Scotland's centre of expertise connecting climate change research and policy

Precipitation: Headlines

Including rain, snow, fog, and hail

	What has happened	What could happen
Rainfall *(more info)*	★★★ High Confidence Rainfall has increased in Scotland since 1960. The strongest positive trend was between 1970 and 1990. Longer time series also show increases in precipitation. Since 1960, there have been increases in heavy winter rainfall and days of heavy rain in winter. An increasing proportion of rainfall has been coming from heavy precipitation events. There is no clear trend in summer rainfall over the last century.	★★☆ Medium Confidence Average winter rainfall is projected to increase. Increases in the intensity of daily to multi day extreme precipitation are also projected for winter, spring (medium confidence) and autumn. ★☆☆ Low Confidence Changes in summer rainfall, both average and extreme, are uncertain. Changes in sub-daily precipitation extremes in any season are currently beyond the scope of projections for Scotland.
Snow *(more info)*	★★★ High Confidence The number of days of snow cover has reduced in all seasons, although the trend is only statistically significant in Autumn. Some localised increases exist, due to increases in winter precipitation.	★★★ High Confidence Projected increases in temperature are projected to lead to reduced snow frequency. However, there is low confidence in the magnitude of these reductions. Projected increases in precipitation are a confounding factor.
Drought *(more info)*	★☆☆ Low Confidence There is a lack of studies assessing trends in the occurrence or magnitude of meteorological drought over the twentieth century.	★☆☆ Low Confidence There is limited evidence regarding future changes in meteorological drought in Scotland.
Hail and Lightning	★☆☆ Low Confidence There are not sufficient observations for assessment of past trends in either hail or lightning.	★☆☆ Low Confidence An increase in frequency of days with thunder (from which lightning is inferred) is projected for Scotland. Results for elsewhere within the UK may not be relevant for Scotland, particularly North West Scotland. Despite projected increases in intense convective storms, one study indicates a reduction in damaging hail.
Fog	★☆☆ Low Confidence There is no evidence on historical trends in fog.	★☆☆ Low Confidence Model simulations suggest future reductions in fog occurrence, but evidence is limited.

Precipitation: Technical Report

Contents

Processes Affecting Precipitation

Spatial Patterns

A map of annual precipitation in Scotland reveals clear spatial patterns. These are dominated by

- The effect of orography (hills and mountains), such that precipitation is enhanced on the upwind side of orography
- A west-east gradient; more rain falls in the west, whereas the east is relatively sheltered from incoming weather systems from the North Atlantic.

Winter

In winter, rainfall (and snowfall) in Scotland is frequently associated with mid-latitude depressions, also known as 'extratropical cyclones' or just 'storms'. The number and behaviour of these storms varies considerably year-to-year and even month-to-month.

The North Atlantic Oscillation (NAO, e.g., Hurrell et al, 2003) is a characteristic pattern of sea level pressure in the North Atlantic and Europe, and can be described as a north-south 'see-saw' of pressure. It is associated with variation in the tracks of storms across the Atlantic. A common index of the NAO is the difference in sea level pressure between the Azores or Portugal and Iceland; when this difference is larger than normal, the NAO is in its positive phase, and northern Europe including Scotland is warmer and wetter than average, and vice versa. In the 20th century, the NAO explained

- 23% of precipitation variability in December, 37% in January and 31% in February in a grid box covering south east Scotland
- 40% of precipitation variability in December, 56% in January and 54% in February in a grid box covering the Hebrides

and intermediate percentages in North Scotland and the Shetlands (Murphy and Washington, 2001). This demonstrates the spatial differences in the influence of the NAO. Future changes in the NAO and related processes are discussed in a separate report.

The west coast of Scotland and the western isles may also have convective showers in winter, due to the warm sea surface (Met Office: UK Regional Climates, cited 2016).

Summer

Scotland is subject to precipitation from midlatitude depressions in summer (as well as in winter), to a greater extent than elsewhere in the UK. Convective showers triggered by heating of the land surface also occur, but severe convective storms are much more infrequent than is the case in southern England (Met Office: UK regional climates, cited 2016).

The summer north Atlantic Oscillation (SNAO; Folland et al, 2009) is the leading pattern of variability of summer sea level pressure across the North Atlantic and Europe. Positive SNAO (SNAO+) is characterised by a positive sea level pressure anomaly centred on the North Sea. There is a strong correlation between the SNAO and precipitation in Europe; in Scotland, a positive SNAO is associated with dry conditions and clear skies. The SNAO here explains around 40% of the variance in high summer (July and August) precipitation.

Challenges in Interpreting Trends: Variability and Signal to Noise

There is very large natural internal variability (i.e., variability arising even without the need for external drivers such as volcanic eruptions or greenhouse gas emissions) on various timescales in precipitation in Scotland. For example, from year to year, or even from decade, the amount of precipitation in Scotland can differ greatly even in the absence of externally forced trends (i.e. average changes resulting from causes such as climate change.) Therefore even where such trends are present, they can be hard to identify due to their small magnitude relative to natural variability (this is known as a small 'signal to noise' ratio). Related to this is the idea that even if there is a trend towards, say, wetter winters on average, individual winters in the future might still have rainfall totals which we would consider a 'dry year' in current climate (Sexton and Harris, 2015).

Scope of Report

This report covers changes in rain, snow, hail and fog. Some findings relevant to river flows and drought are briefly mentioned but since these are affected by drivers other than climate alone, this is not done in depth. Research related to changes in the North Atlantic storm track and North Atlantic Oscillation is also covered elsewhere.

What has happened?

Scotland

Sources of Information and Limitations

This section on past change uses largely the Sniffer "Scotland's Climate Trends Handbook 2014" (Sniffer 2014, hereafter CTH14), as in the accompanying Temperature technical report. CTH14 quantifies recent linear trends in variables both on a 5km x 5km grid and for three Scottish regions; East, West and North. The reader should be aware of limitations, discussed in detail in the accompanying 'Temperature' report, regarding 1) gridded data quality, 2) the limitations of linear trends, and 3) the required caution when interpreting regional and seasonal trend variations. Despite these limitations, CTH14 constitutes the best available source of data. The periods discussed below are those analysed in the cited documentation.

Average Rainfall

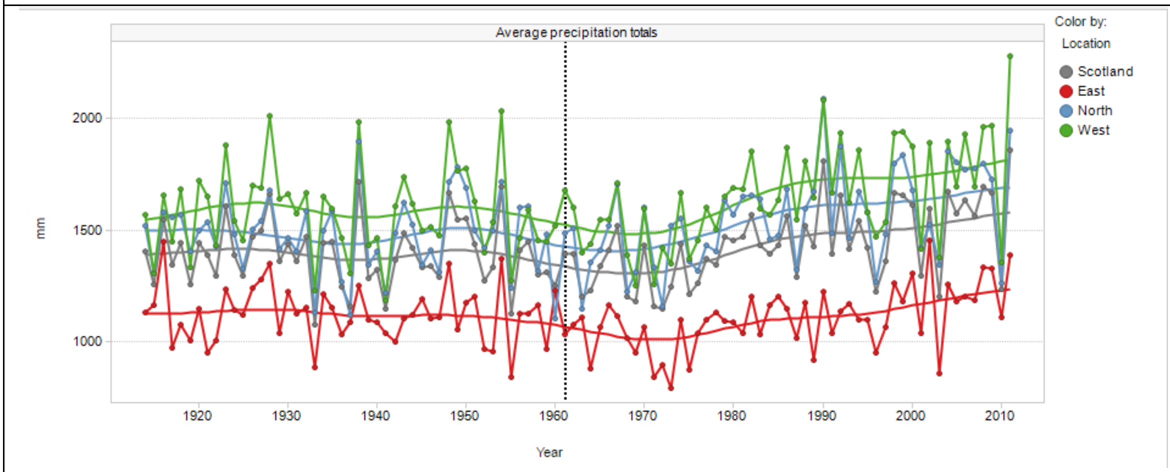
In the period 1961 to 2011, there was a statistically significant increase in average annual rainfall in all three sub regions of Scotland. For Scotland-average rainfall, the increase was 27%, based on a linear trend.

Seasonally, winter rainfall has increased most, especially in the North (51%) and West (45%) compared with the East (24%). (As stated in the accompanying Temperature report, regional differences in trends should not be over-interpreted.) In spring, summer and autumn there is also an increasing trend in this period, although it is significant only for some regions and seasons. Moreover, not every gridpoint has a trend of the same sign as the regional averages. Consistent with this evidence for differing trends between seasons, Afzal et al (2015) found a positive trend in the difference between winter and summer rainfall in Scottish weather station data since 1961.

For the longer period 1914-2011 there are also positive trends in the annual average, winter, spring, and autumn. These trends are weaker than over the short period, and are not significant in the East. There is a non-significant negative trend in summer rainfall for the period 1914-2011.

The sensitivity of estimated trends to the choice of analysis period is related to the high variability of rainfall, on timescales of years to decades (Figure 1). 30-year running averages of annual rainfall are approximately constant or declining slightly between 1914 and 1970 before increasing to the present, particularly between 1970 and 1990 (Figure 1). This highlights the limitations of estimating linear trends.

Figure 1: Total Precipitation (mm) each year for Scottish regions, 1914-2011. Smoothed curve shows 31-year running average centred on target year. (CTH 2014, © Sniffer and Met Office)



Extreme high rainfall

CTH14 assessed two measures relating to heavy rain

- The number of days of with more than 10 mm rainfall, termed 'days of heavy rain' (seasonal and annual, 1961-2011)
    - There has been a statistically significant increase in days of heavy rain annually, and in winter, although in the East in winter changes are non-significant.
- The maximum 5-day precipitation total (annual only, 1961-2004)
    - There was an increase in maximum 5-day precipitation over this period in each region. Absolute precipitation changes are very similar between the regions, although percentage changes differ. The Scotland-average increase was 21%. This cannot be directly compared with the increase in average rainfall, as the final year in the timeseries differs; it is 2004 for average precipitation and 2011 for maximum 5-day precipitation. A series of wet years between 2005 and 2009 is likely to have affected the trend in average rainfall. There is some evidence that for some grid points in the far North of Scotland, 5-day total precipitation has decreased.

For both these measures, changes are most notable in the period 1970-1990, as is the case for average rainfall. Jones et al (2013) examined changes in seasonal and annual maximum 1-, 2-, 5- and 10-day rainfall totals in the period 1961-2009. For Scotland they found significant increases in the average annual, spring and winter maximum at each duration, and also in autumn for East and South but not North Scotland. They also found significant increases in the magnitude of the estimated 10-, 25- and 100-year events in autumn and winter; implying an increase in the most extreme autumn and winter multi-day rainfall totals. There is also evidence of increases in the upper percentiles of rainfall in winter (Simpson and Jones, 2014) and in the percentage of seasonal rainfall coming from individual days of heavy rain (Maraun et al, 2008) in all seasons except summer. There is some evidence of decreasing intensity of rainfall in summer.

Flood

The increases in rainfall and extreme rainfall described above (except in summer) lead to the question of whether flooding events have become either more extreme or more frequent. Floods are by nature extreme and generally rare events, so it is challenging to assess trends. Moreover, flooding is affected not only by weather and climate drivers but also by catchment properties and human interaction with catchments, such that an assessment is much broader than the scope of this report. This section only notes a few studies related to river flows.

An assessment of river catchments relatively unaltered by human activity (Hannaford and Buys, 2012) found increasing trends in median and high flows in Scotland. This is more marked than elsewhere in the UK, where patterns are mixed, especially in summer. Marsh and Dixon (2012), aggregating over catchments, also found statistically significant positive trends in annual, winter, and high flow runoff in Scotland, and statistically insignificant trends in other seasons. Hannaford (2015) discusses trends in river flows and the extent to which they can be linked to climatic factors more fully.

Drought

Evidence of historical changes in drought is lacking. Drought is a complex combination of factors and may be analysed in terms of

- precipitation deficit, its underlying driver
- other meteorological indices, such as aridity, which incorporate temperature and therefore evaporation
- river flows or soil condition; these are also affected by human activity, for example land management practices

CTH analysis of trends in the *maximum number of consecutive dry days in a season* did not provide evidence of trends between 1961 and 2005. However, consecutive dry days do not provide a measure of drought as long dry periods may contain individual wet periods, and evaporation as well as precipitation is key to drought conditions.

Previous reviews of evidence found “little evidence of changes in very low flows and no clear pattern of droughts” (Watts and Anderson, 2013). River flow analysis for 31 Scottish catchments since 1961 found very little evidence of change in severity of low summer flows (SEPA, 2015). However, trends in flow are affected by human activity as well as climate drivers alone, and so a fuller assessment is again beyond the scope of this report.

Hail

In the UK the observational record of hail is restricted to reporting (rather than any automatic observation system, for example). This makes it challenging to assess for trends, since there are potential inconsistencies over time (Webb et al, 2009) and biases towards regions of dense population. Reported hail frequency varies from decade to decade; this may have both meteorological and human factors. For the UK as a whole, hail is most frequent in March, but hail of a size likely to cause damage to crops (diameter above 15 mm) is most common in early summer (Webb et al, 2009). This seasonal distribution may be slightly different for the north-west and west coast of Scotland. Damaging hail is rare in Scotland (Webb et al, 2009) and within Scotland, most common in the south.

Lightning

Lightning is associated with convection in thunderstorms. Cloud-to-ground lightning constitutes only a percentage of the total amount of lightning occurring in the atmosphere, but is of most interest for the potential damage it can cause to infrastructure, crops and people. Lightning is also chemically important, as it results in the release of nitrogen oxides and thereafter ozone (Price, 2009). The global occurrence of lightning is dominated by tropical regions (so few studies have addressed it in regions such as Scotland) and lightning is also more frequent over land than ocean.

Traditionally, the occurrence of lightning was measured through "days of thunder" (e.g. Boorman *et al*, 2010a). This is a subjective measure, where a meteorological observer notes whether they have heard thunder on a day or not. More recently, automatic lightning detection systems have been used, such as the Arrival Time Difference (ATD) network used by the Met Office since 1986 (Holt et al, 2001), which gives more detailed and objective information. A climatology of `days of lightning' for the 1990s (Holt et al, 2001) shows a strong seasonal cycle of lightning in south-east England and to a lesser extent southern Scotland, with most lightning associated with summer convective thunderstorms. However, their climatologies, the thunder climatology of Boorman et al (2010a), and Met Office monthly thunder observations suggest that on the Scottish west coast, winter storms linked to the large scale circulation cause as many days of lightning as summer storms.

There is no published information on trends in either lightning or thunder incidence over the UK. Updates to the ATD network over time have increased its sensitivity (Owens *et al*, 2014) so there are artificial steps in lightning frequency. The `days of thunder' record is longer, but this measure is dependent on the observer. Therefore there is no suitable long record of lightning or thunder for trend analysis.

Snow

The snow climate of Scotland has implications for ecosystems, tourism, and winter infrastructure. It is also important for hydrology, because snow constitutes water storage in the landscape and snow melt may contribute to flood events. Evidence on trends in snowfall is restricted to lying snow, i.e. days when at 9 UTC 50% of the ground is covered by snow. The Climate Trends Handbook shows a reduction in days of lying snow in the period 1971 to 2011, in both the full extended winter season (September to May) and each season (autumn, winter and spring) although there is a statistically significant trend only in Autumn. There is evidence of increases in days of snow cover in coastal and lowland regions. Spencer et al (2014) conducted a detailed analysis of the area around Dalwhinnie. They showed that the UKCP09 data, used for example in the CTH, does not capture high-elevation snow and the elevation dependence of snow well. Snow modelling work (Spencer, 2016) suggests that while there are widespread reductions in snow cover, some high-elevation areas have seen increases in snow cover. These may be linked to the fact that recent climate trends are towards both higher precipitation and warmer temperatures; in high-elevation regions, temperatures remain sufficiently cold that the increase in precipitation may be the dominant driver of changing snow cover.

Fog

Meteorological observers record visibility and the occurrence of fog (visibility less than 1km), usually not more than once each day. Some types of fog are also highly spatially and temporally localised, so such observations do not easily lead to knowledge about fog at other locations. Therefore, there is no gridded dataset of fog for the United Kingdom from which to compute trends. A handful of studies (e.g., Doyle and Dorling, 2002; Vautard et al, 2009) have assessed trends in visibility, rather than fog specifically, at sites in Europe including the UK. These have found an increase in visibility since the 1970s or 1980s (the date is location dependent). This increase has been linked to reductions in aerosol pollution rather than to meteorological or climatological effects.

What might happen?

Global context

Averaged over the globe, precipitation is projected to increase, with an intensification of the hydrological cycle such that both precipitation extremes and meteorological drought (precipitation deficit) would become more intense. Strong regional variations exist in these projections; regions such as the dry subtropics are projected to receive less rainfall in future. Moreover, regional precipitation changes are dependent on uncertain changes in circulation; for example, movement in the favoured paths of midlatitude storms could affect the direction of change in precipitation for regions affected by these systems. There is considerable uncertainty in regional rainfall projections.

Scotland

Sources of Information

The majority of the information in this section comes from UKCP09 and from studies of output from global and regional climate models, either those used in the development of the UKCP09 projections or different sets. The regional model used in the development of UKCP09 is called HadRM3. Eleven slightly different variants (or 'members') of HadRM3 were used. This group of eleven variants is referred to as the perturbed parameter ensemble. The resolution in the regional model is 25km, meaning that gridboxes have sides of length 25km.

Average Rainfall

The IPCC fifth assessment report states 'medium confidence' in an increase in annual mean precipitation in Northern Europe. This is linked to temperature, as warmer conditions cause an increase in atmospheric moisture and possibly in extra-tropical cyclone activity. There is seasonal variation; it is most likely to become wetter in winter, but projections are very uncertain in summer.

An increase in winter precipitation is fairly certain in UKCP09. Central estimates in UKCP09 for the 2080s are; greater than 20% increase in the west, 12% in the east and 17% in the North. There is a range of feasible possibilities from little change in the East, to 40% increase in the west. CMIP5 models assessed for IPCC AR5 also give a consensus for winter rainfall, with a likely increase of 0—20%, adding confidence to this projection.

Table 1: The projected percentage change in mean seasonal precipitation 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% probability of greater change) are in brackets.

		East Scotland	North Scotland	West Scotland
Summer mean precipitation	2050s	**-13.4%** (-27.3%, +0.8%)	**-10.7%** (-23.7%, +1.8%)	**-12.9%** (-26.5%, +1.0%)
	2080s	**-16.7%** (-33.5%, +0.4%)	**-11.9%** (-28.7%, +4.2%)	**-16.1%** (-32.5%, +0.6%)
Autumn mean Precipitation	2050s	**+6.2%** (-4.6%, +19.0%)	**+12.5%** (-0.9%, +28.3%)	**+13.5%** (-0.9%, +30.8%)
	2080s	**+9.0%** (-4.2%, +25.5%)	**+19.0%** (+2.3%, +39.6%)	**+20.6%** (+2.5%, +43.4%)
Winter mean Precipitation	2050s	**+9.7%** (+1.3%, +19.9%)	**+12.7%** (+3.5%, +24.1%)	**+15.4%** (+5.1%, +28.6%)
	2080s	**+11.7%** (+1.3%, +25.2%)	**+17.5%** (+4.4%, +34.6%)	**+21.4%** (+6.0%, +42.1%)
Spring mean precipitation	2050s	**+2.1%** (-5.4%, +10.2%)	**+2.5%** (-5.9%, +11.6%)	**+3.0%** (-6.3%, +13.1%)
	2080s	**+2.8%** (-3.9%, +10.1%)	**+2.2%** (-7.6%, +12.8%)	**+2.6%** (-8.4%, +14.6%)

Summer rainfall projections are uncertain. The Mediterranean region is expected to dry, but model simulations do not show the northern-most extent of the drying region with certainty, and this could extend into the UK (Murphy et al, 2009). The central estimate in UKCP09 under medium emissions is for a reduction of around 11-16% by the 2080s for the three Scottish regions (Table 1, second row of results). However, the range of projections covers a decrease of 30% up to no change. For Scotland as a whole, the newer CMIP5 models, contributing to IPCC AR5, give even less confidence in summer precipitation reductions than the earlier UKCP09 shown here.

For both seasons, projected changes for the 2050s are only slightly weaker and only slightly less uncertain than for the 2080s (Table 1). In Autumn and Spring, UKCP09 also projects increases in precipitation although this is uncertain in particular in Spring.

Given the importance of the summer North Atlantic Oscillation for precipitation over Scotland, it is perhaps not surprising that the trend towards dry summers, and the uncertainty in this trend, in CMIP3 models is strongly affected by the magnitude of positive trends in the SNAO (Blade et al, 2012).

Extreme rainfall

The 'wettest day of a season' (the 99th percentile of daily rainfall totals) is a UKCP09 variable. For winter, UKCP09 implies an increase in precipitation on the wettest day of the season, with a central estimate, for regional means, of up to 10% in the 2050s and up to 13% in the 2080s (Table 2 for these results and those for other seasons). The uncertainty ranges are larger than those for mean change, and span zero change in all locations. Regional mean results in spring and autumn are qualitatively similar to those in winter.

In summer, results are more uncertain; the central estimate is for a small increase in rainfall on the wettest day; the regional mean projection for the 2050s is +0.5% in East Scotland, +2% in North Scotland and 0.3% in West Scotland. Much larger increases in summer wettest-day precipitation are however possible, as are large decreases.

*Table 2: As Table 1 but for the projected percentage change in precipitation on the **wettest day of a season**.*

		East Scotland	North Scotland	West Scotland
Summer wettest day precipitation	2050s	**+0.5%** (-9.6%, +11.8%)	**+2.1%** (-9.1%, +14.2%)	**+0.3%** (-10.1%, +11.2%)
	2080s	+**1.6%** (-9.8%, +14.9%)	**+4.1%** (-9.3%, +18.5%)	**+1.5%** (-10.0%, +13.2%)
Autumn wettest day precipitation	2050s	**+8.5%** (-4.8%, +24.4%)	**+9.7%** (-4.4%, +26.6%)	**+10.1%** (-5.0%, +28.3%)
	2080s	**+12.6%** (-3.3%, +32.5%)	**+14.3%** (-2.8%, +36.1%)	**+14.9%** (-3.2$, +38.3%)
Winter wettest day precipitation	2050s	**+9.5%** (+1.0%, +19.6%)	**+6.0%** (-3.4%, +16.7%)	**+8.4%** (-1.7%, +20.4%)
	2080s	**+13.3%** (+3.3%, +26.2%)	**+8.7%** (-1.6%, +21.0%)	**+12.3%** (+0.7%, +27.0%)
Spring wettest day precipitation	2050s	**+4.4%** (-7.1%, +17.4%)	**+9.8%** (-3.4%, +26.5%)	**+8.6%** (-2.8%, +22.6%)
	2080s	**+7.2%** (-5.8%, +22.1%)	**+12.6%** (-2.6%, +33.5%)	**+10.8%** (-3.3%, +29.2%)

Fowler and Ekstrom (2009) examined 1-day ('short') and 10-day ('long') precipitation extremes in the UK. They used output from a group of regional climate models, at approximately 50 km resolution, driven by a single global model. For the three Scottish regions, in winter, spring and autumn, both 1-day and 10-day rainfall extremes with a given return period are projected to become more intense; the central estimate is of an increase of up to 20%. In summer, the direction of change for 1-day extremes depends on region and for each region the central estimate is near zero; for 10-day extremes, a decrease is more likely than an increase but again there is large uncertainty in the direction of change. This study also highlighted the underestimation of precipitation extremes by climate models, in particular in regions of high precipitation such as the west coast of Scotland.

A more recent study was conducted by Rajczak et al (2013). This used regional models at 25 km resolution (equivalent to the resolution of the UKCP09 projections); this is higher resolution than in the Fowler and Ekstrom (2009) study. Rajczak et al (2013) also considered uncertainty in the driving global models. For Scotland, these newer results agree with the projection of increase mean and moderate-extreme rainfall by the late 21st century in winter, spring, and autumn, but with some uncertainty in spring. Rarer extremes (the 1-day and 5-day totals with a 5 year return period) were also projected to increase in these seasons but with greater uncertainty. For summer, uncertainty again dominates, although there is some evidence of decreasing mean and increasing extreme precipitation. Changes are smaller, or uncertainty is greater, for projections for the early 21st century from the same models (Rajczak et al, 2013).

Very high resolution modelling to increase reliability of projections of summer rainfall extremes, and at sub-daily resolution, has as yet only been employed for the southern UK (Kendon et al, 2014).

Therefore there is large uncertainty over summer precipitation extremes but in other seasons, heavier extreme precipitation is the most likely outcome.

Drought

Burke et al (2010) found varying results for future precipitation-deficit droughts, on timescales from three to eighteen months, for the UK in the HadRM3 ensemble. While the average result was of increase in the severity of droughts, there was considerable spread between different ensemble members, with disagreement on sign at most locations and drought lengths. Some local results contrast with this overall picture; in particular, an increase in severity of 12 or 18 month droughts on the Scottish west coast is unlikely, consistent with increases in winter precipitation (since a 12 month drought would have to contain a winter season). Limitations of the regional models in simulating precipitation deficits over Scotland must be remembered when interpreting such projections.

In support of the UK Climate Change Risk Assessment 2017, 'High ++' scenarios of low risk but high impact change in temperature and rainfall were considered (ASC, 2015). Low rainfall was one of the scenarios developed; however, the report uses global climate models which it states are do not produce credible drought characteristics for Scotland (in part due to its small size) so these scenarios are unfortunately restricted to England and Wales.

Flow projections for Scotland driven by UKCP09 suggest a reduction in flow at average annual low flow and an increase in frequency of very low flow events by 2050 (SEPA, 2015). For the UK as a whole, risks to the public water supply and water for other sectors is a key risk identified by the UK Climate Change Risk Assessment 2017 (ASC, 2016). Projections of water availability were produced for this assessment, considering climate change as well as population change and adaptation actions (HR Wallingford, 2015). These found projections of water deficits for certain regions within Scotland, for certain time periods, population scenarios and adaptation options, although risk of deficit is lower than for other parts of the UK. Further discussion is beyond the scope of this report. Both these analyses were driven by UKCP09 output, so the possibility of an exaggerated probability of reduction in summer rainfall (see 'Average Rainfall') cannot be ruled out.

Flood

Considerable effort has been put into detailed projections of future flood risk in contribution to the Climate Change Risk Assessment 2017 (Sayers and Partners 2015), using in part an earlier Scotland-specific assessment (SEPA, 2011). These incorporate not only climate changes but also differing scenarios of adaptation and population growth. Due to the complexity and considerable non-climatic drivers, this- and river flows- is not further considered here, but readers are referred to the reports referenced above.

Hail and Lightning

Neither hail nor lightning is directly simulated within climate models. Instead, variables which quantify relevant information (for example about cloud properties and available energy) are taken from the climate model. Observed relationships between these variables and the quantity required (such as hailstone diameter, or lightning frequency) are used to estimate the variable of interest. Such methods are known as 'offline modelling'.

Hail: A standard offline model applied to the regional climate model HadRM3 output captures the distribution of UK hailstone diameter well (Sanderson et al, 2015) but overestimates UK hail occurrence. This is challenging to interpret, because there are known limitations in the observational data, the offline model and HadRM3 itself (Sanderson et al, 2015). This combination of HadRM3 and offline model projects a decrease of UK hail in the 21 to 50 mm size range, and no statistically significant change in hail with other diameters. As this is a result from a single study, using a single climate model, with known limitations in skill at simulating the relevant events, the result should be treated with some caution. However it is worth noting, as it shows that the changes in hail size distribution and therefore damage are not necessarily coupled to changes in convective activity in general, which would be expected to increase (see 'lightning', below).

Lightning: A warmer atmosphere would be expected to have more energy for convection, suggesting an increase in the intensity of the types of storms which lead to lightning. Price and Rind (1994) found a 30% increase in both total and cloud-to-ground global lightning frequency with a 4.2°C warming. Other studies have been conducted since and a range of sensitivities of lightning to warming have been suggested (Romps et al, 2014). There is some suggestion of a conflict between decreasing numbers of storms, and increasing intensity of individual storms (Price, 2009). The IPCC AR5 states there is low confidence in future changes in severe thunderstorms globally.

However, changes in UK lightning need not follow global changes. This applies in particular to the west coast of Scotland, where winter storms contribute highly to the annual frequency of lightning such that future changes in winter storminess and not just intense summer storms are important. Flash frequency projections are not available for the UK, but a report accompanying UKCP09 (Boorman et al, 2010a) presented projected changes in days of thunder. Average changes across all 11 regional models in Scotland were, for most of the country, increases of 0 to 1 days in winter and spring, 1 to 4 days in summer, and 0 to 2 days in autumn. However there was evidence of larger increases (up to 3 days in winter and 4 days in autumn) on the west coast of Scotland.

Snow

Brown et al (2010) examined projections of 'frequency of days with falling snow' in the regional climate model HadRM3 which was used in UKCP09. The regional climate model has too many days with snowfall on the west coast, and too few on the east coast. Reductions of at least 40% in numbers of days with snow falling are projected by the 2080s (relative to the period 1960-1990). Projected reductions are weakest in northern Scotland.

Reductions in snowfall are consistent with increasing temperatures. However, the conflicting effect of increasing precipitation, limited ability of the models to recreate spatial variation in snowfall, and limitations in observations against which to evaluate the models, mean that confidence in the magnitude of these reductions is low.

A recent review (Kay, 2016) gives a more detailed discussion on historical trends and future projections in UK snow, and consequences for river flow, water quality and various sectors, as well as highlighting outstanding questions.

Fog

Boorman et al (2010b) found projected reductions in Scottish fog frequency in all seasons, in all 11 members of the HadRM3 ensemble. (HadRM3 calculates the fraction of a gridbox containing fog using within-model calculations of visibility, where visibility of less than 1 km is determined to signify fog. A threshold value of this fraction is then used to determine whether a given day is a fog day.)

Research Gaps

Projections of rainfall will remain challenging, and dominated by the natural variability of the climate system. However, some research gaps which provide potential for progress are identified here.

Current studies of flood peaks and flow regimes generally do not explicitly consider snow melt. Understanding of the contribution of snow melt to recent and future changes in floods is therefore not well understood, and is potentially important for Scotland as well as Northern England and Wales (Kay, 2016).

Hannaford et al (2015) highlight understanding of decade-to-decade variability as a key priority for understanding trends in river flows. Understanding of what drives rainfall variability on these timescales is key to taking this work forward.

The challenge of low signal-to-noise of current and future rainfall changes has already been highlighted. Namely, trends in rainfall are small relative to the natural variability of the system and therefore challenging to formally detect in time series, making changes in rainfall hard to interpret. A related and emerging area is extreme event attribution**.** Here, instead of looking for evidence of trends, models and observations are examined to see if a given extreme event (such as intense rainfall in a particular storm) is more likely, or more intense, in the current climate relative to a 'counterfactual' one without, for example, greenhouse gas emissions.

There is still considerable uncertainty regarding the direction of change in summer rainfall in the future. It is intended that as part of UKCP18, the very high resolution modelling used in Kendon et al (2014) to study the summer extreme precipitation which occurs in convective storms will be extended to cover the whole UK including Scotland. Without such an extension, it is not reasonable to assume that results for England can simply be extrapolated to Scotland due to the different relative importance of different processes for rainfall (see first section).

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