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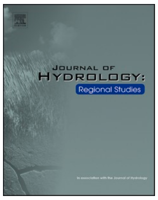

Using sub-daily precipitation for grid-based hydrological modelling across Great Britain: Assessing model performance and comparing flood impacts under climate change

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ABSTRACT

Study region: Great Britain.
Study focus: National-scale grid-based hydrological models are usually run at fine spatial and temporal resolutions, but driving data are often not available at the required resolutions. Here, a recent observation-based hourly 1 km gridded precipitation dataset is applied with a 1 km hydrological model to simulate daily mean river flows. Performance is compared to use of equally-disaggregated and profile-disaggregated daily data, for a large number of catchments. Hourly and daily precipitation from a high-resolution convection-permitting climate model (CPM) are then used to drive the hydrological model for baseline (1980–2000) and future (2060–2080) periods, to investigate differences in potential peak flow changes.
New hydrological insights: On average, use of observation-based hourly data provides a clear improvement over equally-disaggregated daily data for high flows and peak flow bias, a small improvement for average flows and mean flow bias, but little difference for low flows. Performance in faster-responding catchments typically improves more; performance in some catchments degrades. Use of profile-disaggregated daily data provides the small mean flow bias improvement and some peak flow bias improvement, but other factors degrade. On average, future changes in peak flows from hourly CPM precipitation are only slightly larger than from equally-disaggregated daily data. Future work will look at simulation of hourly mean flows.

1. Introduction

National- or regional-scale grid-based hydrological models are usually run at relatively fine spatial resolutions, to better represent the local detail of particular areas and river networks. Such models typically generate runoff for each grid square, then route the runoff along a network of flow paths to simulate river flows (e.g. Lohmann et al., 1998, Oki and Sud, 1998, Bell et al., 2007, Crooks et al., 2014, Thober et al., 2018). If routing is performed from grid cell to grid cell (rather than grid cell to outlet, e.g. Kleinn et al., 2005), then stability of the routing scheme for a finer spatial resolution would also generally require a finer temporal resolution (Sitterson et al., 2018; Crooks et al., 2014). This presents a problem in terms of the driving data required by hydrological models, as these are often not available at the required spatial and temporal resolutions so some form of spatial downscaling and/or temporal disaggregation is then required (e.g. Acharya et al., 2022, Kay et al., 2023b, Bierkens et al., 2015).

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For Great Britain (GB), the Grid-to-Grid (G2G) is a grid-based runoff and routing model that is typically run on a 1 km grid at a 15-minute time-step (Bell et al., 2009). When the model was initially developed (Bell et al., 2007), the best available national-scale gridded observation-based precipitation dataset provided 5 km daily data (Perry et al., 2009). After that, a 1 km daily observation-based precipitation dataset was produced for GB and Northern Ireland (NI), on grids aligned with the GB national grid and the Irish national grid, respectively; CEH Gridded Estimates of Areal Rainfall (CEH-GEAR; Keller et al., 2015). The initial version of CEH-GEAR covered 1890–2012, but it is updated regularly; the most recent version covers 1890–2019 (Tanguy et al., 2021). Versions of these data have been used to drive G2G for both GB and NI (e.g. Bell et al., 2018, Kay et al., 2023a). More recently, a version of CEH-GEAR with an hourly temporal resolution has been produced, covering GB (but not NI) for 1990–2016; CEH-GEAR1hr (Lewis et al., 2018, 2022). This provides the opportunity to compare use of daily versus hourly precipitation data for hydrological model performance across GB.

To investigate the potential impacts of climate change on river flows, data from Global or Regional Climate Models (GCMs/RCMs) are typically used to drive hydrological models (e.g. Zhai et al., 2020, Roudier et al., 2016). Recent computing advances have enabled the application of higher resolution 'convection-permitting' models (CPMs) for climate change projections (Kendon et al., 2021a), and data from such models is increasingly being used for hydrological projections. The finer resolution of CPMs (ranging from ~5 km down to a few hundred metres) means that they can simulate the atmosphere at a scale closer to that of convection so they do not require parameterisation schemes (Fosser et al., 2020), and they better represent landscape details such as orography, coastlines, and urban areas (Kendon et al., 2021a; rLucas-Picher et al., 2021). Poncet et al. (2023) show that data from a CPM is better than its driving RCM at simulating flood peaks for a 543 km^2 highly-responsive catchment in southern France, and that the RCM and CPM project differing future changes in floods. Ascott et al. (2023) apply CPM data with lumped catchment models for five catchments in tropical parts of Africa, and show that the CPM produces greater river flows than the equivalent RCM for both current and future periods, but that large-scale water storage in the catchments (e.g. wetlands) buffers the effect of changes in rainfall extremes.

A recent study used both RCM (12 km) and nested CPM (5 km) data, provided as part of UK Climate Projections 2018 (UKCP18; Murphy et al., 2018, Kendon et al., 2021b), to drive G2G across GB for 1981–2000 and 2061–2080 (Kay, 2022). Analysis of the simulated river flows showed that the CPM almost always gives higher future flow changes than the RCM, but only daily precipitation data were used from both the RCM and CPM. Sub-daily precipitation generated by CPMs is considered more realistic in terms of duration and extent than that from coarser resolution models (Kendon et al., 2012). Since hourly precipitation data are also provided for the UKCP18 CPM, this provides the opportunity to compare use of daily versus hourly CPM precipitation data for simulating potential future changes in river flows across GB.

Thus, the aims and scientific questions of this paper are to

1. Compare the use of observation-based daily versus hourly precipitation data for performance of grid-based hydrological modelling across Great Britain. What aspects of the performance of simulated flows are most affected, and what types of catchment benefit more/less from availability of sub-daily precipitation data?
2. Compare the use of CPM-based daily versus hourly precipitation data for simulating the potential impacts of climate change on peak flows. Could previous assessments based on use of daily precipitation data have underestimated future changes in flood hazard, at least in some places or for some types of catchment?

The observation-based performance assessment looks at a range of aspects of simulated flows, to obtain a fuller picture of the effects of using hourly vs daily driving precipitation data. The assessment of future impacts focuses on peak flows, due to the expected amplification of intense rainfall in warmer future climates (Chan et al., 2023; Kendon et al., 2014). However, it should be noted that changes in intense rainfall will not necessarily directly translate into changes in peak flows or floods, due to interactions with both antecedent conditions and catchment processes (Ledingham et al., 2019; Stein et al., 2021). Indeed, Basso et al. (2023) show that the ability of a catchment to generate extreme floods is well predicted by its intrinsic properties, like the spatial organization of the stream network.

Both assessments focus on simulated daily mean flows, for catchments across GB. Ficchi et al. (2016) showed that catchment-based hydrological modelling at a sub-daily time-step improved median performance of simulated daily flows during flood events across a large set of catchments in France. They state that "There is a need for further investigations to evaluate the usefulness of fine time-step information for hydrological model simulations, by comparing different model time-step outputs at common aggregated time scales, using a large set of catchments". Future work will look at use of sub-daily precipitation data for grid-based simulation of hourly mean flows across GB.

2. Methods

2.1. The observation-based precipitation datasets

The observation-based CEH-GEAR rainfall estimates for the UK were first developed to provide reliable 1 km grids of daily and monthly rainfall to support hydrological modelling, and are derived from rain gauge precipitation totals using natural neighbour interpolation (Keller et al., 2015). The CEH-GEAR1hr dataset was produced using a more limited network of sub-daily gauge data to temporally distribute the daily CEH-GEAR values through the day (Lewis et al., 2018) – thus the CEH-GEAR1hr grids have daily (9–9 am) totals consistent with the CEH-GEAR daily grids. While the CEH-GEAR daily data covers the period 1890–2019, the limited availability of historical sub-daily rain gauge data means that the CEH-GEAR1hr dataset starts in 1990, and it currently only extends to

2016.

There are some locations and days for which it was not possible to directly use sub-daily gauge data to inform the temporal distribution of precipitation in CEHGEAR1hr; i.e where the nearest operating sub-daily gauge was too far away (over 50 km) or the sub-daily gauge gives zero daily rainfall but the daily dataset gives a non-zero value. In these cases, a set of national average storm profiles was used for the daily to hourly disaggregation in CEH-GEAR1hr (Lewis et al., 2018). The average profiles were constructed from all the available sub-daily gauge data across the country, and vary only by season ('winter' Nov–Apr and 'summer' May–Oct) and by the daily rainfall value (determined by exceedance of five thresholds; 0 mm, 1 mm, 5 mm, 10 mm and 20 mm). So there are ten storm profiles in total (Supp. Fig. 1), determining the fraction of daily rainfall occurring in each hour of the water day (9–9 am). The number of grid cells for which profile-based disaggregation was required varies greatly through the dataset, but most of the time it is used for small daily rainfall amounts so is considered unlikely to have a large effect on extreme values or on hydrological simulations (Lewis et al., 2018). Additional grids within each CEH-GEAR1hr data file indicate whether/where the profile disaggregation is used for each day.

2.2. *The hydrological model and observation-based runs*

The Grid-to-Grid (G2G) is a grid-based hydrological model usually run on a 1 km grid (aligned with the GB national grid) at a 15-minute time-step for GB (Bell et al., 2009) or Northern Ireland (Kay et al., 2021a). The optional snow module is included here (Bell et al., 2016). G2G is generally configured using spatial datasets (e.g. soil types) rather than via calibration, and the limited model parameters required (e.g. wave speeds for lateral routing) use nationally applicable values (Bell et al., 2009). River flow simulations perform well for a wide range of catchments (Bell et al., 2009, 2016; Rudd et al., 2017; Formetta et al., 2018), particularly where the flow regime is considered relatively natural (i.e. not affected to a large extent by artificial influences like abstractions and discharges, Rameshwaran et al., 2022). The model requires gridded precipitation, potential evaporation (PE) and temperature data (the latter for the snow module).

Three observation-based G2G runs are compared, driven by different precipitation data:

- CEH-GEAR daily precipitation divided equally over each of the 24 * 4 15-minute model time-steps within a day (hereafter 'Gdly_wEqualDisag'), as the method typically used previously (e.g. Bell et al., 2018, Kay et al., 2023a);
- CEH-GEAR daily precipitation divided over each of the 24 h within a day using the CEH-GEAR1hr average storm profiles (Supp. Fig. 1) for every day and 1 km grid cell, then further divided equally over each of the four 15-minute time-steps within an hour (hereafter 'Gdly_wProfileDisag');
- CEH-GEAR1hr precipitation divided equally over each of the four 15-minute model time-steps within an hour (hereafter 'Ghly').

All three observation-based runs use 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), and daily 1 km grids of min and max temperature from HadUK-Grid (Met Office et al., 2019), interpolated through the day using a sine curve (Kay and Crooks, 2014). Simulations are run for Jan 1990–Dec 2016 (the period currently covered by CEH-GEAR1hr data), with each initialised using the same states file, saved from the end of a prior simulation using daily precipitation to end-Dec 1989. Outputs were only analysed for Oct 1990–Sep 2016, i.e. whole water years (so treating Jan–Sep 1990 as a spin-up).

The simulation using daily data with profile-disaggregation is performed to assess the potential benefits of a simple but non-uniform disaggregation of precipitation from daily to sub-daily, which could be applied for a longer period of time or with other daily precipitation datasets. Alternative disaggregation procedures exist but are more complex and time-consuming to apply (e.g. stochastic disaggregation), or could only be applied for historical periods where other required datasets exist (e.g. reanalysis or radar-based disaggregation; Acharya et al., 2022, Parkes et al., 2013).

2.3. *Comparing performance of observation-based driving data*

The G2G produces time-series of daily mean river flows (m^3/s) for selected 1 km pixels corresponding to gauged catchments in the National River Flow Archive (NRFA; ceh.ac.uk/data/nrfa/). The performance of the use of CEH-GEAR daily versus hourly precipitation data is assessed using several measures comparing simulated daily mean flows (Oct 1990–Sep 2016) to observed daily mean flows from the NRFA, for a large set of catchments across GB.

The performance measures include the Nash-Sutcliffe efficiency calculated directly on the flows (NS, Eq. 1), as well as on the square-root of flows (NSsqrt), and on the natural logarithm of flows (NSlog). NS focuses more on high flows, while NSsqrt focuses on average flows and NSlog focuses on low flows (e.g. Rudd et al., 2017). Two additional measures look at bias, one for mean flow (Bias, Eq. 2), and one for flood frequency (ffr, Eq. 3). The latter is calculated as the average percentage bias in 2-, 5- and 10-year return period peak flows derived from fitted flood frequency curves (as Kay et al., 2015), where the flood frequency curve is derived by fitting a generalised logistic (GLO) distribution to sets of water-year (1st Oct–30th Sep) annual maxima (AM) of daily mean flows using the method of L-moments (Robson and Reed, 1999). The three parameters of the fitted GLO (location ξ, scale α, shape k) are used to calculate flows Q_T corresponding to the required return periods T using $Q_T=\xi+(\alpha/k)(1-(T-1)^{-k})$. For the Nash-Sutcliffe measures, a value of 1 indicates perfect performance and a value less than zero indicates performance worse than mean flow. For the Bias and ffr measures, a value of zero indicates perfect performance, positive values indicate over-estimates and negative values indicate under-estimates. All the measures are calculated after setting simulated flows to missing where observed flows are missing, to provide a fairer comparison.

$$\mathrm{NS} = 1 - \frac{\sum (Q_{obs} - Q_{sim})^2}{\sum (Q_{obs} - \overline{Q_{obs}})^2} \tag{1}$$

$$\mathrm{Bias} = 100\left(\frac{\overline{Q_{sim}}}{\overline{Q_{obs}}} - 1\right) \tag{2}$$

$$\mathrm{ffr} = \frac{100}{3}\sum\nolimits_{T\in\{2,5,10\}} \frac{Q_{T,sim} - Q_{T,obs}}{Q_{T,Obs}} \tag{3}$$

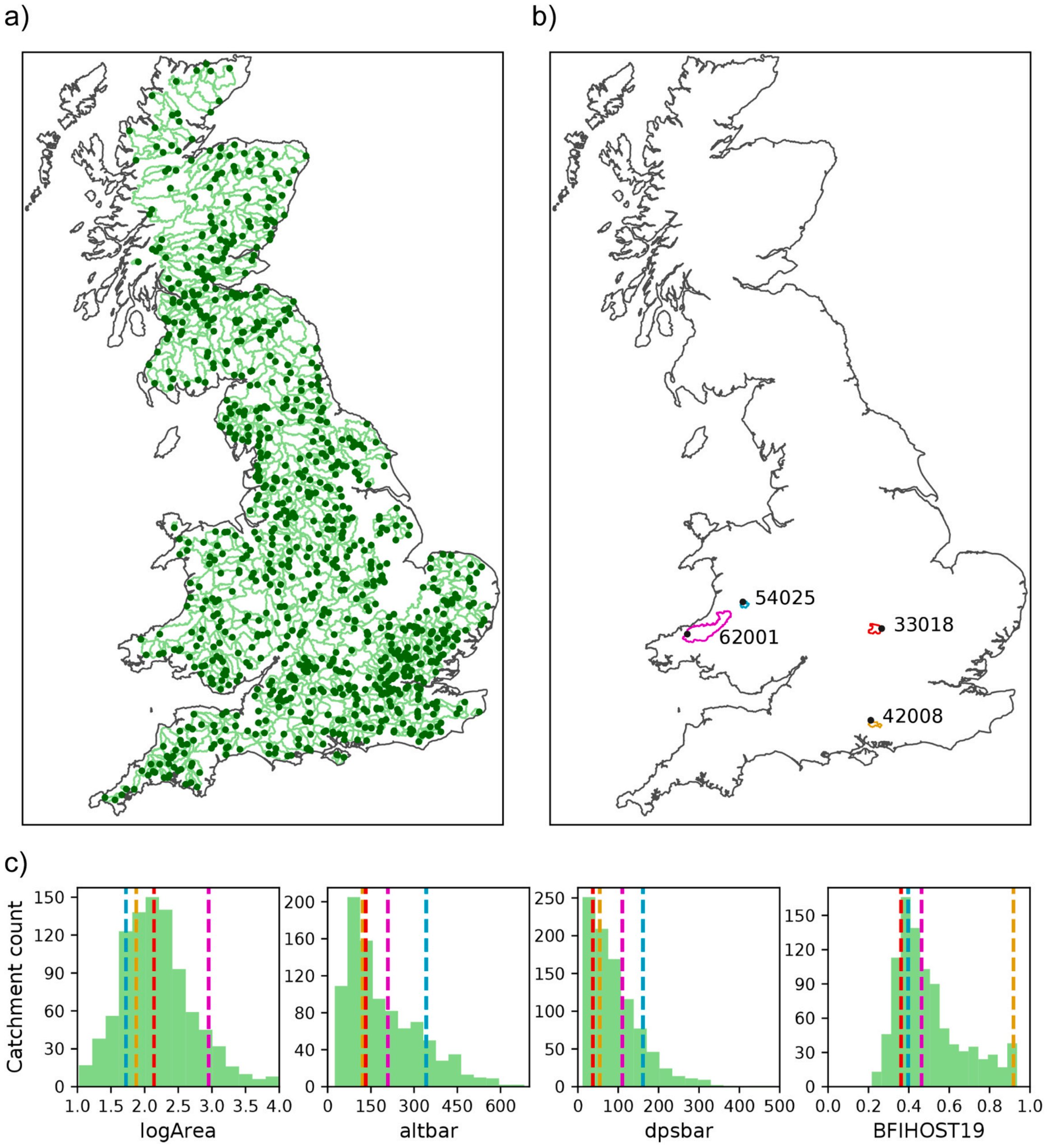

Fig. 1. a) The 931 catchments used to assess performance, b) the four case study catchments, c) distributions of selected catchment properties across the set of 931 catchments. Also on the latter are vertical dashed lines showing the property values for the four case study catchments (from Table 1), colour-coded as in b.

A total of 931 catchments are included in the assessment (Fig. 1a), all with less than 10% missing gauged data in the required period. Of these catchments, 156 have an area of at least 10 km^2 but less than 50 km^2; the other 775 catchments are larger. Previously, when modelling using equally-disaggregated daily precipitation data, only larger catchments have usually been considered (e.g. Kay et al., 2023a), but smaller catchments are included here to assess how well the model can simulate such catchments when hourly driving precipitation data are available. Results for the two sets of catchments are thus shown separately.

As well as differentiating performance by catchment area, the effect of a number of other catchment properties is assessed, including mean catchment altitude (‘altbar’), mean drainage path slope (‘dpsbar’) and a measure of the baseflow index derived from soil classes (‘BFIHOST19′) (see nrfa.ceh.ac.uk/feh-catchment-descriptors). The distributions of these properties across the set of 931 catchments are shown in Fig. 1c.

G2G also outputs gridded time-series data, including monthly mean river flows (m^3/s) and monthly total actual evaporation (m). These grids are used to investigate the reasons behind differences in performance.

2.4. *Climate change projections and their application*

The UK Climate Projections 2018 (UKPC18) provides a range of products enabling investigation of the potential impacts of climate change across the UK (Lowe et al., 2018). This includes UKCP18 Local (Kendon et al., 2021b), which comprise a 12-member ensemble of a CPM (~2.2 km), nested in a 12-member RCM (~12 km) perturbed parameter ensemble (PPE), in turn nested in a 12-member GCM (~60 km) PPE. The UKCP18 Local projections cover three 20-year periods (Dec 1980–Nov 2000, Dec 2020–Nov 2040 and Dec 2060–Nov 2080) under RCP8.5 emissions. The CPM data are available on their 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 CPM data for ensemble member ‘01′ are used here. This ensemble member represents the standard RCM/GCM parameterization (note that the CPM parameters are not themselves adjusted between ensemble members).

Two pairs of CPM-based G2G runs are compared for the baseline (Dec 1980–Nov 2000) and far-future (Dec 2060–Nov 2080) periods. The first pair uses daily CPM precipitation divided equally over each of the 24 * 4 15-minute model time-steps within a day (hereafter ‘SIMCPMdly’), while the second pair uses hourly CPM precipitation divided equally over each of the four 15-minute model time-steps within an hour (hereafter ‘SIMCPMhly’). Although the biases in CPM precipitation are generally smaller than those in the corresponding RCM (Kendon et al., 2021b Sections 3.2–3.4), in winter it is still too wet across (almost) the whole country and in summer it is too wet in the north and too dry in the south (Kendon et al., 2021b Figures 3.2.3–3.2.4). Thus a simple bias-correction is first applied to the 5 km CPM precipitation data to correct these coarse quantitative differences, using monthly factors derived by comparing baseline data against CEH-GEAR (Kay, 2022). The CPM precipitation are then downscaled to 1 km using observed standard average annual rainfall patterns (Bell et al., 2007; Kay et al., 2023b). Kay (2022) shows that this simple bias-correction of (daily) CPM precipitation generally improves the subsequent simulation of median, low and high flows for a large set of catchments across GB, compared to use of raw CPM precipitation data.

Each run also requires temperature and PE driving data. The 5 km CPM daily min and max temperature data are downscaled to 1 km using a lapse rate with elevation data (Bell et al., 2016), and temporally downscaled as for observed temperature (Section 2.2). Daily 5 km PE for short grass is estimated from other climate variables using the method of Robinson et al. (2023). It is then copied down to the 1 km grid and divided equally over each model time-step within a day.

The baseline (Dec 1980–Nov 2000) CPM-based G2G simulations are initialised using a states file saved from the end of a prior observation-based simulation for Jan 1970-Nov 1980, and the far-future (Dec 2060–Nov 2080) simulations are initialised using a states file saved from the end of a prior simulation (Dec 2055–Nov 2060) using data from the equivalent RCM (as in Kay, 2022).

Table 1

The four case study catchments, with values of selected properties, plus the minimum, median and maximum of the properties across the full set of 931 catchments.

		Area (km^2)	altbar (m)	dpsbar (m/km)	BFIHOST19
Case study catchments:					
Catchment number	River@Location				
54025	Dulas@ Rhos-y-pentref	52.7	342	161.3	0.396
62001	Teifi@ Glanteifi	893.6	209	109.8	0.463
42008	Cheriton Stream@ Sewards Bridge	75.1	121	54.2	0.918
33018	Tove@ Cappenham Bridge	138.1	132	37.1	0.362
931 catchments:					
	Minimum	10.6	25	11.4	0.216
	Median	138.1	153	76.0	0.451
	Maximum	9948.0	682	487.9	0.936

2.5. *Assessing impacts on peak flows under climate change*

To enable analysis of potential future changes in peak flows, the SIMCPMdly and SIMCPMhly simulations (Section 2.4) produce 1 km grids of the AM of daily mean flows for the baseline and far-future periods. Data are output for each water year, for each 1 km pixel with a catchment area of at least 10 km^2 (hereafter 'river pixels'). Flood frequency curves are fitted to the sets of AM (19 for each period and each river pixel), and 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 river pixel for SIMCPMdly and SIMCPMhly. Differences in these impacts are explored, for different size catchments across GB. Variation by location is investigated by using a simple West/East split of grid boxes, and a simple North/South split of grid boxes.

2.6. *Case studies*

To help illustrate both the performance of observation-based driving data, and differing peak flow impacts under climate change, plots of flow duration curves, flood frequency curves and sample flow hydrographs are presented for a set of case study catchments. Four catchments are selected to show a range of behaviours. These are listed in Table 1, with values for selected properties (see Section 2.3 and Fig. 1c). The catchment locations are shown in Fig. 1b.

3. Results

3.1. *Comparing performance of observation-based driving data*

Boxplots of the performance measure ranges across the set of 931 catchments (Fig. 2) show that use of hourly CEH-GEAR data

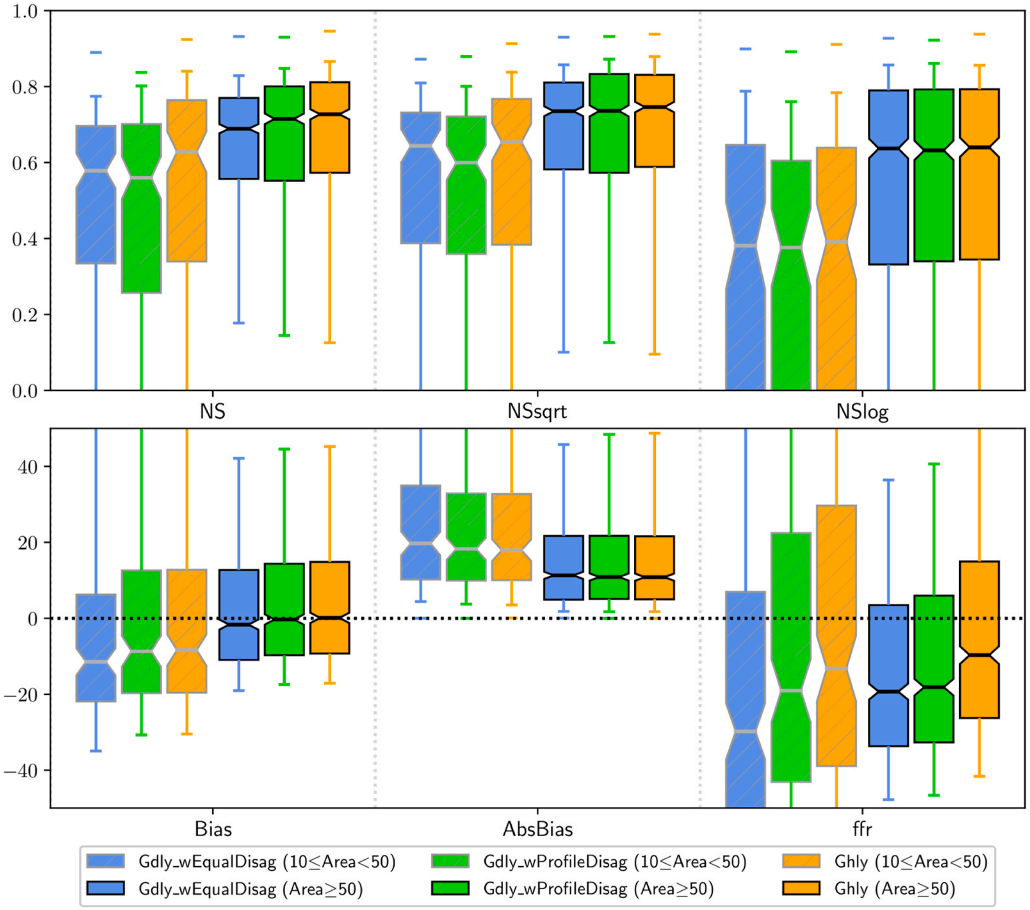

Fig. 2. Summary of model performance for the three runs using CEH-GEAR precipitation ('Gdly_wEqualDisag', 'Gdly_wProfileDisag', 'Ghly'), split by catchment area (grey outline 10–50 km^2 and black-outline ≥50 km^2). The boxes show the 25th–75th percentile range across the set of catchments, with the median 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).

provides a clear improvement over use of equally-disaggregated daily CEH-GEAR data, in terms of median performance across the sets of catchments for high flows (NS) and bias in peak flows (ffr). There is also a small improvement for average flows (NSsqrt) and bias in mean flows (Bias), but little difference for low flows (NSlog). While model performance for smaller catchments (<50 km^2) is generally lower than for larger catchments, the improvements from use of hourly data tend to be greater on average for the smaller catchments.

Maps of the differences in each NS-based measure show that performance in catchments to the north/west typically improves more, although not universally; some catchments in the north/west show degraded performance and some catchments in the south/east show improvements (Fig. 3a). Maps of the differences in the absolute value of each bias measure show no clear spatial patterns in improved/degraded performance, although the absolute bias seems to change little in the north/west (Supp. Fig. 2a).

While there are no strong relationships between performance differences and catchment properties (not shown), boxplots summarising the properties of catchments with improved/degraded performance from use of hourly data (compared to use of equally-disaggregated daily data) show that this has a greater tendency to improve performance for smaller catchments (lower ‘logArea’), higher altitude catchments (higher ‘altbar’), steeper catchments (higher ‘dpsbar’), and catchments with a lower proportion of flow

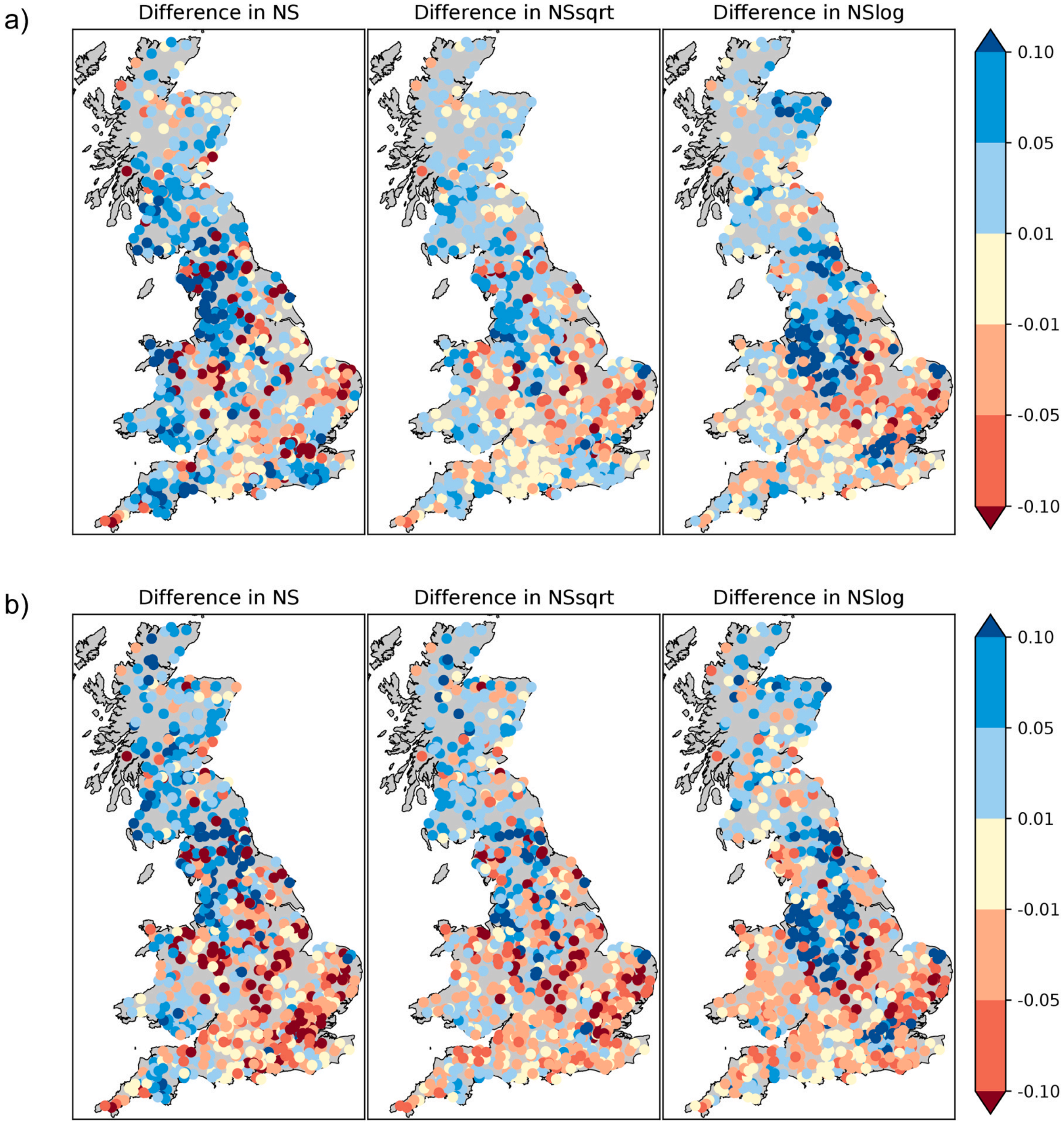

Fig. 3. Maps of the differences in NS-based measures of model performance between pairs of observation-based runs; a) ‘Gdhly’ - ‘Gdly_wEqualDisag’ and b) ‘Gdly_wProfileDisag’ - ‘Gdly_wEqualDisag’. A positive value indicates improved performance (higher NS-based values), while a negative value indicates degraded performance (lower NS-based values).

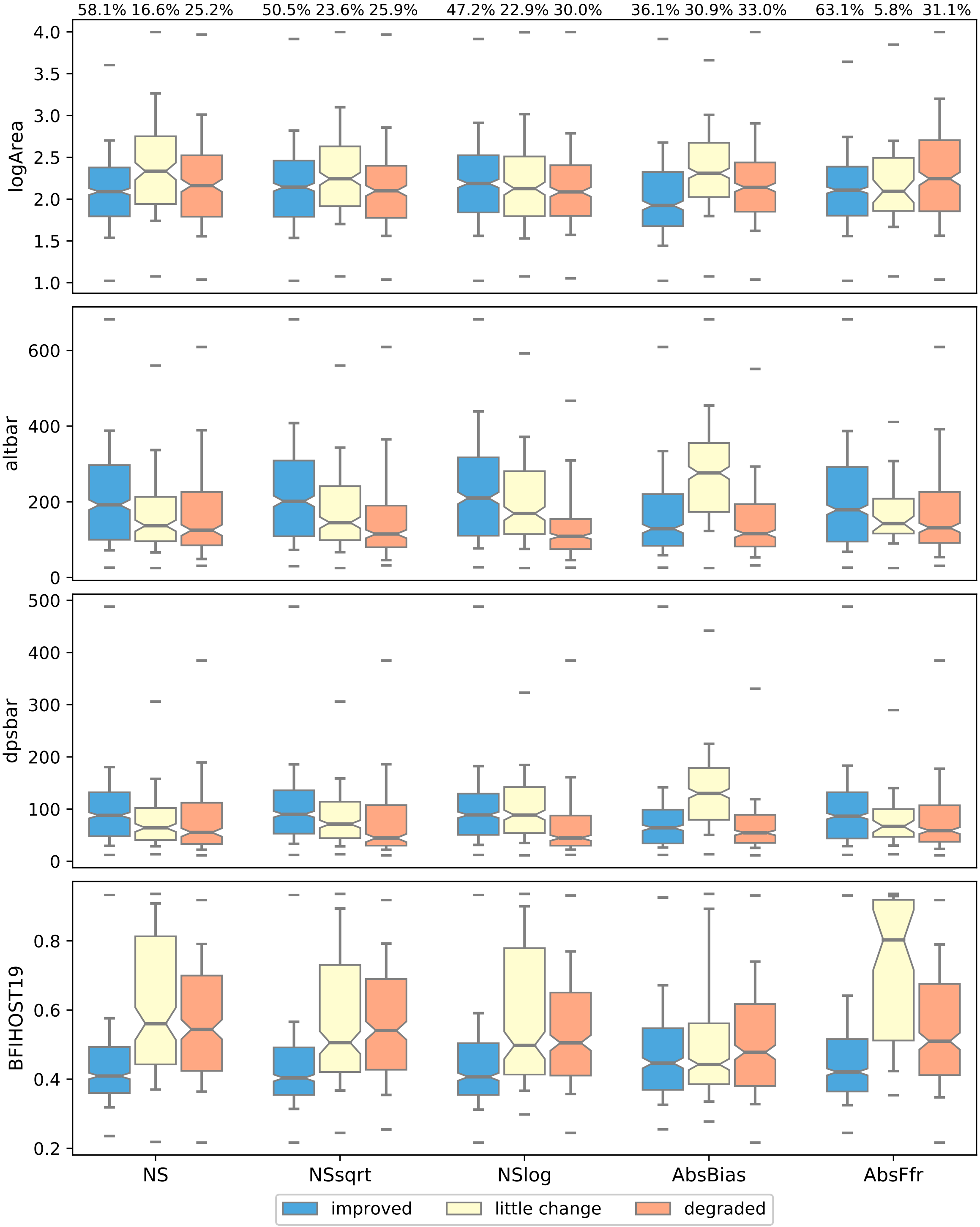

Fig. 4. Boxplots summarising the properties of catchments for which performance improves, degrades, or is similar when using hourly data ('Ghly') compared to use of equally-disaggregated daily data ('Gdly_wEqualDisag'). Results are shown for each performance measure (left to right, using the absolute 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 threshold for the 'little change' category is set to ± 0.01 for the NS-based measures, ± 1% for the bias measures. The numbers at the top show the percentage of the 931 catchments in each category.

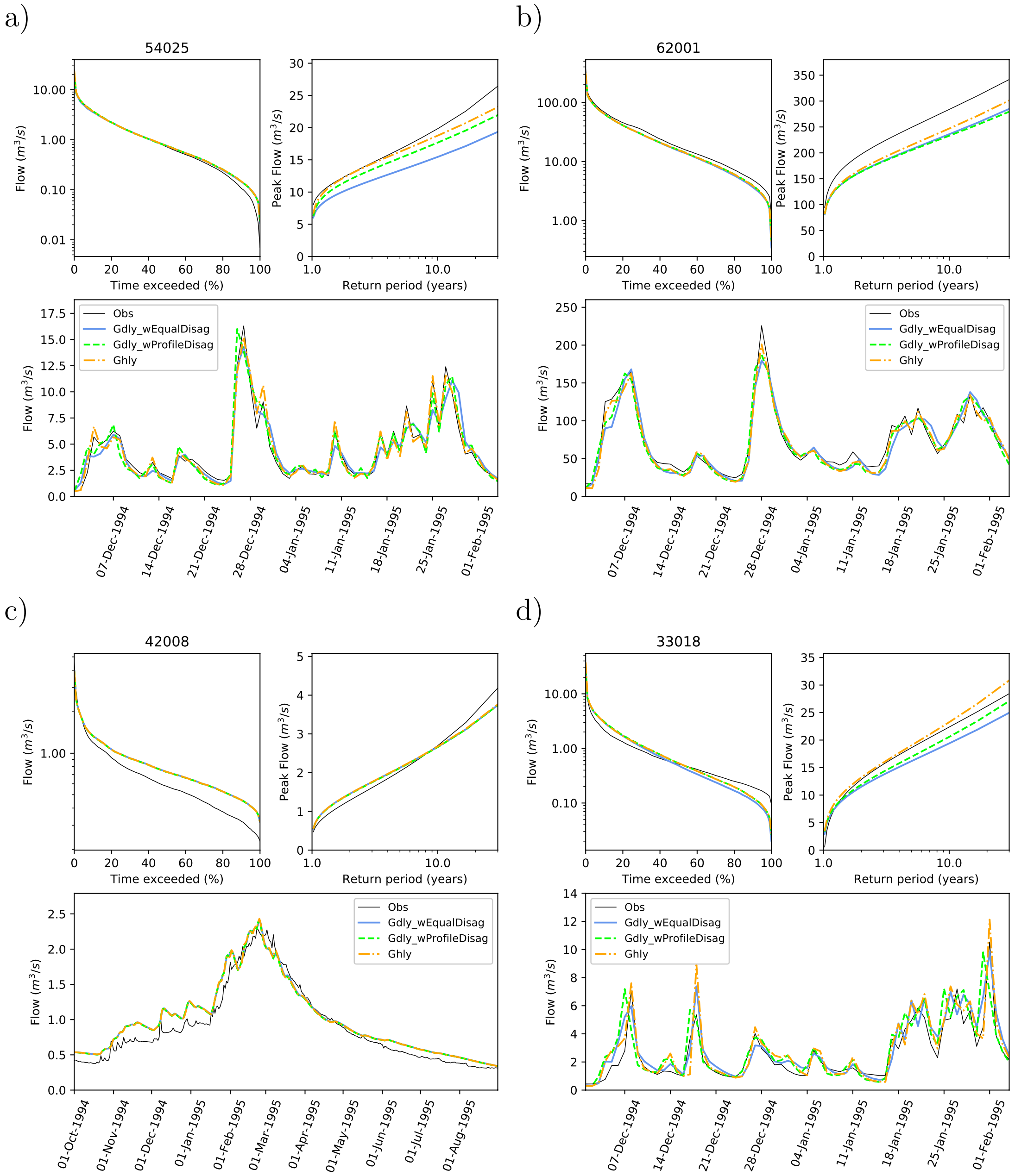

Fig. 5. Flow duration curves, flood frequency curves and a short flow hydrograph for the four case study catchments (Table 1), from flows simulated using equally-disaggregated daily data ('Gdly_wEqualDisag'; blue solid lines), profile-disaggregated daily data ('Gdly_wProfDisag'; green dashed lines), and hourly data ('Ghly'; orange dot-dashed lines), compared to gauged flows (black solid lines).

from groundwater sources (lower 'BFIHOST19′) (Fig. 4). This fits with the maps of performance differences (Fig. 3a), as such catchments are more likely to be located in the hillier north/west of GB. It should be noted that there are some correlations between these catchment properties; steeper catchments tend to have higher altitudes, and catchments with a higher BFIHOST19 generally have lower altitudes and shallower slopes (Supp. Fig. 3).

The use of daily CEH-GEAR data with profile disaggregation also provides the small improvement in mean flow bias and some improvement for peak flow bias (at least for smaller catchments), but makes the median performance worse for high and average flows in smaller catchments (Fig. 2). Maps of the differences in each NS-based measure (Fig. 3b) and in the absolute value of each bias measures (Supp. Fig. 2b) suggest that the use of nationally-derived average profiles generally works less well for catchments in the south/east than for those in north/west.

Various features are illustrated by plots for the four case study catchments (Table 1). For reference, the values of the five performance measures in each of the three model runs for the four case study catchment are given in Supp. Table 1. Catchment 54025 has a high improvement in flood frequency fit and the hydrograph shows better simulation of peak flows from use of hourly rather than daily precipitation (Fig. 5a). This catchment is quite small, high altitude, steep and with a low baseflow index – all factors that make it fast-responding, hence the use of hourly rather than daily precipitation makes a clear difference. In contrast, catchment 62001 is much larger, with lower altitude, shallower slopes and higher baseflow index, so use of hourly precipitation data makes less difference (Fig. 5b). Catchment 42008, although quite small, has shallow slopes and a very high baseflow index and the hydrograph shows it is very slow-responding, thus use of hourly precipitation data makes essentially no difference to the simulated flows (Fig. 5c). Catchment 33018 is relatively similar to 42008 in terms of area, altitude and slope but with much lower baseflow index, and use of hourly data makes some difference to the simulated flows, particularly peaks (Fig. 5d).

3.2. Assessing impacts on peak flows under climate change

Violin plots and scatter plots compare the percentage changes in the 2- and 10-year return period peak flows from SIMCPMdly and SIMCPMhly, for 1 km river pixels across GB (Fig. 6). The violin plots show that, on average, the peak flow changes from SIMCPMhly are only slightly higher than those from SIMCPMdly (GB median 9.1% vs 6.0% for 2-year return period and 8.4% vs 5.1% for 10-year return period). The scatter plots show that, although more river pixels give higher peak flow changes from SIMCPMhly than SIMCPMdly, some river pixels give lower peak flow changes from SIMCPMhly than SIMCPMdly, with more scatter at the 10-year return period. While differences between peak flow changes from SIMCPMhly and SIMCPMdly are relatively small for the majority of river pixels, there are river pixels with large differences.

Boxplots summarising the differences in 10-year return period peak flow impacts from SIMCPMhly and SIMCPMdly for river pixels split by catchment drainage area show relatively limited differences for larger catchments (median ~1%) but greater differences for catchments smaller than 50 km^2 (median ~4%), and some river pixels (of any size) show large differences (Fig. 7 top). Differences in 2-

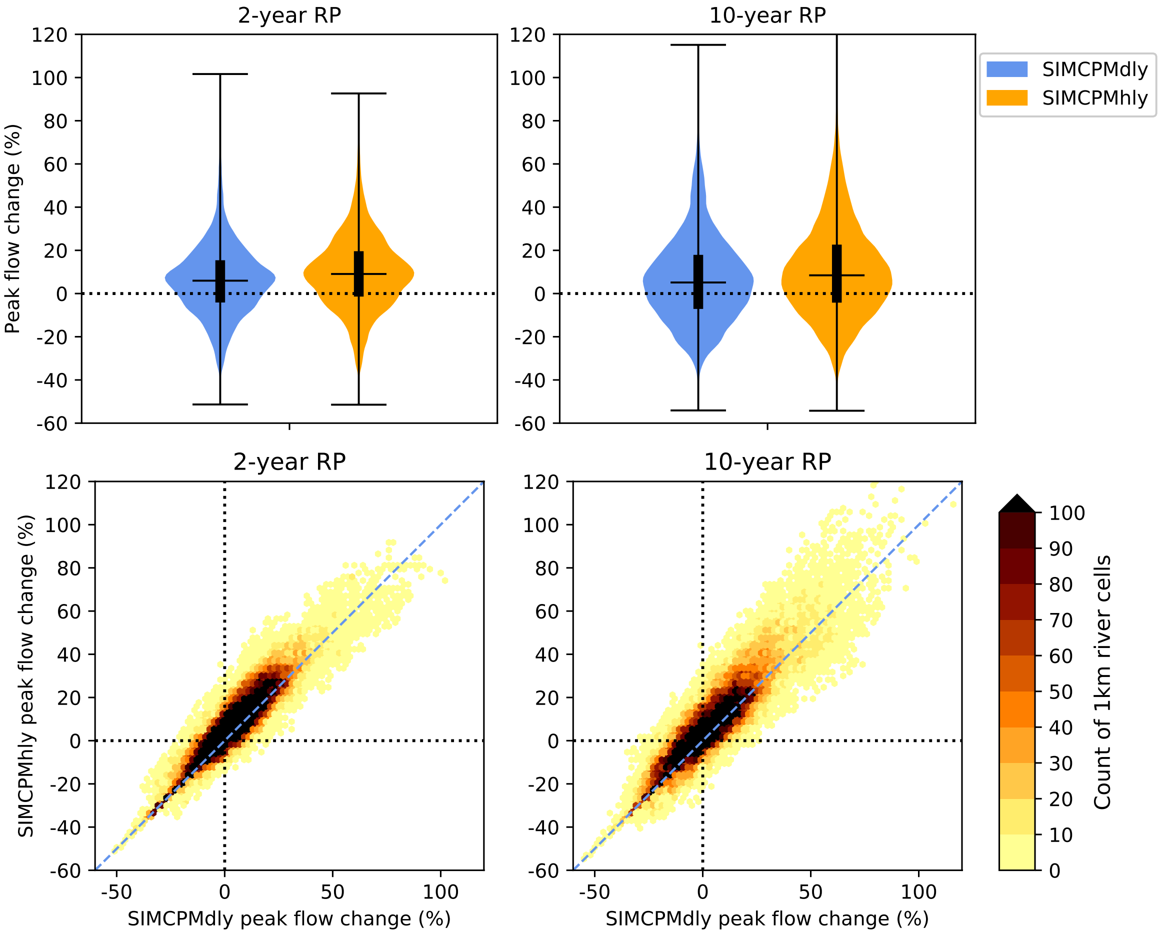

Fig. 6. Violin plots (top) and heatmaps of scatter plots (bottom) comparing percentage changes in the 2- and 10-year return period (RP) peak flow from SIMCPMdly and SIMCPMhly, for 1 km river pixels across GB. For the violin plots, the horizontal lines show the min, median and max changes, and the black box shows the 25th–75th percentile range.

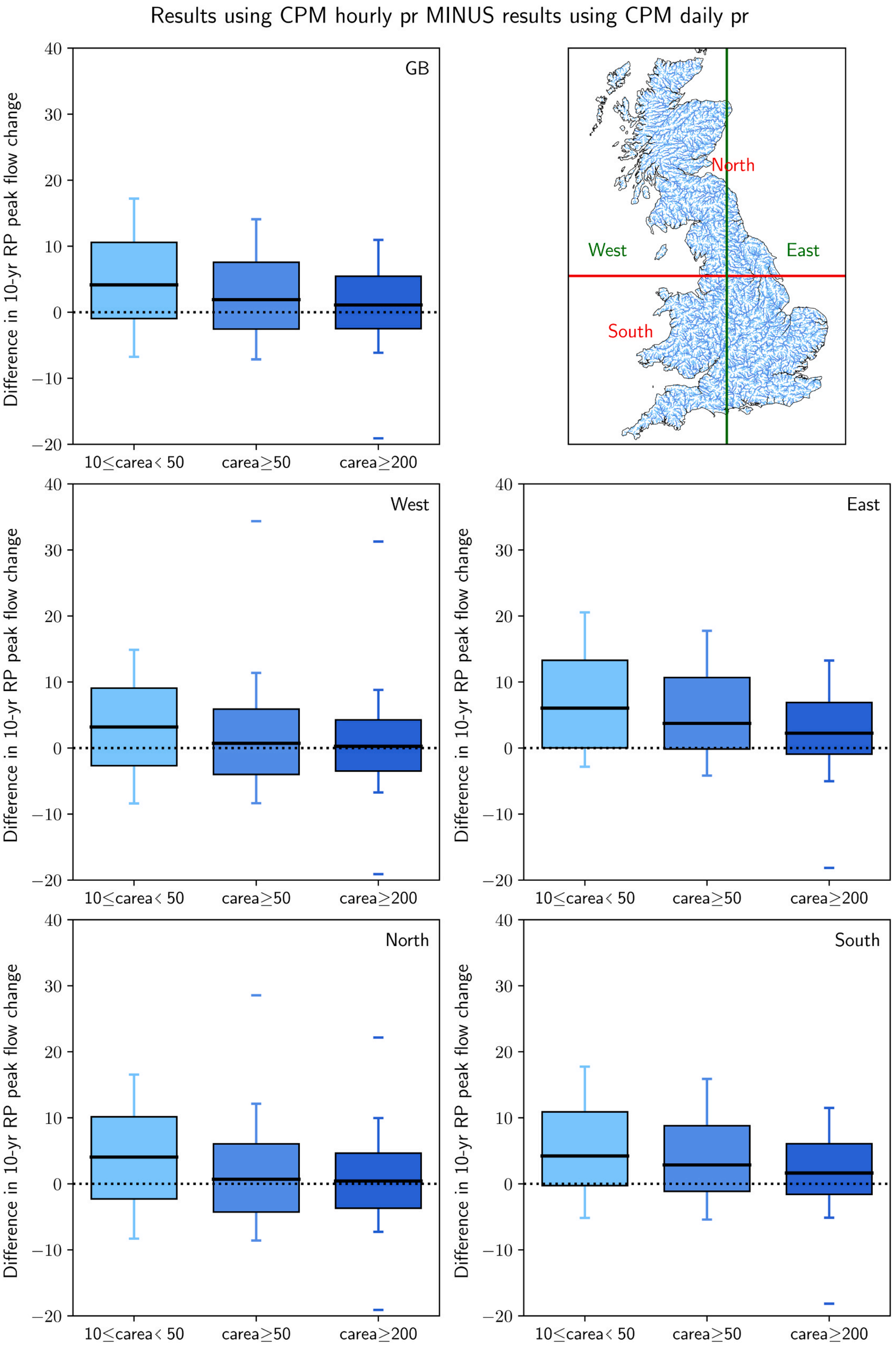

Fig. 7. Boxplots summarising the difference in the percentage change in 10-year return period peak flows from use of CPM hourly precipitation compared to use of CPM daily precipitation (SIMCPMhly minus SIMCPMdly). The results are split by river pixels with a small drainage area

(‘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 middle pair shows results over the West/East, and the bottom pair shows results over the North/South. The West/East and North/South divisions are 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.

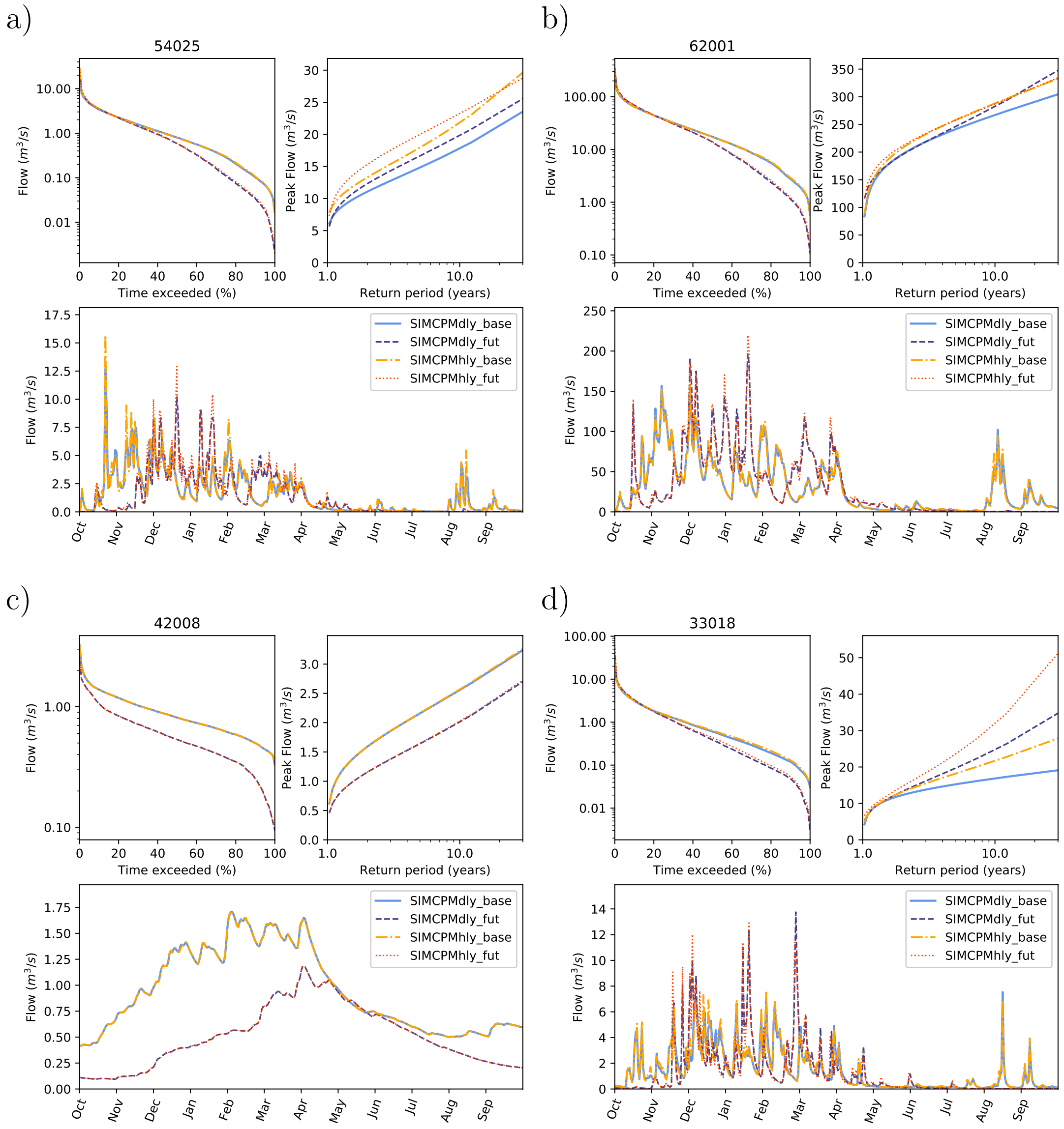

Fig. 8. Flow duration curves, flood frequency curves and a 1-year flow hydrograph for the four case study catchments (Table 1), from flows simulated using daily and hourly CPM data (SIMCPMdly and SIMCPMhly) for baseline and far-future periods.

year return period peak flow impacts show a similar pattern with catchment size, but are generally smaller (Supp. Fig. 4). Catchments in the East (South) tend to show greater differences in 10-year return period peak flow impacts than those in the West (North) (Fig. 7 middle and bottom), although this pattern seems less pronounced for the 2-year return period peak flow impacts (Supp. Fig. 4).

Again, various features are illustrated by plots for the four case study catchments (Table 1). All four catchments show large decreases in the flow duration curve for the future period (Fig. 8), at least for flows below the median (time exceeded > 50%), confirming previous analyses showing decreases in low flows from simulations using UKCP18 RCM data (Lane and Kay 2021). Catchment 54025 (small, high altitude, steep, with a low baseflow index) shows quite a large increase in peak flows from use of daily CPM data and use of hourly CPM data up to the 10-year return period, but using hourly CPM data shows a change in the shape of the curve, suggesting future decreases for higher return period peak flows (Fig. 8a). In contrast, catchment 62001 shows an increase in higher return peak flows from use of daily CPM data, but very little change from use of hourly CPM data (Fig. 8b). Catchment 42008 shows a decrease in peak flows for all return periods, which is the same from daily and hourly CPM data (Fig. 8c). Catchment 33018 shows a large increase in peak flows from both daily and hourly CPM data, which is greater for higher return periods, and the difference in magnitude from use of daily and hourly data is larger for the future than the baseline (Fig. 8d).

4. Discussion

4.1. Comparing performance of observation-based driving data

Driving a grid-based hydrological model for GB with observation-based hourly precipitation data is, on average, better than using daily precipitation data equally disaggregated through the day. However, improvement is not universal; it applies more to catchments in the north/west, and more to high flows (including peak flows) than low flows. The lesser effect for low flows is perhaps not surprising, as these are generally related to prolonged periods of rainfall deficits (or potentially to snow accumulation), so use of sub-daily precipitation data should have less effect on their simulation. Acharya et al. (2022) also showed that hydrological model performance for peak flows and floods was improved by use of sub-daily rainfall (disaggregated from daily using reanalysis data) rather than uniformly disaggregated daily rainfall, for 27 catchments in Queensland, Australia.

The improvement in mean flow bias using hourly data (or daily data with profile-disaggregation) may be surprising, given that the CEH-GEAR hourly data has daily totals equal to those of the daily data. This is explained by modelled actual evaporation (AE) being slightly higher (by up to ~2% in the GB-mean in late spring/summer) when the daily precipitation are equally disaggregated through the day, leading to slightly lower flows than in either of the runs where rainfall is spread unevenly through the day (Fig. 9).

What is perhaps less clear is why the use of sub-daily precipitation data leads to degraded performance in some catchments (Fig. 3a). As discussed by Lewis et al. (2018), the reliability of CEH-GEAR1hr depends on the daily totals from CEH-GEAR and on the quantity and quality of the sub-daily gauge data used to inform the hourly disaggregation. Although a substantial amount of quality-checking was performed, some errors will remain (e.g. related to gauge under-catch), and the (spatially and temporally) variable density of the sub-daily gauge network (Lewis et al., 2018 Fig. 11) means that some locations have inherently lower reliability, especially earlier in the period. Orographically-enhanced and convective rainfall events will be especially difficult to record in areas with a lower density of sub-daily rain gauges. Use of hourly data in periods or areas of lower reliability could lead to reduced flow performance over use of equally-disaggregated daily data, as it may amplify timing errors in simulated flows. Ficchi et al. (2016) also found that use of sub-daily precipitation could make hydrological model performance worse for flood events in some catchments, and explain this with reference to the expected limits of the added value of short time-step data, including greater uncertainty. They found that any improvement or degradation in performance with sub-daily precipitation data was not strongly related to any catchment morphological or hydro-climatic descriptors, including altitude, slope or baseflow index (as here), but performance in catchments with shorter response times benefited more and that in catchments with slower responses tended to be insensitive or degrade (Ficchì et al., 2016). This is likely due to the interaction of various catchment properties.

Possible issues with simulated flow timing likely explain why the use of daily CEH-GEAR data with profile disaggregation makes time-series performance worse in many catchments (Fig. 3b), as the set of nationally-derived average profiles are applied from 9 am on each day (with no rainfall to the end of each water day; Supp Fig. 1) and are unlikely to well-represent storm occurrence in all locations at all times. Issues with peak flow timing are suggested by some of the hydrographs for the case study catchments, particularly catchment 33018 where the peaks are early (Fig. 5d). Deriving and applying sets of average profiles regionally, and applying them from different times in the day, could potentially improve the performance in more locations. Disaggregating using information from reanalysis datasets is another possible approach for historical data (Acharya et al., 2022).

Another factor that could potentially affect performance of simulated flows is the interaction between precipitation and temperature data, for the generation of snowfall rather than rainfall. The snow module uses daily min and max temperature data, interpolated through the day using a sine curve, and precipitation is deemed to fall as snow if the temperature at the time-step is below a threshold (Bell et al., 2016). Thus the use of hourly (or profile-disaggregated daily) precipitation data, rather than equally-disaggregated daily data, could lead to differences in snow occurrence. This would only affect a relatively limited number of locations/events as river flows in GB are generally dominated by rainfall rather than snowmelt, but some upland catchments do have a significant contribution from snowmelt historically (Kay, 2016).

There are likely to be a number of reasons for the generally lower model performance for smaller catchments (<50 km^2), but particularly the fact that there is more opportunity for small errors in the driving data (e.g. in storm characteristics such as location, extent and spatial heterogeneity, or in PE) to be compensated for when water is accumulated across a larger area. Similarly, flow simulation in smaller catchments can be affected more by errors in catchment delineation related to the 1 km discretisation of the flow network (Davies and Bell, 2009). There can also be greater difficulties in gauging flows in smaller rivers; gauging of river levels is more accurate where a reasonable depth of water is present all year round (Marshall and Bayliss, 1994). Although model performance for smaller catchments is generally lower than for larger catchments, it is still reasonable for most catchments (other than for low flows), and the use of hourly precipitation data gives a substantial improvement in performance for high flows and peak flows particularly (Fig. 2). This suggests that it is reasonable to use the model to look at potential future changes in daily mean peak flows for smaller catchments as well as larger ones.

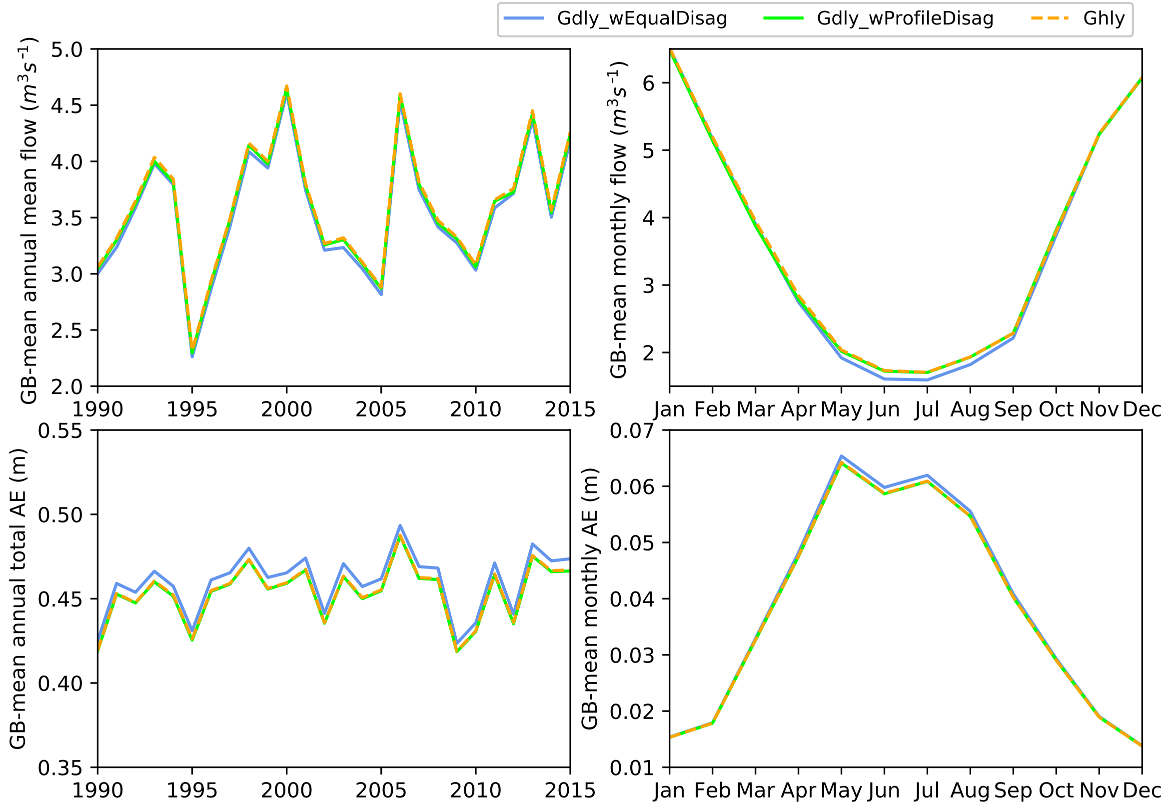

Fig. 9. Plots of GB-mean annual mean flow (top) and annual total AE (bottom), as time-series (left) and monthly climatology over the 26 years (right), for the three runs using CEH-GEAR precipitation (‘Gdly_wEqualDisag’, ‘Gdaly_wProfileDisag’, ‘Ghly’).

4.2. Assessing impacts on peak flows under climate change

For larger catchments (≥50 km^2), the simulated future changes in peak flows from use of hourly CPM precipitation data are, on average, only slightly larger than from use of daily CPM data equally disaggregated through the day. Differences are slightly larger still for smaller catchments (<50 km^2), but still not substantial. This is consistent with the analysis of Beylich et al. (2021), who showed that modelling at an hourly time-step (with stochastic disaggregation of daily data) gave future flood changes of similar magnitude to modelling at a daily time-step, despite underestimation of absolute values of flood peaks by daily modelling, for six catchments in central Germany (areas 39.1–823.5 km^2).

The greater differences in peak flows in smaller catchments are consistent with analyses showing higher future changes in hourly than daily extreme rainfall in the UKCP18 CPM (Chan et al., 2023), as flows in smaller catchments are typically more responsive to extreme precipitation over shorter time-scales than flows in larger catchments (Stein et al., 2021). This suggests that, at least for some locations, use of hourly precipitation data could be important for the development of appropriate adaptation strategies for changes in flood hazard under climate change. The separation of analyses by flood-generating mechanism (Berghuijs et al., 2019) could also be informative for some areas; Zhang et al. (2022) suggest that, globally, it is important to distinguish between mechanisms when assessing flood changes under climate change.

The analysis was limited to 2- and 10-year return period peak flows; rarer peaks were not studied since the 5 km CPM data are only currently available for three 20-year time-slices. Analysis for a range of return periods is useful, as impacts can vary by return period (e.g. Poncet et al., 2023, Brunner et al., 2021); as shown for some of the case study catchments (Fig. 8). It may be possible to investigate higher return period peak flow changes in future, once longer periods of CPM data are made available. Use of the full CPM ensemble may also provide further insights, as it can allow the better identification of climate change impacts from natural variability (Kendon et al., 2023). The existence of flood-rich and flood-poor periods, due to decadal-scale climate variability, can confound trend analyses of observed records (Hannaford et al., 2021), and can also affect future flood change assessments (Kay and Jones, 2012).

Although not tested here, where hourly climate model data are not available it may be possible to apply some form of profile-based disaggregation, or indeed a more complex disaggregation procedure. Application should first be tested with observation-based daily precipitation data for the location. A decision would then have to be made about whether the specifics of the disaggregation (e.g. the profiles, or the stochastic model parameters) derived for a historical period were also applied for future periods, or whether they should be adjusted in some way for application in future periods.

5. Conclusions

The availability of an hourly 1 km gridded observation-based precipitation dataset for GB (CEH-GEAR1hr; Lewis et al., 2018, 2022), produced so that daily totals are consistent with an existing daily 1 km precipitation dataset (CEH-GEAR, Tanguy et al., 2021), provided the opportunity to compare use of daily versus hourly precipitation data for grid-based hydrological modelling across GB. The Grid-to-Grid (G2G) national-scale 1 km hydrological model was driven with hourly data and with daily data equally disaggregated through the day, as well as with daily data disaggregated to hourly using a set of national profiles. Model performance was assessed using several measures comparing simulated and observed daily mean flows, for a large set of catchments across GB.

The assessment showed that, in terms of average performance across the set of catchments, use of hourly data provided a clear improvement over equally-disaggregated daily data for high flows and bias in peak flows, with a small improvement for average flows and bias in mean flows, but little difference for low flows. While model performance for smaller catchments (<50 km^2) was generally lower than for larger catchments, the improvements from use of hourly data tended to be greater. Improvement was not universal; performance in catchments to the north/west (which also tend to be steeper, with higher altitude and lower baseflow) typically improved more, but performance in some catchments was degraded. The use of profile-disaggregated daily data also provided the small improvement in mean flow bias and some improvement for peak flow bias, but performance for other factors was degraded compared to use of equally-disaggregated daily data, likely because of timing issues. The improvement in mean flow bias using hourly data (or profile-disaggregated daily data) was explained by differences in simulated actual evaporation. Future work could investigate how model performance across different catchments relates to the spatial and temporal resolution of both precipitation and PE; although hydrological models are generally considered less sensitive to errors in PE than precipitation, the two can compensate for each other (Wang et al., 2023). It would also be informative to investigate how comparable the results are for different hydrological models.

The availability of hourly and daily 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 et al., 2021b), provided the opportunity to compare potential future changes in peak flows across GB using hourly and daily precipitation data. A simple bias-correction was applied to the precipitation datasets before using them to drive G2G, producing 1 km grids of the water-year annual maxima of daily mean flows. Flood frequency curves were fitted for baseline and future time periods, and differences in baseline to future changes in 2- and 10-year return period peak flows assessed. The results showed that, on average, changes in peak flows from use of hourly CPM data were only slightly larger than from use of daily data (equally disaggregated through the day), with greater but still not substantial differences, on average, for smaller catchments. However, a small proportion of river pixels showed much larger differences.

The analyses here only looked at simulated daily mean flows. Future work will assess performance of G2G with CEH-GEAR1hr data for simulating hourly mean flows, comparing to sub-daily gauged flows for catchments across GB. Future work could also look at the derivation of flood response surfaces from applying regular sets of changes to hourly observed precipitation and investigating hourly peak flow changes, rather than daily (Kay et al., 2021b), and use hourly CPM data to investigate whether the impacts of climate change on hourly and daily peak flows differ. The latter may be of particular importance, at least for some catchments, since an analysis of changes in sub-daily rainfall extremes in the CPM shows that events exceeding 20 mm/h occur four times more frequently by the 2070s with increasing year-to-year variability, and have a tendency to cluster (Kendon et al., 2023). The future availability of more CPM ensembles, from other climate models, may be of significant value, although such datasets are expensive in terms of computational demand and data storage (Knutti, 2019). An alternative may be to use such models to provide improved temporal and spatial resolution data only for specific events selected from lower resolution climate model runs, as is planned in the CANARI programme (ncas.ac.uk/our-science/long-term-collaborations/canari/).

The analyses presented here help to inform where and when use of higher temporal resolution precipitation data may be required for river flow modelling. Orr et al. (2021) similarly suggest use of CPM data for future flood risk in smaller/flashier catchments, where both the increased spatial and temporal resolution could be important. Although not studied here, the simulation of surface water (pluvial) flooding also requires precipitation data with high spatial and temporal resolution (Rudd et al., 2020).

CRediT authorship contribution statement

A Kay: Conceptualization, Methodology, Formal Analysis, Writing – Original Draft, Writing – Review & Editing, Visualization. M Brown: Software, Validation, Formal Analysis, Writing – Original Draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2023.101588.

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