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# The CANARI-LE hydro-SMILE: new insights on UK hydrological extremes using a large initial condition climate ensemble

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**Abstract.** Regional hydrological projections tend to have small ensemble sizes and often mix climate model uncertainty with internal variability. River flow projections driven by initial condition large ensembles (hydro-SMILEs) have emerged as a valuable toolkit to robustly quantify the influence of internal variability. In this study, we develop the CANARI-LE hydro-SMILE for the UK, a set of nationally consistent river flow projections across the 21st century (1955-2099) for a large set of UK catchments driven by the new 40-member CANARI single-model initial-condition large ensemble (CANARI-LE) based on the Met Office HadGEM3 GCM. Seven hydrological models are selected with satisfactory model performance across the full flow regime at most catchments when evaluated against observations. Nationally, projected changes in seasonal river flows generally span a larger range in both direction and magnitude compared to past UK river flow projections (e.g. UKCP18 Regional PPE). Simulations from contrasting hydrological model structures provide an indication of hydrological model uncertainty compared to other sources of uncertainties along the modelling chain, suggesting larger differences in low flow changes between hydrological model structures compared to high flows. The CANARI-LE hydro-SMILE can support a wide range of applications across different sectors. Exemplar applications to address existing research gaps for risk planning show that the large ensemble size is well-suited for separating internal variability from climate-driven low and high flow changes and is ideal to sample for rare events. Results show the occurrence of record-breaking extreme low and high flows arising from strong internal variability are underestimated if based solely on historical observations or small existing ensembles. Long-duration prolonged wet and dry spells are better sampled by the CANARI-LE hydro-SMILE with particularly large changes in multi-season dry spells with future warming across southern England. The average likelihood of coincident droughts across multiple regions in England & Wales increases with warming but the most widespread droughts are possible even at lower global warming levels due to internal variability. Rare hydroclimate extremes can complement existing methodologies to develop stress tests, provided their physical plausibility and climate drivers are evaluated. The CANARI-LE can be used to develop hydro-SMILEs for other regions to assess rare compound and correlated/synchronous hydroclimate risks across borders using a consistent driving climate ensemble.

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## 1. Introduction

Climate change will significantly alter global hydrological regimes, with an intensified hydrological cycle likely leading to increases in the magnitude and frequency of floods, droughts and compound extremes (Swain et al., 2025; Zscheischler et al., 2020). In the UK, successive national climate change projections have suggested a reduction in average summer precipitation and an increase in average winter precipitation with future warming (e.g. UK Climate Projections 2018 - UKCP18; Lowe et al., 2018). Increasing temperature and atmospheric evaporative demand translate into increased meteorological drought frequency and extent across the UK (Reyniers et al., 2023). River flow projections such as the enhanced Future Flows and Groundwater (eFLaG) dataset shows, in general, a widespread reduction in average summer flows and increases in average winter flows particularly for northwestern areas (see review of past projections in Chan et al., 2022; Lane and Kay, 2023 and references therein).

Multi-model ensembles (e.g. CMIP6) and perturbed parameter ensembles (PPEs), have been used to develop national river flow projections (e.g. UKCP18 Regional PPE: Hannaford et al., 2022; Smith et al., 2024). However, analyses of these ensembles often mix two different sources of uncertainties related to (i) climate model parameterisations (stemming from the lack of knowledge in climate processes) and (ii) natural internal variability (stemming from the inherent chaos of the climate system). Their uncritical use in climate impacts modelling often conflates these sources and disentangling them is non-trivial, thus complicating the estimation and interpretation of climate risk (Chandler and Brierley, 2026; Shepherd, 2019). Relatively small ensemble sizes (e.g. from conventional multi-model ensembles) also cannot systematically explore the possibility of record-breaking, high-impact climate extremes that could arise by chance (e.g. Kelder et al., 2025). The influences from internal variability for regional hydrology are thus largely under-sampled in past conventional hydrological projections (Chan et al., 2025; Deman and Boé, 2025; Evin et al., 2026).

Recent years have seen the emergence of single-model initial-condition large ensembles (SMILEs) as a tool in climate risk assessment. SMILEs are designed to sample a large range of possible outcomes from internal climate variability for a given climate model and emission scenarios (Deser et al., 2020). Atmospheric perturbations are applied to initial conditions of each ensemble member which subsequently simulates diverging, but equally likely trajectories of weather sequences that are solely attributed to natural internal variability (Deser et al., 2020; Deser and Phillips, 2023). Given the large sample size, SMILEs are uniquely suited to study compound and rare climate extremes that are otherwise under-sampled in short historical observations and traditional multi-model ensembles (Bevacqua et al., 2021, 2023; Mankin et al., 2020). Studies are increasingly developing hydro-SMILE datasets using outputs from SMILEs to drive hydrological models (Brunner et al., 2021). Hydro-SMILEs have enabled more robust estimation of rarer compound floods (e.g. rain-on-snow events) and river droughts at high return periods (e.g. Poschlod et al., 2026; van der Wiel et al., 2019; Willkofer et al., 2024).

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There has yet to be a fully transient, nationally consistent hydro-SMILE dataset for the UK using multiple hydrological models available for the community. Past studies in the UK based on the weather@home ensemble confirmed the value of large ensembles in capturing rare widespread droughts absent from short historical records, although their time-slice approach relied on single-year simulations stitched together to form long time series (Guillod et al., 2018). Earlier use of large ensemble simulations for UK hydrological applications also recognized their potential to aid decision-making but was hampered by its then temporal resolution (i.e. monthly) and limited sampling of extremes beyond the historical record (Fung et al., 2013). More recent use of a new generation of initialised large climate ensembles in hydrology has provided insights on the drivers of extreme droughts (e.g. Chan et al., 2023), potential for widespread unprecedented floods (Kay et al., 2024) and confirmed internal variability as an important factor in masking emerging climate-driven trends in UK river flows (Chan et al., 2025; also shown in North America by Faghih and Brissette, 2023).

Previous assessments showcased the potential for hydro-SMILEs in the UK but are based on limited catchment selections and a single hydrological model. Additionally, there has yet to be a hydro-SMILE driven by the UK Met Office GCM which is the mainstay of the UK climate impacts community and seen as 'industry standard' for climate adaptation research and implementation (e.g. Dessai et al., 2024). Recently, a 40-member SMILE dataset driven by the UK Met Office CMIP6 HadGEM3 GCM has been developed (CANARI-LE; Schiemann et al., 2026). In this study, we introduce the development of the "CANARI-LE hydro-SMILE" for the UK and illustrate the new insights this large ensemble dataset can provide to advance understanding of hydrological extremes. While this study focuses on the UK, hydro-SMILEs are increasingly developed globally, and similar research areas are mirrored elsewhere. Hence, the approach demonstrated are likely to be relevant in other international contexts and could be applied elsewhere using the same CANARI-LE driving dataset to tackle similar research gaps.

The specific aims of this paper are to:

1. Develop the first UK national river flow projections driven by the CANARI-LE using multiple hydrological models (CANARI-LE hydro-SMILE)
2. Quantify national-scale future river flow changes across UK regions at different global warming levels (GWLs) and;
3. Demonstrate how the CANARI-LE hydro-SMILE can explore effects of internal climate variability and address key research gaps relevant to risk planning and water resources management.

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## 2. METHODS

### 2.1 Observed data

Observed precipitation and temperature at 1km resolution are derived from the HadUK-Grid dataset (Hollis et al., 2019). Estimates of potential evapotranspiration (PET) at 1km resolution over the historical period are derived using the Hydro-PE methodology using input data from HadUK-Grid following a modified Penman-Monteith approach parameterised for short grass with interception correction (Dalle Piagge et al., 2026; further details in Robinson et al., 2023).

The UK catchments selected are 671 catchments within the CAMELS-GB dataset for Great Britain (Coxon et al., 2020) and an additional 9 catchments from Northern Ireland that overlaps with previous national river flow projections (Hannaford et al., 2023) (i.e. 680 catchments in total). Only catchments with at least 30 years of observed river flows within the 1970-2022 period are selected for hydrological modelling. Observed river flows and associated attributes (e.g. gauge location, catchment area and elevation) across all selected catchments are taken from the UK National River Flow Archive (NRFA).

### 2.2 CANARI-LE data

The CANARI-LE is a 40-member ensemble of the UK Met Office CMIP6 HadGEM3-GC3.1 global climate model with a resolution of ~60-km over the UK (Schiemann et al., 2026). The initial conditions of each ensemble member are altered with random atmospheric perturbations and forced with historical climate forcings from 1950-2014, and the SSP3-7.0 shared socioeconomic pathway from 2015-2100. The CANARI-LE uses a simplified 360-day calendar consisting of twelve 30-days months in each year.

Daily temperature and precipitation time series are available for each ensemble member. Potential evapotranspiration (PET) at the native climate model resolution is calculated using the Hydro-PE modified Penmen Monteith approach with interception correction (methodology in Robinson et al., 2023). To adjust for systematic biases within the climate model data over the UK, four methods for bias adjustment are applied for precipitation: 1) monthly linear scaling (LS), 2) parametric quantile mapping (QM), 3) empirical quantile mapping (EQM) and 4) the trend-preserving ISIMIP bias adjustment approach (Lange, 2019). All bias adjustment methods, except for the EQM method, are implemented via the *ibicus* python package (Spuler et al., 2024). Adjustment factors are calculated from the pooled ensemble to preserve ensemble spread (Astagneau et al., 2025). For temperature and PET, only linear scaling is used. Bias adjustment of temperature and precipitation is applied using gridded observations from the HadUK-Grid 5km dataset over the entire reference period 1950-2014 while bias adjustment of PET is applied to match monthly means of the HadUK-Grid Hydro-PE estimates over the observed period 1969-2022.

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Linear scaling applies multiplicative (precipitation) or additive (temperature) adjustments of monthly means to match observations. Quantile mapping maps model quantiles onto observed quantiles, thereby correcting biases across the full distribution, including extremes – done by fitting observations to a gamma distribution. Empirical quantile mapping uses the observed distribution directly, except for extreme values. Above the 99.5th percentile, where observations become sparse and discontinuous, the tail is modelled using a generalized extreme value distribution. The ISIMIP trend-preserving approach extends quantile-based methods by additionally preserving relative climate change signals in the model while correcting historical biases, thereby avoiding distortion of long-term trends (Lange, 2019).

Given the relatively coarse resolution of the meteorological variables from the CANARI-LE, spatial downscaling to 1km resolution follows the method detailed in Kay et al. (2023) prior to hydrological modelling. The bias-adjusted CANARI-LE precipitation fields are scaled by the ratio of observed standard annual average rainfall (SAAR) (1961-1990) at 1km resolution to the equivalent SAAR at grids coarsened to match the CANARI-LE resolution. This ensures that the downscaled CANARI-LE retains the observed spatial precipitation distribution across the UK. Bias-adjusted temperature is downscaled using a lapse rate by comparing high-resolution 1km elevation data with the equivalent data coarsened to match the CANARI-LE resolution.

### 2.3 Hydrological modelling

The CANARI-LE hydro-SMILE comprises of six catchment hydrological models and one national gridded model. The selected models span core differences in architectures of conceptual hydrological models (e.g. soil layers) and parameterisations of hydrological processes. Table 1 shows the six catchment hydrological models used in this study and details of their implementations. The national 1km Grid-to-Grid gridded hydrological model (G2G; Bell et al., 2009) is used to simulate river flows over Great Britain, including in ungauged locations. A companion paper – Kay et al., (under review) outlines broad-scale analyses of the gridded G2G model outputs. Simulated river flows from G2G at the outlets of catchments greater than 50km$^2$ are included in this paper.

All the chosen hydrological models have been applied in the UK previously, such as for seasonal hydrological forecasting and previous river flow climate change projections (Table 1). The Framework for Understanding Structural Errors (FUSE) methodology allows the flexible creation of further model structures but for the CANARI-LE hydro-SMILE, only the four parent models are selected (Clark et al., 2008). Previous evaluation of the four parent FUSE hydrological models in the UK showed that no single model structure performs consistently well across seasons, flow metrics or catchments (Lane et al., 2019).

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**Table 1 The seven hydrological models used for this study and details of their parameterisation and past applications in the UK.**

| Model | No. of parameters | Snow module | Past use in the UK | Software package | Reference |
|---|---|---|---|---|---|
| GR6J (Génie Rural à 6 paramètres Journalier) | 6 | CemaNeige snow module based on altitudinal elevation gradients for catchments with significant snowfall (>15% of time with precipitation falling as snow; Harrigan et al. 2018) | Seasonal forecasting and hydrological projections (Hannaford et al., 2022) | airGR R package (Coron et al., 2017) | Pushpalatha et al. (2011) |
| HBV (Hydrologiska Byråns Vattenbalansavdelning) | 12 | Degree-day snow routine based on temperature thresholds | Climate projections (Sayers et al., 2025; Smith et al., 2024) | HBV R source code (Gannon 2023) | Seibert and Vis (2012) |
| FUSE – ARNO/VIC (Variable Infiltration Capacity) | 9 | No snow module employed | Predictability of high river flows (Lane et al., 2019) and hydrological projections (Reyniers, 2023) | *fuse* R package (Vitolo et al., 2016) | (Clark et al., 2008) |
| FUSE – TOPMODEL | 8 | | | | |
| FUSE – PRMS (Precipitation-Runoff Modelling System) | 11 | | | | |
| FUSE – Sacramento | 12 | | | | |
| Grid-to-Grid (G2G) | Gridded, not calibrated to specific catchments | Snow module based on temperature thresholds for snowfall and snowmelt (Bell et al., 2016) | Flood forecasting (e.g. Price et al., 2012) and climate projections (e.g. Hannaford et al., 2023) | NA | (Bell et al., 2009) |

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Unlike the catchment hydrological models, G2G is not calibrated to any specific catchment but is instead parameterised using national-scale spatial datasets and simulates natural river flows across Great Britain (Bell et al., 2009). The remaining six catchment models are calibrated in a consistent way with an automatic multi-objective calibration algorithm implemented using the *caRamel* R package; technical details can be found in Monteil et al. (2020). In brief, the algorithm is a multi-objective evolutionary annealing simplex method that requires the specification of lower and upper bounds for parameters in each hydrological model (as shown in Table S1 for GR6J and HBV and Table S2 for the FUSE catchment models; following parameter ranges defined in Lane et al., 2019). An initial population size of 100 and maximum model runs of 50,000 are specified for each hydrological model.

Calibration was conducted against mean daily observed river flows over the full period of record for each catchment within the 1970-2022 period. This maximises the observed data available for calibration, in line with past national hydrological projections (Hannaford et al., 2023), with previous work showing that a split-sample calibration strategy yielded little difference in model performance (e.g. Harrigan et al. 2018). The objective metrics chosen to be optimized are presented in Table 2. Behavioural parameter sets are ranked from best to worst for each of the six model performance metrics (i.e. lowest score given to the best parameter set) and the parameter set with the lowest sum of scores across all metrics is retained for subsequent hydrological simulations. Models calibrated against observed flows inplicitly accounts for any artificial impacts (e.g. abstractions) in the historical record. Retrospective simulated river flows over the historical observed period (termed SimObs hereafter) is compared with the CANARI-LE, which provides alternative realisations of weather and flow sequences for both historical and future periods.

**Table 2 Model performance metrics used for calibration of the six catchment hydrological models**

| Metric | Name (Reference) | Range |
|---|---|---|
| KGE2 | Modified Kling-Gupta Efficiency (Kling et al., 2012) | 1 (perfect) to -∞ |
| NSE | Nash-Sutcliffe Efficiency (Nash and Sutcliffe, 1970) | 1 (perfect) to -∞ |
| Q95 | Absolute percent error in flow exceeded 95% of the time (Q95) (%) | 0 (perfect) to ∞ |
| Q5 | Absolute percent error in flow exceed 5$^{th}$ of the time (Q5) (%) | 0 (perfect) to ∞ |
| PBIAS | Absolute percent bias in mean flows (%) | 0 (perfect) to ∞ |

### 2.4 National-scale hydrological changes

Projected changes in river flows and extremes are assessed for both transient horizons (1955-2099) and for specific time slices (2°C and 4°C global warming levels GWL). For GWLs, a time-slice approach is used to select the 25-year time period for which the middle year reaches the desired GWL relative to quasi-pre-industrial conditions (defined as relative to average

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temperature for 1965-2014 minus 0.59°C), following the definition of GWLs in Harvey et al. (2023). A 25-year time slice matches the definition of GWLs in the UKCP18 projections (Gohar et al., 2018). The start and end years of the GWL time slices for each ensemble member are shown in Tables S3 for 2°C and 4°C GWL.

River flow extremes are characterised by high (Q5) and low (Q95) flows, calculated as the 5$^{th}$ and 95$^{th}$ percentile of the flow duration curve, respectively for each GWL and for each hydrological model and ensemble member. Hydroclimate regions defined by merging UK hydrometric areas are used to summarise results (National River Flow Archive, 2014) (Figure S1). An initial comparison with previous national river flow projections is made by comparing equivalent changes from the GR6J hydrological model within the 12-member eFLaG ensemble driven by UKCP18 Regional PPE, although we note that such a comparison is challenging as the CANARI-LE and UKCP18 follows different radiative forcing scenarios (SSP370 and RCP8.5, respectively).

### 2.5 New insights for UK hydrological extremes

Exemplar applications are used to demonstrate the added value of the CANARI-LE hydro-SMILE for the hydrological and climate impacts community. These exemplar applications are chosen to show how the new dataset can be used to provide new scientific insights on critical scientific gaps to inform water management and risk planning, as follows:

1. **Record-breaking extremes** – The potential for unprecedented high (Q5) and low (Q95) flows is assessed by recognizing that the ensemble members of the CANARI hydro-SMILE purely represents the range of internal variability where plausible extremes worse than those observed are possible by chance, following the motivation of the UNprecedented Simulation of Extremes using ENsembles (UNSEEN) framework (Kelder et al., 2025; Thompson et al., 2017). The distribution of trends in annual river flows within the CANARI-LE hydro-SMILE is compared to the SimObs trend over the equivalent period to appraise the possible range of trends that could have occurred by chance in alternative realisations of the historical period. Unprecedented extreme flow events not seen in historical observations are extracted, defined as events where consecutive daily flows remain below a Q95 (low flow events) and above a Q5 (high flow events) threshold, with the average and maximum deviation from threshold computed. The likelihood of record-breaking high and low flows across the 40-member ensemble is then computed by sampling for unprecedented outcomes for present-day and future time-slices across UK regions.
2. **Persistent dry/wet spells** – Prolonged wet or dry sequences across successive seasons can lead to temporally compounding impacts (Zscheischler et al., 2020). There is a current gap in understanding the chance of long-duration extremes and these rare events are not well sampled in short historical observations (e.g. multi-year droughts: Van Mourik et al., 2026). Previous work has explored the possibility of long runs of low precipitation and river flows in UK catchments using statistical methods (Wilby et al., 2015) but a comparable assessment using output from dynamical climate models and in future projections are lacking. Following Wilby et al., (2015), dry

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spells are identified as sequences of two or more consecutive dry (below average) or wet (above average) half-years for precipitation and river flows separately. Anomalies are calculated relative to 1991-2020 for the winter half-year (October-March) and summer half-year (April-September) for different hydroclimate regions of the UK and for river flows at individual catchments.

3. **Spatially coherent droughts** – Severe droughts affecting multiple English regions simultaneously have implications for water transfer schemes with widespread impacts on the environment (Murgatroyd et al., 2022; Tanguy et al., 2023). Contrasting trajectories of change in spatially extensive droughts within large ensembles can be stress tests for the water supply system. Here, spatially coherent droughts are identified using standardised monthly river flow anomalies (relative to 1991-2020) for each catchment following Rudd et al. (2017). Drought periods are months with negative anomalies (flow deficits) and standardised drought severity is drought duration multiplied by average deficit across the event. Regional droughts are defined as periods when at least 75% of catchments within each hydroclimate region are in severe drought (drought severity > 8), following the methodology in Tanguy et al. (2023).

## 3. Results

### 3.1 Bias adjustment

The CANARI-LE shows a notable dry bias in the August and September, wet bias in winter (especially southern areas) and spring and a mixed picture for other months across the UK (Figure 1a). For temperature and PET there is a notable cold bias in spring months and generally warm biases in other months (Figures S2-3).

The four bias adjustment methods applied for precipitation show different residual biases across different quantiles (Figure 1b). Linear scaling reduces the bias in average precipitation, keeping high residual biases (up to 40%) across different quantiles. Parametric quantile mapping (QM) utilises a fitted Gamma distribution but fails to adequately represent the observed distribution and shows large residual biases (up to 25%) in both lower and higher quantiles, notably showing a positive bias in extreme precipitation. Across evaluated quantiles, the EQM and ISIMIP methods produces the smallest residual biases (<10%).

Projected changes in precipitation show wetter winters with more intense precipitation events, with average seasonal precipitation increasing by approximately 5±5% at 2°C warming and 13±5% at 4°C warming across the CANARI-LE (Figure S4). Projected maximum 5-day precipitation (Rx5, Figure S5) increases by 3±3% and 11±4% for the two GWLs respectively. Spring shows small changes in average precipitation (1±5%, 0±5% at 2°C and 4°C GWL), with a modest increase in Rx5 (2±4% and 4±3% at 2°C and 4°C GWL) and decrease in wet day frequencies (-1±4% and -4±4% at 2°C and 4°C GWL), suggesting an increase in more intense precipitation events. Summer projections show a strong drying signal -

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seasonal averages decrease by -7±5%, -16±4% at 2°C and 4°C GWL, accompanied by reductions in Rx5 and wet day frequencies, indicating both lower total precipitation and longer dry periods. Only modest ensemble mean changes are projected for autumn and spring precipitation.

The influence of bias adjustment methods on these projected climate change signals is generally small compared to the spread of the projected change. Linear scaling best preserves the trends of the raw ensemble, as the multiplicative adjustment does not modify the distribution significantly. QM, EQM and ISIMIP all introduce small changes to the projected climate change signals; QM introduces the largest deviations by strengthening winter wetting and summer drying while EQM and ISIMIP provide the best balance between bias reduction and trend preservation.

The following results are shown for hydrological simulations driven by meteorological variables bias-adjusted using the ISIMIP method (for precipitation) and linear scaling (for temperature. Bias-adjusted precipitation using the other methods are provided in the open-access dataset (see Data Availability).

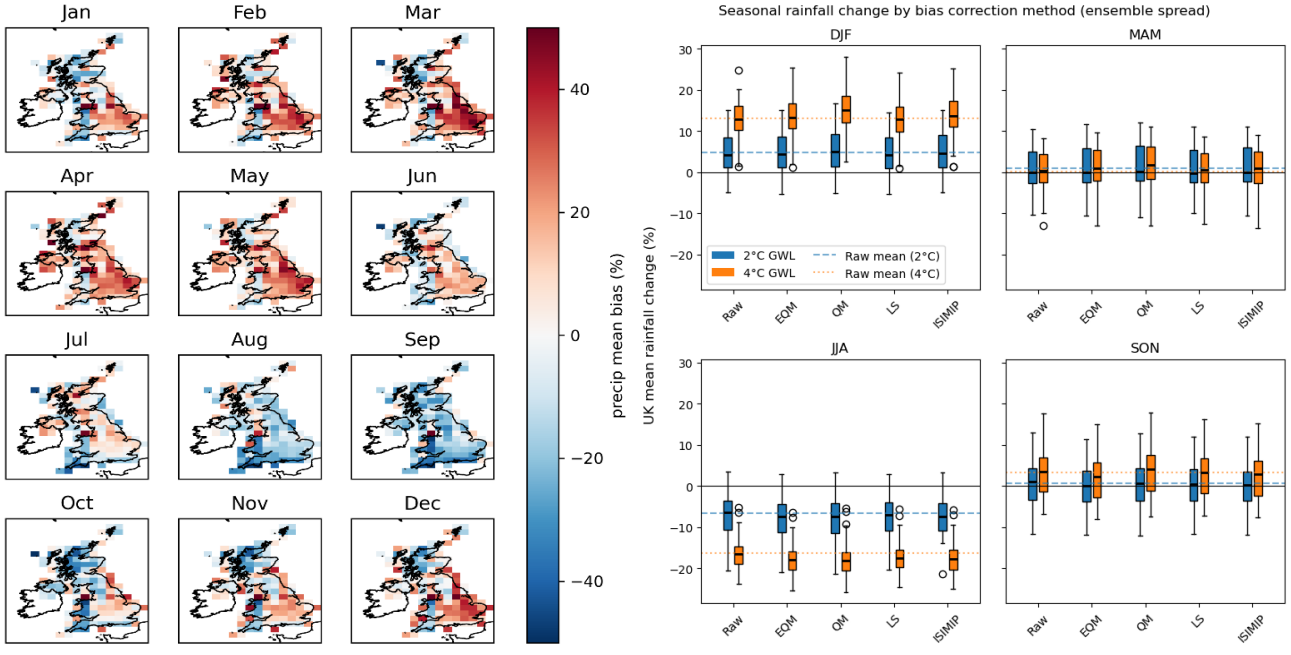



**Figure 1 (a) Monthly percentage bias in precipitation between the pooled ensemble mean of the CANARI-LE compared to HadUK-Grid and (b) UK-averaged seasonal changes in precipitation projected under 2°C and 4°C GWL for the original (raw) data and the four tested bias adjustment methods shown as boxplots representing the spread across the ensemble members.**

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### 3.2 Hydrological model performance

Hydrological model performance is assessed for each catchment model separately for all catchments with at least 30 years of observed river flow data for the 1970-2022 period. All catchment models perform adequately for most UK catchments (Figure 2; other model performance metrics are shown in Figure S6 for all models individually). Model performance for G2G are not explicitly assessed as it is not calibrated specifically to individual catchments and simulates natural flows. The suitability of G2G across catchments in Great Britain was demonstrated in previous studies (e.g. Bell et al., 2009; Rudd et al., 2017). To complement simple metric thresholds, a benchmark is used to help filter catcments with adequate model performance based on an a-priori expectation that for each catchment, individual models should exceed a simple lower benchmark defined as the mean flow for each calander day across the observed period, following Knoben (2024).

Figure S7 shows the spatial distribution of model performance which tends to be higher in northern and western catchments with biases in low flows generally higher than for high flows. Lower performance was seen at some outlier catchments in the southeast primarily attributed to groundwater dynamics (e.g. inter-catchment transfers) and strong anthropogenic influences on river regimes (e.g. Hannaford et al., 2022). Some catchments in northeast Scotland benefits from snowmelt accounting in GR6J and HBV with poorer performance for the four FUSE models where snowmelt processes are not included.

In the full open-access dataset, a catchment is included for an individual hydrological model if it passess a simple model benchmark test, achieves a KGE2 score above 0.75 over the SimObs 1970-2022 period and has absolute percentage bias in average flows below 20%. As hydrological model performance varies by model, the available catchments differe for each model: GR6J (642), HBV (610), TOPMODEL (587), ARNO (618), PRMS (601) and Sacramento (610). For G2G, all catchments in Great Britain that is successfully modelled by at least one catchment model are included (519), excluding small catchments with areas <50km$^2$ (See Data Avaialbility).

For consistency and intercomparison, only a subset of the full catchment list from the CANARI-LE hydro-SMILE dataset is analysed for this paper. All analysis in this paper includes catchments where all six catchment models satisfy the performance criteria outlined above (563 catchments in total). For G2G, catchments selected for inclusion in this paper are the overlapping catchments in Great Britain (461).

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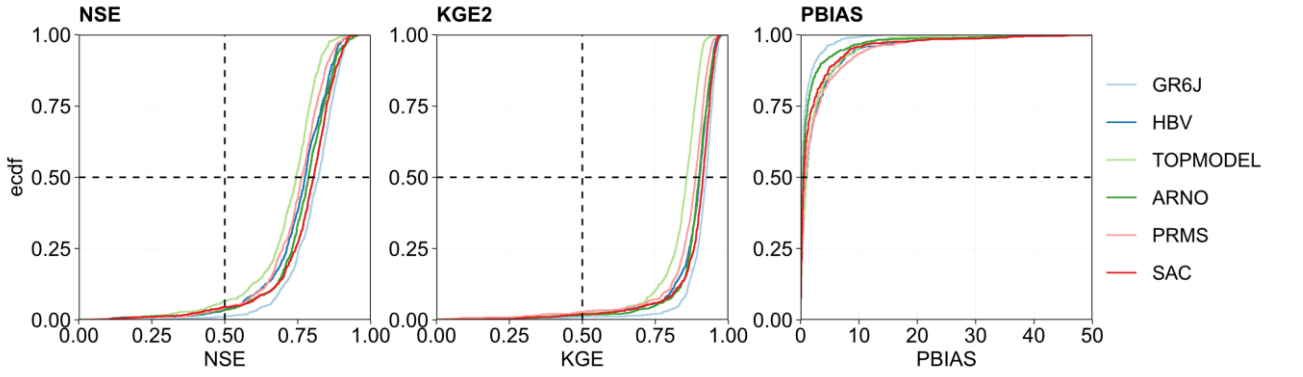



**Figure 2 Model performance assessed with NSE, KGE2 and PBIAS (%) across all CAMELS-GB and Northern Ireland catchments shown as Empirical Cumulative Distribution Function (ECDF), for the six catchment hydrological models (coloured lines). Further evaluation metrics are shown in Figure S6 for each hydrological model. Note simulated results from G2G are not plotted here as G2G is not calibrated specific to catchments but are parameterised at the national scale and simulates natural flows.**

### 3.3 National-scale hydrological changes

Figure 3 shows projected change in UK-averaged seasonal mean river flows for each hydrological model across the 40-member ensemble. Only catchments that are overlapping with the eFLaG ensemble driven by UKCP18 are plotted to enable comparisons with previous national projections at different GWLs. In the CANARI-LE hydro-SMILE, summer flows are projected to decrease with substantial warming, with only a few individual members, and for some hydrological models, simulating an increase in summer flows at 2°C GWL relative to the reference period. The ensemble mean indicates a reduction in autumn flows but there is less agreement amongst ensemble members for projected changes in spring where UK-averaged changes span both positive and negative, with the ensemble mean giving a "washed-out" signal near zero, particularly for 4°C GWL. Compared with the GR6J simulations from the eFLaG ensemble (UKCP18 Regional PPE), projected changes in the CANARI-LE hydro-SMILE generally spans a larger range, particularly for the winter and summer. The spread of changes between ensemble members within the CANARI-LE hydro-SMILE are larger than that between hydrological model structures but there are notable differences, such as TOPMODEL projecting lower reduction in summer flows particularly at 4°C GWL.

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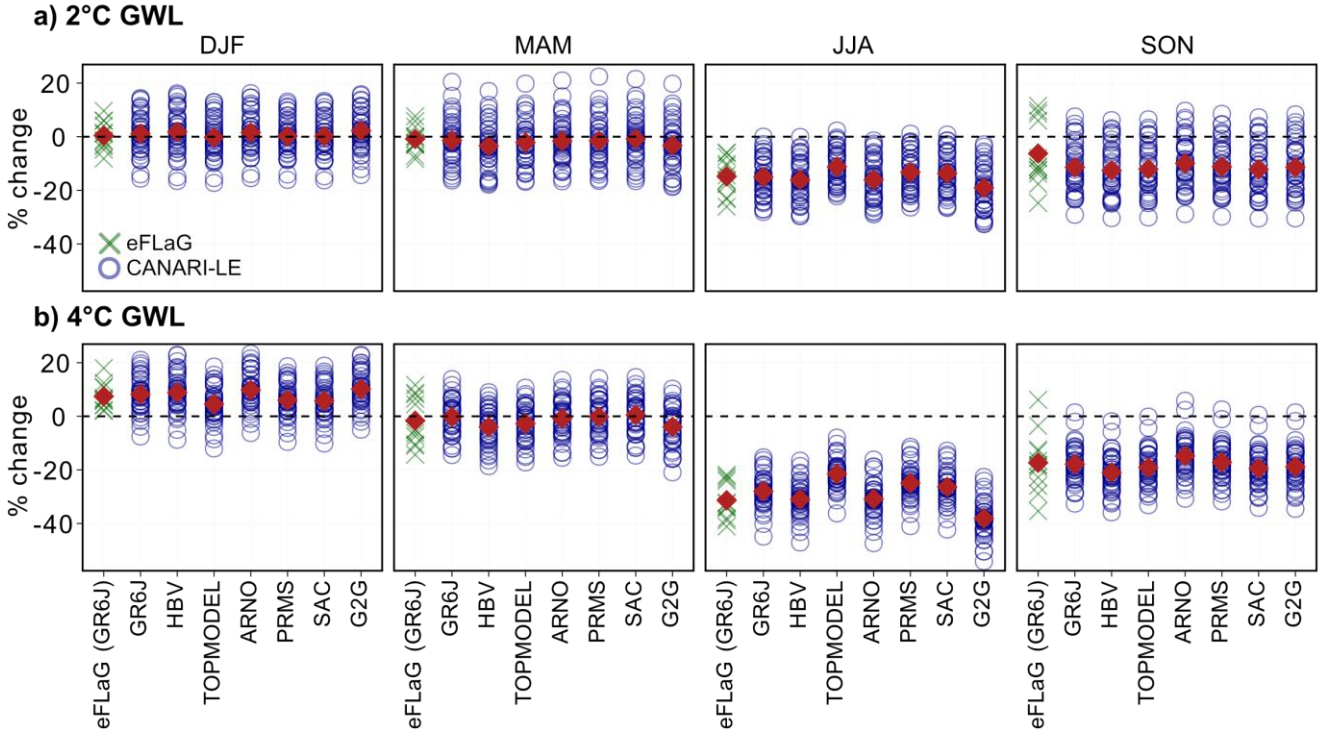



**Figure 3 Change in seasonal river flows for a) 2°C and b) 4°C GWL. Each panel shows the UK-averaged change in river flows for all seasons across the 40-ensemble members for the seven hydrological models (blue circles). Only catchments that are also included within the eFLaG ensemble driven by UKCP18 are selected to calculate the UK average. Green crosses in each panel shows a comparison with the equivalent projected changes within the eFLaG ensemble driven by the UKCP18 Regional PPE projections (12-members). Red diamonds show the ensemble median for each hydrological model projection.**

Figure S8 and S9 shows changes in Q5 and Q95, respectively, across UK catchments for all hydrological models at 2°C and 4°C GWL for the 10$^{th}$, 50$^{th}$ and 90$^{th}$ percentile across the CANARI-LE hydro-SMILE. Results suggest a large range of high flow changes within the 40-member ensemble, with changes ranging from large declines across southern and eastern Britain to widespread increases in high flows at 4°C GWL. Conversely, there is relative agreement across the full ensemble over a decline in low flows with warming but the spread across the ensemble remains large, with changes ranging from widespread decline of >50% to more modest reductions at 4°C GWL. The spatial pattern of changes is consistent across hydrological models but larger differences in the magnitude of change are observed for low flows.

Across all catchments, average projected change varies spatially across hydroclimate regions of the UK and between ensemble members (Figure 4). In northern and western regions, changes in Q5 at 2°C GWL are mixed while more ensemble members agree on a reduction for southeastern regions. More ensemble members show an increase in Q5 for northern and western catchments at 4°C GWL. There is widespread reduction in Q95 across all regions for both GWLs and all ensemble

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members, particularly for southern areas. The magnitude of change at 4°C GWL is higher and differences between hydrological models are more notable for Q95 compared to Q5 (e.g. TOPMODEL projecting smaller reductions in Q95 across most regions compared to HBV and G2G).

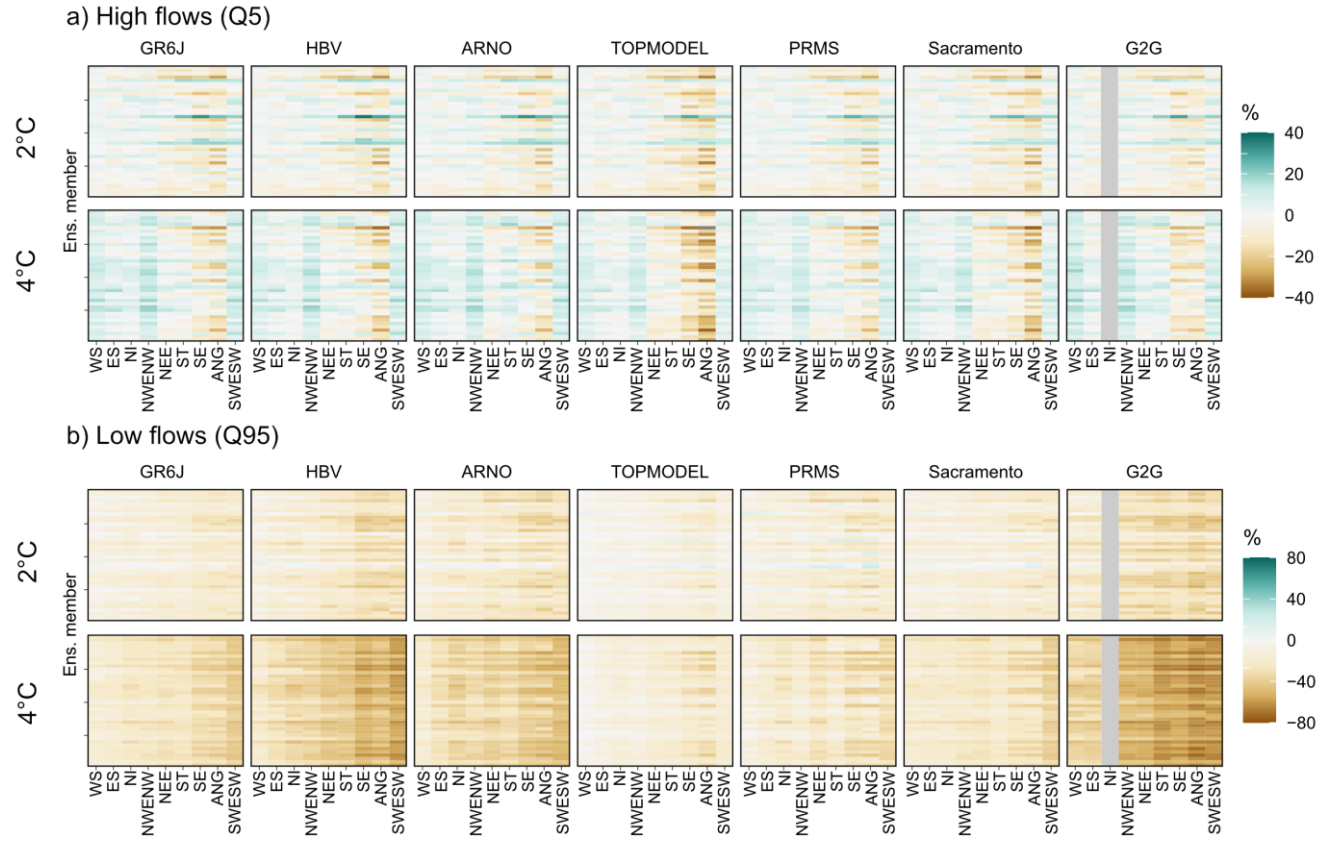



**Figure 4 Change (%) in a) high flows (Q5) and b) low flows (Q95) for 2C and 4C GWL for each of the six catchment hydrological models and G2G relative to 1991-2020. The x-axis represents nine hydroclimate regions as shown in Figure S1 and the y-axis shows the change for each of the 40 ensemble members. Note that Northern Ireland is not included in the G2G simulations. Results are averaged across all catchments which passes the model performance criteria for all six catchment hydrological models. For the purposes of visualisation, only river flow projections driven by bias-adjusted climate data (ISIMIP method for precipitation and linear scaling for temperature) are shown.**

### 3.4 Record-breaking extremes

SMILEs robustly characterise the effect of internal variability, making them ideal for assessing the rarity of historical trends and placing them in wider context (Chan et al., 2025; Jain et al., 2023; Shaw et al., 2024). Whilst long-term anthropogenic warming is robustly detected, river flow trends are often more equivocal (e.g. Hannaford et al., 2024). Figure 5 shows that

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robust increasing and decreasing trends in annual mean river flows over the full historical period (1955-2014) are all possible across the large ensemble and could have happened simply by chance, suggesting the large effect of internal variability in masking externally forced climate-driven trends. In the historical observation period, there has been a positive trend in UK-averaged annual mean flows in the SimObs simulations. This historical trend sits within the wider distribution of modelled trends from the CANARI-LE hydro-SMILE over this period for all hydrological models (Figure S10). Hence, results suggest a strong potential for wetting and drying trends arising from internal variability, recognizing that historical observations are a single realisation out of many that could have occurred by chance.

Extreme high and low flow events extracted across the pooled ensemble for several example catchments show a high potential of record-breaking events with greater intensity that could arise in the present-day climate simply by chance (Figure S11). There is an increasing likelihood of annual high and low flows breaking the historical record (in SimObs) across the UK with warming (Figure 6). Record-breaking high flows increases in likelihood in northern and western regions for the near- (2021-2050) and far-future (2051-2080) while the chance remains stable or slightly declines for other regions (e.g. Severn Trent, Anglian and Southeast). Record-breaking low flows becomes more likely with warming across all regions, with higher likelihood across Southern Britain, although there is considerable spread across the 40 members, suggesting the large effect of internal variability on the occurrence of record-breaking extremes. The chance of record-breaking flows differs across hydrological model, especially for low flows, but generally show an increasing chance of record-breaking low flows and mixed changes for high flows with warming (Figure S12).

In summary, the CANARI-LE hydro-SMILE ensemble members provide multiple realisations of climates purely due to internal variability. A wide range of plausible river flow trends places past observations in context. The expanded archive of plausible extreme flow events contains unprecedented high and low flows not seen in historical observations with their likelihood increasing with warming across most regions.

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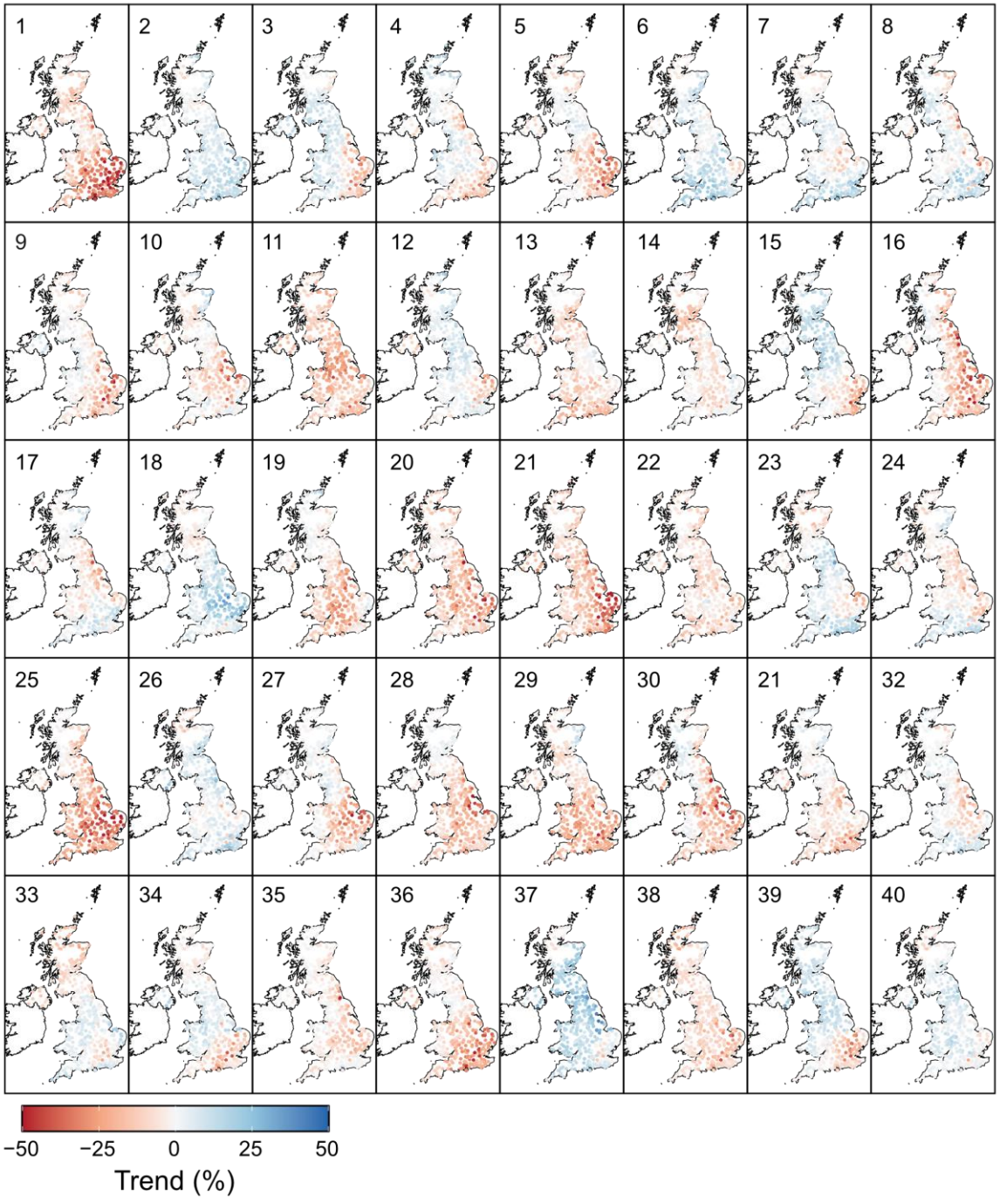



**Figure 5 Relative trend magnitude (%/60-years) in annual mean simulated river flows over 1955-2014 across UK catchments for each of the ensemble member of the 40-member CANARI-LE hydro-SMILE. Only catchments that passess the model performance threshold for all six hydrological models are included. Results from the GR6J hydrological model are shown here for visualisation purposes.**

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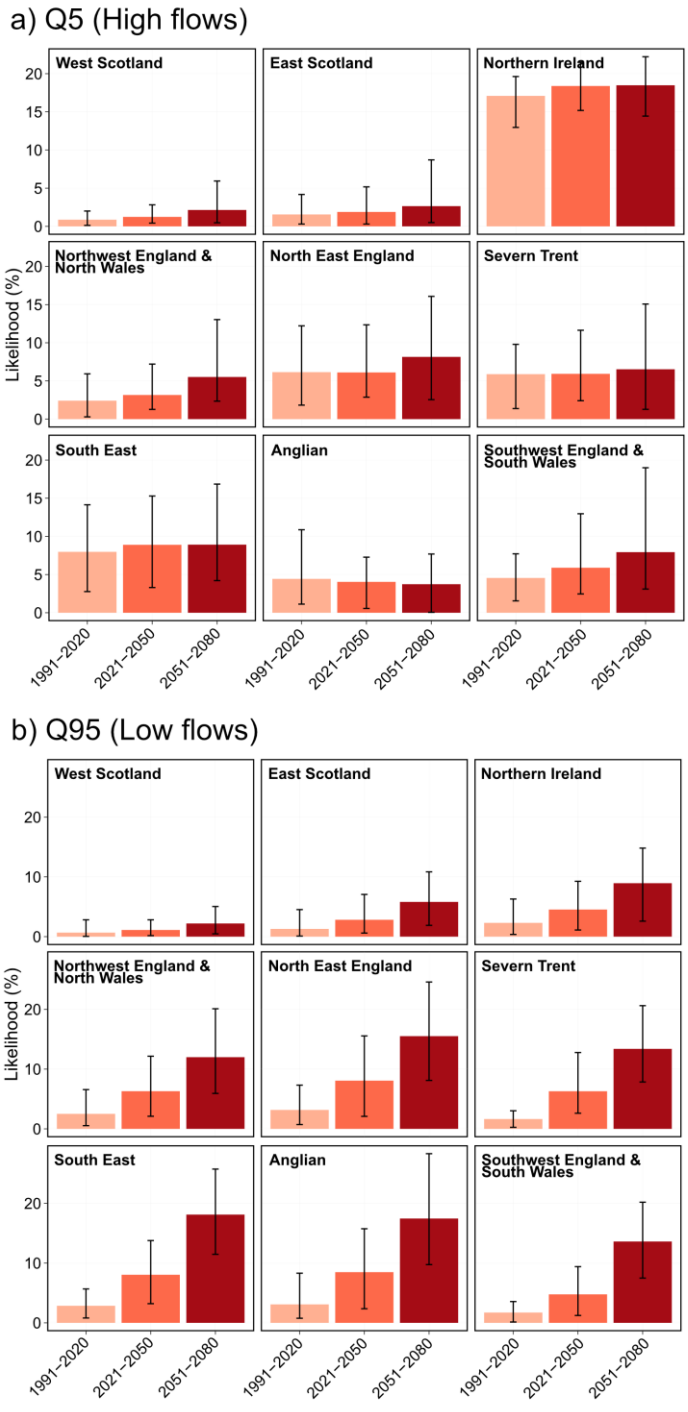



**Figure 6 Chance of record-breaking high and low flows averaged across catchments within each hydroclimate region for three time slices. Record-breaking annual Q5 and Q95 is assessed against the highest Q5 and lowest Q95 value in the SimObs period for each catchment. The error bars indicate the spread across the 40 ensemble members.**

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### 3.5 Sampling for persistent dry/wet spells

Given the rarity and long duration of persistent dry and wet spells, pooling ensemble members from a SMILE can quantify the likelihood of their occurrence (Bevacqua et al., 2023). Figure 7a and b shows the distribution of consecutive dry and wet half-years (based on precipitation) of increasing duration for the baseline, 2°C and 4°C GWLs across the pooled CANARI-
395 LE for the western Scotland and the Anglian regions, chosen to represent contrasting climate conditions. In both regions, the likelihood for three or more consecutive dry half-years increases, especially for the Anglian region where rare dry spells can reach >10 dry half-years in a row (~5 years). The likelihood of 2-3 consecutive wet half-years also increases with warming, but the likelihood of more consecutive wet half-years generally decreases or remains similar to the baseline period for both regions.

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Applying the same approach for persistent wet and dry river flow sequences at contrasting catchments show the potential for rare, persistent dry spells in a warmer climate, with some events at 2°C and 4°C GWLs lasting >15 half-years or longer (i.e. >7 years) possible for the slow-responding groundwater-dominated Stringside catchment in East Anglia (Figure 7c). Conversely, both catchments suggest an increasing likelihood of multi-season wet spells (2-3 wet half-years) with warming
405 but an overall reduction in long duration wet spells beyond 3 half-years. Across hydroclimate regions, the average length of consecutive wet half-years at 2°C and 4°C generally remains similar to the baseline for most northern and western areas but reduces for southern regions (Severn Trent, South East, Anglian and Southwest England and South Wales) (Figure 8a). The average length of consecutive dry spell increases in all regions, with particularly large changes for catchments in Severn Trent, South East and the Anglian regions (Figure 8b).

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In summary, the value of a hydro-SMILE is apparent when sampling for temporally compounding events, such as prolonged wet/dry sequences. Rare long-duration sequences sampled within the CANARI-LE hydro-SMILE can be used as worst-case stress tests. Assessing a large diversity of rare long-duration events were hitherto not possible given small ensemble sizes of existing river flow projections.

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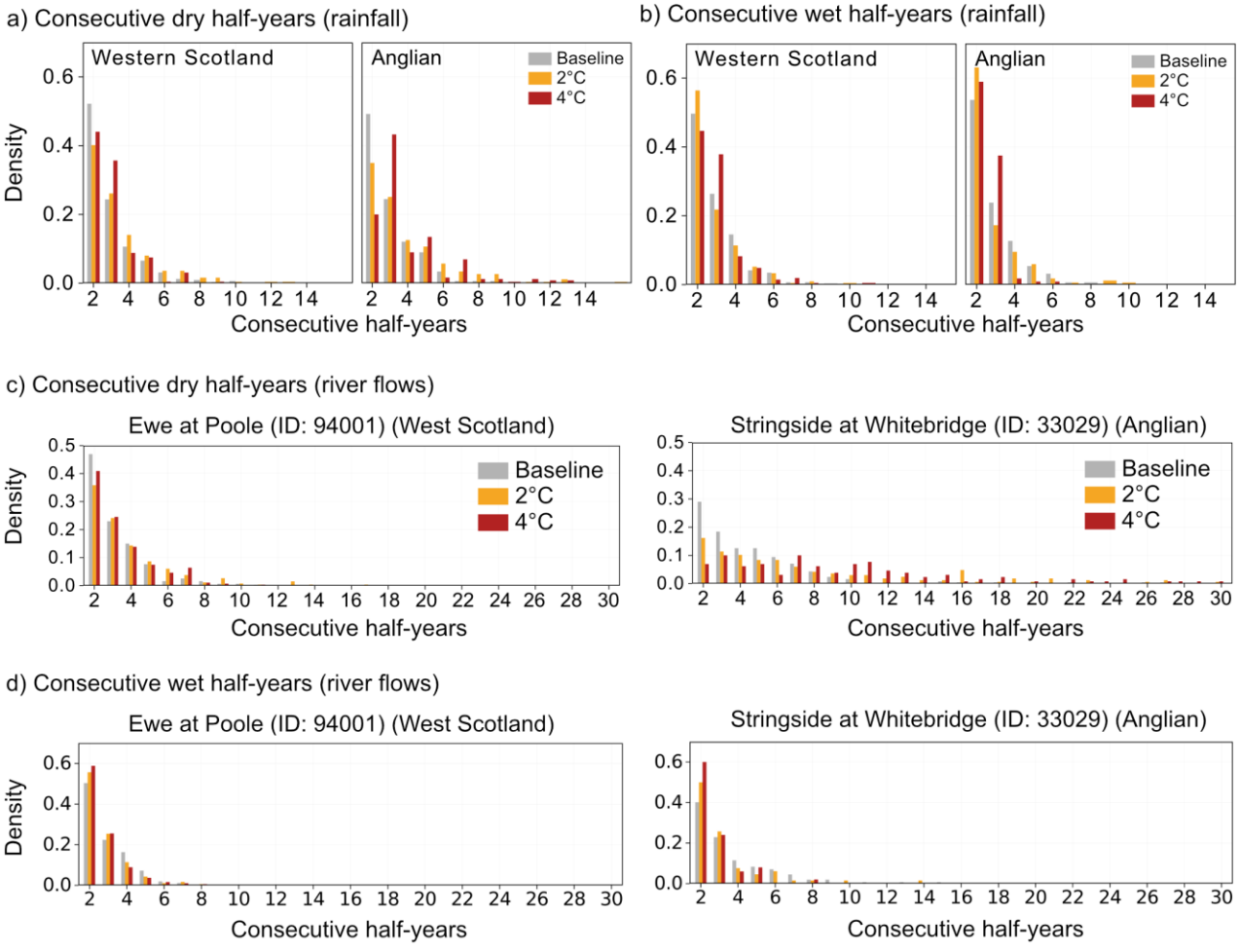



**Figure 7 Distribution of consecutive dry and wet half-years of different durations sampled within the CANARI-LE hydro-SMILE for the baseline (1991-2020), 2C and 4C GWL. Panel a) shows the probability of consecutive dry half-years of various lengths for the west Scotland and Anglian regions by pooling all ensemble members and panel b) shows the equivalent for consecutive wet half-years. Panel c) shows consecutive dry half-years defined with river flows for two contrasting catchments in west Scotland (Ewe at Poole) and Anglian (Stringside) and panel d) shows the equivalent for wet half-years. Results are only shown for the GR6J hydrological model for visualisation purposes.**

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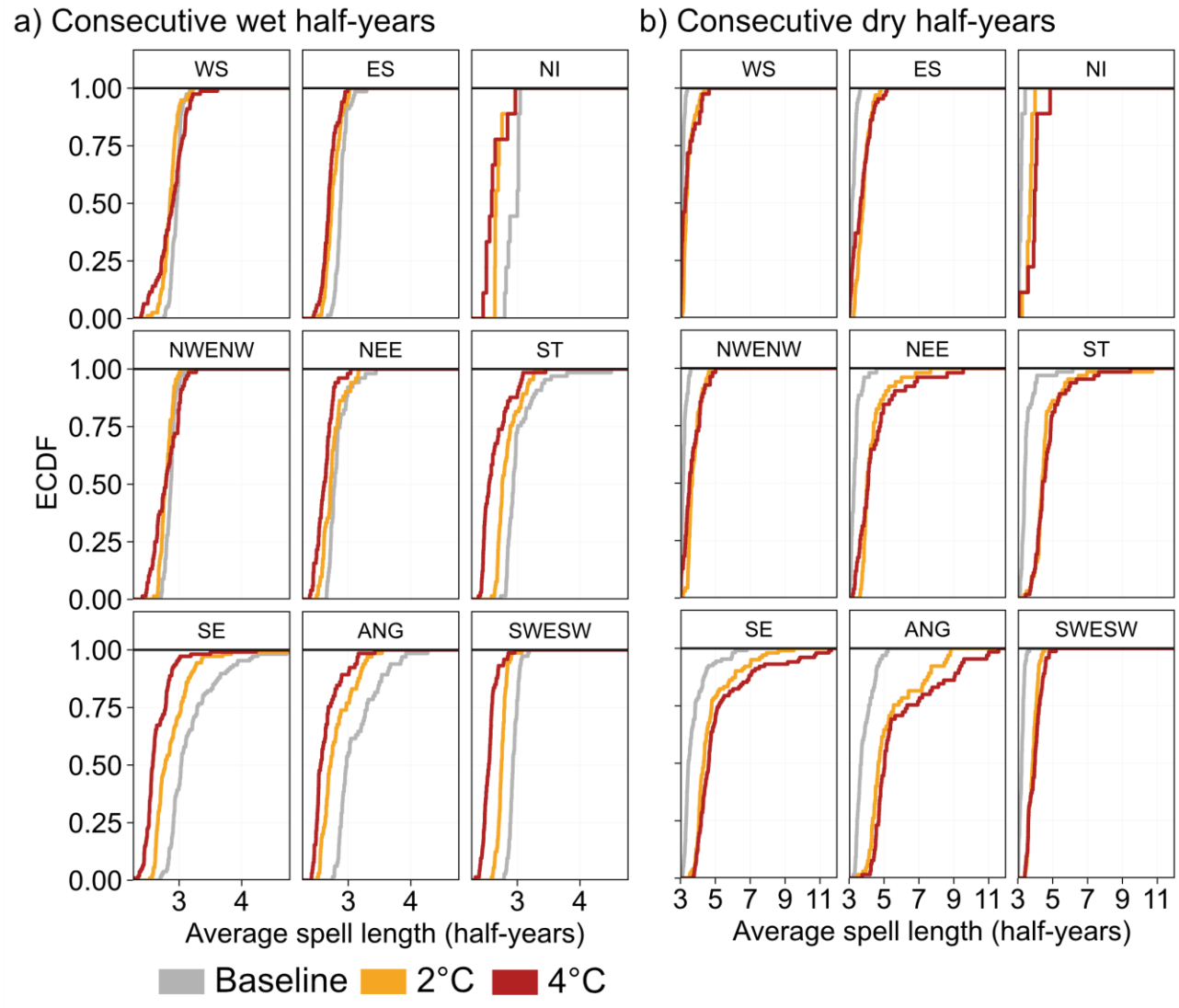



**Figure 8 ECDF of average length of consecutive a) wet and b) dry half-years of different lengths across each hydroclimate region for the baseline period, 2°C and 4°L GWLs (coloured lines). Results are only shown for the GR6J hydrological model for visualisation purposes.**

### 3.5 Spatially coincident droughts

Quantifying the risk of coincident occurrence of severe droughts over multiple regions is crucial for water resources management. Studies of the spatial coherence of UK droughts using earlier UK climate projections found increases in widespread summer droughts but could not quantify the possible range of internal variability (e.g. Rudd et al., 2017; Tanguy

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et al., 2023). Figure 9a shows that the median likelihood of a severe drought affecting the selected regions in England and Wales simultaneously generally increases with warming although there are considerable differences between ensemble members. Large overlaps between the likelihood in the baseline period and that for future GWLs time slices indicates that large ensembles are required to disentangle climate-driven changes from internal variability.

Results from a hydro-SMILE can also inform the development of event storylines, where uncertainties in internal variability can be communicated via multiple discrete plausible future pathways (Shepherd, 2019). Figure 9b shows a 30-year rolling mean of the total number of catchments in the Severn Trent and Anglian regions in severe drought simultaneously over time. Any two randomly selected ensemble members can exhibit large differences in the frequency of widespread droughts under the same long-term externally forced climatic conditions. The ensemble mean signal shows an increasing trend of spatially widespread droughts across both regions, but distinct diverging storylines suggest the potential for plausible, albeit rare, extreme realisations of spatially coincident droughts that are equally possible by chance and may not be captured by small sample sizes. For example, a "high-impact" storyline could see a high number of catchments in severe drought at the same time in the 2070s while a contrasting "low-impact" storyline is equally likely in which a lower proportion of catchments are in simultaneous drought throughout the 21st century.

In summary, the average likelihood of spatially widespread droughts increases with warming. Diverging future trajectories of coincident droughts are equally likely; a large sample size is necessary to sample for widespread droughts as their occurrence are under-sampled in multi-model ensembles relative to internal climate variability.

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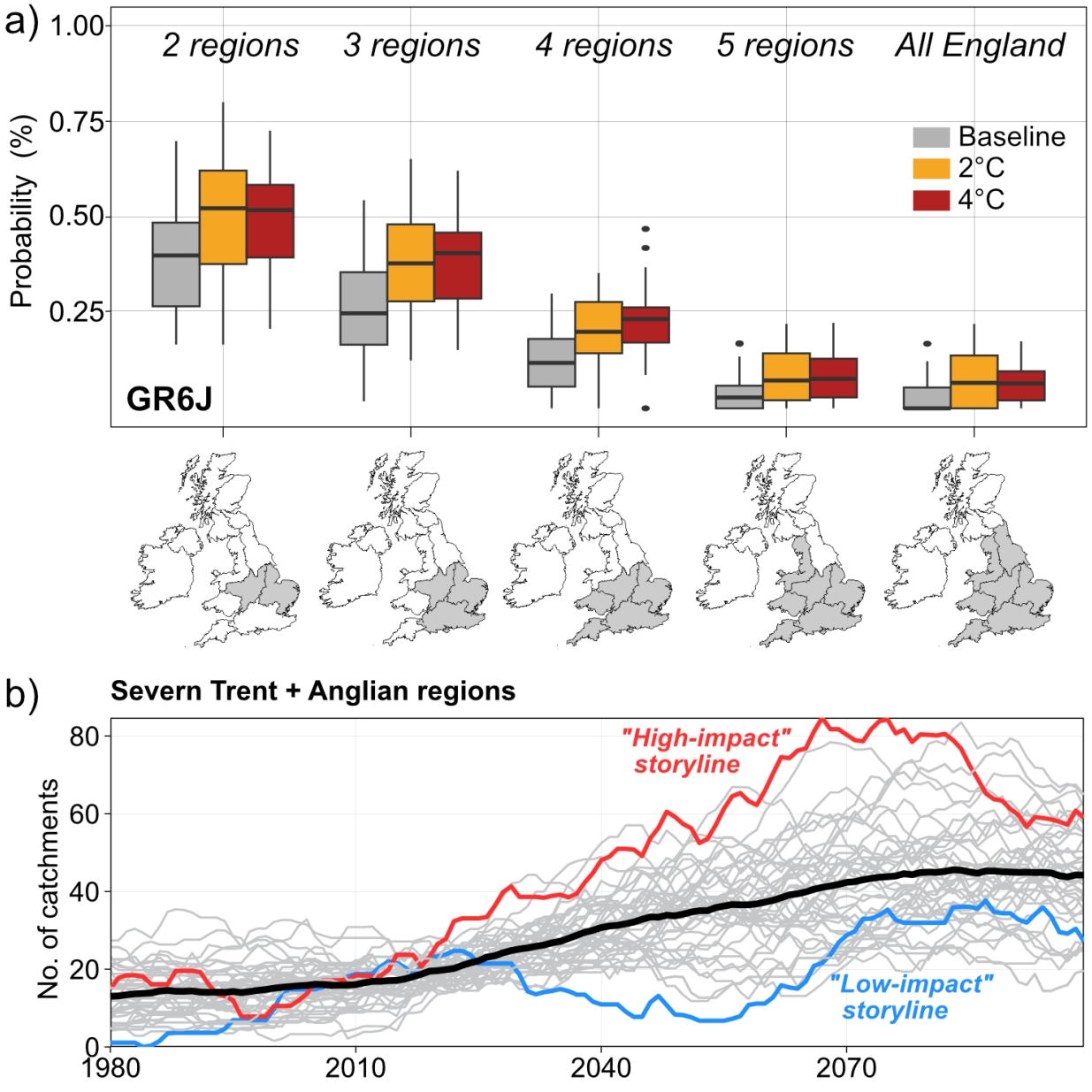



**Figure 9 a) Probability of a given severe hydrological drought affecting multiple regions simultaneously, in England and Wales, for the baseline, 2°C and 4°C GWL across the pooled CANARI-LE hydro-SMILE (coloured boxplots). The inset maps show the corresponding regions in drought at the same time. Spread of the boxplot indicates the range of the ensemble members. Panel b) shows 30-year rolling mean of the total yearly number of catchments in the Severn Trent and Anglian regions in drought at the same time for each ensemble member (coloured lines). Two contrasting ensemble members based on 2°C GWL with a relatively low chance of coincident droughts (i.e. "low impact" storyline in blue) and a high chance of coincident drought (i.e. "high impact" storyline in re) are identified with the black line showing the ensemble mean and grey lines showing other ensemble members. Results are only shown for the GR6J hydrological model for visualisation purposes.**

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## 4. Discussion

### 4.1 CANARI-LE hydro-SMILE dataset

The new CANARI hydro-SMILE dataset complements and updates past national river flow projections and contributes to the increasing availability of hydro-SMILEs across Europe (e.g. Brunner et al., 2021; Poschlod et al., 2026; Willkofer et al., 2024) and globally (e.g. Faghih and Brissette, 2023; Mankin et al., 2017). It provides a larger sample size compared to existing projections with 40 ensemble members over 145 years (i.e. 5800 years of simulated river flows; ~4.7 times the number of years compared to eFLaG) and its fully transient nature (daily simulated flows from 1955-2099) is an advancement compared to most previous time-slice or "stitched" large ensemble datasets in the UK. Combined with a more widespread catchment selection, this new dataset aims to maximise the potential for using transient projections in decision-making with the sampling of a more diverse range of future extremes and a greater ability to appraise their physical plausibility and climate drivers (Durant et al., 2024).

Several bias adjustment techniques were used to adjust systematic biases in the CANARI-LE, recognizing that some form of bias adjustment is required for results from hydrological modelling to be interpretable. However, selecting the appropriate bias adjustment method is challenging given stationary assumptions based on an arbitrary historical period and the univariate nature of most methods (Spuler et al., 2026; Teutschbein and Seibert, 2012). Some methods alter ensemble spread and artificially affect climate-driven signals (e.g. Vaittinada Ayar et al., 2021). To preserve the ensemble spread (and the range of internal variability), we derived adjustment factors from the pooled ensemble, following recommendations from Astagneau et al. (2025), rather than bias correcting each ensemble member independently. Our evaluation demonstrates that the choice of bias adjustment method involves balancing residual biases with respect to observed distributions against preservation of projected climate change signals. Linear scaling of precipitation data best preserves the original ensemble trends but retains significant biases in different distribution quantiles. Quantile mapping methods reduce residual biases but may alter projected changes in extreme events. Local applications of the CANARI-LE may require different approaches and/or bias adjustment methods for specific variables of interest to develop locally relevant storylines and to enhance credibility and close the "usability-gap" identified in Spuler et al. (2025).

It should be noted that the SSP3-70 shared socio-economic pathway differs from the RCP8.5 radiative forcing scenario that is widely used in previous UK river flow projections. While both scenarios represent strong warming and high emissions that likely results in worst-case outcomes, comparisons between them are non-trivial given differences in greenhouse gas concentrations and other emission sources (Meinshausen et al., 2020). The underlying GCM (HadGEM3) of the CANARI-LE belongs to the same family as that used in the UKCP18 Regional projections and, on average, tends to be hotter and drier compared to other climate models (Arnell et al., 2021; Lane et al., 2026). Other initial condition ensembles driven by different GCMs (and regional hydro-SMILEs) are increasingly available; inter-model comparisons may further disentangle

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climate signals with internal variability and guard against conflating differences in model structural uncertainty with that of internal climate variability (Mankin et al., 2020).

The relatively coarse native resolution of the CANARI-LE has implications particularly for the simulation of high flows such as short-duration localised events in small catchments. On-going work is investigating differences in high flows for specific events where dynamically downscaled simulations at regional (12km) and convection-permitting (2.2km) resolutions are used as input data to the same suite of hydrological models. Future work also seeks to apply the CANARI-LE to develop hydro-SMILE projections across the Irish Isles and elsewhere to better disentangle internal variability and climate-driven hydrological changes at larger domains, using a consistent driving large ensemble climate dataset.

Users of the dataset are encouraged to evaluate the appropriate model and/or catchment(s) based on their variable of interest. Individual applications using this dataset will likely require a choice of hydrological model and catchments based on specific performance metrics or different hydrological quantities of interest. While a consistent set of catchments is presented in this paper, the available catchments included in the open-access CANARI-LE hydro-SMILE dataset differ between each hydrological model as model performance was assessed for each model individually. For G2G, data for all catchments that are modelled by the six catchment models are provided, excluding catchments in Northern Ireland and those with small areas ($<50 km^2$). The inclusion of different hydrological models allows users to quantify and compare hydrological model structural uncertainty, which is expected to be largest for low flows, with climate change signals and other uncertainties along the modelling chain (e.g. observational uncertainties; Aerts et al., 2024). Some modelled catchments are heavily influenced by artificial influences, and model performance may be limited without explicit inclusion of reservoir effects, abstraction and discharges. Catchments may be filtered based on artificial influences (e.g. by consulting station descriptors "Factors Affecting Runoff" codes on the UK National River Flow Archive website) or guidance from the UK near-natural benchmark networks (UKBN; Harrigan et al., 2018).

### 4.2 New insights on UK hydrological extremes

At the national scale, the CANARI-LE hydro-SMILE projects on average wetter winters and drier summers with modest average changes for autumn and spring. However, the spread of projected river flow changes across the 40 ensemble members is large and is greater than past UK river flow projections driven by the UKCP18 Regional projections (eFLaG). The spatial pattern of changes is consistent between hydrological models but larger differences in the magnitude of change are seen for low flows. Compared to UKCP18 Regional, the overall ensemble range of the CANARI-LE hydro-SMILE might overlap more with CMIP6 multi-model ensembles, suggesting that internal variability is responsible for some of the differences between model ensembles, although a detailed intercomparison study such as Lane et al., (2026) is needed.

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This study applied the newly developed dataset to tackle a number of identified scientific gaps related to unprecedented extremes with relevance for risk planning. Unlike past ensembles, the CANARI-LE hydro-SMILE robustly isolates the range of internal variability on hydrological extremes, showing the wide range of possible wetting and drying trends. Plausible trends over the historical period places observed hydrological trends in context and aids model evaluation (Chan et al., 2025; Deser and Phillips, 2023). The CANARI-LE hydro-SMILE shows that the chance of record-breaking low and high flows exceeding that in the observed past increase with warming. Potentially large changes in long-duration spells (especially persistent dry spells in southern England) and spatially coincident droughts may result in significant impacts across sectors. The large ensemble spread confirms that large sample sizes are required to robustly sample their occurrence, echoing studies which showed the large role of internal variability on the occurrence of multi-year droughts for western Europe (Van Mourik et al., 2026; van der Wiel et al., 2022). The large overlap in potential changes between GWLs further suggests that adapting to lower warming levels does not fully discount the potential for extreme climate impacts given the role of internal variability (Bevacqua et al., 2026).

Rare events sampled from the pooled hydro-SMILE updates past assessments using statistical methods (e.g. long-duration extremes; Wilby et al., 2015). Current UK drought planning is largely based around historical variability (e.g. worst historical drought or events in stochastically generated replicates of historical climate). Exploring large ensemble river flow projections driven by initial condition climate ensembles may enable robust decision-making against a wider and more diverse range of possible events in both present-day and future climates (Counsell et al., 2025; Wilby, 2022). One advantage of the CANARI-LE hydro-SMILE is the availability of daily weather and river flow sequences that can be coupled with downstream impact models (e.g. water resources and/or water quality models). Further applications of the CANARI-LE hydro-SMILE could include targeted development of event storylines (Sillmann et al., 2021). For example, analogues similar to observed extreme floods or droughts can be sampled from the large ensemble to assess how similar events may have turned our worse and how they could unfold in future climates (e.g. floods: Thompson et al., 2025 and droughts: van der Wiel et al., 2021; Chan et al., 2023). A library of rare and counterfactual storylines could inform reasonable worst case scenarios (e.g. UK National Risk Register; HM Government, 2026).

The CANARI-LE hydro-SMILE is based on a physically-based dynamical climate model, which enables the appraisal of physical plausibility by analysing the associated climate drivers and teleconnection patterns (e.g. Chevuturi et al., 2025; Kay et al., 2020; Kelder et al., 2022; Suarez-Gutierrez et al., 2023). While an initial condition large ensemble is more robust at sampling for rare extremes and includes long-duration extremes, challenges in simulating some atmospheric processes in climate models remain (e.g. persistence of atmospheric blocking) (Schiemann et al., 2020). For example, the occurrence of long-duration extremes could be under-estimated and climate teleconnections during extreme events may be less well represented. Recent research has suggested that existing climate model ensembles (e.g. the HadGEM3 GCM underpinning the CANARI-LE) reproduces observed trends in winter precipitation to some extent but under-estimates its magnitude due to

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biases in the variability of driving weather patterns which will result in potential biases in winter river flow variability and persistence (Carruthers et al., 2026b, a). A priority of future work is thus to appraise the physical plausibility of climate drivers responsible for extreme events sampled within the CANARI-LE hydro-SMILE and compare them with known climate drivers of past observed events. This can form one line of evidence to increase confidence in the plausibility of rare events sampled within the CANARI-LE hydro-SMILE and to inform the appropriate events for stress tests and risk assessments (Counsell et al., 2025; Kelder et al., 2022).

## 5. Conclusions

This paper presents a large ensemble hydrological modelling approach for the UK to develop the CANARI-LE hydro-SMILE dataset. The CANARI-LE hydro-SMILE consists of 40-members, a significantly larger sample size than previous projections and simulations from seven hydrological models. The new dataset is designed to explore the uncertainty in river flow changes attributed solely to internal variability, suggesting its effects on hydrological extremes within a single climate model is large. National-scale river flow changes in response to warming projects on average wetter winters and drier summers but ensemble spread spans or exceed the uncertainty range of past perturbed parameter or multi-model ensembles.

Potential applications of the CANARI-LE hydro-SMILE are wide since climate adaptation across sectors are increasingly capable of deriving climate information from large climate model ensembles, which are currently widely based on UKCP18. The CANARI-LE hydro-SMILE for the UK offers a significantly larger sample size of rare extremes, with a robust quantification of the range of internal variability relative to the climate change signal. Exemplar applications specific to risk planning and water resources management shows that record-breaking high and low flows are estimated to increase in likelihood with warming, and large ensemble sizes are required to sample for rare extremes like persistent dry/wet spells and the occurrence of spatially widespread drought affecting multiple regions simultaneously.

The widespread use of single or a small number of climate model realisations, common in many impact modelling exercises, may risk under-sampling rare, physically plausible extremes that can only be captured by hydro-SMILEs. Nationally consistent river flow projections from the CANARI-LE hydro-SMILE can thus aid flexible and robust decision-making and broaden the range of hydrological extremes considered in past UK projections. Wide application of the dataset in other sectors to better understand the drivers and impacts of rare but physically plausible hydroclimate extremes can increase the UK's resilience in changing climate.

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## Code and data availability

Priority meteorological variables from the CANARI-LE are accessible via the Centre for Environmental Data Analysis (CEDA) repository (Schiemann et al., 2026; https://catalogue.ceda.ac.uk/uuid/4b62fafc68ae4c3784fb2819f652c537/). Version 0 of the CANARI-LE hydro-SMILE dataset is archived on Zenodo (DOI: https://doi.org/10.5281/zenodo.22958664) during peer review. The dataset archived includes catchment-averaged bias-adjusted meteorology and simulated river flows across UK catchments for the seven hydrological models. Please note that the archived dataset on Zenodo should be treated as preliminary during peer review and liable to changes; the final dataset after peer review will be permanently hosted on the open-access UKCEH Environmental Information Data Centre (EIDC) on the acceptance of this manuscript.

Observed river flow data for UK catchments can be obtained from the National River Flow Archive (NRFA) (https://nrfa.ceh.ac.uk/data/). UK precipitation and temperature data are available from the HadUK-Grid dataset (Hollis et al., 2019) and accessible via CEDA (https://catalogue.ceda.ac.uk/uuid/5a248096468640a6bfb0dfda8b018ac5/). HadUK-Grid based estimation of potential evapotranspiration (PET) follows the Hydro-PE method and is available from the UKCEH Environmental Information Data Centre (EIDC): https://doi.org/10.5285/beb62085-ba81-480c-9ed0-2d31c27ff196.

## Author contributions

WC processed the climate model data, led the catchment river flow modelling and curated the dataset. NM led the bias adjustment of the climate data and produced the bias adjustment figures. AK and RL produced river flow simulations from the G2G hydrological model. RL, AK and AC contributed to the derivation of climate model input to the hydrological models, including spatial downscaling, calculation of PET and bias adjustment. JH led funding acquisition and the overall UKCEH contribution to the CANARI programme. WC prepared the manuscript with contributions from all authors. All authors contributed to aims and objectives of the study.

## Competing interests

The contact author has declared that none of the authors has any competing interests.

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