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An investigation of the effect of transient climate change on snowmelt, flood frequency and timing in northern Britain

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Short title: Transient changes in snowmelt in Britain under climate change

Abstract
Climate change is almost certain to affect snow and ice processes. Even at lower latitudes, changes in snow cover at high altitudes can significantly affect catchment hydrology. This paper uses data from a transient Regional Climate Model projection (HadRM3Q0) for 1950-2099 (A1B emissions) to drive hydrological models for three nested catchments on the river Dee in north-east Scotland, to assess potential changes in flood frequency and timing using annual maxima and moving-window analyses. Some results are also shown for an upland catchment in northern England. Modelling is performed both with and without a snow module, to demonstrate the effects of snowfall/melt and how these change through time and vary between catchments. Modelled changes in flood magnitude and timing are non-linear, with most changes for daily mean flows not significant. For longer duration (30-day) flows with snow there are significant decreases in peak magnitude, particularly for the smaller higher altitude Dee catchments, with peaks occurring months earlier in future (changes without snow are generally not significant). There is a general convergence in results with and without snow later in the period, as snow processes become less important, but convergence occurs at different times for different catchments and occurs differently for daily and 30-day peak flows due to the differential effects of snow at different durations. This highlights the importance of including snow processes for such catchments, particularly for longer duration flows, but also highlights the complexity of interactions: Physical catchment properties, the balance between precipitation occurrence and temperature, and how this balance alters as the climate changes will each be critical in determining the impact on the magnitude and timing of peak flows, making it hard to generalise results.

Keywords
Climate change; snow; hydrological impacts; annual maxima; flooding.

1. Introduction
Probably the most certain impact of climate change, according to Global Climate Models (GCMs), is an increase in temperature across the globe, particularly in the northern hemisphere and most especially at higher latitudes (Solomon *et al.* 2007). This will clearly have an impact on snow and ice processes, and one of the biggest concerns is the possible loss of the Greenland ice sheet and the huge rise in sea levels this would

cause (Parry *et al.* 2007). Changes in ice or snow cover could also cause significant changes in hydrology for upland catchments at lower latitudes. A study of observed data from the Spanish Pyrenees for 1950-1999 shows reduced winter precipitation leading to reduced discharge in both winter and spring due to less snow accumulation and melt (López-Moreno and Garcia-Ruíz 2004), while a study of observed streamflow records for 151 catchments in the Nordic countries (Norway, Sweden, Finland, Denmark, Iceland) shows earlier snowmelt peaks in all except Iceland (Wilson *et al.* 2010). For the western US, studies of observed trends also show earlier snowmelt (e.g. Stewart *et al.* 2005, Hamlet *et al.* 2007, Clow 2010). Stewart (2009) provides a useful summary of recent analyses of observed (and projected) changes in snowpack and snowmelt runoff from key mountain regions around the globe.

Stewart (2009) highlights that observed impacts on snowfall/snowmelt runoff are a complex consequence of simultaneous changes in temperature and precipitation, modulated by physical catchment characteristics. The effect of a temperature increase could be masked by a concurrent precipitation increase in the cold-season, giving a greater snowpack and delaying melt. Thus clear changes may only be seen once thresholds of temperature and/or precipitation change are crossed. In a study of trends in measured snow water equivalent (SWE) in Norway for 1931-2009, Skaugen *et al.* (2012) state that the combination of precipitation and temperature determine the threshold elevation at which trends change sign. Several 20th century trend studies for the western US attempt to explain the effects of changes in precipitation and temperature on April SWE (Mote 2006, Hamlet *et al.* 2005) and flood risk (Hamlet and Lettenmaier 2007). The latter found the greatest changes in flood risk for basins with current mid-winter temperatures close to zero, but with large variations due to other competing factors, while both colder and warmer basins showed decreased risk or little change. Potential non-linearity is further highlighted by Molini *et al.* (2011) who develop a toy model of snow accumulation, melting and streamflow at a daily time-step and use it to investigate the role of the seasonal cycle of temperature. They demonstrate existence of an optimal warm-season length, giving the largest flow peak; peaks for a shorter warm-season are limited by slower melt whereas peaks for a longer warm-season are limited by decreased snow accumulation.

A number of studies have used GCM data, generally in terms of delta changes or with some form of statistical downscaling, with hydrological models to assess future changes in catchment hydrology including snowmelt (e.g. Jasper *et al.* 2004, Boyer *et al.* 2010, Jung and Chang 2011, Hamlet *et al.* 2013). Adam *et al.* (2009) use delta changes in precipitation and temperature from a set of 15 GCMs (between 1961-1990 and 2025-2054, under the SRES A2 emissions scenario) to adjust baseline datasets to drive the VIC model at a 0.5^{o} resolution globally. Their results highlight the complexity of the interaction between snow, rain, temperature, evaporation and runoff, as different regions/basins are most sensitive to different aspects of the change in climate. Diffenbaugh *et al.* (2013) also demonstrate regional differences in the response of March SWE and melt runoff in the northern hemisphere, using a relatively large GCM ensemble. However, the resolution of GCMs is generally too coarse for direct use to drive most hydrological models.

The nesting of higher resolution Regional Climate Models (RCMs) within the lower resolution GCMs has enabled the more direct use of climate model data to drive hydrological models at the appropriate scale for flood modelling (e.g. Kay *et al.* 2006a, Horton *et al.* 2006, Graham *et al.* 2007, Dankers and Feyen 2008). Some of these studies have included and analysed the effect of changes in snowfall and snowmelt between baseline (e.g. 1961-1990) and future (e.g. 2071-2100) time-slices. For instance, Horton *et al.* (2006) investigate discharge in 11 catchments in the Swiss Alps, using 19 RCMs, and show that all of these result in an earlier onset of snowmelt for 2070-2099 compared to the baseline period. Dankers and Feyen (2008) use a higher resolution RCM to drive a Europe-wide grid-based hydrological model, and show a decrease in the spring snowmelt peak in north-eastern Europe by 2071-2100. Until very recently however, only time-slice data were available from RCMs. The problem with this time-slice approach is that hydrology is an inherently non-linear process, particularly where snowfall and snowmelt are involved (e.g. Molini *et al.* 2011), so the impact by the 2080s says little about what may happen in the intervening period. There is also the problem of natural variability, the effects of which can be large (Deser *et al.* 2012) and the 'noise' of which could act to enhance or reduce the climate change impact in any given period (Wood 2008, Kerr 2007).

Dettinger *et al.* (2004) made use of transient runs of a GCM covering the period 1900-2099, after downscaling, to drive a hydrological model for three catchments in California. The use of transient runs enabled the authors to conclude that most trends, including those towards earlier snowmelt runoff, would be indisputable by 2025 despite natural climate and hydrological variability. Kay and Jones (2012) made use of three transient regional climate projections for Europe, produced by the UK Met Office Hadley Centre as part of UK Climate Projections 2009 (UKCP09; Murphy *et al.* 2009), using a high-resolution (0.22^o) RCM run for the period 1950-2099. These data were used to drive a hydrological model for two catchments in England, and the resulting flows were analysed in terms of changes in flood frequency and timing in a 30-year moving window. The results suggested that changes are unlikely to occur linearly over the century, partly because of the presence of natural variability but also perhaps due to the inherent non-linear response of hydrological systems. However, the modelling presented in Kay and Jones (2012) did not include snowfall and snowmelt, which could significantly alter results in parts of Britain, particularly Scotland and north-east England.

This paper makes use of one of the same UKCP09 RCM runs to investigate transient changes in flood frequency and timing for three nested catchments in Scotland affected by snow to differing extents. For these catchments, temperatures in the headwaters can be sufficiently low to allow accumulation of a snowpack through the winter. For comparison, some results are shown for a catchment in northern England which has similar annual precipitation and median altitude to the largest Scottish catchment and which can also receive significant snowfall, though in this catchment lying snow is more likely to occur as discrete winter events without sufficient accumulation to form a connecting snowpack. Modelling is performed both with and without a snow module as a pre-processor of the precipitation inputs to the hydrological model, to assess the importance of including snow processes for higher altitude catchments in northern Britain. Moving-window analyses are performed for flood frequency and timing, following the methodology of Kay and Jones (2012). Section 2 describes the catchments modelled, the hydrological models and snow module, the RCM data, and the analysis methods. The results, in terms of modelled changes in flood frequency and timing through the 150-year period, are presented and discussed in Section 3, with conclusions in Section 4.

2. Models, data and methods

2.1 Catchments

The three nested catchments in Scotland used to investigate the affect of snow are part of the River Dee, which begins in the Grampian mountains and flows eastwards to enter the North Sea at the city of Aberdeen. The Dee at Mar Lodge (gauging station number 12007) is nested within the Dee at Polhollick (12003), which is in turn nested within the Dee at Park (12002). An additional catchment, representative of a small upland catchment in northern England — the Greta at Rutherford Bridge (25006) — is used in the analysis of peak timing (Section 3.2). The Greta flows eastwards from the upland moors of the Pennines to join the River Tees, which enters the North Sea near Middlesbrough. Catchment locations and topography are shown in Figure 1, with some catchment details described below and in Table 1. The catchments are essentially rural, but differ in terms of area, topography and current water balance regime. The maximum altitude of the Greta is over 700m lower, with generally shallower slopes and less precipitation, than the Dee (Marsh and Hannaford 2008). The Greta has a temperate maritime climate whereas the upper Dee has a sub-arctic maritime climate. On average, for 1971-2000, the number of days per year with snow falling (lying) is around 100 (85) for the upper Dee and 50 (40) for the Greta; for both, snow is likely to fall on at least one day per month in October-May (www.metoffice.gov.uk/public/weather/climate/). Land cover for the three nested Dee catchments shows an increasing percentage of forest and grass downstream as the typical upland cover (rock, heather, moorland grass and bog) decreases with lower altitude. The Greta has a similar percentage of upland cover to the largest Dee catchment but lacks the forest (Marsh and Hannaford 2008). The same main soil types are present throughout the Dee catchment, though the percentage of soils with an impermeable (or gleyed) layer within the top 1m is highest for 12007 and lowest for 12002 (and vice versa for soils with greater depths to an impermeable substrate). Percentages of peat soils are approximately the same (35-40%) for all three Dee catchments, while the Greta is predominantly peat (80%) (Boorman *et al.* 1995). Response to rainfall is quickest where an impermeable layer is present near the land surface (or at the surface, as with bare rock). Peat soils also have a fast rainfall/runoff response where the high water content can act like an impermeable layer.

Figure 1

Table 1

A trend analysis of Scottish climate between 1961 and 2005 (Barnett *et al.* 2006) shows a general reduction in the number of days of snow cover in each season, and a shorter snow season. Baggaley *et al.* (2009) analyse flow records for the Dee at Woodend (between Park and Polhollick) for 1930-2005, and show a significant increase in spring low and median flows, whereas changes in spring high flows and flows in other seasons were not significant. The spring flow increase, associated with a significant increase in precipitation and mean and minimum temperatures in March, was accompanied by a significant increase in correlation between spring flow and precipitation after 1980. The authors suggest this is due to changing patterns of snow/rain in the catchment in winter/spring, with a threshold being crossed since 1980. A recent study of trends in nine long observational flow records in Britain (Hannaford and Buys 2012) shows clear increases in winter median and high (Q5) flows for the Dee at Woodend — much stronger than for the other catchments, especially for median flows. In spring an increasing trend in both median and high flows for the full record (1929-2008) becomes a decreasing trend when only the later part of the record (from ~1960) is analysed — more similar to the other catchments. The authors again suggest that these flow changes may be due to changes in snow. These studies both highlight the potential non-linearity of flow behaviour in a changing climate particularly when influenced by snowfall/snowmelt.

2.2 The hydrological models and the snow module

The hydrological model used for the two larger catchments (12002 and 12003) is the Climate and LAnd-use Scenario Simulation In Catchments model (CLASSIC; Crooks and Naden 2007). This is a semi-distributed continuous simulation rainfall-runoff model, developed for estimating the impacts of climate and land use change on flows in large catchments. CLASSIC is applied on a grid square framework, where the simulated runoff from each grid square is routed directly to the catchment outlet rather than through successive grid squares. The grid square size is set as appropriate for the catchment area and the variation of climatic and physiographic conditions within the catchment; a 10km grid is applied here. CLASSIC comprises three main modules (soil moisture storage, drainage and channel routing), and requires percentages of six land use types (Fuller 1993) and HOST soil classes (Hydrology Of Soil Types, Boorman *et al.* 1995) for each grid square with physiographic information on hill-slope, altitude and the channel network derived from the Integrated Hydrological Digital Terrain Model (IHDTM; Morris and Flavin 1990). The model is run at a daily time-step, and concurrent daily flow and rainfall data (and monthly potential evaporation, PE, data) for each grid square are available for CLASSIC calibration (which is semi-automatic), for the period 1972-2001 for catchment 12002 and 1975-2001 for catchment 12003.

The hydrological model used for the two smaller catchments (12007 and 25006) is the Probability Distributed Model (PDM; Moore 2007), which forms part of the River Flow Forecasting System for Britain (Moore *et al.* 2005). It is a catchment-based rainfall-runoff model, requiring inputs of catchment-average rainfall and PE. Although the full PDM has a variety of formulations, the version used here has been simplified in order to reduce the potential for equifinality and allow automatic calibration. The version used has six catchment-specific parameters; two are determined by catchment location, one is set using HOST data, and the remaining three require calibration using observed data. This version of the model, and its automatic calibration method, are refinements of those described by Kay *et al.* (2007). The model is run at an hourly time-step, and concurrent hourly flow and rainfall data (and monthly PE data) are available for PDM calibration, for the period 1989-2001 for catchment 12007 and 1985-2001 for catchment 25006.

A snow module can be used as a pre-processor for both the CLASSIC and PDM precipitation inputs, effectively delaying the input of water if snowfall occurs. The module was devised by Bell and Moore (1999) particularly for improved snowmelt forecasting in Britain using the PDM, and uses a simple temperature-related snow store and melt rate with eight parameters, which operates with separate accounting in different elevation zones. The module thus requires a time-series of temperature data, the altitude to which the temperature relates, and information on catchment area within the different elevation zones. Daily minimum and maximum temperature data on a 5km grid over the UK, available from the UK Met Office, were used for model calibration, with data taken from the grid box containing the catchment centroid and a lapse rate used to estimate temperature in each elevation zone. Daily mean temperature time-series are taken as the average of the daily minimum and maximum values for input to CLASSIC. For input to PDM, a sine curve was used to approximate the hourly temperature by assuming that the minima and maxima occur at 2am and 2pm respectively. The altitude of the grid box centre was taken from the corresponding point within the IHDTM (which has a 50m horizontal and 0.1m vertical resolution), which was also used to determine the proportion of the catchment area in the different elevation zones.

Crooks *et al.* (2009) provides more detail on calibration of the hydrological models with the snow module, as used in a classification of flood response to climatic change involving 154 British catchments (Prudhomme *et al.* 2013a) where there was no evidence that results were affected by the hydrological model applied. Calibration used the full period of available climate and observed flow data (a maximum period of 1961-2001), to cover as wide a range of climatological conditions as possible and allow flood frequency curve fit to be used in the procedure. Different models were used, as distributed/semi-distributed models (e.g. CLASSIC) are generally preferred over lumped models (e.g. PDM) for larger catchments, but it is generally better to use a sub-daily time-step (e.g. hourly with PDM) rather than a daily time-step (e.g. CLASSIC) for smaller catchments. All analyses here are for daily (or longer) mean flows (see Section 2.4). A comparatively simple snow module was selected, compatible with the availability of data for calibration and from climate models. The parameter values used in the snow module are those providing generally good simulation of snow-influenced hydrographs throughout Britain. Although use of an average melt rate means that not all snowmelt-affected peak flows are well simulated, and the timing of changes in temperature over a day may not be well replicated with only daily maximum and minimum temperatures, inclusion of the simple snow module nevertheless improves hydrological model performance. Its use allows an assessment of the contribution of snow processes in the current climate and possible effects of changes in the snow/rain balance, without unduly adding to data requirements.

2.3 RCM data

Climate data are taken from the Met Office Hadley Centre RCM HadRM3 (~25km resolution over Britain) nested within their HadCM3 global model (Pope *et al.* 2000). An 11-member perturbed parameter ensemble of this system was produced to guide the development of the latest set of climate scenarios for the UK, UKCP09 (Murphy *et al.* 2009); the standard-parameter run is applied here, termed HadRM3Q0. The run goes from 1 January 1950 to 30 November 2099, under the A1B emissions scenario (IPCC 2000). Note that the length of an RCM year is only 360 days, comprising twelve 30-day months.

Precipitation is a direct output of the RCM (available at an hourly time-step), and simply has to be converted into grid-average precipitation for CLASSIC or catchment-average precipitation for PDM. Area-weighting, along with standard average annual rainfall (SAAR) data, are used for this (Kay *et al.* 2006b). PE from the land surface has to be produced from other RCM variables, as it is not a direct output of the RCM. Previously this was done using meteorological variables along with fixed literature values of canopy resistance for short grass (Kay *et al.* 2006b) using the Penman-Monteith equation (Monteith 1965). Here a new method has been applied to estimate Penman-Monteith PE using time-varying values of canopy resistance from the RCM's embedded land-surface scheme (Bell *et al.* 2011). This could be important for more accurate projections of future flows, since canopy resistance depends on the atmospheric CO_2 concentration (Kay *et al.* 2013a). Daily time-series of PE are thus produced for each RCM grid square, then CLASSIC grid-average and PDM catchment-average PE is produced using area-weighting (Kay *et al.* 2006b). Temperature data, required by the snow module, are obtained from the RCM as daily minima and maxima. As with observed temperature data, the RCM temperature data are taken from the grid box containing the catchment centroid and lapsed for each catchment elevation zone, with the mean daily temperature used for CLASSIC and a sine-curve used to approximate the hourly temperature time-series for the PDM. The corresponding altitude is taken from the RCM's orography ancillary file.

CLASSIC and PDM are then run with the RCM-derived input data for each catchment. This is done both with and without the snow module as a pre-processor for the rainfall inputs, in order to assess the effect that snow processes are having on the catchment, and how this effect could change over the period to 2099. In the absence of the snow module, all of the precipitation is assumed to occur as rain and input straight to the hydrological models. With the snow module, precipitation can occur as snow when the temperature is sufficiently low, thus delaying the input of water to the hydrological models until the temperature increases sufficiently, when the snowpack can begin to melt at a specified rate.

2.4 Annual maxima and flood frequency

Annual maxima (AM) are extracted from the modelled daily mean flow time-series, and for (running) 30-day mean flow time-series, for each catchment. Water years are used (1 October – 30 September), thus 149 AM are saved (with their date of occurrence) from each time-series. Transient changes in flood frequency and timing are then investigated using moving window analyses (following Kay and Jones (2012)), described briefly below.

To investigate transient changes in peak magnitude, flood frequency curves are fitted (using L-moments) to the AM within a 30-year moving window, moved through the time-series year-by-year; thus 120 calculations are performed for each time-series. The fitted curves relate peak magnitudes to return periods (T), using a generalised logistic (GLO) distribution (Eq. 1) with three parameters; location ξ, scale α, shape k.

$$Q_T = \xi + \frac{\alpha}{k}\left(1-(T-1)^{-k}\right) \qquad (k\neq 0) \qquad (1)$$

Fitting assumes approximate stationarity over the (30-year) data period, which is valid as natural variability is likely to dominate climate change over this relatively short period (30 years is the standard time-slice length for climate analyses), but curves should not be extrapolated to return periods far beyond 30 years (return periods up to 50 years are used here).

To investigate transient changes in peak timing, the date of occurrence of each AM is converted to (r,θ) coordinates, with r the year number (1 Oct 1950 – 30 Sep 1951 being year number 1) and θ the day number (1 January day number 1, 1 February day number 31 etc., noting the RCM's 30-day months and 360-day year). Circular statistics are then used to calculate the mean date of occurrence at each position of the moving window. Here a 60-year window is used as it was considered useful to apply greater smoothing to the time-series of AM dates (which are very variable for some of these catchments; see discussion in Section 3.2) to better fit trends to mean AM date series (see below).

2.5 Trend analysis and significance testing

Through use of the moving window new time-series are derived, of three types: a) flood peaks with specific return periods (2, 10 and 50 years), b) GLO parameters (location ξ, scale α and shape k — note that location ξ is equivalent to the 2-year return period flood peak), c) mean AM dates. As in Kay and Jones (2012) trend analysis is performed on each of the derived time-series, using isotonic regression (Barlow *et al.* 1972) to fit the best non-decreasing (or non-increasing) step-function (as the trends are expected to be non-linear). The standard deviation (x2) of this step-function is used as a measure of trend size, signed according to trend direction (+ increasing, - decreasing).

Permutation testing is used to estimate trend significance. That is, for 10,000 random permutations of the original AM data, flood frequency curves and mean AM dates are calculated at each moving window position, and isotonic regression lines fitted to each re-derived time-series. The size of the original trend is compared with the distribution of sizes from the permutations, in a two-sided test (e.g. a trend located in the highest or lowest 0.5% of the distribution is significant at the 1% level). See Kay and Jones (2012; Section 2.6) for example plots of time-series with fitted trend lines, example permuted time-series and results of corresponding significance tests.

3. Results and discussion

3.1 Trends in flood peaks

Figure 2 shows the simulated AM (points) and transient fitted flood peaks at the 2-, 10- and 50-year return periods (lines), for daily and 30-day mean flows for each of the three nested Dee catchments in Scotland. The AM points show that, later in the period for all three catchments, many years have the AM modelled with the snow module (circles) coincident with those modelled without the snow module (crosses). Earlier in the period, the 30-day AM with snow are generally greater than those without snow (especially for the upper two catchments), with almost no coincident pairs, whereas for daily AM some pairs are still coincident and the rest can be either greater or less with snow than without (except for the largest catchment, where daily AM with snow tend to be less than those without). However, it should be noted that the AM with and without snow are not necessarily the same peaks (e.g. for a given AM simulated without snow, the inclusion of the snow module could reduce that peak to such an extent that a completely different peak becomes the AM, or introduce a new peak that becomes the AM).

Figure 2

The increased coincidence of AM later in the period means that the transient flood peaks with snow (Figure 2, dashed lines) and without snow (Figure 2, solid lines) generally converge as time progresses, as the higher temperatures of future climates make snow processes less important for these catchments. However, the convergence occurs differently for daily and 30-day flows. For daily flows the transient flood peaks with snow generally start slightly less than those without snow, especially for the largest catchment (12002). For 30-day flows the transient flood peaks with snow start greater than those without snow, with the difference generally much more pronounced than for daily flows. This demonstrates the considerable contribution of snowmelt to longer duration flows in these three catchments, at least for near-term climates. Differences in timing of convergence reflect the different altitude ranges of the nested catchments; convergence generally occurs by ~2010 for catchment 12002 (the largest catchment, with the lowest altitude), ~2035 for 12003 (the middle nested catchment) and ~2050 for 12007 (the smallest nested catchment, with the highest altitude).

The transient flood peak lines illustrate the generally non-linear nature of the changes through time, and the influence of individual events, especially for longer return periods, as shown in Kay and Jones (2012) for two catchments in England using three transient RCM runs. The positions of the standard 30-year time-slices (1970s, 2020s, 2050s and 2080s; vertical dotted lines) highlight the potential importance of this nonlinearity in studies based on changes between time-slices. They also highlight the importance of including snow processes for these catchments, as quite different conclusions about the impacts of climate change on flood flows would be obtained by comparing current and future time-slices if the modelling did not include snow, particularly for longer duration flows.

As for the transient flood peaks (Figure 2, lines), the transient GLO parameters also generally converge as time progresses (Figure 3). The approximate year of convergence varies between parameters, catchments and duration of peak flows, with convergence often seeming to occur earlier for 30-day flows than for daily flows (despite larger differences at the start of the period for 30-day than daily). As observed by Kay and Jones (2012), the shape parameter k contains more of the noise of natural variability than either the scale or location parameters (α and ξ; equation 1).

Figure 3

The importance of including snow processes in the modelling is clear from Table 2, which gives the size and significance of the flood frequency trends modelled with and without the snow module for each nested catchment. The trends in flood peaks are quite different, and often of the opposite sign, when the snow module is not used. For example, for catchment 12007, 30-day flow peaks at all three return periods have a positive trend (significant at the 5% level for the 2-year return period) when the snow module is not applied, but a negative trend (significant at the 1% level for all three return periods) when the snow module is applied. Almost all of the significant trends (12 out of 14) occur for 30-day flow peaks with snow; the only significant trend in daily flow peaks occurs for catchment 12007 (with snow) at the 50-year return period, and this is only significant at the 10% level. Almost all of the significant trends (12 out of 14) occur for catchments 12007 and 12003; the only significant trends for catchment 12002 (the largest of the three nested Dee catchments, with the lowest median altitude) are for 30-day flows at the 10- and 50-year return periods, and these are only significant

Table 2

at the 5% level. This reduction in numbers of trends and their significance reflects the smaller proportion of 12002 at higher altitudes, with corresponding reduced contribution of snowmelt to flows and so greater resistance of flows to changes in snowmelt as temperatures rise (cf. Capell *et al.* 2014).

Figure 3 and Table 2 also confirm that convergence occurs differently for 30-day and daily flow peaks. For the two larger catchments (12002 and 12003), for daily flows the location and scale parameters with snow generally start less than those without snow and show positive trends, whereas the opposite occurs for 30-day flows. This means that the flood frequency curves are changing in different ways for the different durations of flow, with and without snow. Apart from the effect of snow, the location parameter remains fairly constant over time.

3.2 Trends in timing

Figure 4 shows the AM dates, and the transient mean date of AM occurrence for a 60-year moving window. These plots, like Figures 2 and 3, show a general convergence of results with and without snow as time progresses, although not to the same extent as for flood magnitudes; there is still a clear difference in the mean date of AM occurrence at the end of the period, perhaps because of the longer moving window used for dates. For 30-day AM, the dates converge the most for 12002 (the largest, lowest altitude, catchment) and the least for 12007 (the smallest, highest altitude, nested catchment). For daily AM, the greatest convergence still occurs for 12002, but there appears to be more convergence for 12007 than 12003 (although see discussion below about the difficulties of calculating mean dates for daily AM). Figure 4

The transient mean AM dates with snow are later than those without snow for 30-day flows, but generally earlier with snow than without snow for daily flows (Figure 4). The former may be expected, as the snow module allows accumulations of water to be stored as snow over winter and gradually released as temperatures increase in spring, leading to sustained flows (i.e. high 30-day mean flows) that cannot occur, especially so late in the water year, without the storage of water as snow (also see Figure 2). In contrast, the high daily flows that occur in autumn/winter when the snow module is not applied are prevented from occurring when the snow module is applied, as a lot of the rain in this period is likely to fall as snow, at least over the higher parts of the catchment, thus limiting daily flow peaks at that time of year. Instead, the high daily flows tend to occur either earlier, before the temperatures fall low enough for significant snowfall to occur, or during the spring melt (at least for the period before 2010).

The transient mean daily AM dates also show a progression as one moves downstream, both with and without snow. Catchment 12007 (smallest, highest altitude, most westerly) has mean daily dates around late summer/early autumn, whilst catchment 12002 (largest, lowest altitude, most easterly) has mean daily dates around late autumn/winter, with the catchment in between (12003) having mean daily dates in autumn. This demonstrates the effects of catchment area and spatial distribution of rainfall (summer convective rainfall is more likely to generate flood events in small catchments while longer duration cyclonic rainfall is often the cause of flood events in larger catchments) combined with the delayed flood potential of more easterly catchments in Britain, where soils return to field capacity later in the water year (Bayliss and Jones 1993; Figure 3.3). The differences in the transient mean daily AM dates of the nested catchments are reflected in the greater difference in daily AM flows with and without the snow module for the largest catchment (12002) compared with the upper two catchments (Figure 2, left). The increased likelihood of daily AM occurring in late autumn/winter for catchment 12002 (from cyclonic weather patterns and deeper, slower responding soils), compared with late summer/autumn for 12007 and 12003, means that snow is more likely to be a contributory factor in the generation of the peak flow. For this set of catchments, for current to near-future climates, daily peaks for the largest catchment, with the lowest altitudes, are in fact more affected by snow than are daily peak flows in the headwater catchments.

The plots in Figure 4 highlight how much variation there is in AM dates for all three nested Dee catchments, particularly for daily flows, as no single season predominates. This variation makes the calculation of transient mean dates more difficult, hence the need for a longer (60-year) moving window. However, the extreme variation in the timing of floods in these three catchments is not necessarily typical of catchments elsewhere in Britain. An analysis of observed peaks-over-threshold (POT) flood series for 857 gauging stations across the UK, deriving the modal month of flood (MMF; the month with the greatest number of POT) for each station, showed catchments 12002 and 12003 having a multi-season MMF (two or more months, in different seasons, with equal numbers of POT floods), whereas the vast majority of catchments had a winter or autumn MMF (Bayliss and Jones 1993; Figure 3.2). [Catchment 12007 was not included in the latter analysis.]

To illustrate how unusual these nested Dee catchments are in terms of the timing of peaks, Figure 5 shows the AM dates and the transient mean date of AM occurrence for another catchment, the Greta at Rutherford Bridge (25006) in northern England. This shows the AM occurring much more consistently in winter (December-February) or close to it (November or March), with the transient mean AM date generally falling in January but slipping back to December later in the period for daily flows when the snow module is applied. This catchment had a winter (December) MMF in the POT analysis of Bayliss and Jones (1993). Factors contributing to the non-winter occurrence of daily AM in the Dee, compared with the winter dominance for the Greta, are attributes of topography and the water balance. The upper Dee (12007) has steep slopes, 6% bare rock land cover, and a large runoff proportion (runoff/precipitation; Table 1) so little evaporative loss (preventing accumulation of large soil moisture deficits), meaning that even summer/autumn rainfall can readily generate runoff. In comparison the Greta has shallower slopes, negligible bare rock and a smaller runoff proportion (greater evaporation), which mitigate the quick runoff response from its peat soils during the summer.

Figure 5

The size and significance of the trends in the transient mean date of AM occurrence are given in Table 3, for the three nested Dee catchments in Scotland and the Greta in northern England. This again highlights the importance of the inclusion of snow processes, as the trends vary greatly and can be of opposite sign when the snow module is applied compared to when it is not. For 30-day flows, the trends for the three nested Dee catchments are almost always negative (i.e. a tendency towards earlier AM dates later in the period), but of much greater magnitude (and significance) when the snow

Table 3

module is included; the size of the 30-day AM date trend with snow is nearly two months whereas that without snow is less than half a month (Table 3). None of the trends in transient mean daily AM dates for the three nested Dee catchments are significant, reflecting the fact that the daily AM occur throughout the year; the mixture of snow and non-snow related AM leads to little change over time in the mean dates. In contrast, for the Greta (25006), both the daily and 30-day transient mean AM dates occur in the winter and there is much less difference in timing with and without the snow module (Figure 5). There are significant negative trends when the snow module is applied, but the change is all within the mid-winter period. When the snow module is not applied, the trends are still negative but not significant.

The differences in response of AM timing for the Dee and Greta illustrate the dominant effect of higher latitude and altitude on temperatures in the Dee. The mean temperature difference, although only 1-2^{o}C, is critical when around freezing in giving differences in snow occurrence and speed of snowmelt: On average, in the current climate, the Dee has at least twice the number of days of falling and lying snow as the Greta (Section 2.1). In the Dee the main impact of snow on the flow regime is through accumulation of a snowpack which can last in places for much of the year, with melt affecting flows over durations of weeks or months. In contrast, for the Greta snow is more likely to occur as individual winter events with melt contributing to peak daily flows as well as over longer durations. These differences illustrate the complex nature of the hydrological processes where snow is concerned. A catchment's climatology and topography, the balance between precipitation occurrence and temperature, and how this balance alters as the climate changes will each be critical in determining the impact on the magnitude and timing of peak flows, potentially modulated by other physical catchment properties like soils and land cover.

4. Conclusions

Hydrological modelling has been performed for three nested catchments of the River Dee in north-east Scotland, with and without a snow module, using data from a transient RCM for the period 1950-2099. Time-series of AM were extracted from both daily and 30-day mean flows, and moving-window analyses performed. The results demonstrate the potential importance of the inclusion of snow processes, as quite different conclusions can be obtained when the snow module is or is not applied. This is particularly the case for longer duration (30-day) flow peaks, where all three Dee catchments showed increases (generally not significant and with no significant changes in timing) without the snow module but significant decreases (occurring months earlier in future) with the snow module. Changes in longer duration flows could have important consequences for riverine ecosystems or water resources. Changes in shorter duration (daily) flow peaks were generally not significant, whether modelled with or without snow. The importance of the inclusion of snow processes was also highlighted by Kay *et al.* (2011), when using climate model ensembles to assess change in flood risk attributable to anthropogenic emissions for eight catchments in England. The fraction of attributable risk for flood peaks in October 2000-March 2001 was generally less (and sometimes negative) with the snow module than without, indicating less of an increase (or a decrease) in risk.

The results presented here with the snow module appear consistent with studies of observational flow records for the Dee (Baggaley *et al.* 2009, Hannaford and Buys 2012), and the changes in longer duration flow peaks here are consistent with climate change impact studies in other snow-affected regions of the world, e.g. north-east Europe (Dankers and Feyen 2008) and the western US (Elsner *et al.* 2010, Hamlet *et al.* 2013). However, the results for daily mean peak flows here are slightly different to those for the western US, where decreases or small increases were shown in snow-dominated basins but possibly large increases for more mixed rain/snow basins (Hamlet and Lettenmaier 2007, Hamlet et al 2013). Here, the three nested Dee catchments showed few significant changes in daily peaks despite highly significant changes in 30-day peaks. The three catchments show dominance of different climatic factors in the current/near-future for different duration peak flows: At 30-day duration all three show snow-dominance, but for daily peaks the upper two are rainfall-dominated while the lowest one shows evidence of mixed rain/snow-dominance; none is snow dominated for daily peaks. By the end of the time period (2099) the two upper catchments are likely to be mixed rain/snow at 30-day duration while the lower one has become rain-dominated; daily peaks are likely to have rain-dominated causes for all three catchments.

The results here also highlight the complexity of the interplay between catchment properties, location, the balance between precipitation and temperature and how this might alter under climate change. Each of these factors will be critical in determining the impact on the magnitude and timing of peak flows over different durations in a catchment, so the impact will not necessarily be straightforward to predict for any given catchment. Although physical catchment properties like soils and land-cover appear to have a more minor role than altitude and temperature in affecting AM response for the catchments modelled here, such factors can influence the response of river flows to climatic change. For example, Capell *et al.* (2013) model three very small catchments on a west-east transect across the Scottish Highlands and discuss differences in response of seasonal flows consistent with the different storage characteristics of the catchments, while Tague *et al.* (2008) show that the presence of permeable bedrock mediates the impacts of climate change on summer flows in the western US. More widely, Prudhomme *et al.* (2013a,b) classified and characterised the flood response to climatic changes in British catchments and showed that, although climatic factors were most important, factors like the proportion of high permeability bedrock also affected the response. Consequently, a higher proportion of highly permeable bedrock leads to a greater range of uncertainty in the impacts of climate change on flooding (Kay *et al.* 2013b). None of the catchments modelled here has a permeable substrate, but in high permeability catchments where snow is an important component of the runoff regime, additional uncertainty from climate change could be generated through changes in timing and quantity of recharge and subsequent groundwater flow.

This complexity means that one must be careful not to generalise too much from specific catchment results. In particular, the somewhat different nature of daily peak timing in the three nested Dee catchments, compared to many catchments in Britain, makes general statements difficult, although the directional trends for 30-day flows may be more generally applicable than those for daily flows (at least for catchments currently affected by snow to any significant extent). Similarly, the general changes in longer duration flow peaks are likely to apply if using alternative climate model runs for such catchments (due to the likely dominance of the temperature increase; Diffenbaugh *et al.* 2013), but the specifics are likely to differ somewhat due to differences in climate model structure and/or parameterisation as well as natural variability. This is especially the case if using a different GCM; the GCM is generally acknowledged to be the largest source of uncertainty in such climate change impact assessments and, in particular, GCM uncertainty is usually larger than hydrological modelling uncertainty (Chen *et al.* 2011, Gosling *et al.* 2011, Kay *et al.* 2009), although the latter is still potentially important. Another potential source of uncertainty here is the choice and parameterisation of the snow module used with the hydrological models. Even other runs of exactly the same GCM/RCM combination and parameterisation (a so-called initial-condition ensemble) may give differences in results (e.g. Kay *et al.* 2009), and their use would help distinguish the effects of natural variability from those of climate change (Kendon *et al.* 2008, Deser *et al.* 2012). The latter could be particularly important in studies such as this one, involving snow, where the balance between precipitation occurrence and temperature is so critical.

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Tables

Table 1 Details of the three nested river Dee catchments in Scotland, and the additional catchment in northern England (Marsh and Hannaford 2008).

Catchment name (river @ location)	Dee @ Mar Lodge	Dee @ Polhollick	Dee @ Park	Greta @ Rutherford Bridge
Catchment number	12007	12003	12002	25006
Catchment area [km^2]	289.0	690.0	1844.0	86.1
Median altitude (altitude range) [m]	648 (332-1309)	604 (217-1309)	434 (23-1309)	410 (223-590)
Mean drainage path slope [m/km]	235	220	169	68
Mean annual precipitation [mm]	1412	1290	1108	1129
Mean annual runoff [mm]	1330	1075	805	820

Table 2 Modelled trends in flood frequency for each catchment, both without and with the snow module, at two durations. Flood frequency trends are shown for three return periods (2, 10 and 50 years), and in terms of the GLO parameters. The significance of each trend is indicated beneath it (see key below table).

			Daily mean flows		30-day mean flows	
			w/o snow	w/ snow	w/o snow	w/ snow
12007	Return period	2-year (= location ξ)	2.5 -	-3.2 -	2.4 **	-5.5 ***
		10-year	9.8 -	-10.7 -	2.5 -	-18.5 ***
		50-year	23.1 -	-30.5 *	2.2 -	-46.5 ***
	GLO parameter	Scale α	2.11 -	-2.95 -	0.38 -	-2.77 ***
		Shape *k*	0.10 -	0.11 -	0.10 -	0.31 **
12003	Return period	2-year (= location ξ)	-4.0 -	7.7 -	3.4 -	-7.2 ***
		10-year	-20.4 -	18.3 -	3.2 -	-24.3 ***
		50-year	-44.4 -	-46.7 -	-3.6 -	-59.0 ***
	GLO parameter	Scale α	-5.49 -	3.92 -	-0.77 -	-3.67 ***
		Shape *k*	-0.06 -	0.11 -	0.11 -	0.27 *
12002	Return period	2-year (= location ξ)	23.8 -	39.3 -	3.6 -	-6.6 -
		10-year	-30.8 -	57.3 -	7.4 -	-23.2 **
		50-year	-63.5 -	105.7 -	13.3 -	-54.5 **
	GLO parameter	Scale α	-10.75 -	9.87 -	-2.31 -	-4.13 -
		Shape *k*	0.04 -	0.09 -	-0.10 -	0.13 -

Key: *** significant at 1% level; ** significant at 5% level; * significant at 10% level;
- not significant

Table 3 Modelled trends in the mean date of AM occurrence for each catchment, both without and with the snow module, at two durations. Date trends are given as the number of days (in the 360-day year of the RCM). The significance of each trend is indicated beneath it (see key below table).

Catchment	Daily mean flows		30-day mean flows	
	w/o snow	w/ snow	w/o snow	w/ snow
12007	-30.8	24.6	-14.5	-51.3
	-	-	-	***
12003	-14.2	29.2	4.6	-56.9
	-	-	-	***
12002	24.8	30.7	-3.8	-50.2
	-	-	-	**
25006	-9.5	-21.2	-8.5	-17.4
	-	**	-	***

Key: *** significant at 1% level; ** significant at 5% level; * significant at 10% level; - not significant

Figures

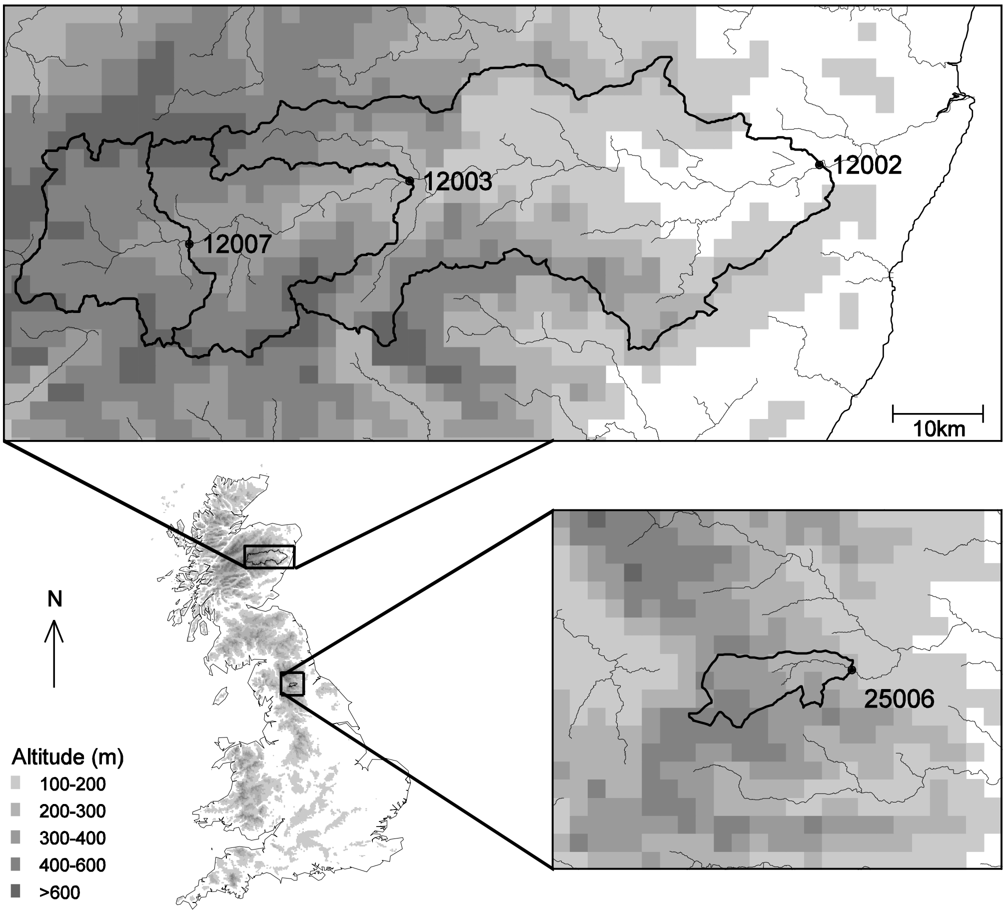

Figure 1 The location and topography of the three nested Dee catchments in north-east Scotland (12007 - Dee @ Mar Lodge, 12003 - Dee @ Polhollick and 12002 - Dee @ Park) and the additional catchment in northern England (25006 - Greta @ Rutherford Bridge).

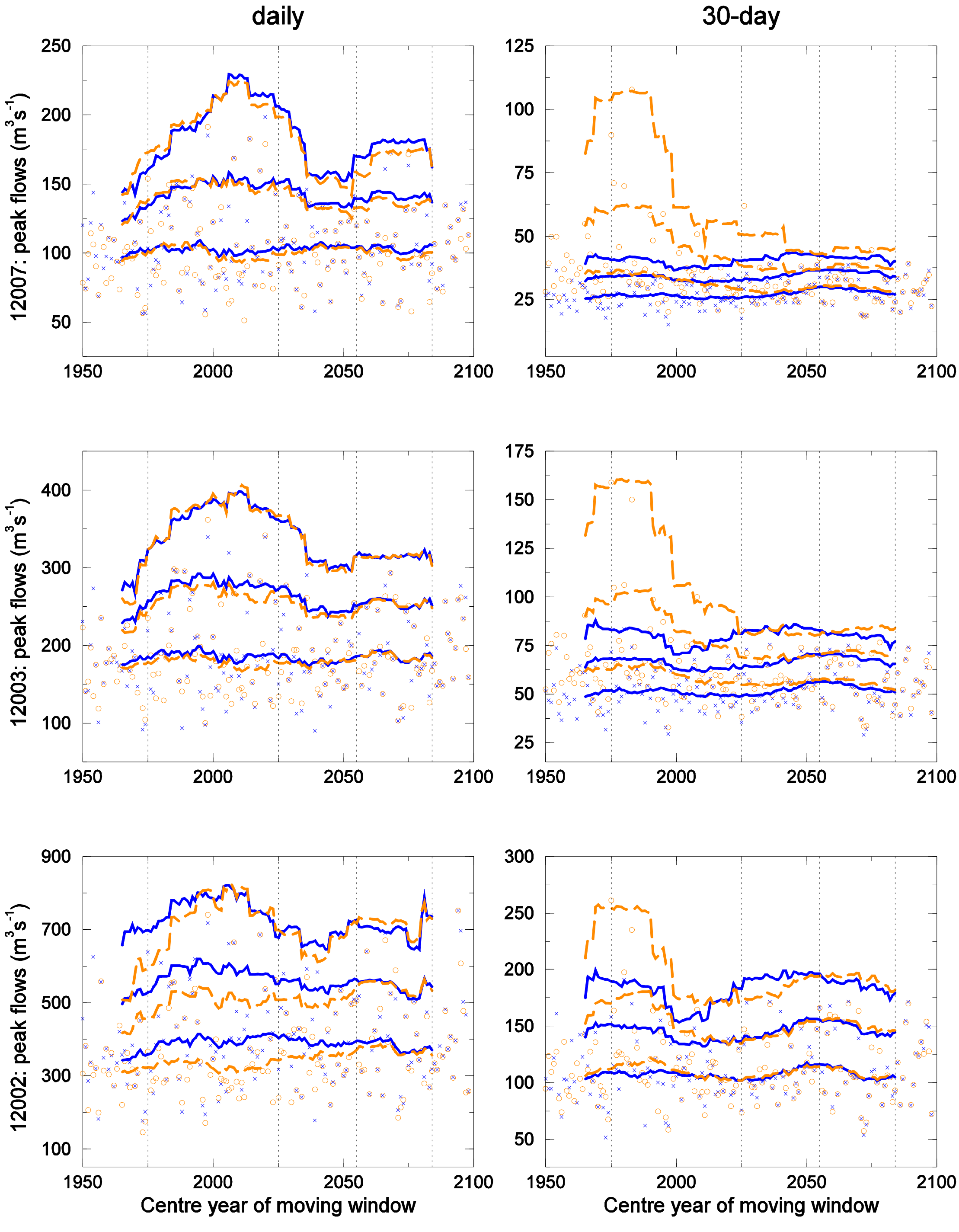

Figure 2 For the three nested catchments (12007 – top, 12003 – middle, 12002 – bottom), plots show simulated daily AM (left panels) and 30-day AM (right panels), with the transient flood peaks (at 2-, 10- and 50-year return periods) derived from fitting flood frequency curves to the AM in a moving window (Section 2.4). The AM are plotted as points and the transient flood peaks as lines, with results shown both with the snow module (orange circles and orange dashed lines) and without (blue crosses and blue solid lines). Note that the bottom-most pair of (dashed and solid) lines in each plot are for the 2-year return period, while the top-most pair are for the 50-year return period. Vertical dotted lines represent the mid-points of the standard 30-year time-slices (1970s, 2020s, 2050s and 2080s).

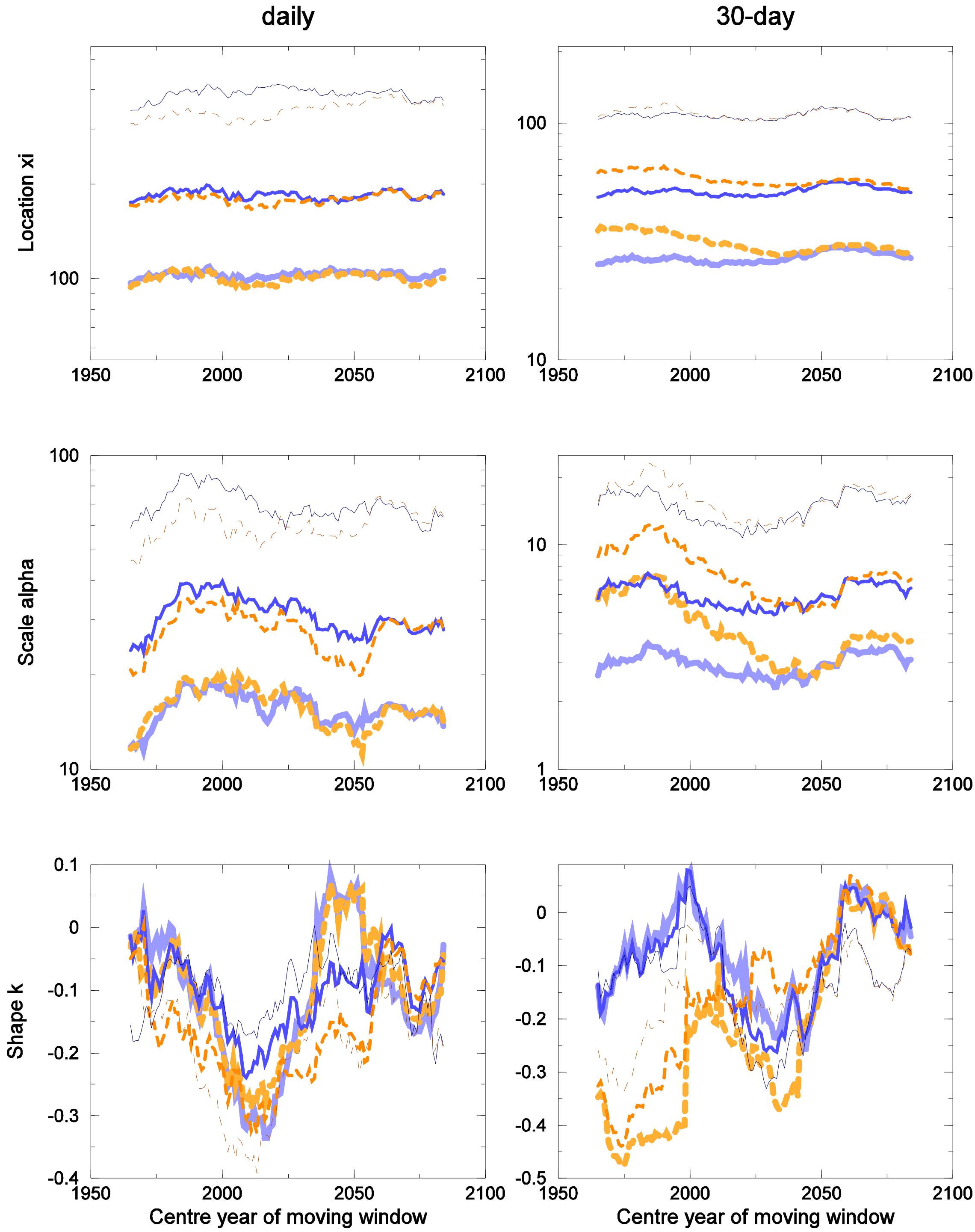

Figure 3 Daily and 30-day transient GLO parameters (location ξ – top, scale α – middle, shape *k* – bottom), both with the snow module (orange dashed lines) and without (blue solid lines), for the three nested catchments (12007 – thick lines, 12003 – medium lines, 12002 – thin lines). Note that paler shades are used for the thick lines (for 12007) and darker shades for the thin lines (12002), to aid catchment discrimination where lines plot over each other. Also note the y-axis log-scale for the location and scale plots.

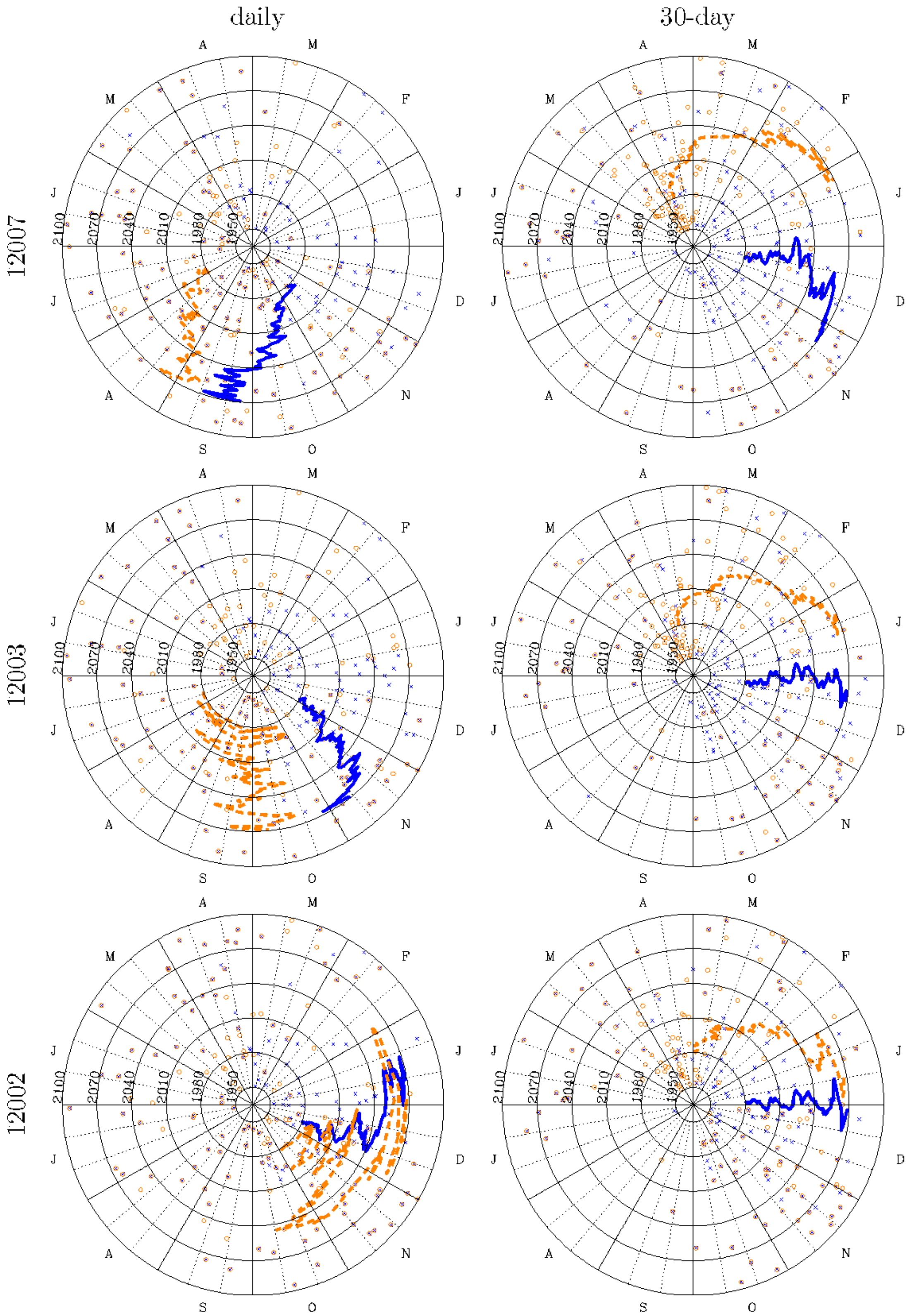

Figure 4 Circular plots for the three nested Dee catchments showing the date of occurrence of the AM (points), with the transient mean for the 60-year moving window (lines), both with the snow module (orange circles / dashed lines) and without (blue crosses / solid lines).

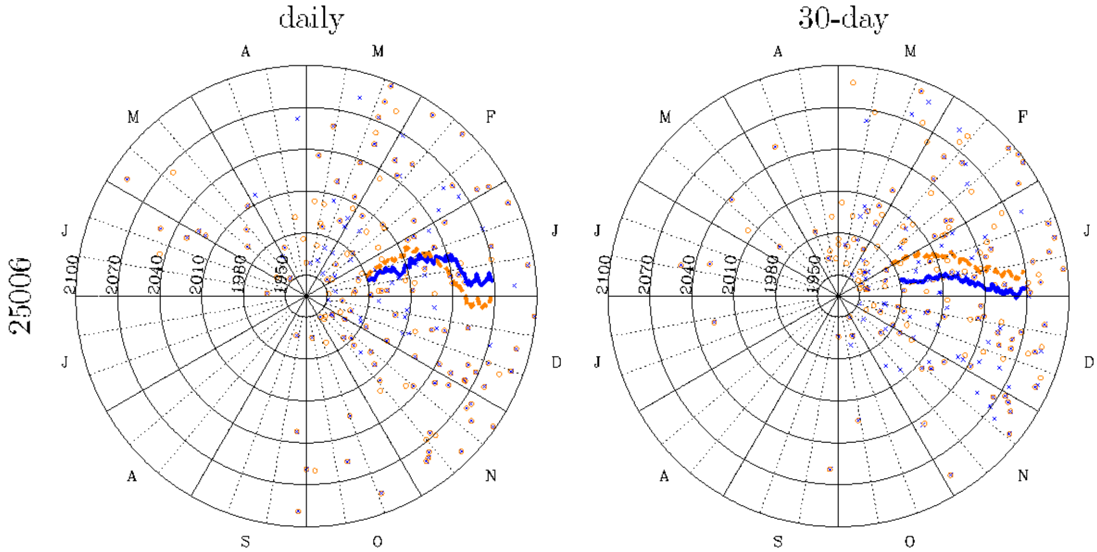

Figure 5 Circular plots for catchment 25006 showing the date of occurrence of the AM (points), with the transient mean for the 60-year moving window (lines), both with the snow module (orange circles / dashed lines) and without (blue crosses / solid lines).