



SCIENTIFIC BRIEFING

Simulation of river flow in Britain under climate change: Baseline performance and future seasonal changes

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Abstract

Climate change is likely to manifest in river flow changes across the globe, which could have wide-ranging consequences for society and the natural environment. A number of previous studies used the UK Climate Projections 2009 (UKCP09) to investigate the potential impacts on river flows in Britain, but these projections were recently updated by the release of UKCP18, thus there is a need to update flow studies. Here, the UKCP18 Regional (12 km) projections are applied using a national-scale grid-based hydrological model, to investigate potential future changes in seasonal mean river flows across Great Britain. Analysis of hydrological model performance using baseline climate model data (1980–2010) shows relatively good agreement with use of observation-based data, particularly after application of a monthly precipitation bias-correction. Analysis of seasonal mean flow changes for two future time-slices (2020–2050 and 2050–2080) suggests large decreases in summer flows across the country (median –45% by 2050–2080), but possible increases in winter flows (median 9% by 2050–2080), especially in the north and west. Information on the potential range of flow changes using the latest projections is necessary to develop appropriate adaptation strategies, and comparisons with previous projections can help update existing plans, although such comparisons are often not straightforward.

KEYWORDS

climate change, hydrological impacts, seasonal mean flow change, UK climate projections 2018, UKCP18

1 | INTRODUCTION

Climate change will affect the hydrological cycle, and likely manifest in changes to flow regimes in rivers across the globe (Jiménez Cisneros et al., 2014). Such flow changes can have important consequences, relating to changes in seasonal flow patterns as well as changes in the frequency or magnitude of extreme flows. Flow regime changes can affect water quality, ecology, and energy production for example.

A range of studies have looked at the potential impacts of climate change on river flows in Britain (Watts et al., 2015). Studies often use

the UK Climate Projections 2009 (UKCP09; Murphy et al., 2009), which provided a range of alternative products including Probabilistic Projections, an 11-member perturbed parameter ensemble (PPE) of a 25 km Regional Climate Model (RCM), and a weather generator (e.g., Kay & Jones, 2012). Table 1 summarizes three studies which used UKCP09 to investigate the potential impacts of climate change on seasonal river flows in the UK (Christierson et al., 2012; Prudhomme et al., 2012; Sanderson et al., 2012). In general, studies suggest decreases in summer flows and possible increases in winter flows.

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TABLE 1 Studies using UKCP09 to investigate the impacts of climate change on seasonal river flows across Britain

Study	Model applied	Climate data used	Changes in flow reported
Prudhomme et al. (2012)	Semi-distributed hydrological model (CERF) with generalized parameters, applied across GB	Change factors derived from UKCP09 25 km RCM PPE for the 2050s	<ul style="list-style-type: none"> Likely decreases in summer flows across GB Predominantly increases in winter flows but decreases in some locations for some ensemble members Spring and autumn flow changes variable, but predominantly decreases in autumn across England
Christierson et al. (2012)	Catchment-based hydrological models, for 70 catchments across UK	UKCP09 Probabilistic Projections + monthly time-series from RCM PPE, for the 2020s	<ul style="list-style-type: none"> Small increase in winter flows in north-west Decreases elsewhere throughout year, with likely significant decreases in summer
Sanderson et al. (2012)	Gridded runoff from RCM itself, across UK	UKCP09 RCM PPE, for the 2020s, 2050s and 2080s	<ul style="list-style-type: none"> Increases in winter in all regions of the UK Little change or decreases in summer, especially by the 2080s Spring and autumn changes variable, but predominantly decreases in autumn across England Climate change signal could be detectable in winter runoff in western regions in 2020s, but much later in eastern England, and much later in summer (2040–2060s)

The UK Climate Projections 2018 (UKCP18; Lowe et al., 2018) provide an update to UKCP09, and there is a need to update corresponding simulations of potential future changes in river flows. One such update was provided by Kay et al. (2020), who applied the UKCP18 Probabilistic Projections with catchment-based models for 10 catchments in England, to look at the range of potential changes in measures of mean, median, high and low flow. The central estimates of change showed reductions in median and low flow in all catchments, with reductions in mean flow in eight catchments, and reductions in high flow in two to three catchments (depending on the emissions scenario). In all 10 catchments for all four flow measures, the central estimate of change from UKCP18 was similar to that from UKCP09 (A1B emissions), but the uncertainty range from UKCP18 was greater than from UKCP09.

Here, time-series data from the UKCP18 Regional (12 km) projections are used, with a fully distributed grid-based hydrological model, to look at seasonal mean flow changes across GB, thus providing an update to the national results of Prudhomme et al. (2012). The methods are described (Section 2), with results (Section 3), discussion (Section 4) and conclusions (Section 5).

2 | METHODS

2.1 | Hydrological model and observation-based driving data

The Grid-to-Grid (G2G) is a national-scale grid-based hydrological model for Great Britain that usually operates on a 1 km grid at a 15-minute time-step, and is parameterized using digital datasets (e.g., spatial soil grids) rather than through catchment calibration (Bell et al., 2009). The optional snow module (Bell et al., 2016) is applied here. G2G simulations of river flow perform well for a wide range of catchments (Bell et al., 2009, 2016; Formetta et al., 2018; Rudd et al., 2017), including those with a high proportion of baseflow (see

Figure 5 in Bell et al., 2009), and particularly where the flow regime is relatively natural. Artificial influences such as abstractions and discharges are not generally included, so the model essentially simulates natural, rather than gauged, flows.

Input gridded time-series of precipitation and potential evaporation (PE) are required, as well as temperature for the snow module. An observation-based simulation was performed for December 1980–November 2010 (hereafter ‘SIMOBS’) using:

- Daily 1 km grids of precipitation (CEH-GEAR; Tanguy et al., 2016), divided equally over each model time-step within a day;
- Monthly 40 km grids of PE for short grass (MORECS; Hough & Jones, 1997), divided equally over each model time-step within a month and copied down to the 1 km grid;
- Daily 1 km grids of min and max temperature (Met Office, 2019), interpolated through the day using a sine curve (Kay & Crooks, 2014).

The simulation was initialized using a states file saved at the end of a prior observation-based simulation (January 1970–November 1980). While the model produces ‘river flow’ for every 1 km ‘land’ box, only data from non-tidal grid boxes with a catchment area of at least 50km² are analysed (hereafter ‘river pixels’). Model outputs include gridded time-series of monthly mean river flows, and time-series of daily mean river flows for selected 1 km pixels corresponding to gauged catchments with flow data in the National River Flow Archive (www.ceh.ac.uk/data/nrfa/).

2.2 | Climate change projections and their application

UKCP18 provides information on potential changes in a range of climate variables over the 21st century, via a number of different products (Murphy et al., 2018). These include the UKCP18 Regional

(12 km) projections (Met Office Hadley Centre, 2018b), which comprise a 12-member PPE of the Hadley Centre RCM, nested in an equivalent PPE of their Global Climate Model (GCM), covering December 1980–November 2080 under RCP8.5 emissions (Riahi et al., 2011). Ensemble member 01 uses the standard parameterization. The data are available re-projected from the native climate model grid to a 12 km grid aligned with the GB national grid. The re-projected daily precipitation and daily min and max temperature are used here.

There are (generally positive) biases in monthly RCM precipitation (see Figure 4.4 in Murphy et al., 2018) so the data are bias-corrected as in Guillod et al. (2018); grids of monthly correction factors are derived by comparing baseline mean monthly precipitation totals (from each PPE member separately) against those from CEH-GEAR averaged up to the 12 km RCM grid, then the factors are smoothed using weights in a 3×3 neighbourhood (Figure S1). There are a number of alternative bias-correction methods of varying complexity (Fung, 2018), and many issues and assumptions inherent in bias-correction (e.g., Ehret et al., 2012) which can potentially introduce artefacts into the ‘corrected’ data (Maraun et al., 2017). So the approach here is deliberately simple, aiming to correct seasonal mean biases while not adversely affecting higher-order moments. The bias-corrected precipitation are downscaled to the 1 km grid using a spatial weighting derived from 1 km standard average annual rainfall patterns (Bell et al., 2007), and temporally downscaled as for observed rainfall (Section 2.1).

No bias-correction is applied to RCM temperature, as the PPE range encompasses monthly observations relatively well (see Figure 4.4 in Murphy et al., 2018). The 12 km RCM temperature are downscaled to 1 km using a lapse rate with elevation (Bell et al., 2016), and temporally downscaled as for observed temperature (Section 2.1).

PE for short grass is not available directly, so is estimated from other (re-projected) daily climate variables using a formulation which replicates MORECS as closely as possible; essentially Penman-Monteith PE (Monteith, 1965) with some minor modifications, including an interception correction (Hough et al., 1997). Since higher atmospheric CO₂ concentrations can lead to stomatal closure and reduced evapotranspiration, potential future changes in stomatal resistance are included in the PE estimation (Guillod et al., 2018; Rudd & Kay, 2016). PE is only estimated for ‘land’ RCM boxes, as direct estimation for ‘sea’ boxes can give unrealistic values. Where necessary for complete coverage of 1 km ‘land’ boxes by 12 km RCM PE, a neighbouring RCM ‘land’ box is identified from which to copy the PE. The 12 km RCM PE are spatially and temporally downscaled as for observed PE (Section 2.1).

The RCM PPE suggests typical decreases in summer precipitation and increases in winter precipitation (see Figure 4.8c,d in Murphy et al., 2018). Summer decreases can be as much as –60% while winter increases are as high as 40% by 2061–2080 for some locations and ensemble members, although winter decreases of –10% or more are suggested for northern Scotland by some members. Temperature increases by ~1–4°C in winter and ~2–7°C in summer by 2061–

2080, depending on location and ensemble member (see Figure 4.8a,b in Murphy et al., 2018). PE between spring and autumn typically increases by ~10–20%, with increases of 30% or more in south/east England for some ensemble members. While winter PE also generally increases, by ~5% on average and up to ~35% in some locations for some ensemble members, there are decreases of as much as ~–15% in places, but these are not likely to be important as winter PE is fairly low.

Each RCM-based G2G simulation (hereafter ‘SIMRCM’) was initialized in Dec 1980 using the same states file as SIMOBS (Section 2.1), and run through to Nov 2080.

2.3 | Analysis of simulated flows

Three 30-year time-slices are analysed from the SIMRCM simulations; baseline (December 1980–November 2010); near-future (December 2020–November 2050) and far-future (December 2050–November 2080). The baseline time-slice is used to assess performance of the SIMRCM simulations, compared against SIMOBS for the same period (Section 2.3.1). The near-future and far-future time-slices are compared against the baseline time-slice to assess potential future changes in flows (Section 2.3.2).

For SIMOBS and SIMRCM, the gridded time-series of monthly mean flows are used to derive seasonal mean flows for each time-slice, using the standard seasons (winter: December–February, spring: March–May, summer: June–August, autumn: September–November).

2.3.1 | Baseline performance assessment

As development of weather features in the RCM PPE will not follow the observed weather over the baseline period, the performance assessment uses measures derived from flow duration curves and seasonal mean flows, thus comparing statistical characteristics rather than day-to-day equivalence.

The flow duration curve assessment uses simulated daily mean flows for 1 km pixels corresponding to a set of 96 gauged GB catchments; those within the UK benchmark network (Harrigan et al., 2018) which have a catchment area of at least 50km² and less than 20% missing data in the baseline period (Figure S2a). The SIMOBS run and each SIMRCM run (with and without bias correction) are compared against gauged flows for these catchments, as is the pooled SIMRCM data. Three measures are derived, quantifying the percentage bias for different parts of the flow duration curve (similar to Kay et al., 2015); low flow volume (l_{fv_70–95}; bias in the 70th–95th quantiles), median flow (mdf; bias in the 50th quantile), and high flow volume (h_{fv_5–30}; bias in the 5th–30th quantiles). Note that the 95th quantile is often termed Q95 (the flow exceeded 95% of the time); the l_{fv} measure is more general than quantifying bias in Q95. Similarly, the h_{fv} measure is more general than quantifying bias in Q5 (the flow exceeded 5% of the time).

To provide a broader performance assessment across GB, grids of baseline seasonal mean flows from the SIMRCM ensemble are compared to corresponding grids from the SIMOBS run. For each river pixel and each season, a value p is assigned as

$$p = \begin{cases} q_{simobs}/(2\sigma_{rcm}) & \text{if } (\mu_{rcm} - 2\sigma_{rcm}) \leq q_{simobs} \leq (\mu_{rcm} + 2\sigma_{rcm}) \\ -1 & \text{otherwise} \end{cases}$$

where q_{simobs} is the SIMOBS seasonal mean flow, and μ_{rcm} and σ_{rcm} are the mean and standard deviation of the baseline seasonal mean flows across the 12-member SIMRCM ensemble. Measure p thus indicates whether the range of the SIMRCM flows (defined by the ensemble mean and standard deviation) contains the SIMOBS flow. If it does, then p further indicates how large the SIMRCM range is compared to the SIMOBS flow; if the SIMRCM range is small relative to SIMOBS then p is large, suggesting that the SIMRCM ensemble gives a robust indication of SIMOBS.

2.3.2 | Future changes in seasonal mean flows

Percentage changes are calculated from the gridded seasonal mean flows for the baseline time-slice to the near- and far-future time-slices, for each SIMRCM run separately and for the pooled SIMRCM ensemble (Section 3.2). Six regions of Britain are used to summarize the seasonal mean flow changes (Figure S2b).

3 | RESULTS

3.1 | Baseline performance assessment

Boxplots summarizing the flow duration curve assessment across the 96 catchments show that, for each of the three measures of fit, precipitation bias-correction makes the pooled SIMRCM ensemble performance more similar to that of the SIMOBS run (Figure 1). The

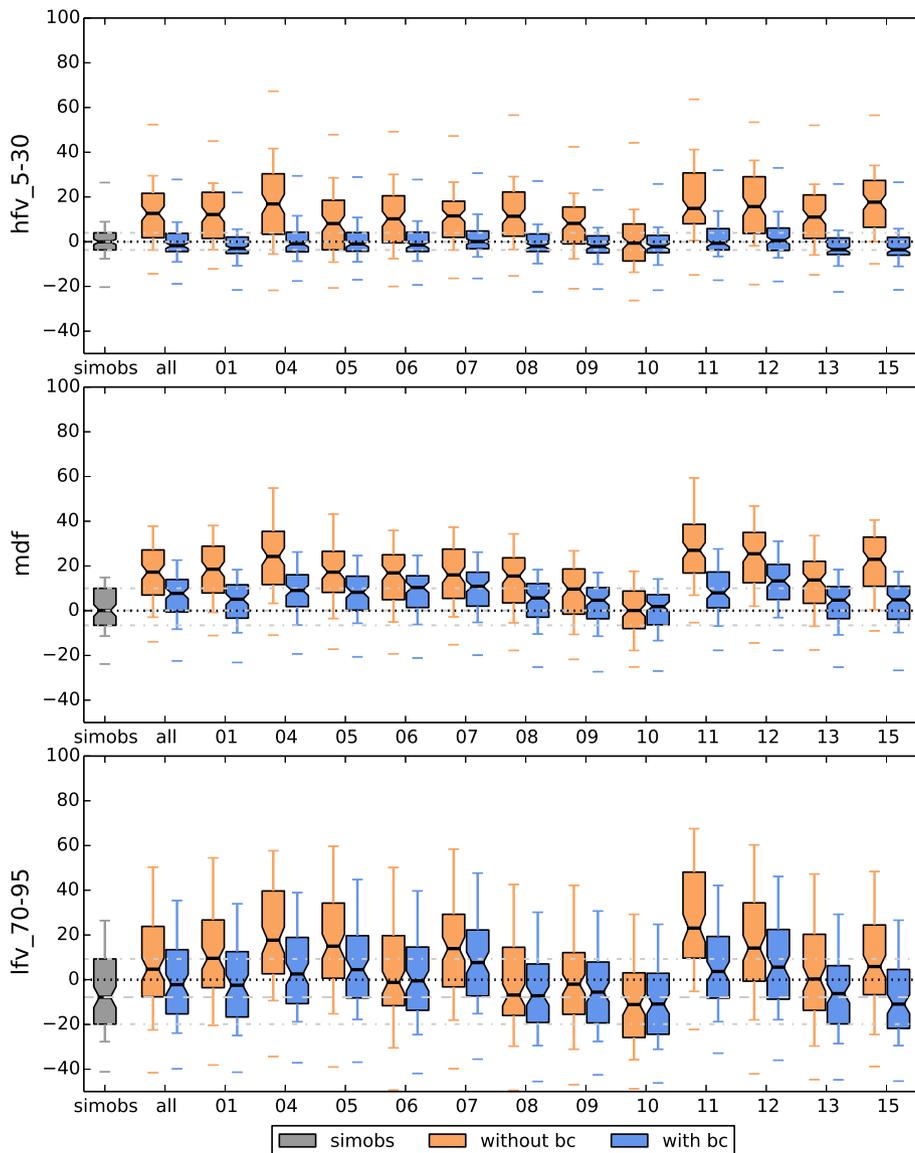


FIGURE 1 Boxplots summarizing the three measures of fit of the flow duration curve—percentage bias in high flow volume (hfv_5–30), median flow (mdf), low flow volume (lfv_70–95)—across 96 gauged catchments, for the SIMOBS run, the pooled SIMRCM ensemble (‘all’), and each of the 12 SIMRCM runs separately. The SIMRCM results are shown with and without bias-correction (bc). Each box shows the 25th–75th percentile range, with the line showing the 50th percentile and the whiskers the 10th–90th percentiles. Lines outside the box show the overall min and max (if within the plotted range)

performance of individual ensemble members varies around that of the pooled performance, particularly without bias-correction when some members show majority positive flow biases (e.g., 11) or more negative biases (e.g., 10, for low flows in particular). The bias-correction reduces the variation in performance between ensemble members, unsurprisingly since monthly mean precipitation in each member is separately corrected to the observed precipitation.

Maps of the flow duration curve assessment for the SIMOBS run and the pooled SIMRCM ensemble (Figure S3) show the variation in performance across the country. In particular, the low flow volume is more likely to be under-estimated in north/west England and over-estimated in south/east England and western Scotland in each case. Without bias-correction, many catchments show over-estimation of median and high flows in particular; this is reduced by bias-correction.

The seasonal mean flow assessment also shows that bias-correction improves performance of the SIMRCM ensemble (Figure 2). Without bias-correction, the SIMRCM range excludes the SIMOBS flow for well over 40% of pixels in winter and spring, over 15% in autumn, but just less than 10% in summer. With bias-correction, this reduces by at least half in winter, spring and summer, but only reduces slightly in autumn. Furthermore, with bias-correction the performance measure p is relatively large everywhere in each season

(except for some pixels in the Scottish highlands in summer), indicating that the SIMRCM ensemble gives a relatively robust indication of SIMOBS. Measure p is generally lowest in summer, when the SIMOBS flows will typically be lowest, making it harder for the SIMRCM range to be much smaller than the SIMOBS flow.

3.2 | Future changes in seasonal mean flows

Maps of seasonal mean flow changes from the pooled SIMRCM ensemble (Figure 3a), suggest increases in winter in the north/west but possible decreases in the south/east (median change 9% and range -42% to 51% for the far-future). Changes in spring flows are typically negative but with some small positive values in the west (median -6%, range -29% to 15%). Summer flows show large decreases across the country (median -45%, range -66% to -5%), and changes in autumn flows are also mostly negative, particularly in the south/east (median -29%, range -59% to 22%).

Results for individual SIMRCM runs for the far-future time-slice (Figures S4 and S5) show some variation from the pooled SIMRCM ensemble, mainly in terms of magnitude of changes; the spatial patterns are relatively similar, particularly for summer and autumn.



FIGURE 2 Performance measure p ; the level of containment of the SIMOBS flow within the SIMRCM ensemble range. The percentage of river pixels where the SIMOBS flow is outside the SIMRCM range ($p < 0$) is at the top right of each map

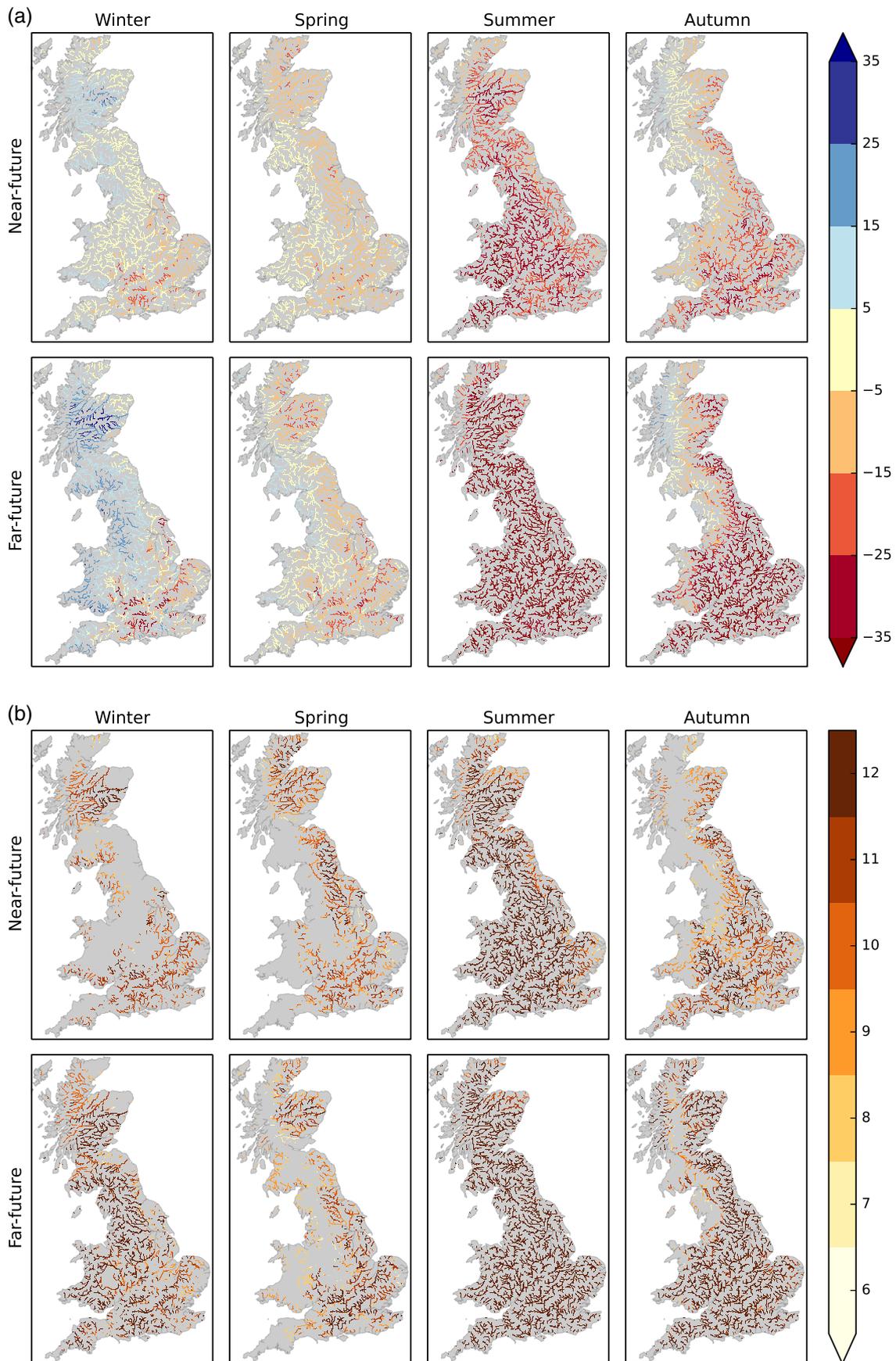


FIGURE 3 (a) Percentage change in seasonal mean flow from the pooled SIMRCM ensemble, for each future time-slice. (b) the number of SIMRCM ensemble members showing the same sign of change in seasonal mean flow as the pooled SIMRCM ensemble, for each future time-slice. Cells where the seasonal mean flow change from the pooled SIMRCM ensemble is small ($\pm 5\%$) are masked

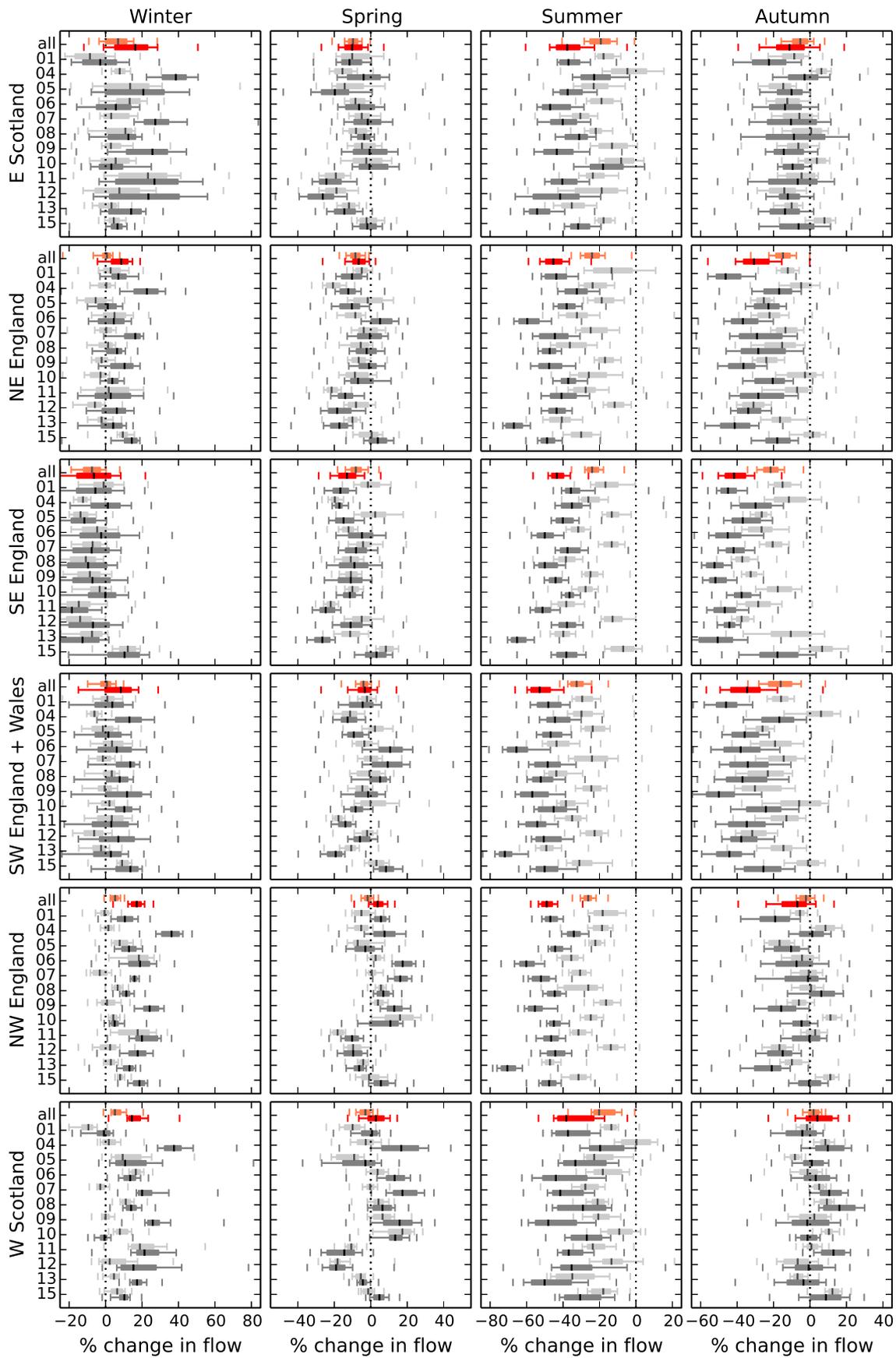


FIGURE 4 Boxplots showing the change in seasonal mean flows summarized over six regions of GB, for each of the 12 SIMRCM runs for the near-future (light grey) and far-future (dark grey), and the pooled SIMRCM results for the near-future (orange) and far-future (red). Each box indicates the 25th–75th percentile range, with the whiskers showing the 10th–90th percentile range, and bars outside the whiskers showing the overall min and max

Changes in winter and spring are more variable between ensemble members, with some showing more decreases in winter, and some showing more increases in spring. Seasonal differences in the level of SIMRCM ensemble consistency are illustrated by counts of the number of SIMRCM ensemble members that agree with the pooled SIMRCM ensemble in terms of the sign of change in flow (Figure 3b). In summer and autumn, most pixels show a consistent sign of change for all (or nearly all) SIMRCM runs. This is also the case for winter, at least for the far-future, but there is more variation for spring flows in both time-slices.

Boxplots summarizing results for six regions show the differences in response by ensemble member, season, and region (Figure 4). Ensemble members generally show greater differences in the magnitude of the flow change in summer than winter (apart from in West Scotland). Regions to the south typically show greater intra-region variation in response (i.e., wider boxplots) in winter than summer.

4 | DISCUSSION

The results of this study cannot be directly compared to Prudhomme et al. (2012) for a number of reasons, including differences in emission scenario (RCP8.5 vs SRES A1B), time-slices (baseline 1981–2010 vs 1961–1990; future Dec 2020–Nov 2050 and Dec 2050–Nov 2080 vs 2040–2069), models (grid-based vs catchment-based) and methods (RCM time-series vs change factors). However, the results do show broad similarities; likely, and possibly large, decreases in summer flows, predominantly decreases in autumn flows, particularly in the south/east, and a more mixed picture for changes in winter and spring flows, varying by location and ensemble member. These broad similarities also apply for Christerson et al. (2012) and Sanderson et al. (2012) (see Table 1).

Possibly large future reductions in summer flows could have a range of implications. For example, where rivers provide important contributions to drinking water or irrigation there may be a greater chance of supply limitations in future, and adaptation measures will be needed to manage this (Harris et al., 2013). Low flows can also adversely affect water quality by reducing dilution of substances (Charlton et al., 2018; Nilsson & Malm Renöfält, 2008), and affect riverine ecology through changes in the physical extent or conditions of aquatic habitat (Laize et al., 2014; Rolls et al., 2012).

Possible future increases in winter flows could also have a range of implications. For example, it may lead to an increased frequency and/or magnitude of floods (Charlton et al., 2006). As well as the direct effects of floods, events can cause pollution and sedimentation through the addition of large amounts of organic and inorganic matter to rivers (Nilsson & Malm Renöfält, 2008; Ponting et al., 2020). Higher flows can also adversely affect riverine ecology, as can changes in the seasonal patterns of river flows (Laize et al., 2014).

Only one hydrological model has been applied, although a number of studies have suggested that the climate model is typically a larger source of uncertainty (e.g., Krysanova et al., 2017). The correction of monthly mean precipitation biases makes the baseline performance of

the pooled climate ensemble more similar to that using observed data to drive the hydrological model, giving some confidence in use of the ensemble for projecting future changes in flows. However, the results use data from only one GCM/RCM combination—the latest Hadley Centre GCM (HadGEM3) and its regional equivalent—albeit as a PPE. Other CMIP5 climate models within the UKCP18 Global projections, and (to a lesser extent) the UKCP18 Probabilistic projections, tend to give smaller decreases (or increases) in summer precipitation and a wider range of changes in winter precipitation than the Regional projections applied here (see Figure 5.2 in Murphy et al., 2018), so could give lower reductions in summer flows but larger or smaller increases in winter flows. The 60 km resolution of the Global projections is generally considered too coarse for direct use in hydrological modelling in Britain though, and the Probabilistic Projections are not spatially coherent so cannot be used for national-scale modelling.

The UKCP18 Regional projections use RCP8.5, which is considered a high-emissions pathway; a lower pathway (e.g., RCP6.0) should give lower eventual impacts (e.g., Arnell et al., 2014). The SRES A1B emission scenario, used for the UKCP09 RCM ensemble, lies between RCP6.0 and RCP8.5 in terms of temperature projections (Met Office Hadley Centre, 2018a).

The projected changes in flow are likely to be predominantly driven by the changes in precipitation (drier summers and wetter winters; Section 2.2), with additional spatial variation due to catchment properties, but the increases in PE could also be important (e.g., Kay & Davies, 2008), and in some locations flows could be additionally affected by changes in temperature via its effect on snow (e.g., Kay, 2016). Projected future changes in evaporation often get less attention than precipitation, yet evaporation is a key part of the hydrological cycle. There is uncertainty in the PE inputs necessary for hydrological modelling, especially under climate change (Kay et al., 2013). While the future PE here includes an increase in stomatal resistance due to stomatal closure under higher CO₂ concentrations, it does not include a potential increase in leaf area (and therefore number of stomata) due to carbon fertilization (Rudd & Kay, 2016). Potential future changes in land-cover and abstractions/discharges are also not included.

5 | CONCLUSIONS

Applying a national-scale grid-based hydrological model with ensemble climate data from the UKCP18 Regional projections has suggested future decreases in summer flows across the Great Britain (median –45% by 2050 to 2080), but possible increases in winter flows (median 9% by 2050 to 2080), especially in the north/west. Such changes in flows could have significant implications, both for the natural environment and for society.

Information on the potential range of changes in river flows from the latest climate projections is necessary to develop appropriate adaptation strategies for water management (e.g., HR Wallingford, 2020), and comparisons with results from previous climate projections can help in the updating of existing plans. However,

comparisons are often not straightforward, due to differences in the setup of projections (e.g., UKCP09 typically used a 1961–1990 base-line but the UKCP18 RCM data only starts in Dec 1980), the way projections are applied (e.g., bias-correction methods etc.), and the models used. Not all of these differences are avoidable, due to the evolution of science and methods.

Further work will investigate potential future changes in high and low flow frequency, as well as soil moisture, which could have important consequences for agriculture (Samaniego et al., 2018) and subsidence hazard (Pritchard et al., 2015). In addition, the UKCP18 Local (2.2 km) projections provide data from a 12-member convection-permitting model ensemble, which shows greater increases in winter mean precipitation than the Regional ensemble (Kendon et al., 2019), so could lead to differences in the simulated impacts on river flows (e.g., Kay et al., 2015).

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DATA AVAILABILITY STATEMENT

Data will be made available via EIDC at some point during in 2021, but before then they are available from the authors upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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