



Met Office

Briefing on the likelihood of severe winter weather over the next 20-30 years

For the Scottish Executive

1 February 2011

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Contents

Executive Summary	2
Past observations	3
Future projections	3
Current scientific understanding and challenges	3
Next steps	4
1. Past observations	5
2. UK climate change projections and implications for severe winter weather	9
3. Current scientific understanding and challenges	13
4. Next steps	18
References	19
Annex I: Civil Contingencies Secretariat severe weather risk assessments	20
Annex II: Past observations data sources	21

Note that this briefing document is based on material provided in response to a commission from Sir John Beddington, Government Chief Scientific Adviser, and the UK Secretary of State for Transport, Philip Hammond.

Executive Summary

- **Prolonged snowfall and low temperatures, comparable with conditions seen during November and December 2010 are within the range of natural climate variability observed over the past 50 years.**
- **Comparable spells of snowfall and cold weather have been observed in parts of Scotland during 12 winters since 1960.**
- **Over Scotland, in terms of snowfall and cold weather, the winter of 2009/10 was the most severe for some 31 years.**
- **The latest available regional climate projections for the UK (UKCP09) indicate a reducing likelihood of severe winters in future, due to the long-term warming climate. Natural climate variability implies that severe events remain possible but with reduced likelihood.**
- **However, there are significant known uncertainties and limitations in our ability to predict the likelihood of severe winters in future using the UKCP09 results.**
- **More sophisticated modelling approaches, such as developing the skill of decadal prediction (for example through increased resolution and better understanding and representing key processes and modes of variability), are required and in progress at the Met Office.**
- **A plan of proposed work over the next year is outlined to address these issues in order to provide improved long-term guidance on severe winter conditions.**

Snow and ice conditions affected many parts of the UK during late November 2010 and early December 2010. In Scotland, December 2010 was the coldest December for over 100 years. This report sets current events in the context of past observations and future climate projections to assess the likelihood of severe winter weather in Scotland over the next 20 to 30 years.

Past observations

The analysis of observations of past weather highlights the natural climate variability in terms of both temperature and snow conditions over the past 50 years. Over Scotland, the winter of 2009/10 was the most severe for some 31 years. December 2010 was the coldest December in Scotland for over 100 years, and the second coldest calendar month on record. Although it is too early to draw any conclusions about winter 2010/11, since 1960 there have been 12 periods of comparable snowfalls and low temperatures over parts of Scotland.

Future projections

Consistent with historical records, climate models projections typically show large fluctuations between consecutive winters. The occurrence of one or two cold winters is therefore not necessarily a good indicator of a further cold winter. European winter temperatures have generally been increasing over the last couple of decades, in line with a gradual warming predicted by climate models as greenhouse gases increase. The probability of severe winters is therefore expected to decrease, along with a gradual increase in the temperature of the typical coldest day of winter as projected by the latest UK regional climate projections, UKCP09. However, natural year-to-year variability is expected to dominate this warming signal for at least the next decade or two.

Current scientific understanding and challenges

Contemporary climate models typically underestimate the observed frequencies of blocking anticyclones. Nevertheless, recent evidence at the Met Office has indicated that the uncertainty reduces as we move towards higher resolution, both horizontally and vertically, along with better physics representation in our climate models. There is no robust evidence to indicate how the frequency of blocking events will change with climate change. Were the frequency of Atlantic blocking to increase, UK winter conditions would likely become colder, at least in the next few decades. The representation of blocking is a major focus in the Met Office Hadley Centre model development.

The possibility of clustering of severe winters, and whether this is predictable, is also an active research issue.

Next steps

Further work will be required in order to provide the evidence required to answer questions regarding the likelihood of severe winters on regional scales in the coming decades. Past observations provide us with the best resource for understanding natural climate variability. The UKCP09 results provide our current regional climate change projections, and are state of the art in their representation of uncertainties. Recent near-term climate prediction studies undertaken at the Met Office indicate potential predictability on seasonal to decadal timescales and it may be possible to extend this to Europe in winter. In order to develop this work to provide regional projections across the UK, we identify three areas that require particular attention – both to better understand the physical processes which influence UK winter conditions and to improve the operational model predictions that underpin advice and decision making.

- 1) improved understanding of the effect of Arctic sea-ice decline on UK winter conditions
- 2) improved understanding of the effect of solar variability on UK winter conditions
- 3) improved decadal predictions of UK winter conditions to address the key uncertainty of representing Atlantic blocking anticyclones in current predictions.

All approaches are technically possible, given sufficient computing resource, and should be considered in a scoping study for progress over the next 3 months. The work would likely be conducted in partnership with UK academia via the JWCRP.

Improved predictability on seasonal and decadal timescales is clearly important for informing decision making across government, and this needs to become a stronger focus within the Met Office Hadley Centre Climate Programme.

1. Past observations

To place the November and December 2010 conditions in context, analysis of observations of past winter conditions has been conducted. Severe winter weather may be analysed in a wide variety of ways, using different combinations of weather parameter, timescale and area. Parameters include air temperature, air and ground frost, snow depth, freeze-thaw cycles and wind-chill. Timescales vary from the whole season, to individual months, to spells of weeks or days. Areas vary from the whole UK, to constituent countries, to districts and places. Annex II provides further detail on the observational data used.

The winter 2010 event in context

December 2010 was the coldest December in Scotland for over 100 years, and the second coldest calendar month on record, with only February 1947 colder. There were some severe frosts, and the number of days with air frost was the highest in December for over 50 years.

Late November and early December 2010 was more generally characterised by spells of more than 7 days when the temperature has failed to rise above freezing widely across almost all UK districts and snow depths of greater than 20 cm in East Scotland and North-East England. Some snow depths of more than 30 cm were also recorded in these areas¹. The recent spell has therefore been compared with snowfall and temperature observations since 1960 using the following criteria.

Snowfall

At least 20 cm of snow lying for 7 consecutive days or more, affecting 10 or more official stations in any Scottish district at some point during the period.

Temperature

A daytime maximum temperature ≤ 0 °C for 7 consecutive days or more, affecting 10 or more official stations in any Scottish district at some point during the period.

Table 1 lists periods of snowfall and cold temperatures comparable to the recent event since 1960 in the 3 Scottish climate districts. Since 1960, there have been 12 different periods of comparable prolonged periods of snowfall and low temperatures. Winters 1962/63 and 2009/10 both saw the longest period with lying snow in Scotland (46 days), while January to February 1984 saw the most stations across Scotland affected (peaking at 50 stations in late January).

¹ Note that not all recent climate station data have yet been received and quality-controlled.

Period	East Scotland	North Scotland	West Scotland
Nov - Dec 2010	✓		
Jan 2010	✓		
Feb 2001	✓		
Dec 1995		✓	
Feb 1991	✓		
Jan 1987	✓		
Jan – Feb 1984	✓		✓
Feb 1978	✓		
Feb 1970		✓	
Dec 1962 - Feb 1963	✓		
Dec 1961 – Jan 1962	✓		
Feb 1960	✓		

Table 1: Periods with at least 20 cm of snow lying and when the temperature failed to rise above freezing for 7 days or more, affecting 10 stations or more in Scottish climate districts (see Figure A2) since 1960.

An additional 2 spells (January 1960 and March 2006) were characterised by prolonged snowfall, but without prolonged low temperatures. Since 1960, there have been 34 different periods of comparable prolonged cold weather.

This analysis reflects the fact that eastern areas of Scotland are those most prone to heavy, prolonged snowfalls, but that the conditions experienced in November and December 2010 are relatively rare.

Seasonal analysis

The areal mean temperatures for Scotland for each winter² from 1910/11 to 2009/10 are plotted in Figure 1. This illustrates large inter-annual variability of winter temperatures.

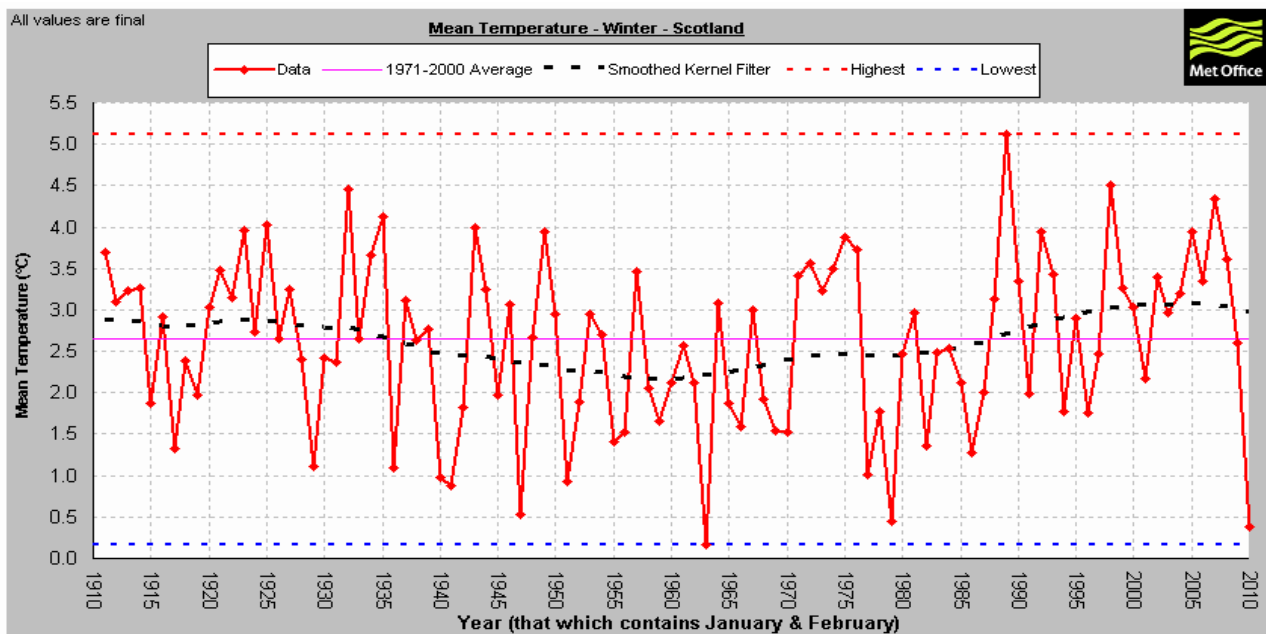


Figure 1: Winter mean temperature across Scotland, 1910/11 to 2009/10

² The winter average is defined as the mean temperature in December, January and February.

Winter 1962/63 is considered the coldest since 1878/79 across Scotland, since 1895 across Northern Ireland and since 1740 across England and Wales. In northern Scotland, winter 2009/10 was the coldest in over 100 years. Across Scotland and Northern Ireland, winter 2009/10 was comparable with those of 1979 and 1947, with only 1963 colder in the last 100 years. Winter 2009/10 was the coldest winter across England, Wales and the UK since 1979. For further background on winter 2009/10 see Prior and Kendon (2011)³.

Average winter temperatures Scotland during the last 20 years have been relatively mild, with 14 winters warmer than the 1971-2000 average.

Figure 2 shows the total numbers of days with snow lying in Scotland in the last 50 years. The 5 winters with the most days of lying snow over Scotland were 1962/63, 2009/10, 1978/79, 1976/77 and 1985/86. Winter 2009/10 saw twice the number of days with snow lying in Scotland than any year in the previous decade.

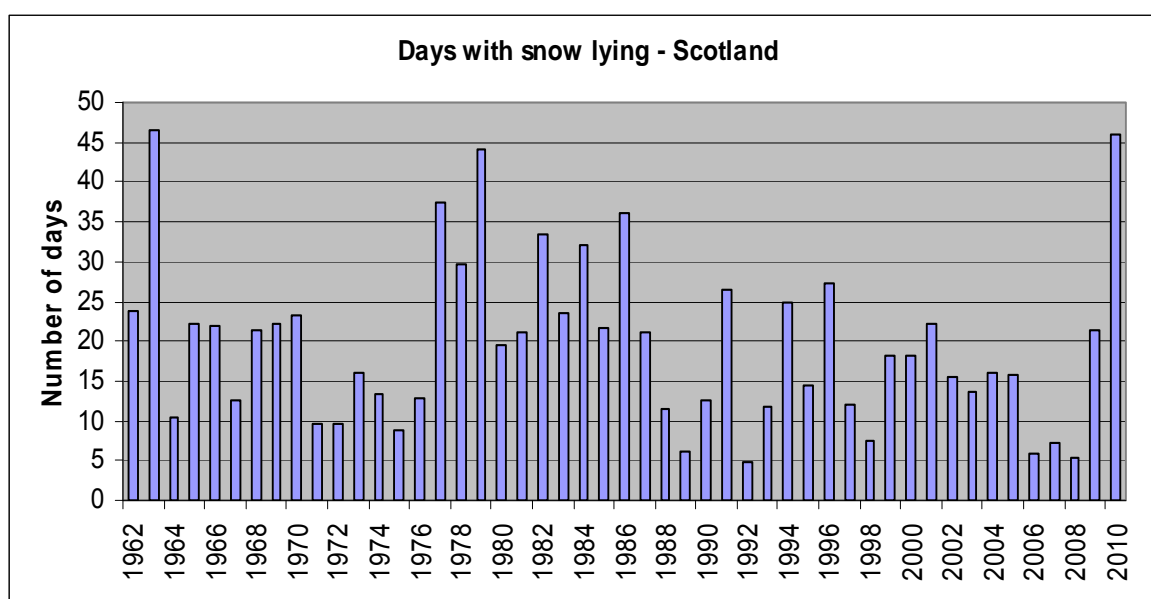


Figure 2: Days with snow lying across Scotland 1961/62 to 2009/10.

In order to characterise the severity of past winters, a broad categorisation for each winter since 1945/46 has been defined. Snow lying data were also taken into account since 1961/62. The results are shown in Figure 3.

Winter categories (anomalies relative to 1971 – 2000)	
Severe	More than 1.5 °C colder than average and/or more than 200% of average days of snow
Cold	1.0 to 1.5 °C colder than average and/or days of snow anomaly between 150% and 200%
Mild	1.0 to 1.5 °C warmer than average and days of snow anomaly less than 100 %
Very mild	More than 1.5 °C warmer than average and days of snow anomaly much less than 100%
Average	All other cases

³ Prior and Kendon (2011) is circulated with this briefing as a background paper for reference.

This approach suggests 4 'severe' winters in Scotland since 1961/62 (1962/63, 2009/10, 1978/79 and 1976/77) and 5 'very mild' ones (1988/89, 1997/98, 2006/07, 1991/92 and 2007/08).

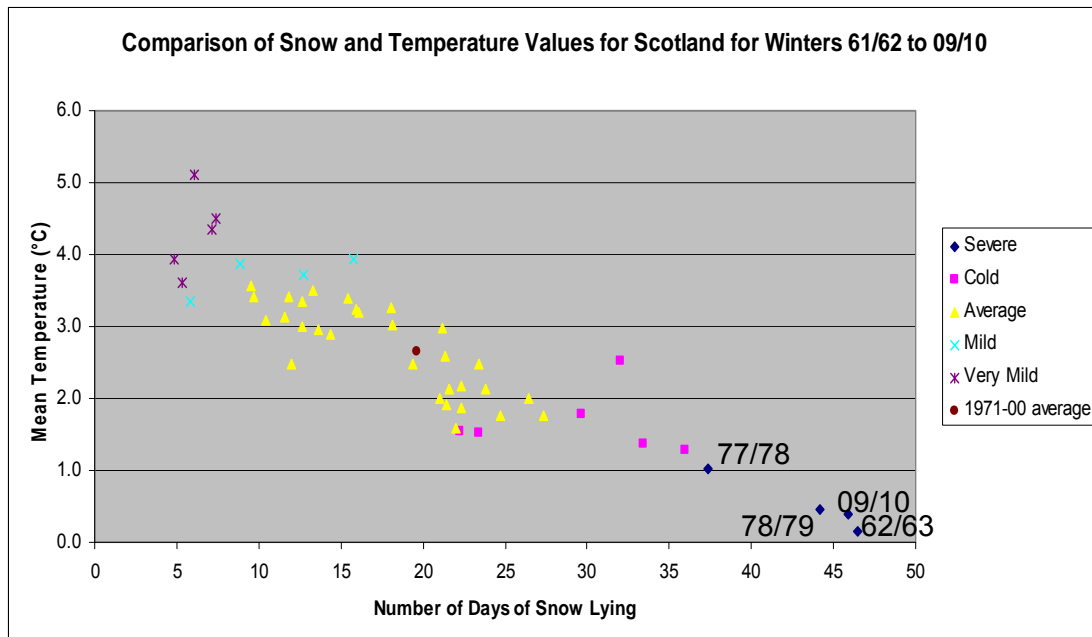


Figure 3: Scotland winter categories analysed by mean temperature and days with snow lying.

Summary

The analysis of observations of past weather highlights the natural climate variability in terms of both temperature and snow conditions over the past 50 years. Over Scotland, the winter of 2009/10 was the most severe for some 31 years. December 2010 was the coldest December in Scotland for over 100 years, and the second coldest calendar month on record. Although it is too early to draw any conclusions about winter 2010/11, since 1960 there have been 12 periods of comparable snowfalls and low temperatures over parts of Scotland.

2. UK climate change projections and implications for severe winter weather

The latest national climate projections (UKCP09, see Murphy et al., 2009) provide future changes for 30-year averaged values of several key climate variables during the 21st century, expressed relative to a historical baseline period of 1961-90. Where possible, projections for a given emissions scenario are presented in probabilistic form, covering uncertainties due to internal climate variability and in the modelling of key physical and biogeochemical processes. The earliest period that UKCP09 provides projections for is 2010-2039, characterised as “the 2020s”.

Note that although the projections include estimates of the uncertainty due to natural variability, they were not initialised from recent observations of ocean, atmosphere or land surface conditions in the manner of recent pioneering decadal prediction studies (see Section 3). Therefore, UKCP09 does not capture potential predictability relating to large scale modes of coupled ocean-atmosphere variability on decadal time scales. At the present time, UKCP09 is our best source of information on winter UK climate for the 2020s and beyond, based on climate modelling technology available at the time that it was produced. However, it is clear that there is potential to provide improved advice, for the next few decades in particular, by developing better climate models allied to prediction strategies involving initialisation of projections from recent observations (see Sections 3 and 4).

Overview

By the 2080s, the central estimates of change (50% probability level) show mean winter temperatures for the medium emissions scenario warming by 3 °C in eastern and southern England, with somewhat lower warming to the north and west (2.2 °C over northern Scotland, for example). The projected changes for given emissions scenarios are subject to considerable uncertainties, and changes also depend significantly on the emissions pathway. In all cases, however, mean winter temperatures are projected to increase.

The projected changes are smaller for the 2020s, and are much less dependent on the assumed emissions pathway compared to the end of the century. The central estimates are typically in the range 1.1-1.3 °C, showing less variation across the UK than later in the century. For this period, natural climate variability plays a more important role in determining the uncertainties (10-90% probability ranges typically range from about 0.5°C to 2°C), although modelling uncertainties are also significant.

Since observed UK temperatures have already warmed by about 0.7 °C compared to the UKCP09 baseline period, the UKCP09 central estimates imply a further warming of about 0.5°C by the 2020s, relative to present day.

What do the projections say about severe winter weather in Scotland?

The UKCP09 projections give little information on changes in climate extremes, recognising that the generation of climate models used to produce them (essentially those contributing to the IPCC Fourth Assessment Report in 2007) possessed limited abilities to simulate the physical mechanisms likely to give rise to the most anomalous events. The large and persistent blocking anticyclones responsible for the sequences of

snow events observed recently, and during the previous winter of 2009/10, are good examples of the type of extreme atmospheric circulation regime that these climate models do not simulate particularly well.

Coollest day

However, UKCP09 did provide limited information on metrics reflecting unusual events more typical of an average winter (recognising that the types of extreme circulation pattern referred to above do not occur every year). UKCP09 therefore does provide projections of changes in the “typical coolest day of winter”. For illustration, Figure 4 shows the spread of future changes in the typical coolest day of winter in the Eastern Scotland district during the 2020s. The central estimate (50% probability level) of the distribution shows an increase of 0.9 °C, consistent with the secular effects of a warming climate. The spread of plausible changes about the central estimate is larger than those seen for changes in mean temperature, because natural climate variability plays a more dominant role in determining uncertainties in extreme events, compared to time-averaged changes. The lower ends of the uncertainty ranges (10% probability levels) therefore show reductions (temperature *decrease* of 0.4 °C or more for Eastern Scotland in Figure 4 for example), demonstrating that the effects of natural variability are potentially large enough to offset the emerging influence of global warming at this time scale.

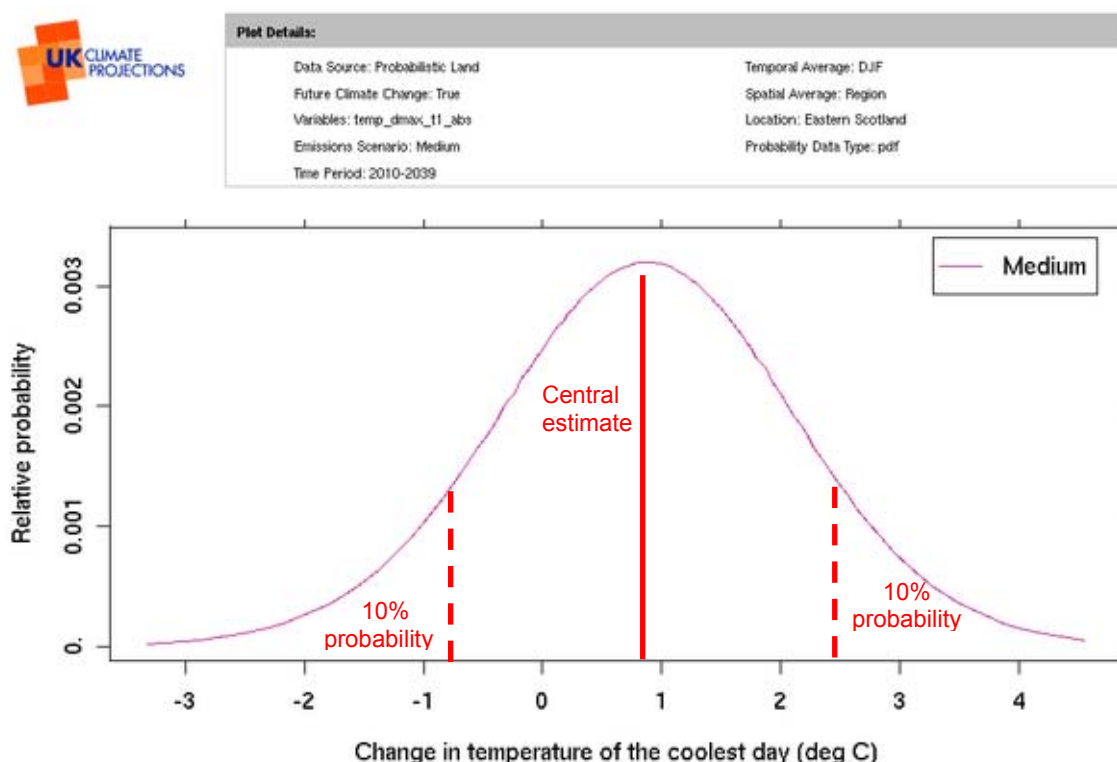
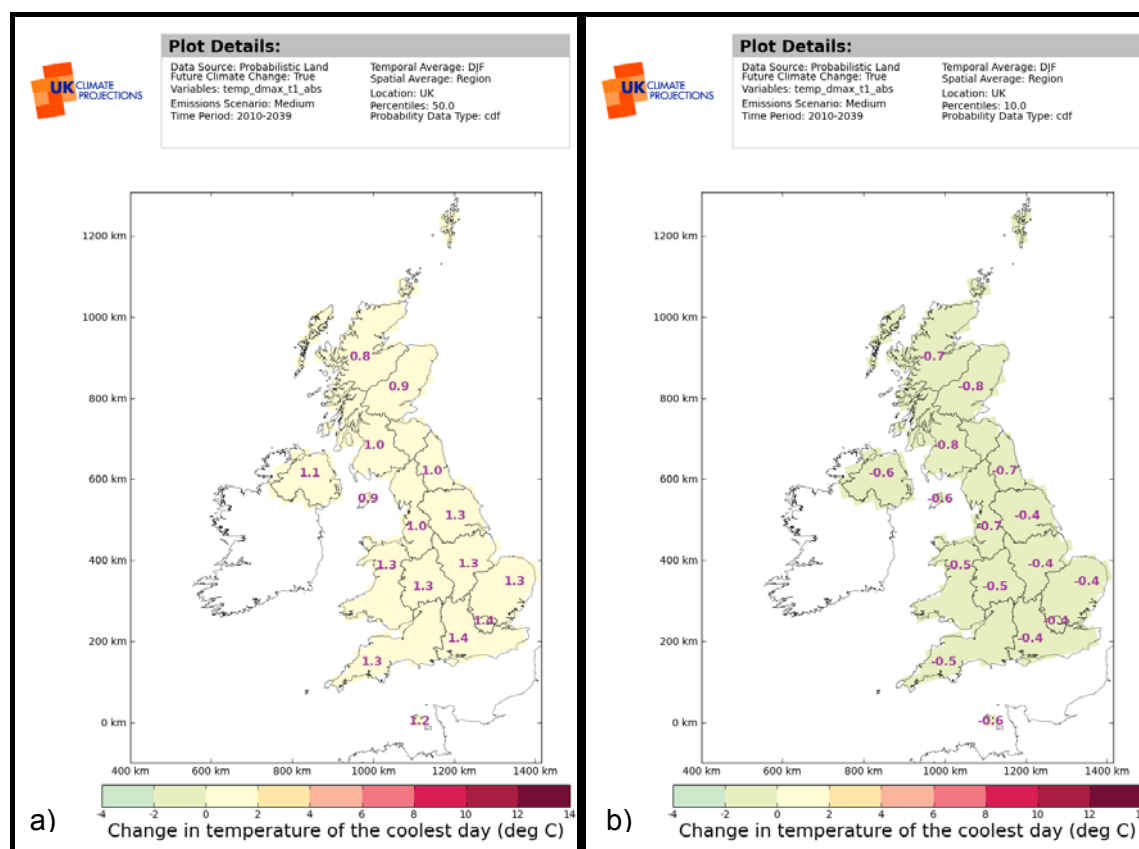


Figure 4: Probability density function (pdf) of the change in temperature of the coolest day in 2020s across Eastern Scotland for the medium emissions scenario.

Figure 5a shows the central estimate of change in the typical coolest day of winter for the 2020s (relative to 1961-1990) across a set of UK administrative regions considered in UKCP09. The increases range from 0.8 °C in northern Scotland to around 1.4 °C in

south east England. Figure 5b shows the lower end 10% probability levels of the distribution, which show possible *decreases* in coolest day in all regions of up to 0.8 °C.



Snow

For snow, it was not possible to produce probabilistic estimates of changes in UKCP09. However, an ensemble of eleven regional climate model projections (one component of the modelling information used in UKCP09 – see Murphy et al, 2009) provides a set of plausible realisations of future changes sampling some of the relevant uncertainties in physical processes and natural variability. To date, analysis of the projected changes has focused mainly on the 2080s (UKCP09, Brown et al, 2010). These results show that reductions in the number of days with snow falling in winter could typically amount to more than 50% (dependent on location), compared with 1961-90. Although there are uncertainties in the projections, there is a robust signal for significant reductions by the end of the century, consistent with the projected levels of warming described above. Changes in the intensity of heavy snow events (defined as the 90th percentile of the distribution of daily events) were also examined. For the 2080s, substantial reductions were again found (typically 50% or more), however the ensemble of projections also contained examples showing that local *increases* in heavy events could not be ruled out, due to the combined effects of natural variability and modelling uncertainties.

For the 2020s, the expected reductions in snowfall days due to greenhouse gas-driven warming would be considerably smaller, due to the smaller projected warming (see

above). For this period, uncertainties in projections of the number of snowfall days, and (in particular) the intensity of heavy events are determined mainly by the effects of natural climate variability. Since natural variability is large compared with the expected effects of global warming at this lead time, the risk of heavy snow events is unlikely to reduce significantly, compared with present day.

UKCP09 does not provide information on the joint probabilities of combined severe weather impacts (e.g. cold temperatures, heavy snow and strong winds) in individual winter seasons. Projections of changes in 30 year mean wind speed show substantial uncertainties, with little evidence of a systematic shift in probabilities towards either stronger or weaker values. However, the models used to produce UKCP09 did not resolve troposphere-stratosphere interactions well. The new generation of projections being produced for the next IPCC Assessment Report (AR5) include several from models with an improved representation of these interactions, which may alter the projections of changes in winter storms and precipitation to some degree (e.g. Huebener et al., 2007). This will become clearer over the next year or so, as AR5 results become available for analysis.

Summary

In summary, the information available from UKCP09 is restricted to projections of changes in temperatures or snowfall events associated with typical individual cold days within a 30 year period. These diagnostics do indicate the likelihood of secular changes consistent with a gradually warming climate, by the 2020s. However, it is not straightforward to infer the implications of these changes for the likelihood of sustained spells of severe weather associated with persistent anomalous atmospheric circulation regimes. The generation of models used to produce UKCP09 does not simulate the mechanisms driving such persistent anomalies (particularly blocking anticyclones) with sufficient skill to allow the UKCP09 advice to be extended to cover projections of such events. However, further investment in the development of higher resolution global climate models and associated supercomputing infrastructure, allied to the development of initialised decadal forecasting techniques (see Section 3), would likely improve our ability to provide credible projections of the risks of episodes of severe weather of the type experienced recently.

3. Current scientific understanding and challenges

Historical records and climate models typically show large fluctuations between consecutive winters. The occurrence of one or two cold winters is therefore not necessarily a good indicator of a further cold winter. European winter temperatures have generally been increasing since about 1980, in line with a gradual warming predicted by climate models as greenhouse gases increase. To illustrate this, Figure 6 shows a time series of winter mean temperature anomalies relative to a baseline period of 1961-90, from the Central England record (red curve). The recent warming trend in the observations is clearly apparent, accompanied by substantial natural variability, including the winter of 2009-10 (last point on the red curve). The recent warming trend is also apparent in the global climate model simulations included in UKCP09, which project further increases into the future. The blue curve in Figure 6 shows one of these simulations, and the grey shading show a wider uncertainty range based on an ensemble of 17 simulations. As the warming develops during the 21st century, the probability of an individual winter as cold as 2009-10 reduces considerably.

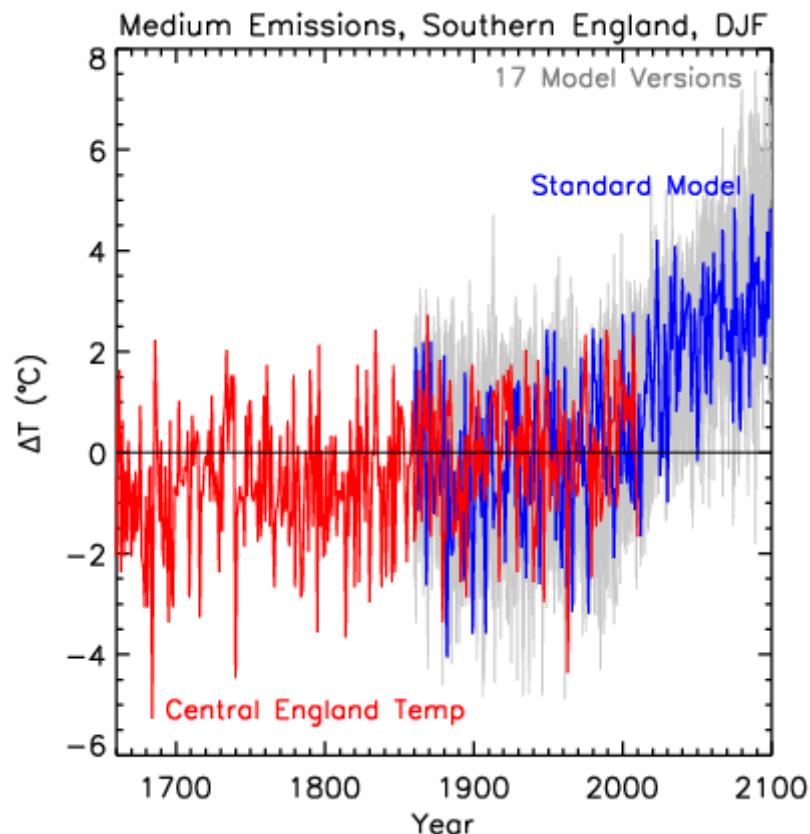


Figure 6: Time series of winter (December-February) average anomalies in observed Central England Temperature (CET) from 1660 to 2010 (red curve). The blue curve shows values simulated values from one of the HadCM3 global climate model projections contributed to UKCP09, extended to the year 2100 assuming the UKCP09 Medium scenario of future greenhouse gas and aerosol emissions. The grey shading shows a wider envelope of anomalies simulated by a 17 member perturbed physics ensemble of HadCM3 projections sampling uncertainties in key surface and atmospheric processes. The modelled time series are extracted from a 300x300 km² grid box centred over Southern England, which overlaps most closely with the area covered by the CET stations. All anomalies are expressed relative to a baseline period of 1961-90.

The probability of severe winters is therefore expected to decrease, along with a gradual increase in the temperature of the typical coldest day in winter as projected by UKCP09 (see Figure 5a). However, natural year-to-year variability is expected to dominate this warming signal for at least the next decade or two. Regarding the possibility of clustering of severe winters, the frequency of occurrence of three consecutive winters below the 1961-90 average has reduced during the past couple of decades: The most recent 30 year period (1981-2010) included only one such occurrence (winters of 1985-87), compared to a typical frequency of 3-4 occurrences for 30 year samples drawn from the period 1930-1990. The UKCP09 projections suggest a further reduction in the likelihood of such a run of cold winters by the 2020s, reflecting the effects of steady warming consistent with an essentially unchanging and unpredictable backdrop of natural variability. However, developing understanding of the mechanisms of natural variability in driving clusters of severe winters, and determining whether these events might be predictable, is an active research issue.

Factors influencing the inter-annual to decadal timescale variability in UK winter climate and potential sources of skill in multi-annual climate forecasts

There are several factors that can influence UK climate in winter. One of the most important is the natural chaotic year-to-year variations in winter climate, which dominates the long-term increasing temperature trend associated with a warming climate. In addition to these, there are a number of potential mechanisms that could enhance the probability of cold European winters and might provide some predictability on inter-annual to decadal timescales.

i) Solar radiative output varies with an average period of about 11 years. Observations (Figure 7) indicate that low solar activity, which typically lasts for about 3 years as part of the 11 year cycle, is associated with a negative North Atlantic Oscillation (NAO)⁴, and hence a tendency for more easterly winds and cold temperatures over Europe. Solar activity has been particularly low since about 2008, but is starting to increase again in line with the 11 year cycle.

⁴ The North Atlantic Oscillation (NAO) is a large scale mode of natural climate variability having large impacts on weather and climate in the North Atlantic region and surrounding continents. The NAO is a north-south shift (or vice versa) in the track of storms and depressions across the North Atlantic Ocean and into Europe. The storm track exhibits variations from winter to winter in its strength (i.e., number of depressions) and position (i.e., the median route taken by that winter's storms), but a particularly recurrent variation is for the storm track to be either strong with a north-eastward orientation taking depressions into NW Europe (a *positive* NAO winter) or weaker with an east-west orientation taking depressions into Mediterranean Europe (a *negative* NAO winter). Since the Atlantic storms that travel into Europe control our rainfall, there is a strong influence on European precipitation patterns (with a wet northern Europe and a dry Mediterranean Europe during a positive NAO winter, and the opposite during a negative NAO winter).

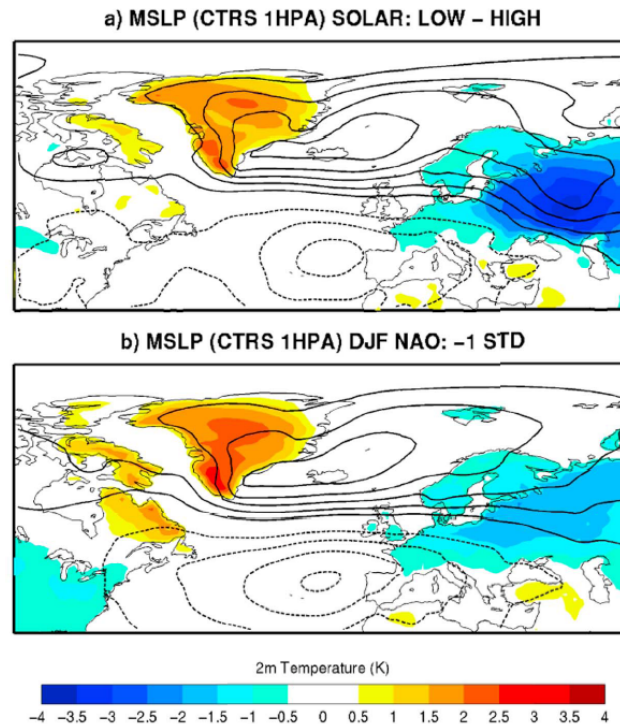


Figure 7: (a) Composite difference map of winter mean sea level pressure (contours) and 2 m temperature (colours) between low and high solar winters. (b) Scaled anomalies associated with the NAO for comparison. (From Woollings *et al.* 2010).

ii) Arctic sea ice cover has decreased over the last few decades, consistent with projected warming as greenhouse gases increase. There is observational and modelling evidence (e.g. Petoukhov and Semenov 2010, Overland and Wang 2010) suggesting that increased local warming of the atmosphere by the ocean as the sea ice cover decreases, particularly in the Barents and Kara Seas, could alter atmospheric circulation patterns, leading to enhanced probabilities of a negative NAO and cold conditions in Europe (Figure 8).

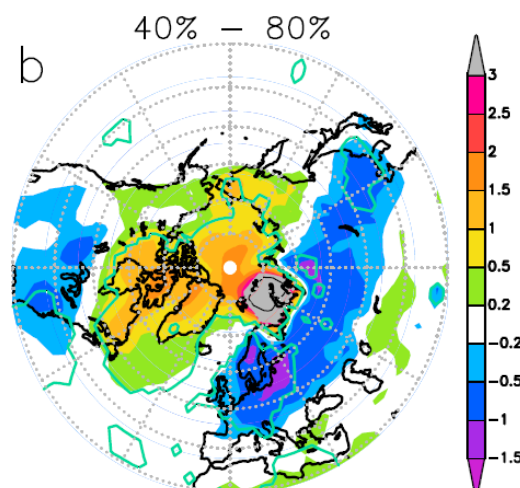


Figure 8: Model simulated surface air temperature anomalies ($^{\circ}\text{C}$) for February with sea ice concentrations between 40 and 80% in the Barents and Kara seas. (From Petoukhov and Semenov 2010).

iii) North Atlantic sea surface temperature varies on decadal timescales (usually referred to as Atlantic multidecadal variability or AMV). Observations (e.g. Smith *et al.* 2011) suggest that a positive phase of AMV is associated with high pressure and cold winters over Europe (Figure 9). AMV has been positive since the mid 1990s.

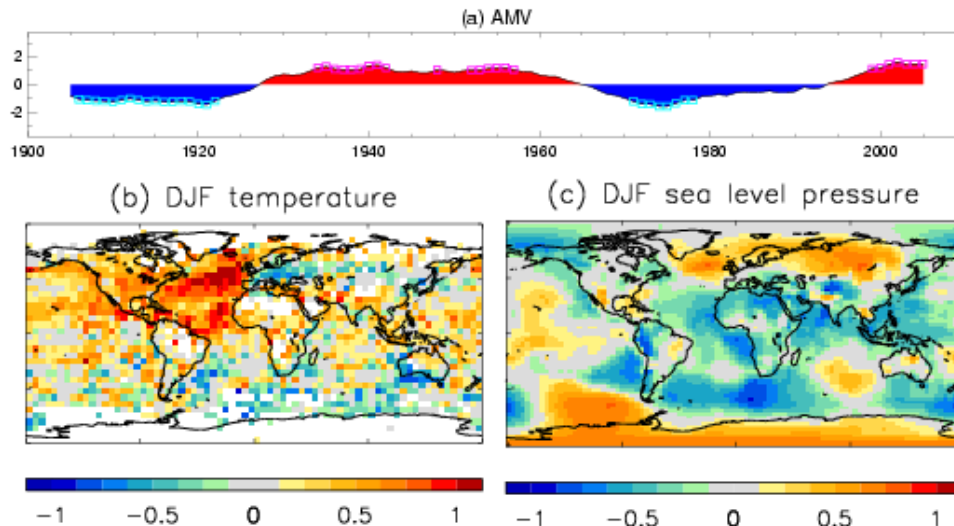


Figure 9: Observed AMV teleconnections. (a) Normalised time series of AMV. (b)-(c) Normalised composite differences between positive and negative phases of AMV for boreal winter (DJF). All time series were smoothed and normalised with a 9-year running mean. Positive years are 1934-42, 1948, 1952-57, 1999-2005. Negative years are 1906-22, 1971-78. Composite differences are divided by 2 to show the amplitude of the variability. (Adapted from Smith *et al.* 2011).

iv) Sea surface temperatures in the tropical and north Pacific also vary on decadal timescales (referred to as Pacific decadal variability or PDV). A cold (warm) phase of PDV is associated with enhanced probability of La Niña (El Niño), and hence a cold (warm) early winter but warm (cold) late winter over Europe (e.g. Smith *et al.* 2011). PDV has been in a negative phase since about 2000.

v) The quasi-biennial oscillation (QBO) is a wave-driven reversal of tropical stratospheric winds between easterly and westerly with a mean period of about 28 months. The QBO influences the stratospheric polar vortex and hence the winter NAO and Atlantic-European climate especially in winter (e.g. Smith *et al.* 2011). The QBO is predictable a couple of years ahead, and provides moderate predictability of European winter climate (Marshall and Scaife 2009). The QBO was in the correct phase to enhance the probability of a cold winter in 2009/10, but not 2010/11.

vi) El Niño Southern Oscillation (ENSO) is the dominant source of year-to-year variability in tropical climate. It involves a warming and cooling cycle of the tropical Pacific, with a frequency of 2 to 10 years. Recent evidence points to a robust influence on extra-tropical winter climate, with El Niño driving an increased occurrence of cold European winters. Winter 2009/10 experienced El Niño conditions whereas winter 2010/11 is under a strong and opposite (La Niña) phase. If the current winter turns out to be very cold then ENSO can not possibly explain both cold winters.

Current levels of skill in climate forecasts on multi-annual timescales and future prospects

Climate models typically show a weaker response to solar variability than is apparent in observations. However, recent satellite observations (Harder *et al.* 2009) suggest that changes in ultra-violet radiation over the solar cycle may be much larger than previously thought. Recent modelling studies at the Met Office show an increased response in the NAO using these new satellite measurements. This may lead to improved seasonal to decadal predictions of European winters in future.

The potential impact of a declining Arctic sea ice cover on European winters will be investigated further. Current climate change simulations capture the overall decline in Arctic sea ice reasonably well. However, whether regional details and in particular a response in the NAO can be predicted on inter-annual timescales requires investigation. Given that Arctic sea ice is expected to continue to decline over the coming decades, this is a potentially important mechanism that could lead to more frequent severe winters.

Simulating, and therefore predicting, the QBO requires a well-resolved stratosphere. The Met Office seasonal forecasting system has recently been upgraded to achieve this, but the decadal forecasts are currently unable to capitalise on any predictability associated with the QBO. Simulating the teleconnections between PDV and European winters is also likely to require a well-resolved stratosphere (Ineson and Scaife 2008).

Decadal forecasts are in their infancy, and levels of skill are uncertain. However, there is some evidence for predictability of AMV and PDV out to about 5 years ahead (Smith *et al.* 2010). This is shown by improved predictions of 5-year mean surface temperature in both the Pacific and Atlantic when climate models are initialized with observations (Figure 10).

Skilful multi-year predictions of AMV are also underpinned by skilful predictions of the Atlantic meridional overturning circulation (AMOC, Pohlmann *et al.* 2011). The AMOC transport heat from the Equator to mid and high latitudes, and is therefore expected to influence European climate. However, skilful inter-annual to decadal predictions of European winter have not yet been achieved. This will require some degree of predictability in low frequency variations of the NAO and it is not clear whether this will be possible. If it is, it will require the models to provide a better representation of some of the key physical mechanisms e.g. atmospheric blocking. In particular, it will require a stronger forcing of the atmosphere from the ocean than is achieved in most current climate models. This is a key area of research for decadal predictions. However, there is some evidence that the atmosphere is more strongly coupled to the ocean in higher resolution models (e.g. Minobe *et al.* 2008), suggesting that improved predictions might be possible with further model development.

Seasonal predictive skill

Current near term climate predictions show very limited skill in predicting European winter climate when tested on their ability to forecast past winters from weeks to years ahead. Nevertheless, it is worth noting that seasonal predictions for the winters of 2009/10 and 2010/11 both contained a clear signal for cold conditions over the UK and wider area of Europe several weeks ahead of the winter. This suggests that when the forcing is particularly strong, there is improved predictability, and work is ongoing to understand this further.

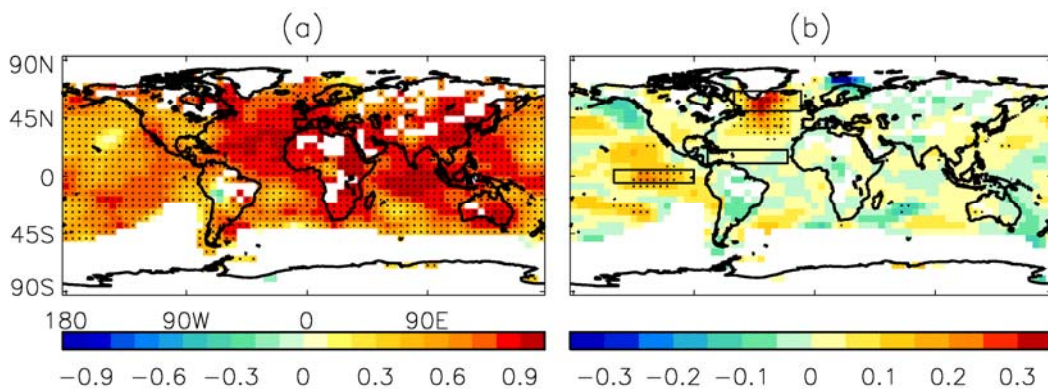


Figure 10: Skill and impact of initialization for five-year mean surface air temperature. (a) Anomaly correlation between five-year mean (June–November) surface temperature predicted by the Met Office decadal prediction system and observations from HadCRUT3. (b) Difference in anomaly correlation between initialized and uninitialized forecasts. (From Smith *et al.* 2010b).

4. Next steps

Further work will be required in order to provide the evidence required to answer pressing questions regarding the likelihood of severe winters on regional scales in the coming decades. Past observations provide us with an invaluable resource for understanding natural climate variability. The UKCP09 results are currently our best regional climate change projections. Recent near term climate prediction studies undertaken at the Met Office indicate improved predictability on seasonal to decadal timescales and it may be possible to extend this to Europe in winter. In order to develop this work to provide regional projections across the UK, we identify three areas that require particular attention:

The effect of Arctic sea-ice decline on UK winter conditions. Since 2007 Arctic sea ice has been severely depleted and there is evidence that this can drive colder conditions in Europe. Work is ongoing in this area.

The effect of solar variability on UK winter conditions. There is growing evidence that decadal variations in solar output can impact Europe in winter. Work is ongoing in this area.

Improved predictions of UK winter conditions. The latest version of the Met Office Hadley Centre climate model would need to be run at higher horizontal resolution (N216) with sufficient vertical levels (85), coupled to the 0.25° resolution ocean model, initialised with recent observations of the ocean, atmosphere and land surface if we are to address the key uncertainty of the lack of Atlantic blocking anticyclones in current predictions.

All three are technically possible, given sufficient computing resource, and should be considered in a scoping study for progress over the next 3 months. The work would likely be conducted in partnership with UK academia via the JWCRP programme.

References

Brown, S.J., Boorman, P.M. and Murphy, J.M. (2010) UK Climate Projections Science Report: Interpretation and use of future snow projections from the 11-member Met Office Regional Climate Model ensemble, Met Office Hadley Centre, Exeter, UK

Harder, J. W., Fontenla, J. M., Pilewskie, P., Richard, E. C. and Woods, T. N. (2009) Trends in solar spectral irradiance variability in the visible and infrared, *Geophys. Res. Lett.* 36, L07801

Huebener, H., Cubasch, U., Langematz, T., Spangehl, T., Niehörster, F., Fast, I. and Kunze, M. (2007) Ensemble climate simulations using a fully-coupled ocean-troposphere-stratosphere general circulation model. *Phil. Trans. R. Soc. Lond.*, 365,2089-2101.

Ineson S. and A. A. Scaife (2008) The role of the stratosphere in the European climate response to El Nino, *Nature Geoscience*, 2, 32-36.

Marshall, A. G. and A. A. Scaife (2009) Impact of the QBO on surface winter climate, *J. Geophys. Res.*, 114, D18110, doi:10.1029/2009JD011737

Minobe, S., A. K. Yoshida, N. Komori, S-P. Xie and R. J. Small (2008) Influence of the Gulf Stream on the troposphere, *Nature*, 452, doi:10.1038/nature06690

Murphy, J.M., Sexton, D.M.H., Jenkins, G.J., Boorman, P.M., Booth, B.B.B., Brown, C.C., Clark, R.T., Collins, M., Harris, G.R., Kendon, E.J., Betts, R.A., Brown, S.J., Howard, T., Humphrey, K.A., McCarthy, M.P., McDonald, R.E., Stephens, A., Wallace, C., Warren, R., Wilby, R., Wood, R.A., (2009) UK Climate Projections Science Report: Climate change projections, Met Office Hadley Centre, Exeter, UK

Overland, J. E. and M. Wang (2010) Large-scale atmospheric circulation changes are associated with the recent loss of Arctic sea ice, *Tellus*, 62A, 1-9

Pohlmann, H., D. M. Smith, M. A. Balmaseda, E. D. da Costa, N. S. Keenlyside, S. Masina, D. Matei, W. A. Muller and P. Rogel (2011) Skillful predictions of the mid-latitude Atlantic meridional overturning circulation in a multi-model system, *Geophys. Res. Letts.*, submitted

Petoukhov, V. and V. A. Semenov (2010) A link between reduced Barents-Kara sea ice and cold winter extremes over northern continents, *J. Geophys. Res.*, 115, D21111, doi:10.1029/2009JD013568

Prior, J. and Kendon, M. (2011) The UK winter of 2010 compared with severe winters of the last 100 years, *Weather* to be published in January 2011 – see background paper.

Smith, D. M., R. Eade, N. J. Dunstone, D. Fereday, J. M. Murphy, H. Pohlmann and A. A. Scaife (2010) Skillful multi-year predictions of Atlantic hurricane frequency, *Nature Geoscience*, DOI: 10.1038/NGEO1004

Smith, D., A. Scaife and B. Kirtman (2011) What is the current state of scientific knowledge with regard to seasonal and decadal forecasting? *Foresight report*, submitted

Woollings, T., M. Lockwood, G. Masato, C. Bell and L. Gray (2010) Enhanced signature of solar variability in Eurasian winter climate, *Geophys. Res. Letts.*, 37, L20805, doi:10.1029/2010GL044601

Annex I: Civil Contingencies Secretariat severe weather risk assessments

Based on proposals by the Met Office, the Civil Contingencies Secretariat define the risks of 3 types of prolonged severe weather – wind storms, cold spells and heat waves. These have been assessed for the UK, England, Wales, Scotland, Northern Ireland, 9 English regions and 8 Scottish regions. The last update was in 2008.

Each country and region has been assessed in terms of a risk using scores 1 to 5 as shown in the following likelihood table. Figure A1 shows the current risk map.

Score	Descriptor	Likelihood over 5 years	Return Period	Likelihood over 30 years
1	Low	< 0.05%	> 10,000 years	< 0.3%
2	Medium-Low	0.05% to 0.5%	1,000 to 10,000 years	0.3% to 3%
3	Medium	0.5% to 5%	98 to 1,000 years	3% to 26%
4	Medium-High	5% to 50%	8 to 98 years	26% to 98%
5	High	> 50%	< 8 years	> 98%

It has been assumed that these assessments are intended to reflect the risk over the next 5 years, and so research has concentrated upon weather records for the last 40-50 years as being representative.

A mixture of resources have been used to make these assessments – a literature search, analyses of station records (e.g. spells of weather exceeding certain thresholds), extreme value analyses and maps of long-term climate averages. An estimate of the return period was required and in many cases a decision about whether this was <8 yrs or <98yrs was involved.

The definition of a ‘cold snap/heavy snow’ is

“Snow falling and lying over most of the area for at least one week. After an initial fall of snow there is further snow fall on and off for at least 7 days. Most lowland areas experience some falls in excess of 10cm, a depth of snow in excess of 30cm and a period of at least 7 consecutive days with daily mean temperature below -3°C”.

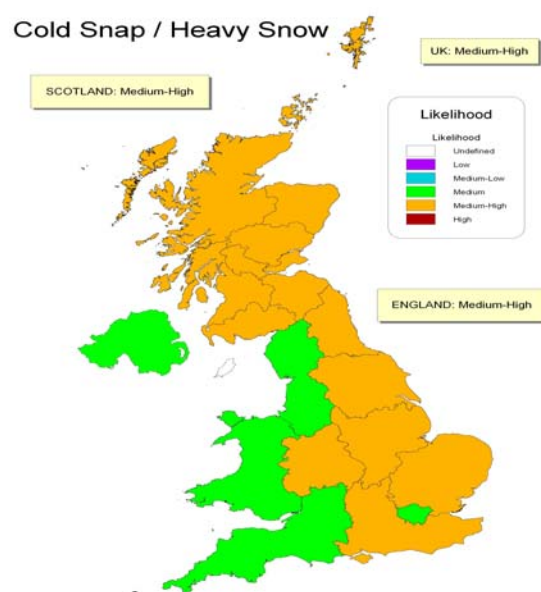


Figure A1: Civil Contingency Secretariat assessments of the risk of a cold snap/heavy snow

Annex II: Past observations data sources

This paper uses readily available observational data from a dense network of surface weather stations to examine the last 100 winters in terms of temperature and the last 50 winters in terms of snowfalls. Other analyses are possible, using the comprehensive digital archive of UK climate data⁵. For example, station data may be used to analyse freeze-thaw cycles and coincidence of snowfall and strong winds.

For temperature, we can analyse monthly series from 1910 and daily series from 1960, based on 5km gridded data. These have been used to create monthly, seasonal and annual series for the UK, England, Wales, Scotland, Northern Ireland and a number of smaller districts, including 3 regions in Scotland and 6 regions in England, shown in Figure A1. For snowfall, there are monthly 5km grids of days with snow lying available from 1961 (based on snow depth measurements at 0900).

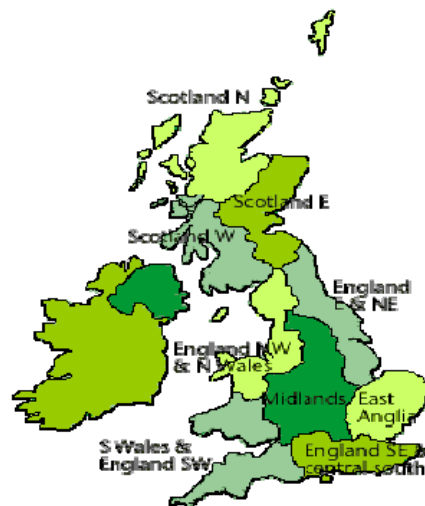


Figure A2: UK climate districts

The main input to the gridding process was the Met Office archive of daily observations at synoptic and climate stations. The climate station network varies from about 200 in 1910 to about 550 from 1960 to 2000, before declining to about 400 currently. Upland areas have been least well-represented, particularly before automation in the late 20th century.

The monthly gridded datasets have been used to create monthly, seasonal and annual series for the UK, England, Wales, Scotland, Northern Ireland and various districts including 6 in England (Figure 2). The monthly Central England Temperature series from 1659 is available for a longer-term perspective (see Figure 6).

The daily station observations have been digitised mainly from 1959; these include maximum and minimum air temperature, 0900 snow depths and daily mean wind speed.

⁵ Examples of available data sets and possible analyses may be found on the Met Office climate web pages at <http://www.metoffice.gov.uk/weather/uk/climate.html>.

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