Hydrological Processes

WILEY

RESEARCH ARTICLE OPEN ACCESS

Using Sub-Daily Precipitation for Grid-Based Hydrological Modelling Across Great Britain: Hourly Model Performance and Flood Impacts Under Climate Change

Alison L. Kay

UK Centre for Ecology & Hydrology, Wallingford, UK

Correspondence: Alison L. Kay (alkay@ceh.ac.uk)

Received: 30 July 2025 | **Revised:** 3 March 2026 | **Accepted:** 7 April 2026

Keywords: CPM | hydrology | precipitation | rainfall | rainfall-runoff model | UKCP18

ABSTRACT

Gridded sub-daily precipitation data are increasingly available to drive national or regional hydrological models, and sub-daily river flows can be required for high flow analyses in some areas. Here, observation-based hourly 1 km precipitation data are applied with a 1 km hydrological model to simulate hourly mean river flows across Great Britain (GB). On average, performance across a large set of catchments for hourly flows is less than that for daily flows, with less difference for low than high flows and little difference in overall bias, but performance is still reasonable for most catchments. Hourly precipitation data from a convection-permitting climate model are then used to simulate hourly river flows for baseline (1980–2000) and future (2060–2080) periods, to investigate potential differences in peak flow changes derived from annual maxima (AM) of daily and hourly mean flows. On average, future changes in peak flows derived from hourly AM are higher than those from daily AM, with greater differences for higher return period peak flows and for smaller catchments in the north/west. Analysis of AM occurrence dates shows that most daily and hourly AM pairs across GB are from the same event, but some pairs for some locations have large date differences, indicating separate events. Both daily and hourly AM date distributions are generally bimodal, with more peaks in autumn and winter, but with a strong future reduction in autumn peaks and increase in winter peaks. These analyses help to inform where and when use of hourly flows may be required.

1 | Introduction

The principal driving dataset required by hydrological models is generally precipitation, with national or regional models typically requiring data at relatively fine spatial resolutions. The temporal resolution of the driving data and the simulated flows can also be important, depending on the size of catchments being modelled, catchment characteristics (responsiveness) and the part of the flow regime of interest. Daily, or even monthly, river flows are likely sufficient for low flow/drought analyses in most catchments (e.g., Sharma and Panu 2008; Nicolle et al. 2014; Rudd et al. 2017; Ho et al. 2021), but sub-daily river flows can be required for flood/high flow analyses, especially in small/responsive catchments (e.g., Ficchì et al. 2019; Schaller et al. 2020; Fileni, Fowler, Lewis, McLay, et al. 2025; Poncet et al. 2025).

Previously, the best available gridded observation-based precipitation data for Great Britain (GB) was at a daily time-step on a 1 km grid; either from CEH Gridded Estimates of Areal Rainfall (CEH-GEAR; Keller et al. 2015), the latest version of which covers 1890–2019 (Tanguy et al. 2021) or from HadUK-Grid, the latest version of which covers 1891–2024 (Hollis et al. 2025). Recently, a version of CEH-GEAR with an hourly time-step was produced, covering GB for 1990–2016: CEH-GEAR1hr (Lewis et al. 2018, 2022). This provided the opportunity to compare national-scale grid-based hydrological model performance using daily versus hourly precipitation data for simulation of daily mean river flows (Kay and Brown 2023). The analysis showed that, on average, use of hourly precipitation data provided a clear improvement for high flows and a small improvement for average flows but little difference for low flows. Performance in faster-responding catchments typically improved more. But performance for simulation of sub-daily river flows was not assessed.

Recent computing advances have also enabled the use of higher resolution 'convection-permitting' models (CPMs), nested in lower resolution global or regional climate models (GCMs/RCMs), for climate change projections (Kendon, Prein, et al. 2021). The finer resolution of CPMs better represents landscape details like orography and coastlines (Kendon, Prein, et al. 2021; Lucas-Picher et al. 2021), and simulates the atmosphere at a scale closer to that of convection so parameterisation schemes are not required (Fosser et al. 2020). Sub-daily precipitation data generated by CPMs are considered more realistic in terms of duration and extent than those from coarser resolution climate models (Kendon et al. 2012), and the characteristics of sub-daily precipitation may be particularly affected by climate change (Kendon et al. 2014; Chan et al. 2023). For example, analysis of CPM sub-daily rainfall extremes showed that events exceeding 20 mm/h occur much more frequently by the 2070s than in a historical baseline period, with increasing variability and a tendency to cluster (Kendon et al. 2023). Such changes in sub-daily precipitation could have consequential effects on future river flow projections. Kay and Brown (2023) used daily and hourly precipitation from UKCP18 Local CPM Projections (Kendon, Short, et al. 2021) with a national-scale grid-based hydrological model for GB and showed that future changes in annual maxima derived from daily mean flows simulated using hourly precipitation were only slightly larger than those simulated using equally disaggregated daily precipitation. But changes in sub-daily peak flows may differ, for smaller catchments in particular.

Thus, the aims of this paper are to first assess the performance of a grid-based hydrological model for simulating hourly mean river flows across GB using hourly observation-based precipitation data, before using the model with hourly CPM precipitation data and comparing future changes in peak flows derived from hourly and daily mean flows. More specifically:

1. How does hydrological model performance for hourly flows compare to that for daily flows, and vary with catchment properties?
2. Could previous assessments of future changes in flood hazard based on daily flows have under-estimated the potential impacts compared to estimates derived from hourly flows, at least in some places or for some types of catchments?

A broad-scale assessment is presented, across the whole of GB. While a small set of case study catchments is used to help illustrate hourly versus daily flows, an in-depth analysis of specific catchment issues is beyond the scope of this paper.

2 | Data and Methods

2.1 | The Observation-Based Precipitation Data and Gauged Flow Data

The 1 km CEH-GEAR daily data are derived from rain-gauge data using natural neighbour interpolation (Keller et al. 2015). The daily rain-gauge data undergo several stages of quality control before use, including manual checking of very high daily totals (Keller et al. 2015, Section 4). The CEH-GEAR1hr dataset uses a more limited network of sub-daily rain-gauge data to distribute CEH-GEAR daily values through the day (Lewis et al. 2018), so CEH-GEAR1hr daily (9 AM–9 AM) totals are consistent with CEH-GEAR daily. The sub-daily rain-gauge data also undergo several stages of quality control before use (Lewis et al. 2018, Section 3). The limited availability of historical sub-daily rain-gauge data means that CEH-GEAR1hr only starts in 1990 and currently only extends to 2016.

For days/locations for which it was not possible to directly use sub-daily gauge data to temporally distribute precipitation in CEHGEAR1hr (i.e., where the nearest operating sub-daily gauge was too far away or the sub-daily gauge gives zero daily rainfall but the daily dataset gives a non-zero value), a set of national average storm profiles was used for the daily to hourly disaggregation (Lewis et al. 2018). The average profiles were constructed from all available GB sub-daily gauge data, varying only by season ('winter' Nov–Apr and 'summer' May–Oct) and by a daily rainfall threshold (0, 1, 5, 10 and 20 mm). The number of grid cells requiring profile-based disaggregation varies but it is mostly used for small daily rainfall totals so is considered unlikely to have a large effect on hydrological simulations (Lewis et al. 2018).

Observed quality-controlled daily mean flows are available from the National River Flow Archive (NRFA; nrfa.ceh.ac.uk/) for over 1500 catchments across the UK. Recently, a quality-controlled dataset of 15-min observed flows for the UK has been made available (UK-Flow15; Fileni, Fowler, Lewis, Fry, et al. 2025), covering a large subset of the NRFA catchments. The dataset is used here to assess performance of hourly mean flow simulations driven by CEH-GEAR1hr (see Section 2.3).

The UK-Flow15 dataset includes a flag for each time-step, indicating the outcome of several quality control procedures including checks against daily mean flow data and cross-validation with rainfall data and with flow data from neighbouring stations. Only data for those time-steps with no issues flagged (Flag = 000) were used here, with remaining values set to missing. For the performance assessment, the 15-min observed flows are then averaged up to hourly mean flows in a way which makes them as consistent as possible with the hourly mean flow derivation within the hydrological model (Section 2.2). Hours with any missing 15-min data are set to missing.

2.2 | The Hydrological Model and Observation-Based Run

The Grid-to-Grid (G2G) is a grid-based hydrological model that is typically run for GB on a 1 km grid at a 15-min time-step (Bell et al. 2009), with an optional snow module that is included here (Bell et al. 2016). The model requires 1 km gridded precipitation, potential evaporation (PE) and temperature data (for the snow module). It is generally configured using spatial datasets (e.g., soil types) rather than via specific calibration to observed flows, with the limited number of model parameters (e.g., routing wave speeds) using nationally-tuned values (Bell et al. 2009). Most previous applications of G2G for climate change assessment have used daily precipitation equally disaggregated to the 15-min model time-step, then averaged the 15-min simulated flows up to daily for output. These simulations perform well for a wide range of catchments (Bell et al. 2009, 2016; Rudd et al. 2017; Formetta et al. 2018), especially where the regime is not affected significantly by artificial influences like abstractions or discharges (Rameshwaran et al. 2022). A previous application focussing on the Thames basin, Southeast England, used a limited period of 1 km gridded 15-min rainfall data for a regional calibration against 15-min gauged flow data for 34 catchments (Bell et al. 2012). The Thames regional parameterisation using 15-min rainfall data was only slightly different to the national one using daily data; the latter is used with the hourly rainfall data here as it has been assessed over a wider range of catchments and soil types. Note that application of G2G for operational flood guidance and warning across GB employs 15-min precipitation inputs, incorporates data assimilation of gauged river flows, and outputs forecasts as gridded time-series of 15-min instantaneous river flow out to ~6 days (Moore et al. 2012; Price et al. 2012; Cranston et al. 2012).

The observation-based G2G run (hereafter 'SIMOBSh') uses:

- Hourly 1 km CEH-GEAR1hr precipitation divided equally over each of the four 15-min model time-steps within an hour.
- Monthly 40 km grids of short grass PE from MORECS (Hough and Jones 1997), copied down to the 1 km grid and divided equally over each model time-step within a month (as used originally by Bell et al. 2009).
- Daily 1 km grids of min and max temperature from HadUK-Grid (Hollis et al. 2019), interpolated through the day using a sine curve (Kay and Crooks 2014).

The simulation covers Jan 1990–Dec 2016, initialised using a states file saved at the end of a prior simulation using CEH-GEAR daily precipitation to end-Dec 1989. Outputs were only analysed for Oct 1990–Sep 2016 (i.e., whole water years).

The G2G outputs time-series of daily mean river flows (m^3/s) for selected 1 km grid cells corresponding to NRFA catchments, and was adapted to also output hourly mean river flows (m^3/s) for the same grid cells. Previously, when using daily precipitation, outputs have usually only included catchments of at least 50 km^2 (e.g., Kay, Bell, et al. 2023), but smaller catchments (down to 10 km^2) are included here using hourly precipitation data.

2.3 | Comparing Daily and Hourly Flow Performance Using Hourly Observation-Based Driving Data

The performance of the SIMOBSh daily and hourly flows (Oct 1990–Sep 2016) is assessed using several measures comparing to observed flows for 692 catchments across GB (Figure 1a). Catchments with more than 10% missing (hourly or daily) gauged flow data in the required period are excluded. As in Kay and Brown (2023), the performance measures are as follows:

- The Nash-Sutcliffe efficiency calculated directly on the flows (NS), on the square-root of flows (NSsqrt) and on the natural logarithm of flows (NSlog).
- Bias in mean flow (bias, %).
- Bias in fitted flood frequency (ffr, %).

The ffr measure is calculated as the average percentage bias in 2-, 5- and 10-year return period peak flows extracted from flood frequency curves (as Kay et al. 2015), derived by fitting a generalised logistic (GLO) distribution to sets of water-year (1st Oct–30th Sep) annual maxima (AM) (Robson and Reed 1999). All the measures are calculated with simulated flows set to missing where observed flows are missing to provide a fairer comparison.

For the Nash-Sutcliffe measures, NS focuses on high flows, NSsqrt on average flows and NSlog on low flows (Rudd et al. 2017). A value of 1 indicates *perfect performance* and a value less than zero indicates *performance worse than mean flow*. Threshold values are used to delineate performance bands: Good, ≥ 0.7; Acceptable, ≥ 0.5 but < 0.7; Poor, < 0.5. For the bias-based measures, a zero is perfect performance, positive values are over-estimates and negative values are under-estimates. Threshold values are used to delineate performance bands for the absolute values of bias (ffr): Good, $\leq 10\%$ (20%); Acceptable, $\leq 20\%$ (40%) but $> 10\%$ (20%); Poor, $> 20\%$ (40%). The band thresholds are similar to those used by Crooks et al. (2014), and while their definition is somewhat arbitrary, they provide a useful means of comparing performance for hourly and daily mean flows.

Of the 692 catchments, 102 have an area of at least 10 km^2 but less than 50 km^2; the other 590 catchments are larger. Results for the two sets of catchments are shown separately, to differentiate performance by catchment area. Dependence of performance on several other catchment properties is also assessed, including mean catchment altitude ('altbar'), mean drainage path slope ('dpsbar') and an estimate of the proportion of river flow that comes from groundwater sources (the baseflow index derived from soil classes, 'BFIHOST19') (see nrfa.ceh.ac.uk/feh-catchment-descriptors); Figure 1c shows the distributions of these properties across the set of 692 catchments. BFIHOST19 is an estimate of the baseflow index (BFI) of a catchment but is derived from the proportions of hydrologically described soil classes in a catchment rather than via hydrograph separation, and is thus unaffected by artificial influences (Griffin et al. 2019).

2.4 | Climate Change Projections and Their Application

One component of UK Climate Projections 2018 is UKCP18 Local (Kendon, Short, et al. 2021). This comprises an ~2.2 km CPM 12-member ensemble, which is nested in an ~12 km RCM 12-member perturbed parameter ensemble (PPE) nested in an ~60 km GCM 12-member PPE, under RCP8.5 emissions. Originally, only three 20-year periods were covered (Dec 1980–Nov 2000, Dec 2020–Nov 2040 and Dec 2060–Nov 2080), although data for the intervening periods have now been provided. Data are available on the native ~2.2 km rotated lat-lon grid and re-projected to a 5 km grid aligned with the GB national grid (Met Office Hadley Centre 2019). The re-projected 5 km

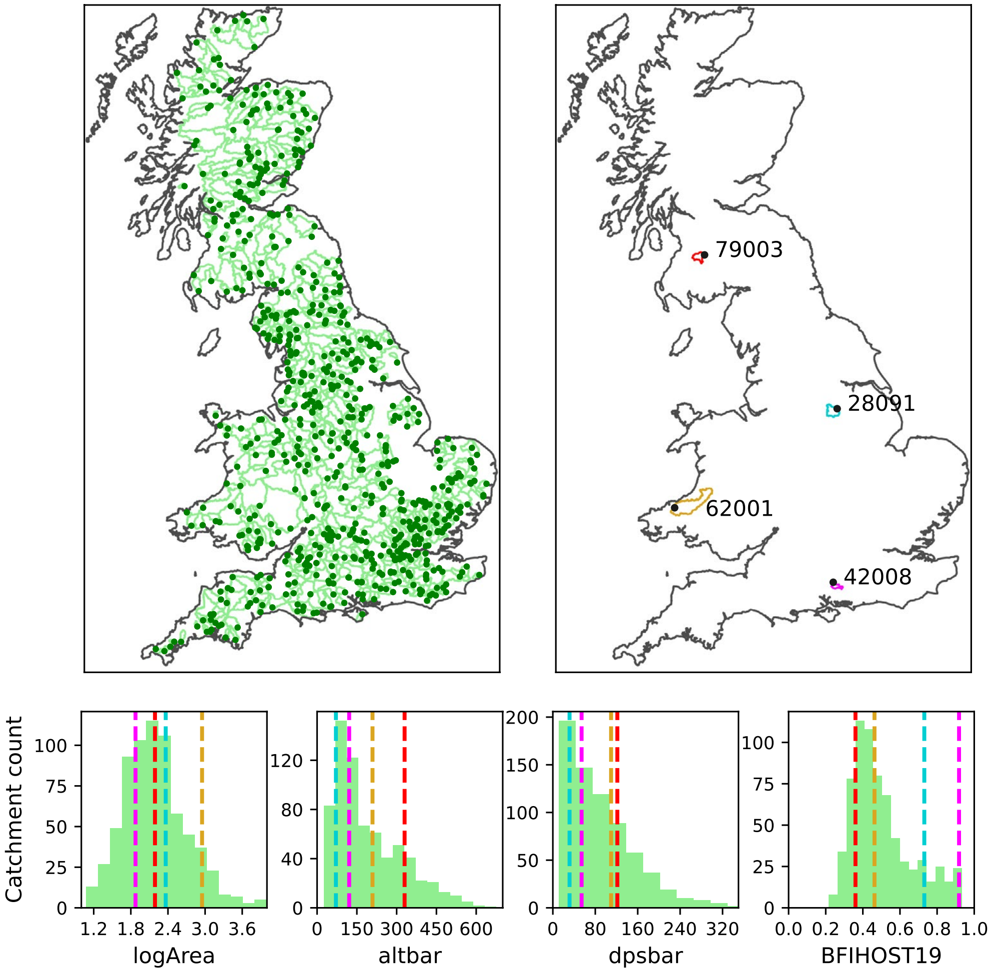

FIGURE 1 | The 692 catchments used to assess performance (top-left; green boundaries plus outlet points), the four case study catchments (top-right; coloured boundaries plus black outlet points) and distributions of selected catchment properties across the 692 catchments (bottom; green histograms). Also on the latter are vertical dashed lines showing the property values for the four case study catchments (from Table 1), colour-coded as in the top-right map.

TABLE 1 | The four case study catchments, with values of selected properties and the ranges of those properties across the full set of 692 catchments.

		Area (km^2)	altbar (m)	dpsbar (m/km)	BFIHOST19
Case study catchments					
Catchment number	River @ location				
28091	Ryton @ Blyth	231.0	71	31.5	0.731
42008	Cheriton Stream @ Sewards Bridge	75.1	121	54.2	0.918
62001	Teifi @ Glanteifi	893.6	209	109.8	0.463
79003	Nith @ Hall Bridge	155.0	330	121.6	0.360
692 catchments					
Minimum		12.0	25	11.4	0.216
Median		141.4	149	75.3	0.462
Maximum		9948.0	675	487.9	0.934

CPM data for ensemble member ‘01’ are used here; this member represents the standard RCM/GCM parameterization (the CPM parameters are not adjusted between members). Using a single ensemble member is sufficient here, where the aim is to compare peak flow changes derived from daily versus hourly flows simulated using hourly precipitation. For a fuller picture of the potential impacts of climate change, use of the full ensemble would be recommended.

The precipitation, PE and temperature data required to drive the hydrological model are derived from the available CPM data as follows:

- Hourly 5 km CPM precipitation data are corrected by applying a simple bias-adjustment, using monthly factors derived by comparing baseline data against CEH-GEAR (Kay and Brown 2023). These data are then downscaled to 1 km using fixed patterns derived from observed standard average annual rainfall (Kay, Rudd, and Coulson 2023). The hourly 1 km data are then divided equally over the four 15-min model time-steps within an hour.
- Daily 5 km CPM PE data are estimated using the Hydro-PE method of Robinson et al. (2023) (based on Penman-Monteith), copied down to 1 km, and divided equally over the model time-steps within a day.
- Daily 5 km min and max CPM temperature data are downscaled to 1 km using a lapse rate with elevation (Bell et al. 2016), and interpolated through the day using a sine curve (as for observed temperature, Section 2.2).

The precipitation, PE and temperature data are then used to drive G2G for baseline (Dec 1980–Nov 2000) and far-future (Dec 2060–Nov 2080) periods (hereafter 'SIMCPMh baseline' and 'SIMCPMh far-future', respectively). The baseline simulation is initialised using states saved at the end of a prior simulation (Jan 1970–Nov 1980) using observed driving data, and the far-future simulation is initialised using states saved at the end of a prior simulation (Dec 2055–Nov 2060) using data from the equivalent RCM (as in Kay 2022).

2.5 | Assessing Impacts on Peak Flows Under Climate Change

The SIMCPMh runs (Section 2.4) produce 1 km grids of AM extracted from daily mean flows and hourly mean flows for the baseline and far-future periods. AM is extracted for each water-year, for each 1 km grid-cell with a catchment area of at least $10\,\text{km}^2$ (hereafter 'river cells'). Flood frequency curves are fitted to the sets of daily mean and hourly mean AM (19 for each period and each river cell), and corresponding grids of 2-, 5-, and 10-year return period peak flows for each period are derived as for the observation-based simulation (Section 2.3). The percentage change in peak flows between the baseline and far-future periods is calculated for each return period and river cell, for the flood frequency curves derived using daily mean AM and hourly mean AM. Note that AM are used, rather than peaks-over-threshold, since they are straightforward to calculate and output on the 1 km grid during the model run.

Differences in these impacts are investigated for different size catchments across GB. There are a total of 45 865 1 km river cells across GB, with 27 315 of these having catchment areas of between 10 and $50\,\text{km}^2$, and just 7866 having catchment areas of $200\,\text{km}^2$ or more. Variation by location is explored using a simple north/west to south/east split; the majority of higher-elevation areas are in the north/west, while the south/east is flatter and has the majority of groundwater-dominated catchments. Of the 45 865 1 km river cells, 30 658 are to the north/west and 15 207 to the south/east.

2.6 | Case Studies

For a small set of case study catchments, flow duration curves, flood frequency curves and sample flow hydrographs are plotted to help illustrate both the performance of observation-based driving data and differing peak flow impacts under climate change. Four catchments are selected (Table 1 and Figure 1b), covering a range of catchment properties (Figure 1c) and showing a range of behaviour. The Ryton at Blyth (28091) in central England is a mid-sized catchment with relatively low relief but a relatively high proportion of high permeability bedrock. The Cheriton Stream at Sewards Bridge (42008) in southern England is small with moderate/low relief but a very high proportion of high permeability bedrock. The Teifi at Glanteifi (62001) in Wales is quite large with higher relief and mainly impermeable bedrock. The Nith at Hall Bridge (79003) in Scotland is mid-sized and high relief with a mixture of bedrock permeabilities. The two western catchments (62001 and 79003) are wetter than those to the east (28091 and 42008), and all four are mainly rural.

Note that catchments 42008 and 62001 are part of the UK Benchmark network (UKBN2; nrfa.ceh.ac.uk/hydrometry-uk/benchmark-network), which means that they are 'near-natural'; they 'can be considered reasonably free from human disturbances such as urbanisation, river engineering, and water abstractions' (however 42008 has a warning about low flows potentially being affected by abstraction). Catchments 28091 and 79003 are not in the UKBN2: The NRFA notes a 'moderate net effect on flows by WRWs [water treatment effluent returns] and abstraction' for 28091 and 'largely natural with controlled storage of Afton Reservoir having occasional significant effect' and 'public water supply only affects low flows' for 79003.

2.7 | Dates of Occurrence of Daily and Hourly AM

Typical dates of occurrence of peak flows, and potential future changes in these, could be important for river ecology, due to damage occurring at critical times for different species. As well as outputting grids of AM flows, G2G outputs grids of the date of occurrence of each AM (as the day in the year). These are used to investigate any differences in the date of occurrence of daily and hourly AM, and changes in each between SIMCPMh baseline and far-future.

3 | Results

3.1 | Comparing Daily and Hourly Flow Performance Using Hourly Observation-Based Driving Data

Boxplots of the SIMOBSh performance measures across the set of 692 catchments (Figure 2) show that, on average, performance for hourly mean flows is less than that for daily mean flows.

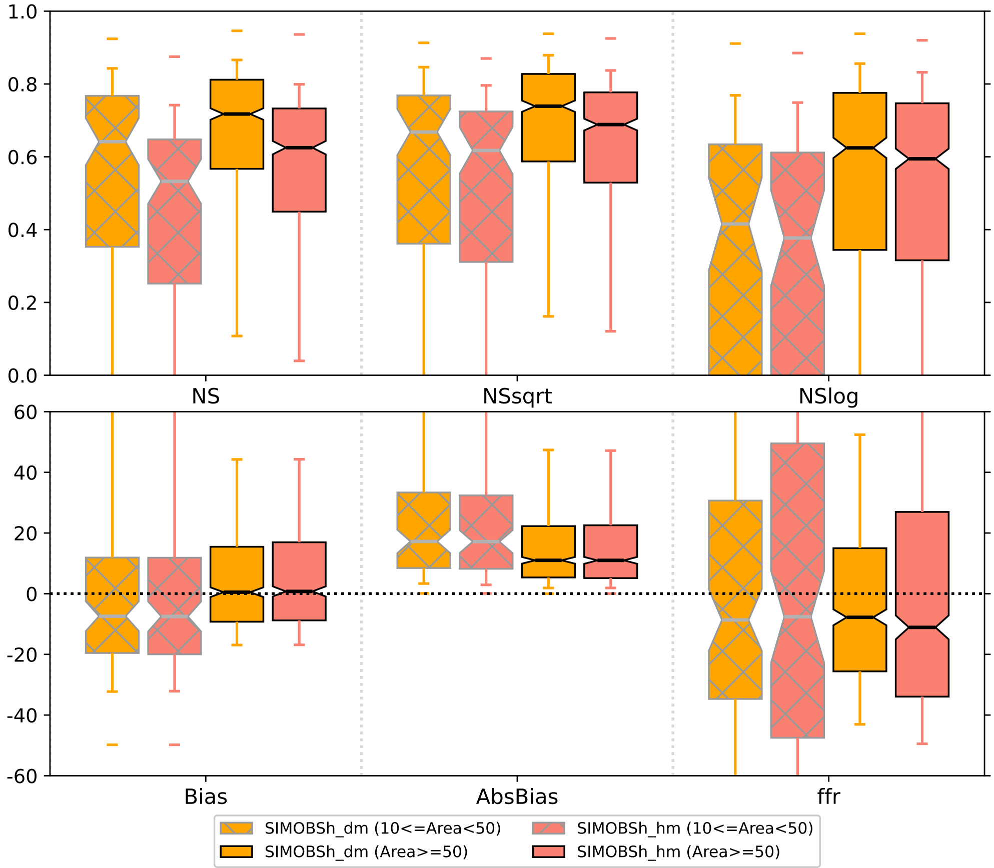

FIGURE 2 | Summary of SIMOBSh performance for daily and hourly mean flows ('SIMOBSh_dm', 'SIMOBSh_hm'), split by catchment area (grey outline 10–50 km^2; black outline $\geq 50\,\text{km}^2$). The boxes show the 25th–75th percentile range across the set of catchments, with the median shown by the line across the box. The whiskers show the 10th–90th percentile range, with overall min and max shown by dashes beyond the whiskers (if within the plotted range).

There is less difference for low flows (NSlog) than high flows (NS and ffr), and little difference in terms of overall bias in simulated flows. Performance for peak flows (ffr) shows an underestimation of the order of 10% on average, but the range is substantially wider for hourly than daily mean flows. On average, performance for smaller catchments (area 10–50 km^2) is worse than for larger catchments (area > 50 km^2), and the set of smaller catchments shows a wider variation in performance than larger catchments, particularly for low flows (NSlog) and peak flows (ffr).

Maps of each NS-based and bias measure, for daily and hourly mean flows, are provided in Figures S1 and S2 respectively, using the Good/Acceptable/Poor classification for each measure defined in Section 2.3. Corresponding maps of the difference in performance for daily and hourly flows clearly show that most catchments have better simulation from daily flows, but some are better with hourly flows, particularly in the south/east. For most measures, about 68%–89% of catchments perform better for daily mean flows, compared to only about 3%–27% of catchments performing better for hourly mean flows, with little difference for about 8%–15% of catchments. For the absolute bias though, there is little difference between performance for daily and hourly mean flows for 82% of catchments, with only 10% being better for daily and 8% better for hourly.

Figure 3 presents boxplots summarising properties across subsets of catchments for which performance is categorised as Good, Acceptable or Poor for each of the five performance measures, for daily and hourly mean flows. These confirm that performance is, on average, better for larger catchments, but also those with a higher mean altitude, higher mean slope and lower baseflow index. For most measures there is little difference in dependence of daily and hourly mean flow performance on these catchment properties. But for high flows (NS) and flood peaks (AbsFfr), where performance was most reduced for hourly compared to daily flows (Figure 2), there are greater differences between the properties of the catchments falling into the 'Poor' performance category.

Plots for the four case study catchments (listed in Table 1) illustrate a range of features (Figure 4). For all four catchments, hourly peaks in observed flows are larger than daily peaks, so the flood frequency curve is higher, but the daily and hourly flow duration curves are practically indistinguishable. Catchment 28091 is low altitude with shallow slopes and a relatively high baseflow index. The simulated hourly and daily mean flows match the observed reasonably well, although higher return period peak flows are over-estimated and the low flow portion of the flow duration curve is under-estimated for both daily and hourly flows (Figure 4a). Catchment 42008, although small, has low latitude and shallow slopes and a very high baseflow index and is very slow-responding. The simulated hourly and daily mean flows are basically indistinguishable from each other, indicating that the model is not

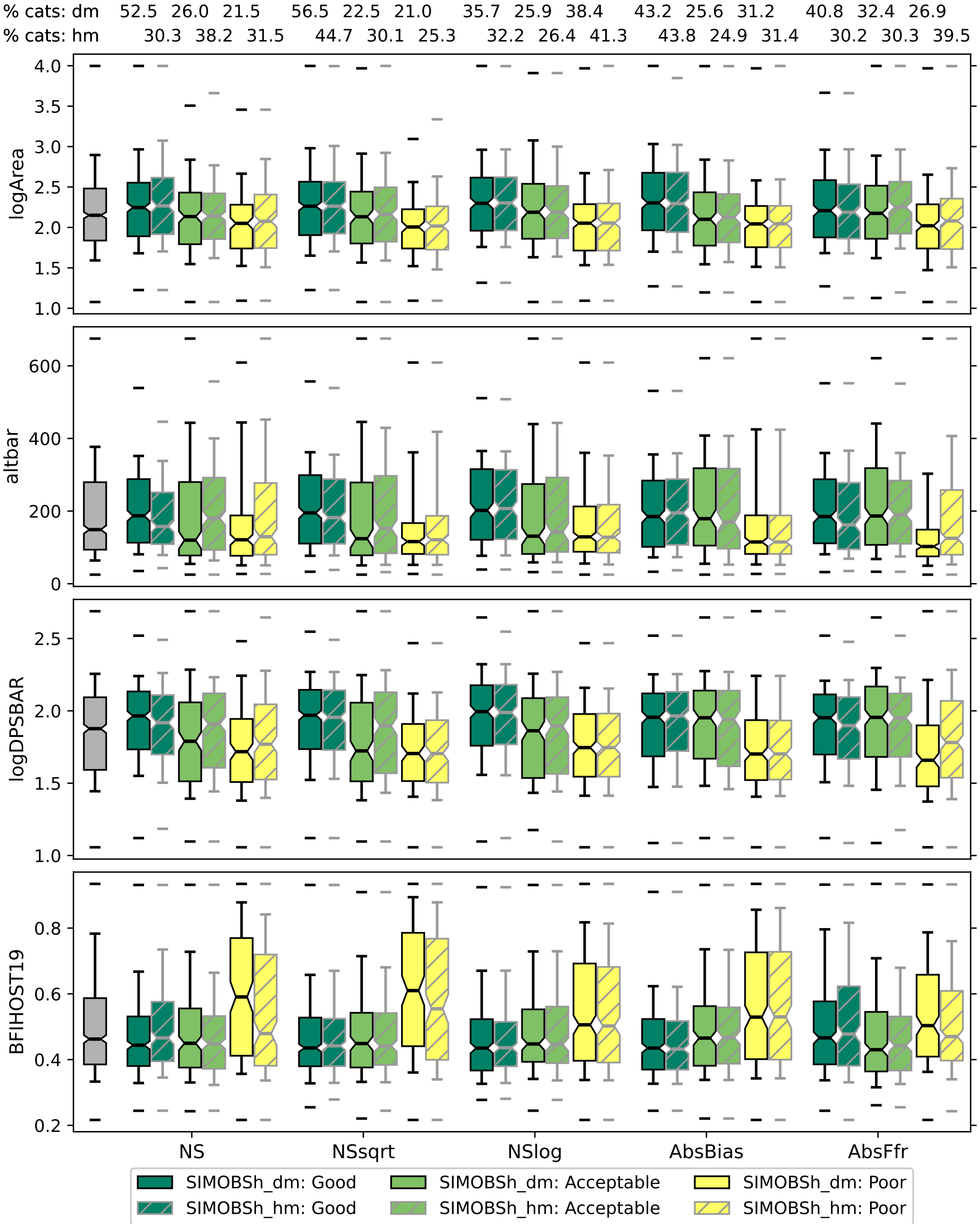

FIGURE 3 | Boxplots summarising properties across subsets of catchments for which SIMOBSh performance is categorised as good, acceptable or poor for daily and hourly mean flows ('SIMOBSh_dm', 'SIMOBSh_hm'). Results are shown for each performance measure (left to right, using the absolute value of the bias and ffr measures), for a range of catchment properties (top to bottom; catchment area, mean catchment altitude 'altbar', mean drainage path slope 'DPSBAR' and baseflow index derived from soil classes 'BFIHOST19'). The thresholds for the performance categories are defined in Section 2.3. The numbers at the top show the percentage of the 692 catchments in each performance category, for daily mean flows (first) and hourly mean flows (second). The grey boxplots on the left show the range of each catchment property across the 692 catchments, for comparison.

responding sufficiently to sub-daily precipitation inputs in this catchment (Figure 4b). Catchment 62001 is quite large, with relatively high altitude and steep slopes but a near-average baseflow index. The simulated hourly and daily mean flows match the observed very well, although hourly peak flows are under-estimated more than daily peak flows (Figure 4c). Catchment 79003 is high altitude with steep slopes and a low baseflow index, so is fast-responding. The simulated hourly and daily mean flows match the observed relatively well, although peak flows are under-estimated, and there is a difference in the shape of the observed and simulated hourly flood frequency curves (Figure 4d).

3.2 | Assessing Impacts on Peak Flows Under Climate Change

Violin plots and scatter plots compare the percentage changes in the 2-, 5- and 10-year return period peak flows derived from daily and hourly AM from SIMCPMh, for 1 km river cells across GB (Figure 5). The violin plots show that, on average, the peak flow changes derived from hourly AM are higher than those from daily AM. The difference increases by return period (GB median 14.8% vs. 9.1% at 2-year return period, 18.0% vs. 8.5% at 5-year return period and 20.2% vs. 8.4% at 10-year return period). The scatter plots show a relatively linear relationship

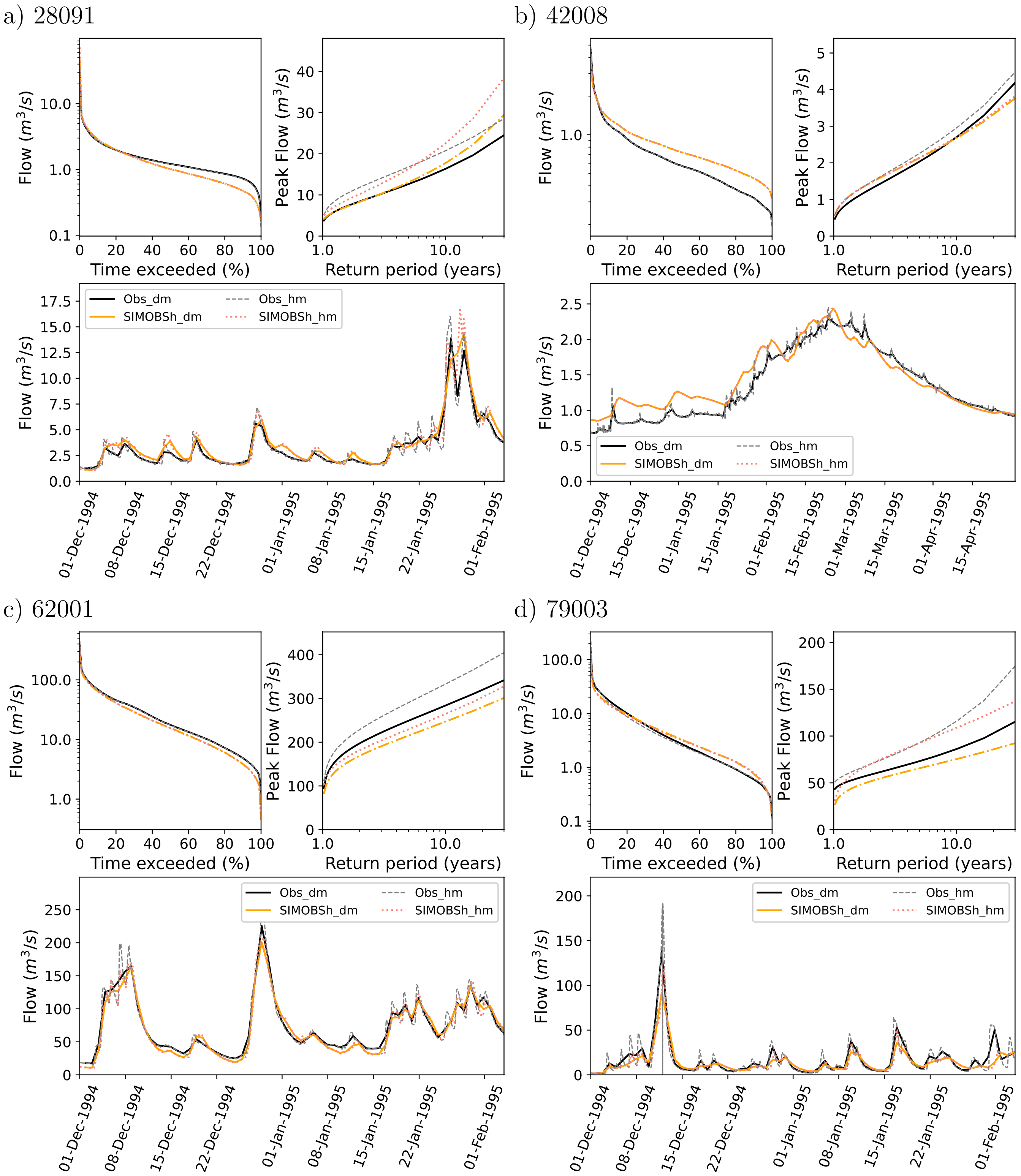

FIGURE 4 | Flow duration curves, flood frequency curves and a short flow hydrograph for the four case study catchments (Table 1), from SIMOBSh daily and hourly mean flows ('SIMOBSh_dm', orange dashed lines; 'SIMOBSh_hm', red dot-dashed lines), compared to gauged daily and hourly flows ('Obs_dm', black solid lines; 'Obs_hm', grey dashed lines).

between peak flow changes from hourly and daily AM, although the scatter increases with return period. Some river cells show very large differences.

Boxplots summarising the differences in 10-year return period peak flow impacts from hourly and daily AM for river cells split by catchment drainage area show relatively limited differences for larger catchments (median ~6%) but greater differences for catchments smaller than 50 km^2 (median ~12%), and some river cells (of any size) show large differences (Figure 6 top). For larger catchments, those in the SE tend to show greater differences in peak flow impacts than those in the NW (Figure 6 bottom), but

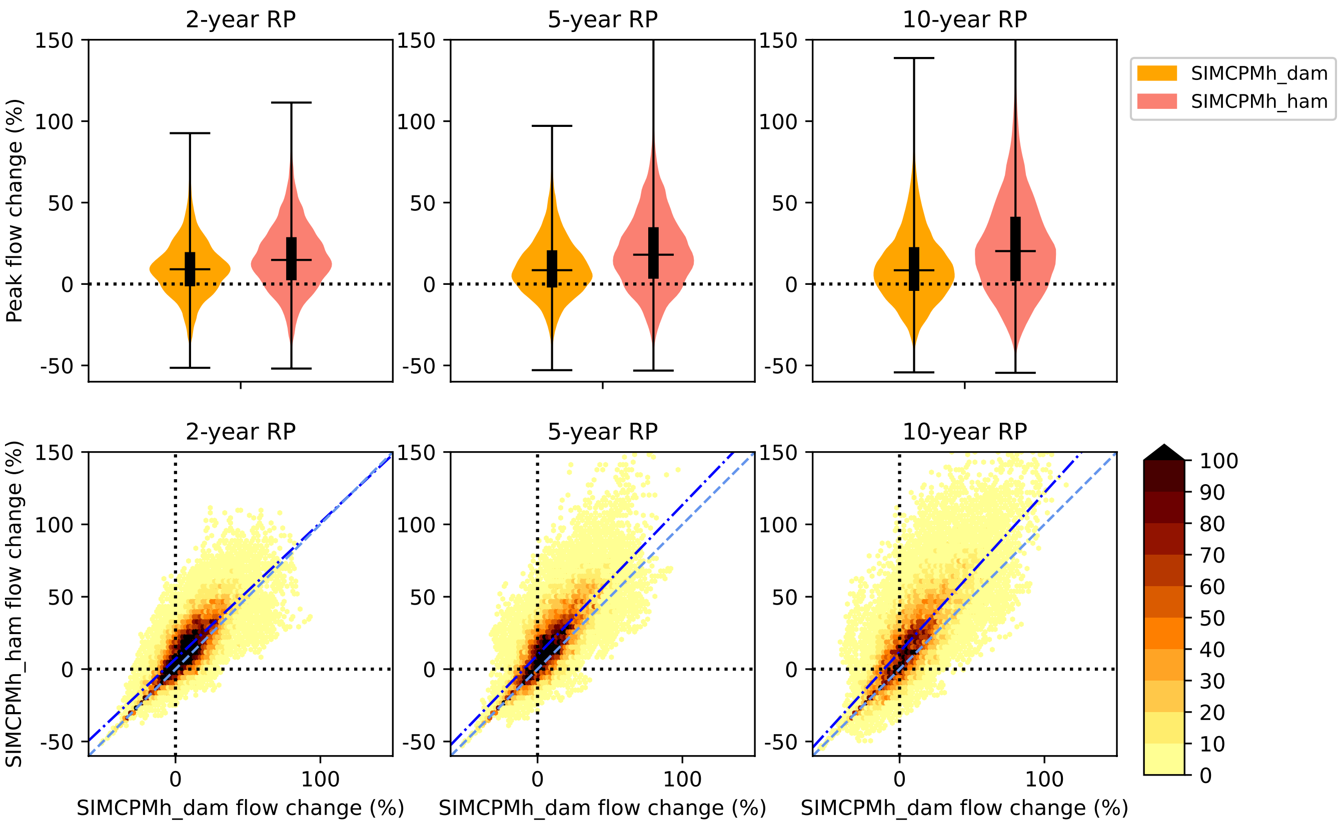

FIGURE 5 | Violin plots (top) and heatmaps of scatter plots (bottom) comparing percentage changes in the 2-, 5-, and 10-year return period (RP) peak flow derived from daily and hourly AM from SIMCPMh, for 1 km river cells across GB. For the violin plots, the horizontal lines show the min, median and max changes, and the black box shows the 25th–75th percentile range. For the scatter plots, the 1:1 line (light blue dashed) and best fit lines (blue dot-dashed) are shown.

the opposite is true for smaller catchments, with those in the NW tending to show greater differences than those in the SE. Differences in 2-year return period peak flow impacts are generally smaller than for 10-year peak flows, and show much less influence by catchment size (Figure S3).

Again, various features are illustrated by flood frequency curve plots (Figure 7) for the four case study catchments (Table 1). Catchment 28091 shows a decrease in higher return period daily peaks, which is less clear for hourly peaks (although may be happening at even higher return periods). Catchment 42008 shows a future increase in flood peaks at all return periods, which is exactly the same for daily and hourly peaks (cf. Figure 4b). Catchment 62001 shows essentially no change in daily flood peaks, but some small changes in hourly flood peaks, which vary by return period due to a change in the shape of the curve. Catchment 79003 shows relatively small changes in daily flood peaks, which vary by return period, but large increases in hourly flood peaks.

3.3 | Dates of Occurrence of Daily and Hourly AM

To assess any differences in daily and hourly AM dates of occurrence (given by the day number in the water-year), the hourly dates are subtracted from the daily dates for each annual event at each river cell. Histograms of these date differences, across all years (19) and all river cells (46865), show that the majority of daily and hourly AM are from the same (or a very near) event (Figure 8); the date difference is zero for 53% of events in SIMOBSh, 68% in SIMCPMh baseline and 66% in SIMCPMh far-future, with the equivalent percentages for a date within ±5 days being 77%, 77% and 75%. Some annual events have much larger date differences though, especially for smaller catchments and more negative date differences (less than around −150; Figure 8).

Contours on the 2D-histograms suggest little difference between the SIMOBSh, SIMCPMh baseline and SIMCPMh far-future runs, although there may be a slight tendency towards some more positive date differences for mid-sized catchments in the far-future compared to the baseline (Figure 8).

Polar plots illustrate the distributions of the daily and hourly AM through the year for the SIMCPMh baseline and far-future runs (Figure 9). These show that, across GB in the baseline period, there is a bimodal distribution with more peaks in both autumn and winter but few in summer, with autumn hourly peaks more likely than daily, and vice-versa in winter. In the far-future there is a strong reduction in both daily and hourly autumn peaks and an increase in winter peaks, with some peaks also occurring into early spring. This pattern of changes is similar for river cells in the NW, although the occurrence of autumn peaks is enhanced. The pattern is much more complex for river cells in the SE, with some baseline peaks in late summer, and a much-increased occurrence of peaks in early spring in the far-future. There is less difference in the AM date distribution patterns for either smaller

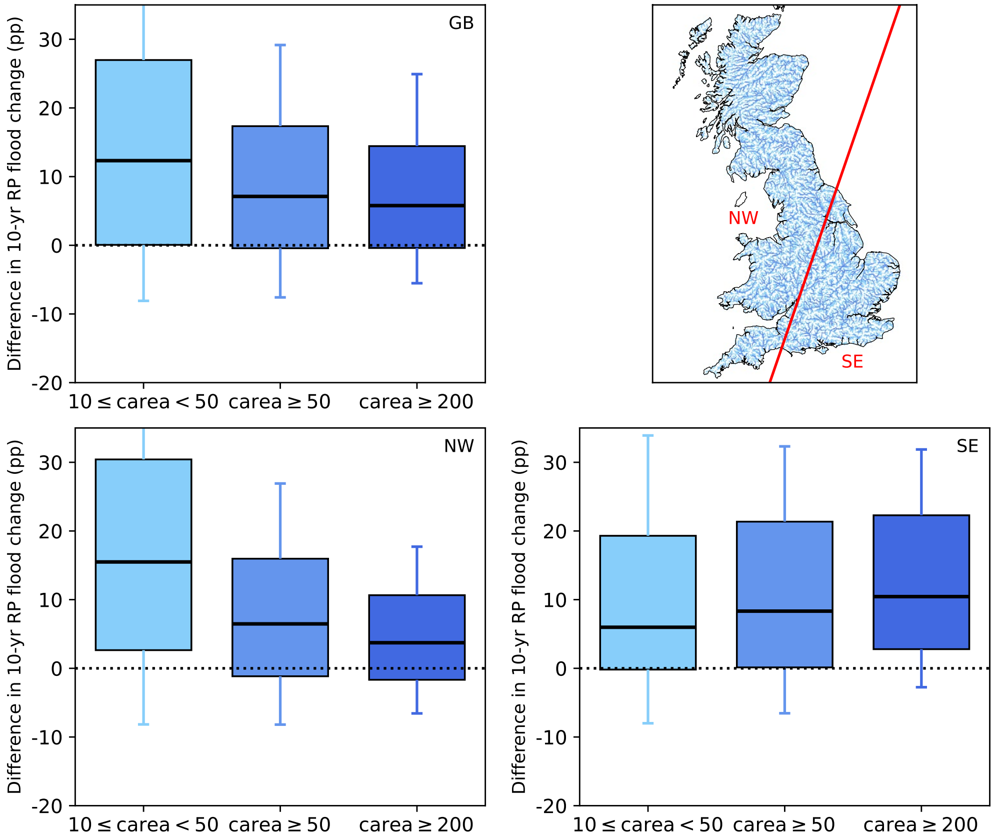

FIGURE 6 | Boxplots summarising the difference in the percentage change in 10-year return period peak flows from daily and hourly AM (SIMCPMh_ham–SIMCPMh_dam; percentage point, pp). The results are split by river cells with a small drainage area ('10 ≤ carea < 50'), a drainage area above the threshold typically used with daily driving data ('carea ≥ 50'), and a larger drainage area ('carea ≥ 200'). The top-left plot shows results over GB, while the lower pair shows results over the North/West (left) and South/East (right). The NW/SE division is shown top-right. In each case, the boxes show the 25th–75th percentile range, with the median shown by the line across the box, and the whiskers show the 10th–90th percentile range.

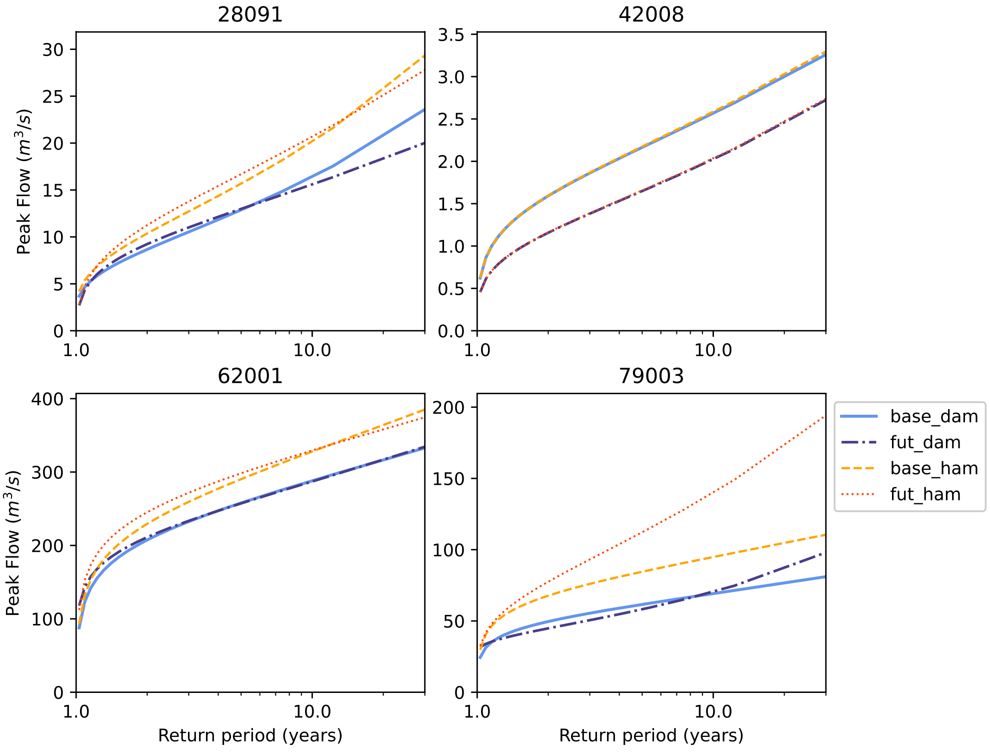

FIGURE 7 | Flood frequency curves for the four case study catchments (Table 1), derived from daily and hourly mean AM flows from SIMCPMh ('dam' and 'ham') for baseline and far-future periods ('base' and 'fut').

(10–50 km^2) or larger ($\geq$200 km^2) catchments, compared to GB as a whole. The date distributions for SIMOBSh (Figure S4) are relatively similar to those for SIMCPMh baseline (bimodal, with autumn and winter peaks and few summer peaks), although there are less clear differences between the distributions of daily and hourly AM for SIMOBSh than SIMCPMh (Figure 9).

4 | Discussion

4.1 | Comparing Daily and Hourly Performance Using Observation-Based Driving Data

A grid-based hydrological model has been driven with observation-based hourly precipitation data, and the performance of simulated daily mean and hourly mean river flows compared against observed daily and hourly river flows (respectively). On average, the performance for hourly mean flows is less than that for daily mean flows, with more difference for high flows and flood peaks (Section 3.1). For both hourly and daily mean flows, on average, the performance is better for larger catchments and those with a higher mean altitude and slope and lower baseflow index, but for high flows and flood peaks, there is some broadening of the range of properties of the catchments falling into the 'Poor' performance category for hourly mean flows.

Others studies show that performance for flows aggregated over longer time-steps is better than for the model time-step, whether that is sub-daily aggregated to daily (e.g., Tudaji et al. 2025) or sub-daily or daily aggregated to monthly (e.g., Rudd et al. 2017; Ahmed et al. 2022). Similarly, Baroni et al. (2019) show increased temporal agreement between both evaporation and surface soil moisture outputs from two hydrological models when these data

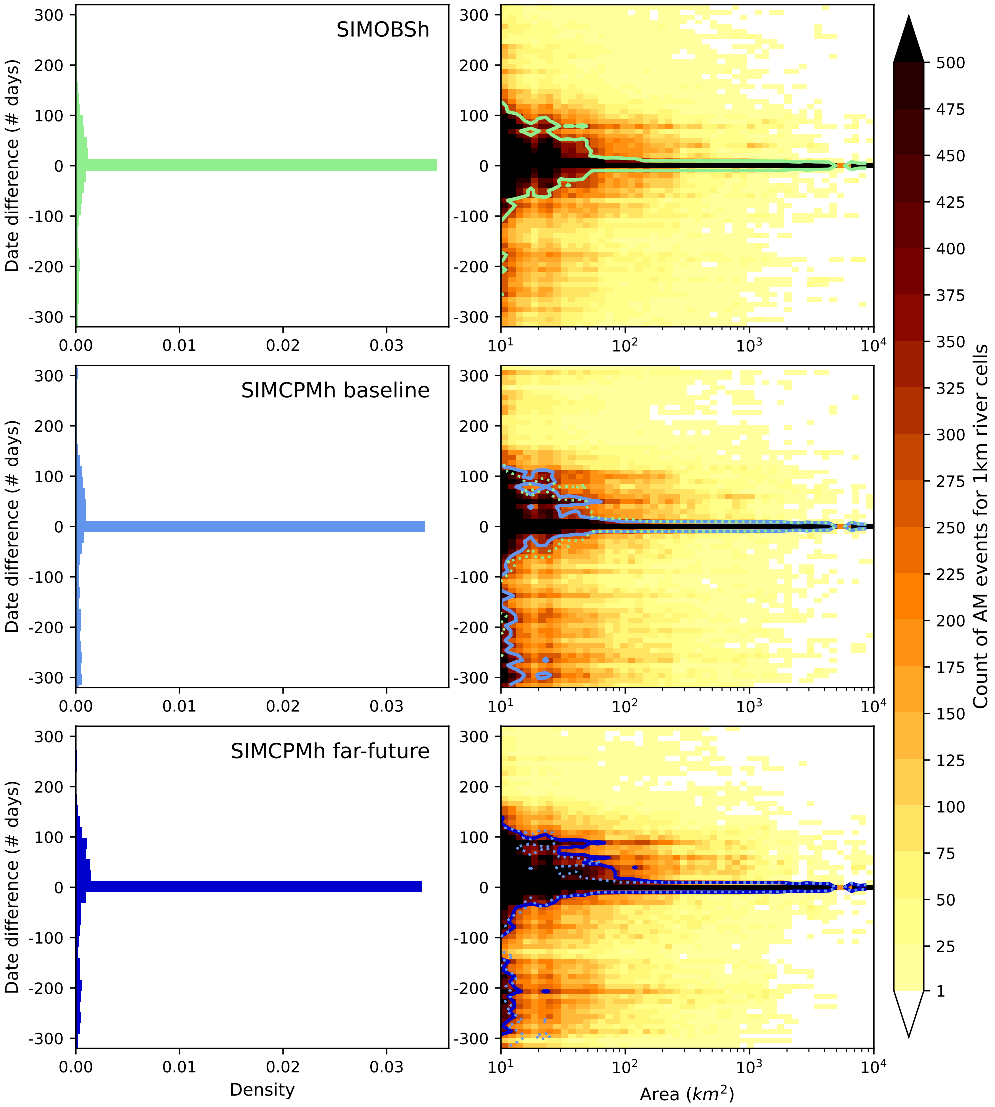

FIGURE 8 | Histograms of the difference in dates of occurrence of daily mean AM and hourly mean AM, for SIMOBSh (top), SIMCPMh baseline (middle) and SIMCPMh far-future (bottom). A positive value indicates that the daily AM occurs later in the water-year than the hourly AM. Standard histograms are on the left, with 2D histograms on the right showing the date differences by catchment area. Contours on each 2D histogram delineate areas with a count of least 300 events per bin, with the contour from the SIMOBSh histogram (light green solid line) also shown with the SIMCPMh baseline histogram (light green dotted line), and the contour from the SIMCPMh baseline histogram (light blue solid line) also shown with the SIMCPMh far-future histogram (light blue dotted line), alongside the contour from the SIMCPMh far-future histogram (dark blue solid line).

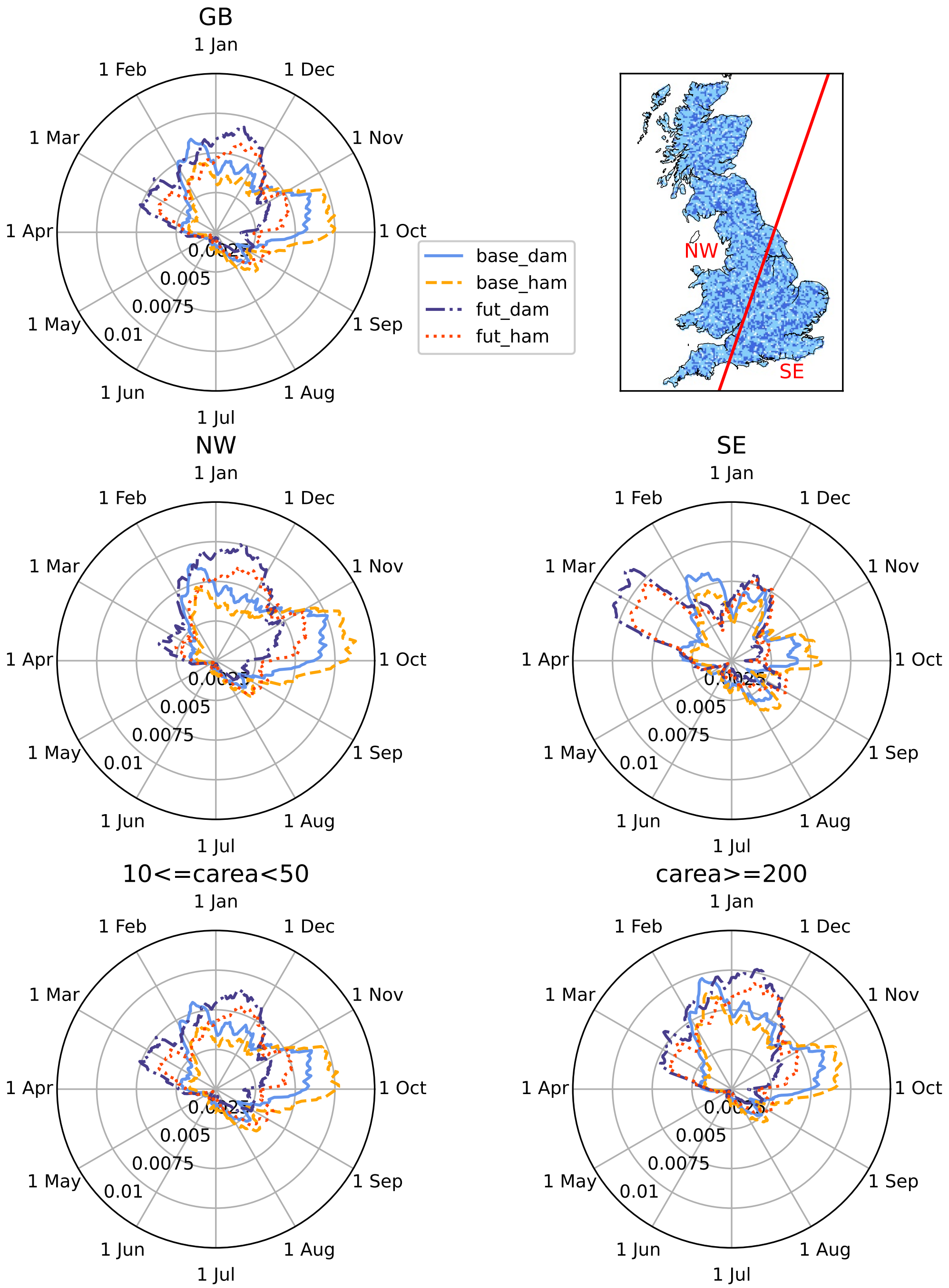

FIGURE 9 | Polar plots showing the dates of occurrence of the daily (blues) and hourly (oranges) AM from SIMCPMh baseline (solid/dashed) and far-future (dot-dashed/dotted). A 30-day running-mean smoothing is applied to each line (plotted at the middle day) to reduce noise. The top-left plot shows dates across GB, while the middle pair shows dates over the NW (left) and SE (right) (the NW/SE division is shown top-right), and the lower pair shows dates only for smaller (10 km^2 ≤ carea < 50 km^2; left) and larger (carea ≥ 200 km^2; right) catchments.

are aggregated over longer time-steps (although, interestingly, this did not hold for deeper soil moisture). Potential issues with the timing of flow variations make good time-series performance for hourly mean flows harder than for daily mean flows, particularly if focussing on high flows (NS) or small catchments. It is difficult to derive accurate sub-daily rainfall timing/distribution across wide areas from limited numbers of rain-gauges (and for some locations/days it was necessary for CEH-GEAR1hr to use profile disaggregation). Tudaji et al. (2025) note that '... model input data, particularly rainfall, may have a lower signal-to-noise ratio at higher temporal resolutions due to difficulties in data validation and increased uncertainty in areal average rainfall estimates'. For smaller or more responsive catchments in particular, there is less opportunity for errors in the driving data (e.g., storm location, extent and heterogeneity) to be compensated for when water is temporally and spatially accumulated across the area. There can also be greater difficulties in gauging river flows in smaller catchments, and they can be affected more by errors related to the 1 km flow network used by G2G.

A large set of catchments has been applied here, with no consideration given to flow gauge reliability at different stages, or to the presence of artificial influences like abstraction and discharges. This could potentially skew performance for types of catchments that may be more likely to have artificial influences or data issues—a factor also noted by Formetta et al. (2018). Previous G2G performance assessments have generally used more limited catchment sets (e.g., Bell et al. 2009; Rudd et al. 2017), often comprising catchments with limited artificial influences and where gauging is considered reliable (e.g., Formetta et al. 2018; Kay 2022), and showed no clear relationships between performance and catchment properties. Kay et al. (2021) showed that performance of standardised high flows for a large set of catchments had a much broader spread of values compared to that for a more limited set of benchmark catchments (with reliable gauging and limited artificial influences), although both sets had median values close to zero.

While model performance for hourly mean flows is generally lower than for daily mean flows, it is still reasonable for most catchments, even smaller catchments (other than for low flows). This suggests that it is reasonable to use the model to look at potential future changes in hourly as well as daily mean peak flows, for smaller catchments as well as larger ones. Fileni, Fowler, Lewis, McLay, et al. (2025) recommend 'implementing [models used for flood impact studies] at a sub-daily (−hourly) resolution to accurately capture flood peaks in smaller catchments'.

4.2 | Assessing Impacts on Peak Flows Under Climate Change

On average, future changes in peak flows derived from hourly AM are higher than those from daily AM (GB median 20.2% for hourly AM vs. 8.4% for daily AM at 10-year return period), with greater differences for higher return period peak flows. Some river cells show very large differences, while some cells give lower peak flow changes from hourly AM than daily AM. Smaller catchments ($<50\,\text{km}^2$) in the north/west tend to show larger differences. River flow in smaller catchments is typically more responsive to short time-scale extreme precipitation than flow in larger catchments (Stein et al. 2021), so future increases in hourly extreme rainfall in the UKCP18 CPM (Chan et al. 2023) will have a greater impact in such catchments. This suggests that, at least for some locations, use of hourly CPM precipitation data and analysis of changes in hourly mean peak flows could be important for the development of appropriate adaptation strategies for changes in flood hazard under climate change.

The results here are consistent with an analysis of the impacts of climate change on peak flows in 120 Norwegian catchments (Carr et al. 2023), which showed that 3-h peak flow changes can be considerably greater than daily peak flow changes, and that catchment area was an explanatory factor (albeit weakly) for the 3-h changes. Similarly, Kim et al. (2018) show, using a bottom-up sensitivity framework for a catchment in South Korea, that use of daily flow indices can considerably underestimate the impact of climate change on flood hazard compared to use of hourly indices. Instantaneous peaks may be even more affected than hourly peaks.

Peaks with higher than 10-year return periods were not studied here since only 20-year time-slices of 5 km CPM data were used. But changes in higher return period peak flows are important in flood risk planning (Willkofer et al. 2024), particularly as impacts vary by return period (Figure 6 and e.g., Brunner et al. 2021; Poncet et al. 2025). Increased availability of CPM data will enable investigation of higher return periods, and applying the full UKCP18 Local CPM ensemble may allow better identification of the effect of natural variability (Kendon et al. 2023), although this is complicated by the use of perturbed parameter driving ensembles in UKCP18. Application of a single model initial-condition large ensemble (SMILE) with hydrological models can enable improved estimation of very rare floods (e.g., Willkofer et al. 2024), but the expense of very high-resolution CPMs means that CPM-based SMILEs have so far not been possible.

4.3 | Dates of Occurrence of Daily and Hourly AM

Analysis of the dates of occurrence of daily and hourly AM showed that the majority of annual pairs across GB are from the same event, but some annual pairs for some locations have large date differences (Figure 8). Many of the larger date differences are likely to be where there were two events of a similar size in a year, but the distribution of hourly rainfall pushes what was the second highest event in terms of daily mean flows up to the highest in terms of hourly mean flows. The large negative differences for smaller catchments are likely to be when the largest daily AM occurred in winter but the largest hourly AM occurred from an intense event in the following summer; such intense summer events are more likely to cause high flows in smaller fast-responding catchments (Stein et al. 2021). The possible tendency towards some more positive date differences for mid-sized catchments in the far-future compared to the baseline may be due to an increase in the occurrence of hourly events in autumn (near the start of the water-year) rather than summer, with the daily event in winter; the CPM analysis of Chan et al. (2020) shows the season with the most hourly precipitation extremes shifts from summer to autumn (or no clear seasonality) for much of GB.

AM date distributions were generally bimodal, with more peaks in both autumn and winter but few in summer, with a strong reduction in both daily and hourly autumn peaks and an increase in winter peaks in the far-future (Figure 9), likely due to significant summer drying. A more complex picture of AM date distributions, and changes in these, for the SE is likely due to differing behaviour of slowly-responding groundwater-dominated catchments versus catchments without significant long-term water storage.

A number of other studies have shown possible shifts in the timing of AM under climate change (e.g., Schneider et al. 2013; Xu et al. 2021; Lane and Kay 2021; Dembélé et al. 2024), but they have not looked at AM derived from daily versus hourly mean flows. Xu et al. (2021) note that '... the timing of peak daily average runoff can be different from the timing of peak instantaneous runoff'. Only dates of AM were studied here—analysis of peaks-over-threshold may give a more complete picture.

5 | Conclusions

The availability of an hourly 1 km gridded observation-based precipitation dataset for GB (CEH-GEAR1hr; Lewis et al. 2018, 2022), along with sub-daily gauged flows for a large number of catchments (Fileni, Fowler, Lewis, Fry, et al. 2025), enabled an assessment of the performance of hourly versus daily mean flow simulation using a grid-based hydrological model (G2G) across GB. The assessment showed that, on average, performance for hourly mean flows is less than that for daily mean flows, although with less difference for low than high flows and little difference in overall bias. Future work could investigate how performance across different catchments varies between hydrological models, potentially helping to highlight pros and cons of different model components. How model performance relates to rainfall type (e.g., frontal or convective) and the spatial and temporal resolution of PE and temperature in different catchments could also be investigated.

The availability of hourly precipitation data from a convection-permitting model (CPM) for baseline (Dec 1980–Nov 2000) and far-future (Dec 2060–Nov 2080) periods, from the UKCP18 Local projections (Kendon, Short, et al. 2021), provided the opportunity to compare potential future changes in peak flows derived from daily mean flows and hourly mean flows across GB. A simple bias-correction was applied to precipitation before using it to drive G2G, producing 1 km grids of the water-year annual maxima of daily and hourly mean flows. Flood frequency curves were fitted for baseline and far-future time periods, and differences in baseline to far-future changes in 2-, 5- and 10-year return period peak flows assessed. On average, peak flow changes derived from hourly AM are higher than those from daily AM, with greater differences for smaller catchments in the NW and larger catchments in the SE. The former might be expected but the latter result is somewhat unexpected, and highlights the importance of understanding and distinguishing between flood-generating mechanisms when assessing flood changes under climate change (Zhang et al. 2022). Future work will assess impacts using alternative CPM ensembles (nested in a range of GCMs rather than just the Hadley GCM/RCM; Short and Kendon 2024) and alternative hydrological models.

An analysis of the dates of occurrence of hourly and daily AM showed that these were often, but not always, from the same event. Future work could investigate where, when and why differences occur. There was also a reduction in autumn peaks and an increase in winter and early spring peaks in the far-future. Future work will investigate whether this is also the case for CPMs driven by alternative GCMs.

The analyses presented here help to inform where and when use of hourly mean flows may be required. Orr et al. (2021) suggest use of CPM data in applications that are sensitive to small-scale variability in climate inputs and dominated by short-term evolution of processes/events, such as future flood risk in smaller/flashier catchments, but the analysis here suggests it may be important in a wider range of catchments. The analysis of potential future changes in pluvial flooding also requires precipitation at high spatial and temporal resolution (Rudd et al. 2020; Rong et al. 2024), as can analyses of urban drainage system design (Chan et al. 2023) and soil erosion (Ciampalini et al. 2023).

Acknowledgements

This work was supported by the Natural Environment Research Council, award numbers NE/S017380/1 (Hydro-JULES) and NE/W004984/1 (CANARI). Thanks to UKCEH colleagues Matt Fry and Oliver Swain for help with the sub-daily gauged flow data, and Vicky Bell, Rosie Lane and Bob Moore for comments on the draft manuscript.

Funding

This work was supported by the Natural Environment Research Council (Grants NE/S017380/1 and NE/W004984/1).

Conflicts of Interest

The author declares no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Ahmed, E., F. Al Janabia, W. Yanga, A. Alib, N. Saddiquec, and P. Krebsa. 2022. "Comparison of Flow Simulations With Sub-Daily and Daily GPM IMERG Products Over a Transboundary Chenab River Catchment." *Journal of Water and Climate Change* 13, no. 3: 1204.

Baroni, G., B. Schalge, O. Rakovec, et al. 2019. "A Comprehensive Distributed Hydrological Modelling Intercomparison to Support Process Representation and Data Collection Strategies." *Water Resources Research* 55: 990–1010. https://doi.org/10.1029/2018WR023941.

Bell, V. A., A. L. Kay, S. J. Cole, R. G. Jones, R. J. Moore, and N. S. Reynard. 2012. "How Might Climate Change Affect River Flows Across the Thames Basin? An Area-Wide Analysis Using the UKCP09 Regional Climate Model Ensemble." *Journal of Hydrology* 442–443: 89–104.

Bell, V. A., A. L. Kay, H. N. Davies, and R. G. Jones. 2016. "An Assessment of the Possible Impacts of Climate Change on Snow and Peak River Flows Across Britain." *Climatic Change* 136, no. 3: 539–553.

Bell, V. A., A. L. Kay, R. G. Jones, R. J. Moore, and N. S. Reynard. 2009. "Use of Soil Data in a Grid-Based Hydrological Model to Estimate Spatial Variation in Changing Flood Risk Across the UK." *Journal of Hydrology* 377, no. 3–4: 335–350.

Brunner, M. I., D. L. Swain, R. R. Wood, et al. 2021. "An Extremeness Threshold Determines the Regional Response of Floods to Changes in Rainfall Extremes." *Communications Earth & Environment* 2: 173.

Carr, S., D. Lawrence, T. Skaugen, and W. K. Wong. 2023. "Projected Future Changes in Peak Flows and Implications for Climate Change Allowances." NVE Rapport nr. 26/2023. The Norwegian Water Resources and Energy Directorate. https://publikasjoner.nve.no/rapport/2023/rapport2023_26.pdf.

Chan, S. C., E. J. Kendon, S. Berthou, G. Fosser, E. Lewis, and H. J. Fowler. 2020. "Europe-Wide Precipitation Projections at Convection Permitting Scale With the Unified Model." *Climate Dynamics* 55: 409–428.

Chan, S. C., E. J. Kendon, H. J. Fowler, B. D. Youngman, M. Dale, and C. Short. 2023. "New Extreme Rainfall Projections for Improved Climate Resilience of Urban Drainage Systems." *Climate Services* 30: 100375.

Ciampalini, R., E. J. Kendon, J. A. Constantine, M. Schindewolf, and I. R. Hall. 2023. "Soil Erosion in a British Watershed Under Climate

Change as Predicted Using Convection-Permitting Regional Climate Projections." *Geosciences* 13: 261.

Cranston, M., R. Maxey, A. Tavendale, et al. 2012. "Countrywide Flood Forecasting in Scotland: Challenges for Hydrometeorological Model Uncertainty and Prediction." In *Weather Radar and Hydrology*, edited by R. J. Moore, S. J. Cole, and A. J. Illingworth, vol. 351, 538–543. IAHS.

Crooks, S. M., A. L. Kay, H. N. Davies, and V. A. Bell. 2014. "From Catchment to National Scale Rainfall-Runoff Modelling: Demonstration of a Hydrological Modelling Framework." *Hydrology* 1, no. 1: 63–88. https://doi.org/10.3390/hydrology1010063.

Dembélé, M., M. Vrac, N. Ceperley, et al. 2024. "Future Shifting of Annual Extreme Flows Under Climate Change in the Volta River Basin." *Proceedings of IAHS* 385: 121–127.

Ficchì, A., C. Perrin, and V. Andreassian. 2019. "Hydrological Modelling at Multiple Sub-Daily Time Steps: Model Improvement via Flux-Matching." *Journal of Hydrology* 575: 1308–1327.

Fileni, F., H. J. Fowler, E. Lewis, et al. 2025. "Sub-Hourly River Flow Data Observations From 1369 River Gauges in the UK, 1948–2023 (UK-Flow15)." NERC EDS Environmental Information Data Centre. https://doi.org/10.5285/211710ac-f01b-4b52-807f-373babb1c368.

Fileni, F., H. J. Fowler, E. Lewis, F. McLay, E. Bruce, and M. Becker. 2025. "Flood Risk Assessments for Small Catchments Under Climate Change—How Can Scotland Improve Its Policy for Enhanced Flood Resilience and Preparedness." *Journal of Flood Risk Management* 18: e70035.

Formetta, G., I. Prosdocimi, E. Stewart, and V. Bell. 2018. "Estimating the Index Flood With Continuous Hydrological Models: An Application in Great Britain." *Hydrology Research* 49: 123–133.

Fosser, G., E. Kendon, S. Chan, A. Lock, N. Roberts, and M. Bush. 2020. "Optimal Configuration and Resolution for the First Convection-Permitting Ensemble of Climate Projections Over the United Kingdom." *International Journal of Climatology* 40: 3585–3606.

Griffin, A., A. Young, and L. Stewart. 2019. "Revising the BFIHOST Catchment Descriptor to Improve UK Flood Frequency Estimates." *Hydrology Research* 50, no. 6: 1508–1519.

Ho, S., L. Tian, M. Disse, and Y. Tuo. 2021. "A New Approach to Quantify Propagation Time From Meteorological to Hydrological Drought." *Journal of Hydrology* 603: 127056.

Hollis, D., E. Carlisle, M. Kendon, S. Packman, A. Doherty, and Met Office. 2025. "HadUK-Grid Gridded Climate Observations on a 1 km Grid Over the UK, v1.3.1.ceda (1836–2024)." NERC EDS Centre for Environmental Data Analysis. https://doi.org/10.5285/f02cc6ddd92f45b18b9ab6ab544df7d9.

Hollis, D., M. McCarthy, Met Office, et al. 2019. "HadUK-Grid Gridded Climate Observations on a 1 km Grid Over the UK, v1.0.0.0 (1862–2017)." NERC EDS Centre for Environmental Data Analysis. https://doi.org/10.5285/2a62652a4fe6412693123dd6328f6dc8.

Hough, M. N., and R. J. A. Jones. 1997. "The United Kingdom Meteorological Office Rainfall and Evaporation Calculation System: MORECS Version 2.0—An Overview." *Hydrology and Earth System Sciences* 1: 227–239.

Kay, A. L. 2022. "Differences in Hydrological Impacts Using Regional Climate Model and Nested Convection-Permitting Model Data." *Climatic Change* 173, no. 1–2: 11. https://doi.org/10.1007/s10584-022-03405-z.

Kay, A. L., V. A. Bell, H. N. Davies, R. A. Lane, and A. C. Rudd. 2023. "The UKSCAPE-G2G River Flow and Soil Moisture Datasets: Grid-to-Grid Model Estimates for the UK for Historical and Potential Future Climates." *Earth System Science Data* 15, no. 6: 2533–2546. https://doi.org/10.5194/essd-15-2533-2023.

Kay, A. L., and M. J. Brown. 2023. "Using Sub-Daily Precipitation for Grid-Based Hydrological Modelling Across Great Britain: Assessing Model Performance and Comparing Flood Impacts Under Climate Change." *Journal of Hydrology: Regional Studies* 50: 101588.

Kay, A. L., and S. M. Crooks. 2014. "An Investigation of the Effect of Transient Climate Change on Snowmelt, Flood Frequency and Timing in Northern Britain." *International Journal of Climatology* 34: 3368–3381.

Kay, A. L., A. Griffin, A. C. Rudd, R. M. Chapman, V. A. Bell, and N. W. Arnell. 2021. "Climate Change Effects on Indicators of High and Low River Flow Across Great Britain." *Advances in Water Resources* 151: 103909.

Kay, A. L., A. C. Rudd, and J. Coulson. 2023. "Spatial Downscaling of Precipitation for Hydrological Modelling: Assessing a Simple Method and Its Application Under Climate Change in Britain." *Hydrological Processes* 37, no. 2: e14823. https://doi.org/10.1002/hyp.14823.

Kay, A. L., A. C. Rudd, H. N. Davies, E. J. Kendon, and R. G. Jones. 2015. "Use of Very High Resolution Climate Model Data for Hydrological Modelling: Baseline Performance and Future Flood Changes." *Climatic Change* 133: 193–208.

Keller, V. D. J., M. Tanguy, I. Prosdocimi, et al. 2015. "CEH-GEAR: 1 Km Resolution Daily and Monthly Areal Rainfall Estimates for the UK for Hydrological and Other Applications." *Earth System Science Data* 7: 143–155.

Kendon, E., C. Short, J. Pope, et al. 2021. *Update to UKCP Local (2.2km) Projections*. Met Office Hadley Centre.

Kendon, E. J., E. M. Fischer, and C. J. Short. 2023. "Variability Conceals Emerging Trend in 100yr Projections of UK Local Hourly Rainfall Extremes." *Nature Communications* 14: 1133.

Kendon, E. J., A. F. Prein, C. A. Senior, and A. Stirling. 2021. "Challenges and Outlook for Convection-Permitting Climate Modelling." *Philosophical Transactions of the Royal Society A* 379: 20190547. https://doi.org/10.1098/rsta.2019.0547.

Kendon, E. J., N. M. Roberts, H. J. Fowler, M. J. Roberts, S. C. Chan, and C. A. Senior. 2014. "Heavier Summer Downpours With Climate Change Revealed by Weather Forecast Resolution Model." *Nature Climate Change* 4: 570–576.

Kendon, E. J., N. M. Roberts, C. A. Senior, and M. J. Roberts. 2012. "Realism of Rainfall in a Very High-Resolution Regional Climate Model." *Journal of Climate* 25: 5791–5806.

Kim, D., J. A. Chun, and C. M. Aikins. 2018. "An Hourly-Scale Scenario-Neutral Flood Risk Assessment in a Mesoscale Catchment Under Climate Change." *Hydrological Processes* 32: 3416–3430.

Lane, R. A., and A. L. Kay. 2021. "Climate Change Impact on the Magnitude and Timing of Hydrological Extremes Across Great Britain." *Frontiers in Water* 3: 684982. https://doi.org/10.3389/frwa.2021.684982.

Lewis, E., N. Quinn, S. Blenkinsop, et al. 2018. "A Rule Based Quality Control Method for Hourly Rainfall Data and a 1 km Resolution Gridded Hourly Rainfall Dataset for Great Britain: CEH-GEAR1hr." *Journal of Hydrology* 564: 930–943.

Lewis, E., N. Quinn, S. Blenkinsop, et al. 2022. "Gridded Estimates of Hourly Areal Rainfall for Great Britain 1990–2016 [CEH-GEAR1hr] v2." NERC EDS Environmental Information Data Centre. https://doi.org/10.5285/fc9423d6-3d54-467f-bb2b-fc7357a3941f.

Lucas-Picher, P., D. Argueso, E. Brisson, et al. 2021. "Convection-Permitting Modeling With Regional Climate Models: Latest Developments and Next Steps." *WIREs Climate Change* 12: e731. https://doi.org/10.1002/wcc.731.

Met Office Hadley Centre. 2019. "UKCP Local Projections on a 5 km Grid Over the UK for 1980–2080." Centre for Environmental Data Analysis. catalogue.ceda.ac.uk/uuid/e304987739e04cdc960598fa5e4439d0.

Moore, R. J., S. J. Cole, and A. J. Robson. 2012. "Weather Radar and Hydrology: A UK Operational Perspective." In *Weather Radar and*

Hydrology, edited by R. J. Moore, S. J. Cole, and A. J. Illingworth, vol. 351, 429–434. IAHS.

Nicolle, P., R. Pushpalatha, C. Perrin, et al. 2014. "Benchmarking Hydrological Models for Low-Flow Simulation and Forecasting on French Catchments." *Hydrology and Earth System Sciences* 18: 2829–2857. https://doi.org/10.5194/hess-18-2829-2014.

Orr, H. G., M. Ekström, M. B. Charlton, K. L. Peat, and H. J. Fowler. 2021. "Using High-Resolution Climate Change Information in Water Management: A Decision-Makers' Perspective." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 379: 20200219. https://doi.org/10.1098/rsta.2020.0219.

Poncet, N., Y. Tramblay, P. Lucas-Picher, G. Thirel, and C. Caillaud. 2025. "Projections of Extreme Rainfall and Floods in Mediterranean Basins From an Ensemble of Convection-Permitting Models." *Climatic Change* 178: 141. https://doi.org/10.1007/s10584-025-03983-8.

Price, D., K. Hudson, G. Boyce, et al. 2012. "Operational Use of a Grid-Based Model for Flood Forecasting." *Water Management* 165, no. 2: 65–77.

Rameshwaran, P., V. A. Bell, M. J. Brown, et al. 2022. "Use of Abstraction and Discharge Data to Improve the Performance of a National-Scale Hydrological Model." *Water Resources Research* 5, no. 1: e2021WR029787.

Robinson, E. L., M. J. Brown, A. L. Kay, et al. 2023. "Hydro-PE: Gridded Datasets of Historical and Future Penman-Monteith Potential Evaporation for the United Kingdom." *Earth System Science Data* 15: 4433–4461. https://doi.org/10.5194/essd-15-4433-2023.

Robson, A. J., and D. W. Reed. 1999. "Statistical Procedures for Flood Frequency Estimation." In *Flood Estimation Handbook*, vol. 3. Institute of Hydrology.

Rong, Y., P. Bates, J. Neal, L. Archer, S. Hatchard, and E. Kendon. 2024. "Impact of Soil Moisture Dynamics and Precipitation Pattern on UK Urban Pluvial Flood Hazards Under Climate Change." *Earth's Future* 12: e2023EF004073.

Rudd, A. C., V. A. Bell, and A. L. Kay. 2017. "National-Scale Analysis of Simulated Hydrological Droughts (1891–2015)." *Journal of Hydrology* 550: 368–385.

Rudd, A. C., A. L. Kay, S. C. Wells, et al. 2020. "Investigating Potential Future Changes in Surface Water Flooding Hazard and Impact." *Hydrological Processes* 34: 139–149.

Schaller, N., J. Sillmann, M. Müller, et al. 2020. "The Role of Spatial and Temporal Model Resolution in a Flood Event Storyline Approach in Western Norway." *Weather and Climate Extremes* 29: 100259.

Schneider, C., C. L. R. Laizé, M. C. Acreman, and M. Flörke. 2013. "How Will Climate Change Modify River Flow Regimes in Europe?" *Hydrology and Earth System Sciences* 17: 325–339. https://doi.org/10.5194/hess-17-325-2013.

Sharma, T. C., and U. S. Panu. 2008. "Drought Analysis of Monthly Hydrological Sequences: A Case Study of Canadian Rivers." *Hydrological Sciences Journal* 53: 503–518.

Short, C., and L. Kendon. 2024. *Augmenting UKCP Local (2.2 km) Projections by Down-Scaling Global Models From CMIP5*. Met Office Hadley Centre.

Stein, L., M. P. Clark, W. J. M. Knoben, F. Pianosi, and R. A. Woods. 2021. "How Do Climate and Catchment Attributes Influence Flood Generating Processes? A Large-Sample Study for 671 Catchments Across the Contiguous USA." *Water Resources Research* 57: e2020WR028300.

Tanguy, M., H. Dixon, I. Prosdocimi, D. G. Morris, and V. D. J. Keller. 2021. "Gridded Estimates of Daily and Monthly Areal Rainfall for the United Kingdom (1890–2019) [CEH-GEAR]." NERC EDS Environmental Information Data Centre. https://doi.org/10.5285/dbf13dd5-90cd-457a-a986-f2f9dd97e93c.

Tudaji, M., Y. Nan, and F. Tian. 2025. "Assessing the Value of High-Resolution Data and Parameter Transferability Across Temporal Scales in Hydrological Modeling: A Case Study in Northern China." *Hydrology and Earth System Sciences* 29: 2633–2654. https://doi.org/10.5194/hess-29-2633-2025.

Willkofer, F., R. R. Wood, and R. Ludwig. 2024. "Assessing the Impact of Climate Change on High Return Levels of Peak Flows in Bavaria Applying the CRCM5 Large Ensemble." *Hydrology and Earth System Sciences* 28: 2969–2989.

Xu, D., V. Y. Ivanov, X. Li, and T. J. Troy. 2021. "Peak Runoff Timing Is Linked to Global Warming Trajectories." *Earth's Future* 9: e2021EF002083. https://doi.org/10.1029/2021EF002083.

Zhang, S., L. Zhou, L. Zhang, et al. 2022. "Reconciling Disagreement on Global River Flood Changes in a Warming Climate." *Nature Climate Change* 12: 1160–1167.

Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** hyp70523-sup-0001-Supinfo.pdf. **Figure S2:** hyp70523-sup-0001-Supinfo.pdf. **Figure S3:** hyp70523-sup-0001-Supinfo.pdf. **Figure S4:** hyp70523-sup-0001-Supinfo.pdf.