-to-decadal variability and will not be regionally uniform."
- "Cumulative emissions [rather than e.g. rate of emissions] of CO_2 largely determine global mean surface warming [for fixed climate sensitivity] by the late 21st century and beyond".
- Continued emissions of greenhouse gases will cause further warming and changes in all components of the climate system. Limiting climate change will require substantial and sustained reductions of greenhouse gas emissions."

Scotland

In addition to the above statements regarding warming of global mean temperatures, the IPCC's Fifth Assessment Report (AR5) states that it is:

- "Very likely that temperatures will continue to increase" in Europe; and,

- “likely that winter mean temperature will rise more in NEU [Northern Europe] than in CEU [Central Europe] or MED [the Mediterranean]” and the opposite is true for summer.

This section contains some information for the UK as a whole, as there is a broader evidence base, and findings for the UK may be applicable to Scotland.

Sources of information and continued validity of UKCP09

The majority of the information in this section comes from UKCP09. Sexton et al (2016) have evaluated the validity of UKCP09 projections in the light of new information from UKCP09. For annual, summer and winter mean temperatures, the UKCP09 range of temperature projections is still valid.

Mean Temperature

Projections for change in climatological (30 year average) mean temperature were produced as part of UKCP09. (The consequences for temperatures in individual years and seasons are discussed in later sections).

Table 1: The projected change in temperatures from UKCP09 for the period 2040-2069 ('2050s') and 2070-2099 ('2080s') relative to the baseline period 1960-1989. The central estimate is in bold, and lower (10% probability of smaller change) and upper (10% of greater change) uncertainty bounds, in brackets. Given for medium emissions scenario (A1B).

		East Scotland	North Scotland	West Scotland
Summer mean temperature	2050s	**+2.3°C** (1.1,3.9)	**+2.0°C** (0.9,3.4)	**+2.4°C** (1.1, 3.8)
	2080s	**+3.5°C** (1.8,5.7)	**+3.0°C** (1.5,4.9)	**+3.5°C** (1.8, 5.4)
Winter mean temperature	2050s	**+1.7°C** (0.7,2.9)	**+1.6°C** (0.6,2.8)	**+2.0°C** (1.0,3.0)
	2080s	**+2.2°C** (1.0,3.7)	**+2.2°C** (0.9,3.6)	**+2.6°C** (1.4,4.0)

The projections from UKCP09 for each region are shown in Table 1; these are temperature changes relative to the period 1961-1990 under medium emissions (A1B). The central estimate is for winter warming of 2.0ºC or below and summer warming of 2.0ºC or above by the 2050s, increasing by the 2080s. Significant uncertainty, of 1 to 2 ºC either way, exists around these estimates, but confidence is high that the direction of change will be warming. Average daily-maximum and daily-minimum temperatures are also projected to increase.

These projected anomalies are given relative to 1961-1990. The 1981-2010 average temperature is warmer than that in 1961-1990 (Figure 3) in every month except October and December, for each region. Therefore the best estimate of change relative to `current’ climate, of which the 1981-2010 average is a better measure, is a few tenths of a degree less than that in Table 1.

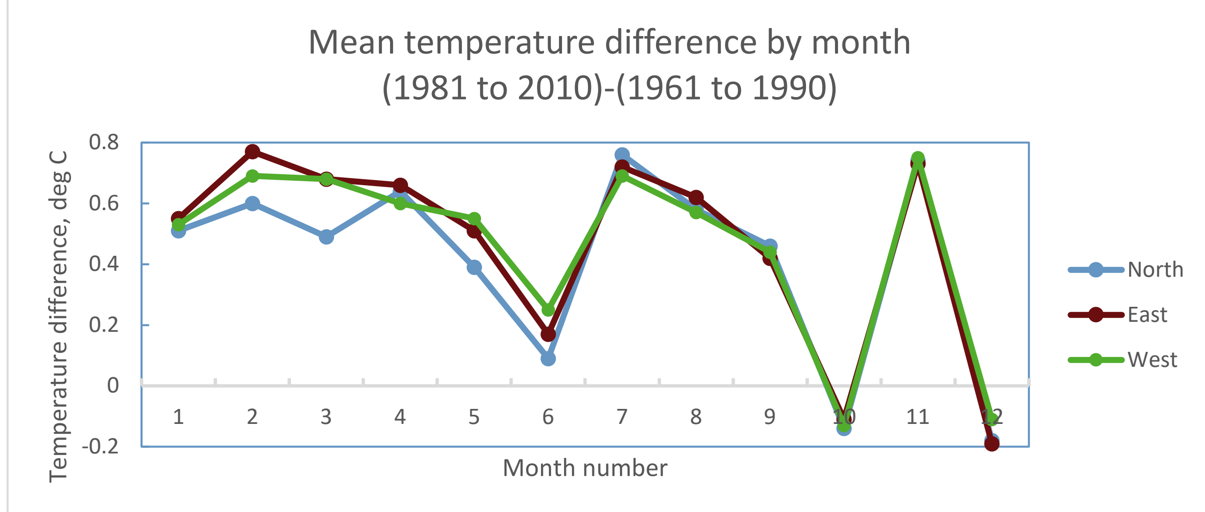

Figure 3: Difference in climatology between 1961-1990 and 1981-2010, for each Scottish administrative region. Produced from UK Climate Projections Data, © Crown Copyright 2009; see "Data" section below for full citation.

Hot summers and cold winters

The projections in the previous section cover the range of outcomes possible for the change in 30-year average temperature. Due to year-to-year variability in temperature, individual years may have a broader range of expected temperature anomalies. Sexton and Harris (2015) extended the UKCP09 analysis to investigate, for England and Wales, the probability of an individual year being colder or hotter than past climate (their Figure 2). Therefore, while the table above shows that it is virtually certain that future climate (30-year average temperature) will be warmer than that in the past, there is a non-zero probability that an individual year within a future thirty-year period would be colder than past climate. That is, we might still expect `cold winters' or `cool summers', although they will become less cold, and less likely, as the 21st century passes. Likewise, hot summers and mild winters will become hotter, and more likely. Unfortunately this analysis is not available for Scotland so it is not possible to quantify these probabilities.

Stott et al (2004) analysed the extremely hot summer of 2003 for southern Europe (south of 50N). They found rapid increases of the expected frequency of such a hot summer in the future. The emissions scenario and region they analysed gave much larger warming than that shown in Table 1 for Scotland. Therefore, the quantitative results of their analysis are unlikely to be appropriate for Scotland, but the general conclusion is likely applicable.

Heat waves and cold spells

Projections of changes in heat wave and cold spell frequency depend on the definition of heatwaves.

As the mean temperature increases in each season, it may be expected that what is currently viewed as a heat wave (i.e. days above a fixed temperature) becomes more frequent, and what is currently thought of as a cold spell becomes less frequent. The mean changes also lead to the expectation of changes in how *intense* hot and cold spells are; it may be expected that the hottest days or periods become hotter and the coldest days or periods become milder. UKCP09 provides projections of the hottest day of summer, and the coldest day of winter. The uncertainty around these changes is much large than those around mean changes, due to their extreme and therefore rare nature.

However, heat waves and cold spells may also be defined according to the climate in which they occur, for example '3°C above the long term (30 year) mean'. In this case, as the underlying long term mean warms, it is the variability of temperature about that mean that affects heat wave frequency (and equivalently for cold spells). Projections of such measures of heat waves and cold spells were not produced as part of UKCP09 and have not been assessed for Scotland.

There is some evidence in the literature that variability of temperatures at various timescales in winter will decrease in Scotland in the future. For example there is evidence of future changes in variability of 5-day-mean temperatures (de Vries et al, 2012) which could imply a reduction in cold spells. This has been linked to the fact that, as the Arctic warms more than lower latitudes, the effect of changing wind direction on temperature is reduced (as 'cold northerlies' become less cold).

For summer, there is evidence of projected increases in summer temperature variability in Europe on day-to-day or year-to-year timescales (e.g. Fischer et al, 2012), which might imply an increase in heat waves. However, this evidence on this is weak for Scotland relative to other locations in Europe. It has been physically linked to land surface feedbacks and reductions in soil moisture, the relevance of which to Scotland merits further work.

A recent document by the Met Office (2015) produced H++ scenarios, namely, representative cases of "plausible high-end climate change scenarios" in order to inform adaptation planning. This included what a hot summer or hot day could be like in the 2080s under a high emissions scenario. Again, these are plausible scenarios and not projections. For Scotland, this scenario was found be above 28°C (south and east) or 26°C (west and north away from coastal areas) for a hot summer; and above 32°C for a hottest day in most of Scotland, with the far south east of Scotland potentially having temperatures above 38°C. A similar analysis was done for cold-weather (this time under a low emissions scenario), but regional information was not given in this analysis.

Further work on both cold spells and heat waves would be required to reduce the uncertainties around future changes in hot and cold spells in Scotland, and prior work would need to determine what thresholds or type of events were of interest.

Growing Season Length

The growing season would be expected to lengthen with increases in mean temperature in spring and autumn, as these are the seasons in which the growing season currently begins and ends. Harding et al (2014) examined the average projected change in a number of regional climate models, and found this ranged from approximately 0 days in the highlands to an increase of 50 days in certain areas of the lowlands. However, these findings do not give the uncertainty in spatial projections and used a higher threshold (5.6˚C) for the growing season than CTH14.

Frost

(Snow is covered in our Precipitation report)

There is a projected increase in average daily minimum temperature. This would be expected to reduce the incidence of frost. For example, the UKCP09 projection is that it is unlikely (less than 10% probability) that winter-mean daily-minimum temperature will change by less than +0.4 ˚C for any grid box in Scotland by the 2050s (2040-2069, relative to 1961-1990). However, there are not quantitative probabilistic projections of days of ground or air frost, either for Scotland as a whole or for individual locations.

To obtain projections of frost would require new work. A possible route would be to estimate of future frost occurrence from the weather generator or directly from climate model data. However estimation of changes in days below a threshold is very sensitive to model biases in temperature mean and variability so these biases would have to be accounted for. An alternative route would be to build an empirical model of 'days of frost', for example as a function of monthly mean temperature, to gain a first estimate of future frost days from the UKCP09 projections.

Harding et al (2014) examined future changes in accumulated air frost in the HadRM3 model underlying UKCP09. Accumulated air frost takes account not only of the number of days of frost but of their severity. However, there are limitations in the methodology used; it does not apply any bias correction to the underlying temperature distribution, which is known to be biased cold over much of Scotland.

Research Gaps

As stated in the text above, there is an absence of literature on projections of temperature extremes and particular temperature thresholds (such as frost) for Scotland.

Regarding hot or cold spells of various duration, research done for continental Europe is likely not to be applicable for Scotland due to the large maritime influence on Scotland, in contrast to the continental interior, such that different mechanisms may lead to hot and cold spells. This distinction even applies when comparing Scotland, particularly the west, to south east England. The UKCP09 probabilistic methodology could potentially be extended to considering individual summers or winters, following Sexton and Harris (2015).

For specific metrics, such as growing degree days or frost days, future projections would require new analysis including careful treatment of biases in climate models. The best methodology for bias correction is the subject of current research. In all the above cases, work should be motivated by understanding of impacts, which may require new work; for example, the relevant temperature threshold for dangerous heat waves is not necessarily well established in Scotland, in comparison to other countries where heat waves are already a major concern.

Data

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