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A review of snow in Britain: the historical picture and future projections

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Abstract

Climate change is likely to have a significant effect on snow globally, with most effect where current winter temperatures are close to 0°C, including parts of upland Britain. There is evidence of decreasing trends in observations of snowfall and lying snow in Britain, and climate projections suggest a continuation of this trend. Although river flows in Britain are generally dominated by rainfall rather than snowmelt, some upland catchments have a significant snowmelt contribution. There is evidence of changes in observed and projected river flows in some catchments in Britain, linked to changes in snow, but it can be difficult to distinguish the effects of snow changes from those of other concurrent changes (climatic and non-climatic). Flow regime changes in catchments with widespread and prolonged winter snow cover usually involve increases in winter flow and decreases in spring flow, but the effect on catchments with more transient snow cover is less clear, as is the effect on high flows and water quality. Snow can also affect a number of other factors of socio-economic or environmental importance (e.g. transport and farming). There is some evidence that disruption due to snow may be less frequent in future, but disruption from other types of weather event may increase. The impacts of snow tend to be worse in areas where events occur less frequently, due to unpreparedness, so there is a need to guard against complacency when it comes to future snow events in Britain, which can still be expected despite a likely reduction in frequency. Further modelling of the potential impacts of climate change, including modelling the influence of snow changes as well as other climatic and non-climatic changes, would aid adaptation and encourage mitigation.

Keywords

Snowfall, snowmelt, trends, river flows, transport disruption, climate change

I Introduction

The sensitivity of snow and ice to temperature change means that they may provide one of the most obvious signals for climate change (Vaughan et al. 2013). Global warming is already influencing snow and ice processes, with reductions in annual average snow cover extent and earlier snowmelt observed in regions across the northern hemisphere (Stewart 2009, Derksen and Brown 2012). However, the effect of changes in temperature on snowfall and snowmelt (and subsequently on river flows) may be complicated by coincident changes in precipitation, to the extent that impacts may be masked until thresholds are crossed (Stewart 2009). The effects are thus likely to vary by location, for example depending on altitude (Skaugen et al. 2012, Trivedi et al. 2007, Harrison et al. 2001) and atmospheric circulation patterns (Irannezhad et al. 2016, Stewart 2009). Studies suggest that the areas most affected have been those where current winter temperatures are close to 0°C, with less impact in colder or warmer regions (Stewart 2009, Hamlet and Lettenmaier 2007). In parts of Britain, particularly Scotland, the climate is in this transitional zone where only a small temperature increase can have a significant effect by changing winter precipitation from snow to rain (Johnson and Thompson 2002, Carey et al. 2010, 2013), so the effects of climatic change may be seen first in areas like the Cairngorms in Scotland (Soulsby et al. 1997). Potential changes in snow are also important because of the feedback of snow cover on vegetation and climate (Cohen 1994, Stewart 2009, Tetzlaff et al. 2013, Irannezhad et al. 2016). A recent review of climate change and water in the UK highlighted the influence of snow and snowmelt as an area that would benefit from more detailed consideration (Watts et al. 2015).

Snow forms within clouds by condensation of water vapour onto the surface of a small initial ice crystal. When the crystals become sufficiently large and heavy they fall out of the cloud. Depending on conditions below the cloud, the snow crystals may just evaporate again (so never reach the ground), or they may aggregate to form larger snowflakes (if temperatures below the cloud are close to 0°C), or they can remain as small snowflakes (at temperatures below about -5°C). In Britain, snow is most often seen as the larger aggregate snowflakes (Lachlan-Cope 1999). When snow reaches the ground it can melt relatively quickly or can remain for periods ranging from days to months, although most of Britain does not usually experience very sustained periods of lying snow (Dunn et al. 2001, Soulsby et al. 2002a, Johnson and Thompson 2002, Spencer et al. 2014). The presence of snow cover can be important, for example by providing habitats for terrestrial flora and fauna, protecting over-wintering crops and vegetation from frost, and for winter sports and tourism (Trivedi et al. 2007, Harrison et al. 2001). But lying snow can also cause significant disruption to lives and livelihoods, even if it does not remain for long. Disruption to transport is probably the most obvious impact, but it can also affect power supplies, health services and farming for example. Such disruption can have economic consequences, and can be worse in regions where snow is more infrequent, due to unpreparedness and unfamiliarity (Mayes 2013, Jones et al. 2012).

When precipitation falls as rain it can become river flow relatively quickly (unless channelled to deep groundwater stores for example). In contrast, when precipitation falls as snow it will be stored in the snowpack until temperatures rise sufficiently for melt to begin; only then can the water held in the snowpack make progress towards becoming river flow (Johnson and Thompson 2002). Thus snowfall and subsequent snowmelt can have a significant effect on river flows, especially flow seasonality (Trivedi et al. 2007, Carey et al. 2010, 2013); winter flows can be reduced by snow accumulation, and spring/summer flows can be augmented by snowmelt. Flow regimes in some parts of the world are snow dominated (nival), especially the more northerly latitudes in Eurasia and North America (Stewart 2009), and seasonal snowpacks are important water sources for large populations globally (Diffenbaugh et al. 2013, Stewart 2009). Flow regimes in British catchments are generally dominated by rainfall (pluvial) rather than snow, although snowmelt can be a major component of the regime for catchments draining parts of the Scottish Highlands (Hannaford and Buys 2012, Soulsby et al. 2002a).

Snowmelt can influence peak river flows, but the effect is highly non-linear so any individual snow event could increase or decrease peak flows, compared to what would have occurred had all the precipitation fallen as rain (Kay and Crooks 2014). For example, a flow peak may be increased when rapid snowmelt is combined with rainfall, but may be decreased when melt from heavy snowfall occurs gradually. The effect will thus depend on the circumstances surrounding the event (e.g. the amount of snow and the timing of any temperature rise and rainfall occurrence) and on the catchment (e.g. via differences in timing of runoff from different altitudes) (Kay et al. 2014). Examples of significant flood events in Britain that are thought to have been made worse by the influence of snow include the major flooding of March 1947 across much of the country (RMS 2007), flooding on the River Tay in Scotland in January 1993 (Black and Anderson 1994) and, most recently, flooding on several rivers draining the Scottish Highlands in March 2015 (Centre for Ecology & Hydrology 2015). Snowmelt can also affect river water temperatures (Wilby et al. 2015), water quality and hydro-ecology (Helliwell et al. 1998), and hydro-electric power generation (Harrison et al. 2001).

This paper presents a review of snow in Britain, both historically (including observed trends) and projections for the future. The review covers snowfall and lying snow (Section II), the influence of snow on quantity and quality of river flows (Sections III and IV), and the effect of snow on a number of other factors of socio-economic or environmental importance (Section V). A discussion (Section VI) summarises the findings and highlights some knowledge gaps. Although the focus is Britain, studies covering other parts of the world are discussed in places, either to put results in a wider European or global context, or to help fill gaps in UK-based knowledge.

II Snowfall and lying snow

1 Snow recording

Accurate measurement of depth of snowfall and depth of lying snow, and their water equivalents, is not straightforward (NOAA 2013). The UK Met Office has a relatively dense network of raingauges, but these do not distinguish rainfall and snowfall (and have a relatively narrow aperture which can easily become blocked by too much snow) (Met Office 2010). However, observers measure and report the water equivalent of fresh snowfall at some weather stations, and the Met Office has point observations of presence/absence and total depth of lying snow from its network of weather stations (some of which now have automated snow depth sensors; Met Office 2010). These data were used to produce 5km grids of the number of days of falling and lying snow for 1971-2006 (Perry and Hollis 2005b), but the sites are all relatively low-lying so interpolation for higher altitude grid boxes is likely to be less reliable. Point observations of snow depth can also be unrepresentative of snow depths over larger areas (Grunewald and Lehning 2015, Stewart 2009).

The Snow Survey of Great Britain (SSGB), which operated from ~1937 to 2007, involved volunteer observers at fixed locations. They were asked to note, at ~9am each day, whether snow was falling at the location, the depth of any lying snow at the location, and the elevations of surrounding hills at which snow cover was over 50%. The paper records from the SSGB covering Scotland for 1945/46 to 2006/07 have recently been digitised (Spencer et al. 2014), providing an alternative dataset for lying snow that provides better coverage of higher elevations than does the Met Office point data. A comparison of the SSGB data for one site with the corresponding Met Office gridded data suggests that the Met Office data underestimates days of lying snow at higher altitudes (Spencer et al. 2014). However, the SSGB dataset itself has issues with missing data (from obscured views, absence of the observer or lost records) and sometimes what should be missing values can be confused with absence of snow. Jackson (1977) used the SSGB paper records to complete a snow catalogue describing the 100 winters from 1875/76 to 1975/76, begun by Bonacina (Bonacina 1966). An up-to-date version of the Bonacina snow catalogue is available from www.neforum2.co.uk/ferryhillweather/bonacina.html.

Remote sensing of snowfall, snow cover extent and snow water equivalent (SWE) is possible (Butt 2006, Schafferhauser et al. 2008, Noh et al. 2009), but satellite mapping can have problems with missing data due to cloud cover (Poggio and Alessandro 2015) and application of global products at regional scales can be problematic (Kelly 2000, Butt 2009). Kinar and Pomeroy (2015) highlight the need for improved instrumentation for automated snow measurements.

2 The historical picture

There is substantial geographic variation in snowfall in Britain, with altitude clearly an important factor, but on average north-eastern parts of Britain experience more days of both falling and lying snow (Wheeler 2013, McClatchey 2014) than southern or western regions (Mayes 2013, Perry 2014) including Ireland (Sweeney 2014, SNIFFER 2002). The UK Met Office provide maps of the UK showing the average number of days of falling and lying snow for several time periods (see examples in Figure 1, and www.metoffice.gov.uk/public/weather/climate/; Perry and Hollis 2005a). Factors affecting the spatial occurrence and distribution of snow more locally include snow-shadow (Currie 2004), urban pollution (Wood and Harrison 2009), and re-distribution by wind (Johnson and Thompson 2002, Dunn et al. 2001).

Given the relatively warm, maritime climate of Britain, few areas experience sustained periods of falling or lying snow (Hirschi and Sinha 2007). Instead, even in Scotland, snowfall generally occurs in distinct cold weather events interspersed by warmer periods when much of the lying snow can melt (Dunn et al. 2001), although some isolated and sheltered snow patches can remain right through from one winter to the next (e.g. Cameron et al. 2014). Occurrence of substantial snow events varies greatly from year-to-year, both in terms of spatial coverage and depths (e.g. Soulsby et al. 1997, Jackson 1977). Notably snowy winters include those of 1875/76, 1878/79, 1885/86, 1916/17, 1946/47 and 1962/63, each classed as “very snowy” in the original Bonacina snow catalogue covering 1875/76 to 1975/76 (Jackson 1977). More recently, the extension of the Bonacina snow catalogue has only classified 1978/79 and 2009/10 as “very snowy”.

Several widespread and heavy snowfalls occurred in Winter 2009/10, starting in mid-December, and snow covered much of the country by mid-January. Individual snowfalls exceeded 20cm even in parts of southern Britain. Following a period of warmer temperatures, and some snowmelt, more snow arrived in February (Prior and Kendon 2011a). However, a comparison with previous winters (back to the 1960s) showed that winter 1962/63 was snowier than 2009/10 in terms of the total number of days of lying snow, for the UK as a whole and for England and Wales, but that 2009/10 was snowiest for Northern Ireland. Winter 1962/63 was also snowier than 2009/10 in terms of number of consecutive days with snow depth at least 10cm, in all regions except north Scotland and north-west England (Prior and Kendon 2011a). For example, snow persisted at East Bergholt in Suffolk (a relatively low-lying location) from 31st December 1962 to 28th February 1963 (Dent 2013). It is less clear how the winter of 1946/47 compares to those of 1962/63 or 2009/10 in terms of particular snow measures (due to lack of comparable data), but in February 1947 snow covered much of the country (from Kent to Orkney) for the full month, with average depths commonly exceeding 50cm and drifts reaching depths of 3m or more (Hawke 1947). Further very heavy snowfalls occurred in early March 1947, but these were followed by a sudden thaw combined with heavy rainfall from mid-March which resulted in widespread flooding (Booth 2007, RMS 2007). December 2010 was also a very snowy period in Britain that many people will remember (Prior and Kendon 2011b). Of course, heavy snowfall events can be less widespread, or even highly localised. For example, an event severely affected Lancaster on 5-7th Feb 1996, with 13cm of level snow but 1-2m drifts (Bowker 1998).

An analysis of gridded data shows significant decreases in the number of days of lying snow for 1961/62-2004/05, in all regions of the UK, with the greatest percentage decreases in parts of southern and central England and Wales (Perry 2006). The decreases are still significant when only using data from 1963/64, to exclude the potential for the very snowy winter of 1962/63 to skew the results. The trends are most significant in autumn but absolute decreases are greatest in winter, when most snow occurs. Decreases in both autumn and spring suggest that the snow season is getting shorter. Analyses of changes in the number of days of lying snow in Wales and winter season snow depth in northern Snowdonia for 1977-2005 show similar results (Biggs and Atkinson 2011), as do analyses for Scotland (Barnett et al. 2006, Harrison et al. 2001). However, these analyses do not include the substantial events experienced in more recent winters. Analysis of regional averages of the number of days of snowfall and lying snow (Figure 2), derived from the Met Office's 5km gridded datasets for 1971-2011, shows decreasing trends in both variables for all regions (Scotland, northern England, southern England, Wales and Northern Ireland), but none of the trends in lying snow are significant at the 10% level ($p>0.1$). In contrast, all of the trends in snowfall are significant, at least at the 5% level ($p<0.05$), and those for Scotland, northern England and Northern Ireland are significant at the 1% level ($p<0.01$).

Spencer and Essery (2016) demonstrate a negative correlation between the winter North Atlantic Oscillation Index (NAO) and snowiness in Scotland, particularly for lower elevations and more easterly locations. Such relationships may be useful for seasonal forecasting of snow, and so aid preparedness for severe winters, provided factors like the winter NAO can be reliably forecast (Scaife et al. 2014).

3 Future projections

The UK Climate Projections 2009 (UKCP09; Murphy et al. 2009) did not specifically include probabilistic changes in snowfall or lying snow, but analysis of data from the UKCP09 Regional Climate Model (RCM) ensemble shows future reductions in the number of days of falling snow and in snowfall rates across Britain (Brown et al. 2010). Reductions in the ensemble mean number of days of winter snowfall by the 2080s (A1B emissions) ranged from -55% in western Scotland to -85% in the south of England, but with large variations between ensemble members. The 90th percentile winter snowfall rate (a measure of heavy snow events) decreases by more than -80% over most of the UK (~-60% over Scotland) except for one ensemble member, which generally shows decreases below -30% but with increases of over 20% for some parts of southern England. The previous set of climate projections for the UK (UKCIP02) also suggested decreases in snowfall across the country, with the largest decreases in the lowlands and around the coasts, and decreases below -90% for much of the country by the 2080s under a high emissions scenario (Fig. 49 of Hulme et al. 2002). However, the resolution of the UKCP09 and UKCIP02 RCM projections (25km and 50km respectively) is rather coarse, given the importance of altitude for snow.

Bell et al. (2016) present maps of the average number of days of lying snow per year, for the 1970s and 2080s (A1B emissions), simulated using a temperature-based snow model on a 1km grid with precipitation and temperature data from the UKCP09 RCM ensemble. These maps show large reductions in snow days in the future, with reductions to near-zero in the south-east of the country and in many coastal locations. This is consistent with the reductions in snowfall suggested by Brown et al. (2010). It is also consistent with the small-scale study of Trivedi et al. (2007), who develop a regression model of snow cover duration for an area in the Central Highlands of Scotland using daily mean temperature and monthly mean precipitation at a range of elevations. They use the model to project future snow cover, using temperature and precipitation data from the HadRM3 RCM, and show significant reductions in snow cover by the 2050s, ranging from -100% at 130m to -32% at 1060m under a high emissions scenario (-93% and -21% under a low emissions scenario).

A recent study, based on the UKCP09 methodology, looks at climate variability in relation to past and future occurrence of extreme seasons (Sexton and Harris 2015). It shows that the probability of a winter at least as cold as that of 2009/10 in England and Wales was 6% at that time, but that this probability drops to 0.6% by the end of the 21st century. This suggests that, although there is likely to be a reduction in the frequency of cold snowy winters in Britain, such winters can still be expected to occur at times over the 21st century.

More widely, analysis of data from the CMIP5 ensemble (comprising 56 runs of 26 Global Climate Models with RCP8.5 anthropogenic forcings) suggests reductions in March snow water equivalent for most regions of the northern hemisphere by the end of the 21st century, along with an increase in occurrence of low and extremely low snow years through the century (Diffenbaugh et al. 2013). However, parts of Eurasia and arctic North America show a decrease in occurrence of low snow years and an increase in occurrence of high snow years, due to increases in cold-season precipitation but temperatures remaining below freezing (Diffenbaugh et al. 2013).

III River flows and snow: water quantity

Snowfall and snowmelt can affect river flows by modifying water quantity, in terms of seasonal mean flows, low flows and water resources, and high flows and floods. These aspects are reviewed in this section, in terms of the historical picture and future projections.

1 The historical picture

Snow accumulation can result in reduced river flows, while subsequent melt can enhance river flows, thus affecting the variation of flows through the year and reducing the correlation between precipitation and flow (Carey et al. 2010, 2013). In Scotland, several major rivers have headwaters in mountainous regions and thus have a significant snowmelt component to flows (Dunn et al. 2001).

A detailed study of a small sub-arctic catchment in Scotland showed periods of snow accumulation in winter resulting in very low flows only sustained by groundwater, followed by high flows in spring produced by snowmelt (often combined with rainfall), with intermediate periods showing smaller flow peaks from rapid melt of snow at lower altitudes (Soulsby et al. 1997). The later melting of snow at higher altitudes sustained flows into early summer in a year with moderate snow cover, but summer flows were reduced in years with less snow cover (Soulsby et al. 1997). The analysis also showed a distinct diurnal cycle to flows during melt events, with maxima in the late afternoon/early evening and minima in the early morning, although the occurrence of rain coincident with snowmelt damped this diurnal pattern. Such flow patterns are likely to be the case for other catchments in Britain with similar patterns of snowfall and snowmelt, but catchments where lying snow is more transient, or larger catchments with some areas covered by snow and some not, are likely to show more intermediate-type peaks and not show such significant spring snowmelt peaks.

In general in Britain, changes in catchments affected by snow seem to have led to increases in winter flows, from more snowmelt and more rain, and reduced spring flows, from reduced overall snowmelt (Harrison et al. 2001). This is consistent with Stahl et al. (2010), who discuss observed trends in seasonal river flows in Europe and link some of the flow changes to snow. However, it is not always straightforward to link observed changes in seasonal flows to changes in snow, due to concurrent changes in precipitation. For example, an analysis of flows for 1929-2004 in the River Dee in north-east Scotland (strongly influenced by snowmelt from the Cairngorms) showed increases in spring flows and decreases in summer flows, but these were coincident with seasonal precipitation trends (Baggaley et al. 2009). However, higher coherence between spring precipitation and flow in the latter part of the catchment record (from 1980) was considered to be due to reduced snowfall, and the authors hypothesised that a threshold had been crossed at that time, leading to more significant periods with temperatures above 0°C. They thus suggest that the changes in spring flows are linked to changes in snow in the Cairngorms. An analysis of seasonal river flow trends for a set of 89 UK catchments with near-natural flow regimes shows different spring flow trends for the River Dee (in the later part of the record) than for the other catchments (Hannaford and Buys 2012); the authors suggest that the influence of changes in snowmelt on these trends is an area that needs further research. For Scotland, Harrison et al. (2001) suggest that changes in snow may already have led to changes in seasonal water resources and to the management of reservoirs, and state that reduced spring flows have led to reductions in electricity generation by hydro-electric plants, and thus a requirement to buy more power from the national grid.

The influence of snow on peak flows can be highly nonlinear. For example, using a simple lumped model of snow (with distinct snow accumulation and snowmelt seasons) and daily streamflow (with a linear reservoir), Molini et al (2011) demonstrated that the largest flow peak occurred for a mid-length warm-season; peaks for a longer warm-season were limited by decreased snow accumulation whereas peaks for a shorter warm-season were limited by slower melt. Of course, the behaviour of real catchments will be more complex. The analysis of Ali et al. (2015), for nine small catchments at mid- to high-latitudes (three in Scotland), showed differences in threshold behaviour for generation of snowmelt-driven events compared to rainfall-driven events, which differed markedly between catchments. The catchment analysis of Soulsby et al. (1997) showed that, even for a small catchment in Scotland with a sub-arctic climate, the annual maximum flows that were influenced by snowmelt also had a rainfall component. Snowmelt is however a key factor in flooding in late winter and spring on several rivers in Scotland (Black and

Werritty 1997). In Britain, the Flood Estimation Handbook (FEH) methods (Institute of Hydrology, 1999) and subsequent updates do not specifically include snowmelt, but the rainfall-runoff method used to assess reservoir flood safety can include a snowmelt contribution to the event rainfall and antecedent rainfall (Houghton-Carr 1999, Hough and Hollis 1997).

The evidence for observed changes in floods due to changes in snow is variable. A study of the Severn uplands in Wales over the last 30 years suggests that annual maximum flows have generally increased as snow cover has decreased (Biggs and Atkinson 2011), and a study in Scotland suggests that more sudden thawing of heavy snow, and wetter catchments, may have led to increases in the frequency of winter floods (Harrison et al. 2001), but these are not proven as cause and effect. On the other hand, a study of the River Thames suggests that no trends are seen in flood magnitude partly because of a decline in the contribution of snowmelt to major floods (Marsh and Harvey 2012), and an attribution study of the winter 13/14 floods shows that changes in snowmelt have moderated the increases that would otherwise have occurred for the Thames at Kingston (Schaller et al. 2016). A similar attribution study of the autumn/winter 2000 floods for several catchments in England also suggests that snow changes have moderated the increased chance of floods (in October-March) in the current (industrial) climate compared to a non-industrial climate (without the past emissions of greenhouse gases), particularly for the catchments in north-east England compared to those in the south (Kay et al. 2011).

A study of the River Tay, Scotland, suggests that snowmelt was more influential in floods in the 18^{th} and 19^{th} centuries than more recently (McEwen 2006). However, Macdonald (2012) looks at flood events on the River Ouse, North Yorkshire, using records dating back to the year 1600, and shows that the proportion of flood events including a snowmelt component (compared to those due only to rainfall) has been relatively stationary since 1800, and that larger flood events are not more likely to have a snowmelt component.

2 Future projections

For the northern hemisphere, Diffenbaugh et al. (2013) suggest that the CMIP5 ensemble projection of more widespread and frequent occurrences of high early-season snowmelt could lead to increased flood risk, whilst the projection of more widespread and frequent occurrences of low late-season snowmelt could lead to increased water stress. A study of the potential effect of climate change on flow regimes in Europe by the 2050s suggests that regions where snowfall becomes less important will experience the most change in the flow regime, with increases in winter flows, decreases in spring flows, and large changes in the timing of maximum and minimum flows (Arnell 1999). Another European study, driving a hydrological model with data from a 12km resolution RCM, shows decreases in the 100-year return period flood peak in parts of north-east Europe, which the authors link to a shorter snow season and reduced peak from spring snowmelt (Dankers and Feyen 2008). Some other parts of Europe (including Northern Ireland) also showed decreases in the 100-year return period flood peak, which may not be linked to snow changes, whilst many parts of central and western Europe showed increases (including much of Great Britain, although results for Scotland were more variable).

There are concerns over the effect that climate change may have on the regimes of rivers in Britain, particularly those which currently have a strong snowmelt influence

(Wilby et al. 2015, Soulsby et al. 1997, 2002b), but very few studies in Britain specifically analyse, or even include, the influence of snow changes on projected changes in flows. For example, two analyses of changes in seasonal river flows using UKCP09 data (Prudhomme et al. 2012, Christierson et al. 2012) do not include modelling of snow at all, and while the flow time-series produced for 282 rivers across Great Britain (using UKCP09 RCM time-series data for 1951-2098) do include the influence of snow (Prudhomme et al. 2013a), it would be difficult to distinguish the influence of snow changes from that of other concurrent changes.

Capell et al. (2014) use a hydrological model and data from the UKCP09 weather generator, to assess the potential impacts of climate change on the flow regime of the River North Esk, in north-east Scotland, and two of its sub-catchments (one upland and one lowland). They find a reduced influence of snow in the upland sub-catchment, with increases in winter flows and decreases in spring flows, while in the lowland sub-catchment they find that changes in the seasonal distribution of precipitation lead to reduced summer flows. Flow changes in the main catchment are a moderated version of the differing changes from the sub-catchments, due to the complex integration of the various processes involved. Capell et al. (2013) further highlight the varied response of flow regimes of catchments in Scotland under climate change. If snowmelt no longer sustains summer flows sufficiently in the future, then the abstraction of water may have to be limited (Dunn et al. 2001)

Kay and Crooks (2014) use catchment hydrological models to investigate the potential impacts of climate change on daily and 30-day annual maximum (AM) flows in three nested catchments of the River Dee, north-east Scotland. The hydrological models were run both with and without a snow module, to highlight the effects of snow on flows, and used data from the HadRM3Q0 RCM for 1950-2099 (A1B emissions). There were few significant trends in daily AM, whether modelled with or without snow, suggesting that snow has relatively little effect on daily AM in these nested catchments. However, for 30-day AM modelled with snow there were significant negative trends, and peaks occurred months earlier in the future. When modelled without snow, these trends were often of the opposite sign but generally not significant, showing the importance of including the snow module for such catchments. Later in the period there was a clear convergence of (daily and 30-day) AM modelled with and without snow, showing that snow was having less effect on flows in all of the catchments towards the end of the 21st century. However, variations in convergence between catchments and between durations demonstrated the complexity of the effect of snow, and changes in snow, on flows. Furthermore, a comparative analysis of peak timing for another upland catchment (a tributary of the River Tees in northern England) showed both daily and 30-day AM occurring earlier in future. The authors suggest that this complexity will make impacts on flows difficult to predict a priori for a particular catchment where flows are currently affected to some extent by snowmelt. A sensitivity-based approach to the impacts of climate change on flood peaks in Britain suggests that some of the more damped responses to changes in precipitation inputs are influenced by snow (Prudhomme et al. 2013b, Kay et al. 2014).

Bell et al. (2016) use a grid-based hydrological model to assess the potential impacts of climate change on peak river flows across Britain, using the UKCP09 RCM ensemble, and run the model both with and without a snow module. The variation in impacts across the country is larger than differences at any location due to the inclusion or exclusion of the snow module (Figure 3), but there are still quite large differences in simulated changes in flood peaks in parts of Scotland and north-east England, and smaller differences in many other areas of the country, showing the importance of including the snow module in these regions. Analysis of AM dates confirms the importance of including the snow module, particularly for eastern Scotland, and shows changes in timing of AM in all regions of the country, but with a particular shift towards AM occurring earlier in the water year in the north of the country.

Vormoor et al. (2015) suggest that understanding future changes in underlying flood generating mechanisms is crucial for understanding changes in the seasonal distribution of floods, which is in turn key to understanding changes in flood magnitudes and frequencies. They investigate the potential impacts of climate change (up to the 2080s under A1B emissions) on floods in six catchments in Norway which have a mixed snowmelt/rainfall flood regime in the current climate. The two catchments which currently have mainly autumn/winter flood peaks (i.e. generally rainfall-dominated) shift to greater autumn/winter dominance, and of the four catchments which currently have mainly spring/summer flood peaks (i.e. generally snowmelt-dominated), two shift to mainly autumn/winter dominance and two shift towards weaker spring/summer dominance (with the least change for the catchment which currently has the strongest spring/summer dominance). The changes in seasonal dominance (and therefore rainfall- or snowmelt-dominance) are shown to occur as a result of changes in both the frequency and magnitude of peaks-over-threshold in each season. The results of this study may be relevant to catchments in Britain that currently have a mixed snowmelt/rainfall flood regime.

IV River flows and snow: water quality

As well as affecting the quantity of flow in rivers, snowfall and snowmelt can directly affect water quality, including water chemistry and water temperature. Water quality and quantity in turn influence hydro-ecology (Langan et al 2001, Gibbins et al. 2001). These aspects are reviewed in this section, in terms of the historical picture and future projections.

1 The historical picture

A study of eight catchments in the northern high-latitudes of the globe, including three small catchments in Scotland, showed that the seasonality of dissolved organic carbon (DOC) in river flows varied significantly between catchments (Laudon et al. 2013). A positive correlation between winter temperatures and winter export of DOC and a negative correlation between winter temperatures and spring export of DOC were linked to the effects of winter snow accumulation. Soulsby et al. (2001) analysed data for four small sub-arctic catchments in the Cairngorms, and showed significant seasonal patterns in water temperature and water chemistry that they suggest are strongly influenced by snowmelt. Chemical factors affected were concentrations of nitrate, sodium and calcium ions and silica, along with alkalinity and pH, but concurrent seasonality of water quantity makes interpretation of the results complex. Further analyses for a sub-arctic catchment in Scotland (Soulsby et al. 1997; Helliwell et al. 1998) also showed a significant influence of snowmelt on water chemistry, with peaks in concentration of certain ions (particularly chlorine ions) and peaks in acidity (troughs in pH) coinciding with snowmelt events. The chemistry of the snowpack itself was shown to vary with altitude and with the amount of snowfall in the winter, and some of the variations are linked to the presence of anthropogenic pollution in the atmosphere (Helliwell et al. 1998).

As well as affecting water quality from upland headwater catchments, snowmelt can influence water quality in other regions by flushing high concentrations of anthropogenic chemicals into rivers. For example, in agricultural regions elevated concentrations of nutrients like phosphorus have been observed during rapid snowmelt events (Tiemeyer et al. 2009), and in urban areas high concentrations of organic contaminants and pesticides have been observed during snowmelt (Meyer et al. 2011). Rapid snowmelt events can also trigger (hillslope and river bed) sediment transfers (Johnson et al. 2010) and movement of surface peat (Warburton et al. 2004).

Analysis of water temperatures for two rivers in the Peak District showed that snowmelt events can cause rapid decreases in river water temperature, whereas rapid increases in river water temperature can be caused by bright sunshine during low flow conditions, or by intense summer storms (Wilby et al. 2015). Rapid changes in water temperature or water chemistry can potentially be detrimental to in-stream ecology (Wilby et al. 2015, Helliwell et al. 1998).

Analyses of river water from a small sub-arctic catchment over 12 years (1985-1997) showed trends in several water chemistry variables, including in-stream pH, but many of these trends are more likely related to changes in factors other than snowmelt, like reduced anthropogenic emissions of sulphur, and longer time-periods would be required to properly distinguish trends from variability (Soulsby et al. 2001). An analysis of trends in river water temperature in a small sub-catchment of the River Dee in north-east Scotland, over the course of 30 years, showed increases in winter and spring daily maximum temperatures but no change in mean annual temperature (Langan et al 2001). A strong correlation between stream temperature and air temperature suggested that the changes in water temperature were related to changes in climate, but it was also suggested that reduced influence of snow and snowmelt in winter and spring may have had an impact, and that the effects of snow make the prediction of water temperatures from air temperatures less reliable (Langan et al 2001). Long-term changes in seasonal water temperature and chemistry can have important implications for in-stream ecology. For example, Langan et al. (2001) highlight that the changes they found in water temperature in spring coincide with an important stage in the life-cycle of young salmon, when they leave the freshwater for the sea, and suggest that this event has been occurring earlier in spring.

2 Future projections

Laudon et al. (2013) hypothesise that climate change, and warmer winters, will lead to a change in the seasonality of DOC export in northern latitude catchments around the globe, from the current spring peak to a more even distribution through the year. Similar changes may apply to other aspects of water quality affected by snow, although future changes in concentrations of anthropogenic pollutants, like pesticides and fertilisers, are likely to depend as much on changing patterns of use of such chemicals as on changes in snow. However, if snowmelt no longer sustains summer flows sufficiently in the future then pollutant concentrations may increase as there is less dilution (Baggaley et al. 2009) and effluent returns may have to be restricted if there would be insufficient dilution (Harrison et al. 2001). Changes in water quality can have knock-on effects for water purification costs and ecosystems (Laudon et al. 2013).

The potential reduced frequency of snowfall in future suggests that rapid reductions of river water temperature due to snowmelt events may occur less frequently, but rapid increases in river water temperature due to intense rainfall events may occur more frequently in future, as might increases due to bright sunshine during low flow periods in the summer (Wilby et al. 2015). The value of rivers as fisheries may be affected by changes in the flow regime or changes in water temperature caused by changes in snow (Dunn et al. 2001, SNIFFER 2002) and changing flow regimes can influence passage and spawning of salmon (Moir et al. 2002).

V Other effects of snow

As well as influencing river flows, snow affects various other factors of socio-economic or environmental importance, including transport services (road, rail, air), other services/businesses (e.g. power supplies, health services, winter tourism), and farming and wildlife. These aspects are reviewed in this section, in terms of the historical picture and future projections.

1 The historical picture

Transport services. Even relatively small amounts of snow can cause disruption to transport systems, with blockage or closure of roads, train delays or cancellations, and closure of airport runways leading to flight delays, cancellations or diversions. In Winter 2009/10 and in late 2010 there were a number of such incidents, including people stranded on motorways and trains overnight (Prior and Kendon 2011a,b). In February 1996 in Lancaster “The gritting lorries were scarcely able to keep up with the intensity of the snow, since roads became covered again only a short time after they were salted” (Bowker 1998). In January 1963 a train travelling from Edinburgh to St Pancras was snowbound in Cumbria for four days (Canovan 1971). In February 1947 there was “Serious and repeated dislocation of travel, both by rail and road” and in March 1947 “All roads connecting London with the north became blocked and rail traffic was very badly disorganized” (Hawke 1947).

Of the range of weather conditions that can affect road travel, snow is often found to have the worst impact on accident rates (Koetse and Rietveld 2009) and on travel times and speeds (Tsapakis et al. 2013, Koetse and Rietveld 2009). An analysis of average travel times in the Greater London area showed that light snow increased travel times by 5.5-7.6% and heavy snow increased travel times by 7.4-11.4%, compared to travel time increases of 0.1-2.1% for light rainfall, 1.5-3.8% for moderate rainfall and 4.0-6.0% for heavy rainfall (Tsapakis et al. 2013). Interestingly, although snow increases road accident rates it tends to decrease accident severity, probably due to reduced traffic speed, and also tends to reduce traffic volumes, as people choose to postpone or cancel non-essential journeys (Koetse and Rietveld 2009). The management of roads under snow (and ice) conditions is difficult, with safety clearly a key factor but also a need to keep roads open wherever possible. These factors are discussed by Norem and Thordarson (2000) and Burtwell (2001) in relation to roads across Europe, including Britain, with the aim of identifying best practise. Lott and Stephens (2002) discuss the management of roads in Kent when a ‘snow or ice emergency’ is declared (when snow is over 50mm deep). The infrequency of such events in Kent means they are much less routine than in some other parts of the country, and can severely stretch council resources. Some local authorities in Scotland have reported reductions in the size of their fleet of vehicles for winter road maintenance services (Harrison et al. 2001).

Snow and ice can be a significant source of disruption to train services, but research in this area is sparse (Koetse and Rietveld 2009). The temporal variability and type of snow in Britain can make it more of a problem than in many colder countries (Canovan 1971). In many areas of Britain it may simply be uneconomic to invest in major snow-clearance measures, due to infrequency of disruptive snow events (Canovan 1971), but after the problems in late 2010 the House of Commons Transport Committee recommended improvements to make parts of the network more resilient (Prior and Kendon 2011a).

Other services/businesses. Snow (and ice) can bring down trees and power lines, cutting supplies of electricity to homes and businesses. In 2010 around 45,000 homes were cut off in Scotland on one day in February (Prior and Kendon 2011a), and in December the East Coast mainline was affected after overhead power lines were brought down (Prior and Kendon 2011b). A snow and ice load map for Great Britain (Nygaard et al. 2014) could help to highlight locations where better design of power lines may reduce the chance of failures. In Winter 1946/47, severe power supply problems were caused by already low coal stocks (as a consequence of the Second World War) and difficulties in transporting the coal to where it was needed (Prior and Kendon 2011a, Jones et al. 2012). Disruption of power supplies and transport can have knock-on effects, for example school closures, and loss of productivity if workers are unable to get to work and businesses are unable to transport goods. Thousands of schools were closed during snow events in Winter 2009/10 and late 2010 (Prior and Kendon 2011a,b), and the contraction in the UK economy in the last quarter of 2010 was blamed on the weather that winter (Prior and Kendon 2011b).

During snow events, hospital and emergency services can be severely stretched due to increased emergency admissions from accidents and falls, and non-urgent surgery and outpatient clinics may be cancelled to ensure that emergencies can be dealt with (Eaton 2010). Parsons et al. (2011) show that, on average, the presence of snow increases adult admissions to emergency departments in England and Wales by 7.9%, and Beynon et al. (2011) show an exponential increase in emergency hospital admissions in England from falls on snow and ice as temperatures fall, with rates varying by age and gender. Orthopaedic referrals in a particular hospital over the period April 2009-April 2010 averaged 74.9/day on snow days but only 33.5/day on non-snow days (Weston-Simons et al. 2012), leading the authors to recommend that orthopaedic doctors be located in A&E departments during periods of heavy snow, so that specialists can see patients more quickly and complications can potentially be avoided. The cost of inpatient admissions in England due to snow and ice in Winter 2009/10 was estimated to be £42m, emphasising the need to balance the costs incurred by implementing measures like gritting with the potential costs incurred by not implementing such measures (Beynon et al. 2011).

Snow-based winter tourism (e.g. skiing) clearly depends on the presence of snow, but temporal variability of snow cover (within a winter, and from one winter to the next) can make management of such businesses difficult (Harrison et al. 1999). An analysis of the number of days of operation of six ski-lifts (a proxy for ski-season length) in Cairngorm, Scotland (1972-1996) shows a reduction in the average number of days, but with large year-to-year variations and wide variations between ski-lifts, with the highest altitude lift showing little reduction over time (Harrison et al. 1999). Harrison et al. (2001) state that changes in snow in Scotland have already led to the need for investment to make better use of depleted snow resources (e.g. snow fencing and transport services to higher altitude slopes), but that overall there is an impression that Scottish skiing has become unreliable. Hopkins and Maclean (2014) also identify a reduction in snow reliability for a ski area in Scotland. Similar problems apply to activities like snow/ice climbing, and businesses have begun to diversify into activities less reliant on snow (Harrison et al. 2001, Hopkins and Maclean 2014).

Farming and wildlife. Farmers can be severely affected by snow, by losses of crops or livestock and by damage to farm buildings. The roofs of hundreds of farm buildings collapsed under the snow in late 2010 in eastern Scotland and north-east England (Prior and Kendon 2011b). An extreme example of the effect of snow on a farming community is the abandonment of Cwm Tywi (an upland area in the Cambrian Mountains of mid Wales) following winter 1946/47, after the loss of a large proportion of their sheep stocks (Jones et al. 2012). The effects on this Welsh sheep-farming community were severe despite high levels of preparedness (due to several snowy months in the earlier years of the 1940s), but the impact was made worse by a poor harvest the previous summer (leading to low stocks of animal feed), and the impact may have been lessened by the community not being connected to the mains electricity network at that time, so not being affected by the power cuts that resulted from coal shortages (Jones et al. 2012). Harrison et al. (2001) suggests that there are now fewer losses of sheep due to snow, but perhaps greater losses due to wetness, but several snowy winters since 2001 have led to large losses of sheep (Defra 2013).

Some species of mosses, liverworts and lichens are dependent on snow beds, and surveys of some snow beds show evidence of vegetation shifts (Ellis 2013). The presence (or absence) of snow cover can also influence the behaviour and survival of a number of mammal species. For example, vole numbers oscillate, wildcats move to areas with less depth of snow, and deer may have trouble accessing food (Newman and Macdonald 2013). Harrison et al. (2001) suggests that there has been a reduction in winter deaths of deer in Scotland as vegetation is now not covered in snow for so long.

2 Future projections

The fact that snow events are likely to occur less frequently in future implies a reduction in the frequency of incidents of disruption due to snow. However, Koetse and Rietveld (2009) suggest that, although climate change is likely to reduce future incidences of road travel disruption due to snow, incidences due to heavy rainfall may increase. Similarly, they suggest that climate change is likely to decrease snow/ice-related disruption to rail transport, but increase heat-related disruption. Similar conclusions are reached for transport infrastructure in Northern Ireland, with decreased problems from snow cover but possible increases from other factors (SNIFFER 2002). Also, faults on the UK's electricity network due to snow may decrease in future, but faults due to other causes (e.g. lightning) may increase (McColl et al. 2012). Using an analysis of past climate, Smith and Lawson (2012) develop a threshold-based approach to climate risks for Greater Manchester, suggesting that a daily snowfall amount exceeding 6cm (along with thresholds for temperature, wind speed etc.) has in the past been linked with impacts on health, urban infrastructure or other disruption. Such models could provide a way of estimating weather-related risks in the future using climate change projections.

A review of the impacts of climate change on the ski industry generally shows future reductions in the duration of the ski season (Gilaberte-Burdalo et al. 2014), although this varies between resorts (mainly depending on their altitude) and the study does not cover anywhere in Britain. In Scotland, less reliable snow cover at lower altitudes in future suggests increasing use of higher altitude areas, which modelling suggests may still have sufficient snow cover, although this presents possible problems with both access and safety (Harrison et al. 1999, 2001). A shorter snow season, together with improved summer conditions, may also provide extended opportunities for other activities, like hill-walking, if businesses and infrastructure can adapt and diversify (Harrison et al. 1999).

Less snow in future could result in the loss of snow bed habitats (Johnson and Thompson 2002, Ellis 2013). Trivedi et al (2007) develop a statistical model of the spatial distribution of a particular type of snow-dependant vegetation and show that, of the 153 10km grid cells in Britain that are currently occupied by this vegetation, 52% become unsuitable for it by the 2050s under a high emissions scenario (27% under a low emissions scenario). Less snow in future would also mean less frost protection for over-wintering crops, but possible extension of the growing season (Harrison et al. 2001), and the ranges of some mammal species (e.g. wildcat and red fox) may expand (Newman and Macdonald 2013).

VI Discussion and Conclusions

There have already been decreases in snow, globally and in Britain. There are likely to be further decreases in snowfall and lying snow in future, but this may be complicated in some locations by concurrent increases in precipitation. However, the range of uncertainty from climate models does not rule out future increases in snow, especially for heavy snow events (Brown et al. 2010). Furthermore, scientific understanding of complex atmospheric interactions is continually evolving, as is the representation of these interactions within climate models (e.g. Scaife et al. 2012), so projections of snow changes from new climate model versions will not necessarily be completely consistent with existing projections. Harrison et al. (2001) call for improved routine snow monitoring, including extent, duration and depth, and further development of methods for remote sensing of snow may help.

In studies of changes in observed river flows it can be difficult to separate the effects of changes in snow from those of concurrent climate-related changes (precipitation and temperature), and changes in other factors like land-use, abstractions or effluent returns may also confound such analyses (e.g. Marsh and Harvey 2012). This is particularly the case if only relatively short time-series are available, especially given the existence of clear flood-rich and flood-poor periods (McEwen 2006). The relative lack of reliable snow measurements, particularly for long periods, also makes such analyses difficult. It may be useful to reconstruct long time-series of fine-scale gridded data on snowfall and lying snow using available long time-series of gridded precipitation data (e.g. the 1km CEH-GEAR data; Keller et al. 2015) and temperature records, although the reliability of such snow reconstructions would have to be carefully tested. Long time-series of snow data may also be useful for assessing the historical influence of snow on other environmental or socio-economic factors, like species abundance or transport disruption, although such analyses are also likely to be confounded by concurrent changes in factors like land-use, agricultural practices and technology.

Future changes in flows due to climate change are much more complex when snow is involved, due to the highly nonlinear nature of snow processes. The combination of change in temperature and change in precipitation, and factors like the range of altitudes present in the catchment, will each affect the transformation of precipitation into river flows, as well as the usual factors affecting this transformation, like catchment permeability, land-cover and loss of water via evaporation (Prudhomme et al. 2013b), some of which may also change in future (Price 2000, Kay et al. 2013). Carey et al. (2013) state that "To date, few P-Q [precipitation-flow] studies have included specific analyses of snowmelt-dominated systems, and there remains a lack of insight into fundamental questions in these systems related to moisture thresholds for flow generation, modulation by soil depth and frozen ground, bedrock topography, catchment morphometry, and how short and longer-term climate drivers may influence streamflow variability in northern catchments." Ali et al. (2015) investigate some of these issues, but gaps in process-understanding remain in such regions (Tetzlaff et al. 2015). Vormoor et al. (2015) highlight that, in catchments influenced by snow, changes in flood seasonality cannot be directly predicted from seasonal changes in temperature or precipitation; hydrological modelling is required. A detailed study of the seasonality, magnitude and frequency of flood peaks and their generating mechanisms under climate change, like that of Vormoor et al (2015), would be useful for catchments in Britain, particularly those in Scotland, northern England and Wales.

Future changes in water quality and hydro-ecology will also be more complex when snow is involved. This is due to the direct effect of changes in snowfall changing the chemical composition and temperature of water delivered to the rivers (e.g. Helliwell et al. 1998, Wilby et al. 2015), but also to the indirect effect of changes in flow seasonality and quantity (e.g. Baggaley et al. 2009). In addition, as well as being affected by climatic changes, water quality is likely to be affected by changes in non-climatic factors (e.g. air pollution) (Curtis et al. 2014), so a holistic approach is required.

Although the likely reduced frequency of snow events in Britain in future is likely to mean fewer incidences of snow disruption, there are several cases highlighted where this may be countered by increased incidences of disruption from other weather-related events (e.g. heat, heavy rainfall or lightning). Further modelling of the potential impacts of climate change on river flows and other environmental or socio-economic factors, including modelling the influence of changes in snow as well as other climatic and non-climatic changes, would aid understanding of the full range of possible futures, both negative and positive, and encourage mitigation against them or aid adaptation to prepare for them.

Despite the likely reduced frequency of snow events in Britain in future, events can still be expected to occur even by the end of the century, and there will not automatically be a reduction in the overall impact of snow. Jones et al. (2012) suggest that future projections of less frequent snowfall in the UK could in fact lead to lower levels of preparedness, both personally and at the community level, and that the implementation of measures to alleviate the impacts of snow may be reduced. They further suggest that perceptions of severity may change, with events of lower weather severity being considered more extreme than they are now and potentially leading to greater consequences than equivalent events now. There is thus a need to guard against complacency when it comes to future snow events. Both better forecasting and improvements in the communication of the possible effects of snow could help increase levels of preparedness and decrease the impact of snow events when they occur.

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Figures

Days of falling snow/sleet | **Days of lying snow**

1961-1990

1981-2010

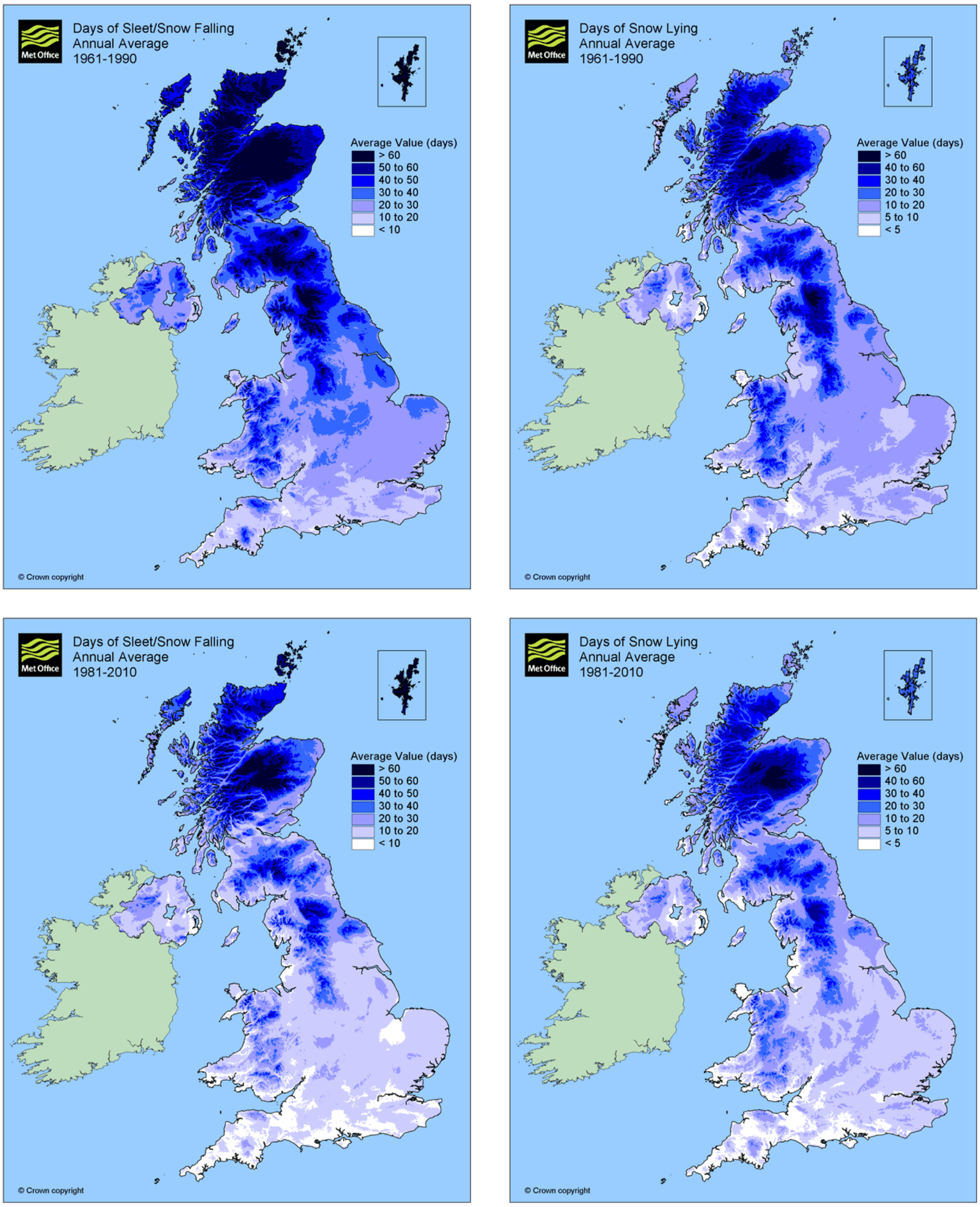

Figure 1 Example maps from the Met Office National Climate Information Centre (NCIC) (www.metoffice.gov.uk/public/weather/climate/), showing the annual average number of days of falling snow or sleet (left) and lying snow (right) for 1961-1990 (top) and 1981-2010 (bottom). (Reproduced with the permission of the NCIC.)

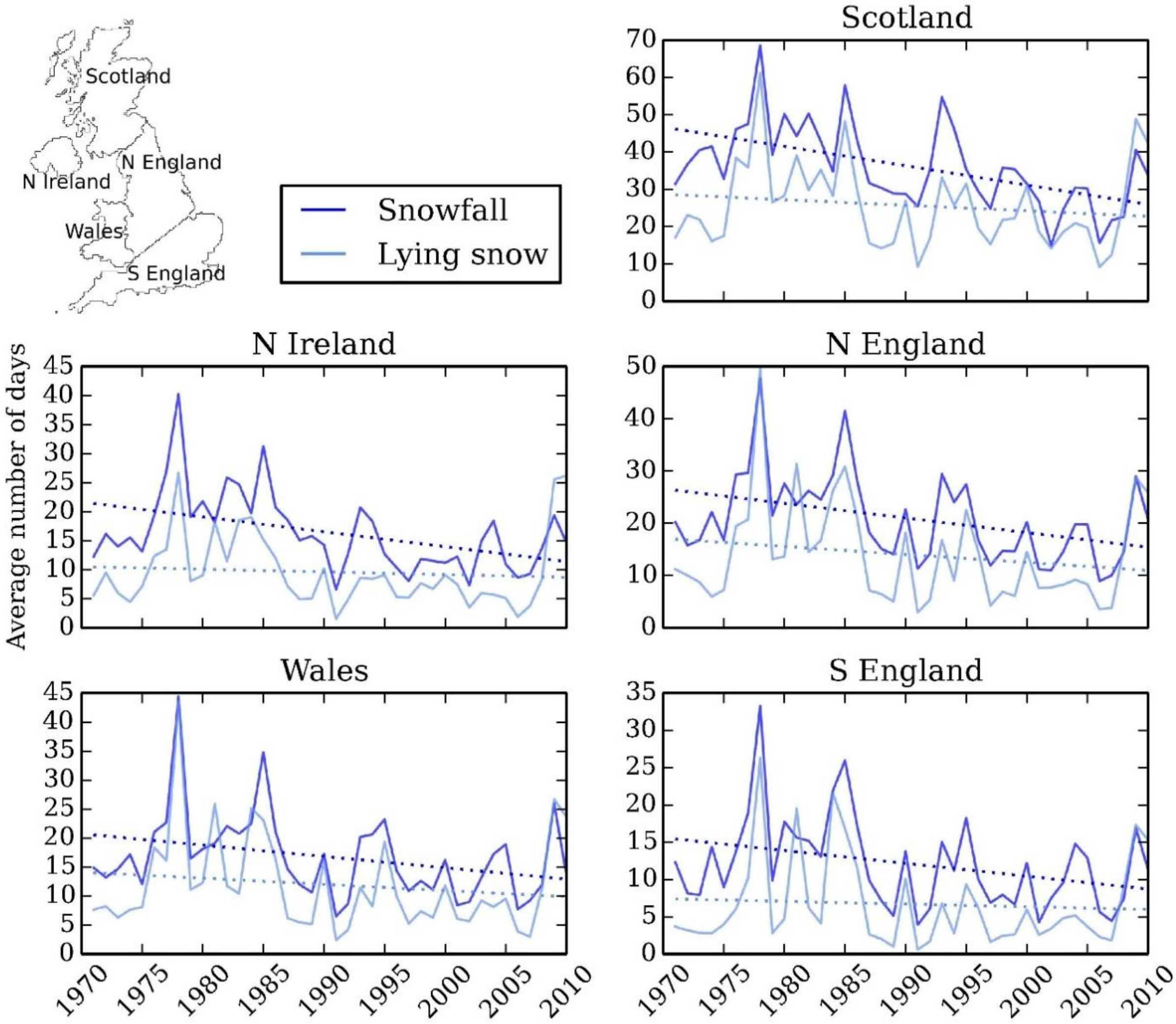

Figure 2 Regional averages of the number of days of snowfall and lying snow for each water year in 1971-2011 (solid lines), with corresponding linear trends (dotted lines).

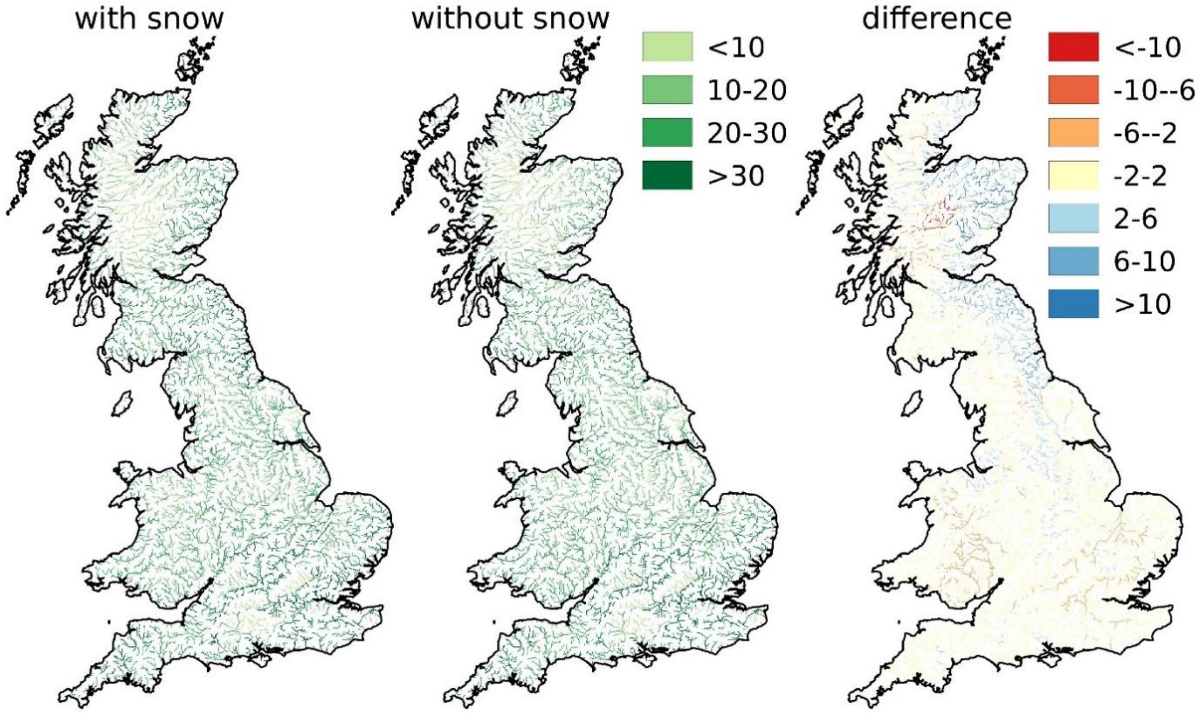

Figure 3 Maps showing the percentage change in 10-year return period flood peaks across Britain, when modelled with snow (left) and without snow (middle), and the difference (with snow minus without snow) (right). The changes are modelled with the G2G hydrological model combined with a snow module and driven with UKCP09 RCM ensemble data; the ensemble mean changes between the 1970s and the 2080s (A1B emissions) are shown.