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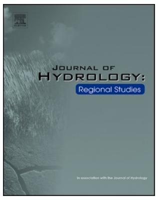

Climate change impact on hydrological droughts: Differences between two ensembles of regional climate projections across Great Britain

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ABSTRACT

Region: This is a national-scale study covering Great Britain.
Focus: Understanding the impact of climate change on hydrological droughts, and the uncertainty surrounding these projections, is crucial to support water resources management and adaptation planning. Research indicates potentially severe increases in hydrological drought for Great Britain, but most studies are underpinned by a single climate model structure through the widespread use of UKCP18 Regional projections. Here, we compare changes to hydrological droughts modelled using two different ensembles of regional climate projections (the EuroCORDEX-UK multi-model ensemble and the UKCP18 Regional perturbed-parameter ensemble) as input to a national-scale gridded hydrological model.
New Hydrological Insights: We find considerable differences in drought projections between the two ensembles, with UKCP18 Regional generally indicating more extreme scenarios. The EuroCORDEX-UK ensemble indicates little overall change to drought severity by 3 °C warming (-19 to +33%), with increases in drought intensity in some ensemble members generally offset by decreases in drought duration. By contrast, the UKCP18 Regional ensemble indicates large increases in drought severity (up to 73%), intensity and duration with only one member showing potential reductions. Both ensembles indicate increasing summer droughts, with most UKCP18 Regional ensemble members showing year-round increases in drought occurrence. Our results give context to previous studies based solely on UKCP18 Regional projections, and highlight the importance of considering climate modelling uncertainties in future drought impacts.
Plain Language Summary: Hydrological droughts, here defined as sustained periods of unusually low river flow, can have serious and long-lasting impacts that may be exacerbated by climate change. Nationwide drought projections are therefore needed to inform water resources management and adaptation planning. Much of the literature on climate change impacts for UK droughts is underpinned by a single climate model, yet models often disagree on seasonal precipitation and temperature changes. Here, we evaluate climate change impacts on droughts using two ensembles of regional climate projections for Great Britain (GB). The climate model data is used to drive a national-scale gridded hydrological model to simulate river flows and subsequently droughts. We find considerable differences in drought projections between the two climate ensembles. While projections from one ensemble indicate increasing drought severity, duration and intensity with increased global warming, the other ensemble indicates little change to GB-average drought severity. Spatial patterns also differed, with one ensemble highlighting

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south-east England as particularly vulnerable to increased drought severity, and the other ensemble suggesting a wider range of possibilities. However, most outputs point towards an increase in summer droughts. Our results give context to previous GB-wide drought projections and highlight the large climate uncertainties in future drought impacts.

1. Introduction

Droughts are a natural feature of the climate cycle of many regions worldwide, with impacts that can be long lasting and widespread (Van Loon, 2015). Broadly, droughts can be defined as sustained periods of below normal moisture conditions and subsequent limitations in water availability (IPCC, 2021). Within this, hydrological or streamflow droughts are periods of unusually low river flows, which can have serious impacts for water supply alongside other sectors such as crop production, power generation, and navigation (Van Loon, 2015). Compared to floods, where impacts are clear and obvious, droughts have been described as a “creeping disaster” with a slow onset leading to devastating impacts on the ecological system and economy (Van Loon, 2015).

Climate change is expected to exacerbate drought risk globally, with an intensification of the hydrological cycle leading to increased climate variability, lengthening dry spells, and more frequent and widespread extremes (IPCC, 2023). There are regional variations in projected climate change impacts for hydrological drought due to regional differences in climate projections and variations in catchment properties (such as wetness, geology, land-use, snow fraction), that exacerbate or mitigate how climatic changes propagate to changing river flows and subsequently droughts (Charlton and Arnell, 2014; Van Loon and Laaha, 2015). To manage drought risk and build resilient water supply systems, it is crucial that we understand how the characteristics of extreme drought events may change in response to global warming.

For Great Britain, projections generally indicate reduced river low flows and more severe droughts, albeit with variations in magnitude between studies (Cammalleri et al., 2020; Dobson et al., 2020; Forzieri et al., 2014; Lane and Kay, 2023, 2021; Parry et al., 2024; Rudd et al., 2019). Hotter, drier summers and less predictable rainfall could be expected to exacerbate droughts, although this may be mitigated by wetter winters replenishing stores (Hughes et al., 2021). Increases in drought severity could have major implications for water supply and water resources management, particularly alongside expected increases in population. Estimates suggest that without action there could be shortfalls in public water supplies of 5 billion litres per day by 2055 for England alone (Environment Agency, 2025).

A substantial portion of the literature on climate change impacts for low flows and droughts across Great Britain is based on the UK Climate Projections produced by the UK Met Office, specifically the perturbed-parameter ensemble (PPE) of regional climate model (RCM) projections that comprises UKCP18 Regional (e.g. Cloke et al., 2010; Hannaford et al., 2022; Lane and Kay, 2023, 2021; Parry et al., 2024; Reyniers et al., 2023; Smith et al., 2024). Other GB-wide studies looking at future drought and water scarcity have used the weather@home simulations (Dobson et al., 2020; Guillod et al., 2018; Rudd et al., 2019). Both UKCP18 Regional and weather@home are based on versions of the UK Met Office Hadley Centre climate model, and while the use of a PPE does capture some of the climate modelling uncertainties, they are ultimately based on a single climate model structure. Climate model choice is one of the largest sources of uncertainty in river flow projections (Addor et al., 2014; Vetter et al., 2017). Furthermore, the Hadley Centre model is known to sample the warmer end of possible outcomes compared to other CMIP5 models (Lowe et al., 2019), which could have implications for its representativeness when modelling low flows and droughts. Widespread use of the Hadley Centre model over other climate projections may therefore result in the literature not appropriately reflecting uncertainties in future UK droughts.

A broader range of high-resolution climate projections have recently been released for the UK. The EuroCORDEX-UK project have provided a large multi-model ensemble of climate model output at the same spatial and temporal domain as UKCP18 Regional projections, derived from the EuroCORDEX ensemble (Barnes, 2023). This presents an opportunity to explore how projections of future droughts underpinned by the UKCP18 Regional PPE compare to drought projections from a wider sample of global and regional climate models.

Future drought projections are typically presented as changes between baseline and future time slices. Since the Paris agreement of 2015, there has been a move towards characterising climate impacts for various levels of global warming from the pre-industrial period, rather than for set time-slices or emissions scenarios (Arnell, et al., 2021; Marx et al., 2018). Looking at changes between time-slices associated with different global warming levels (GWLs) can improve understanding of how much worse impacts may become if GWLs continue to rise. This approach also has benefits when comparing simulations between different climate models as, 1) it accounts for the warming that has already occurred before any ‘baseline’ period, 2) it allows a fairer comparison of variations in local impacts between models with different global climate sensitivities, and 3) it removes the focus on emissions scenario.

Here, we model climate change impact on drought characteristics across Great Britain at different GWLs and between a fixed baseline and future period. We include EuroCORDEX-UK climate data alongside the more widely applied UKCP18 Regional projections to give context to previous UK drought impact studies based solely on UKCP18 Regional.

Our research questions are:

- What are the projected changes in hydrological drought severity, duration, intensity, frequency and seasonality across Great Britain?
- Are there substantial differences in drought impacts derived from different climate model ensembles?
- What further changes to drought characteristics do we see at GWLs of 2 °C and 3 °C, compared to 1 °C warming?

To answer these questions, we analyse river flow simulations produced using UKCP18 Regional and EuroCORDEX-UK climate data to drive a national-scale grid-based hydrological model across Great Britain (Kay, 2025). We extract drought events from monthly mean flows using a threshold approach and then explore how drought characteristics change between specified time slices. These results will help to inform UK climate and adaptation policy by providing context for previous research based solely on UKCP18 Regional, and also demonstrate how important climate model selection can be for the portrayal of drought impacts more generally.

2. Methodology

Precipitation, temperature, and potential evapotranspiration (PET) data were derived from 12 UKCP18 Regional and 42 EuroCORDEX-UK climate projections (Section 2.1). These were used to drive the Grid-to-Grid (G2G) hydrological model across Great Britain, generating 54 continuous monthly mean flow time series grids from Dec 1980 to Nov 2080 (Section 2.2). Time slices of 30 years which corresponded to global warming levels (GWLs) of 1 °C, 2 °C and 3 °C from the pre-industrial period, as well as fixed baseline and far-future time slices, were extracted (Section 2.3). Drought characteristics, including mean severity, mean intensity, mean duration, percentage of time in drought each month and extreme drought frequency, were then calculated from the time slices of monthly mean flows for all river grid cells (Section 2.4).

2.1. Climate projections

2.1.1. UKCP18 Regional

The UK Climate Projections 2018 (UKCP18) is a set of tools and climate data produced by the UK Met Office to assess how the climate of the UK may change over the 21st Century. These include the UKCP18 Regional projections, originally released as a 12-member PPE of the Hadley Centre RCM, nested within an equivalent PPE of the Hadley Centre GCM, covering the UK at 12 km resolution (Murphy et al., 2018). They run from Dec 1980 to Nov 2080 under the RCP 8.5 emissions scenario. UKCP18 Regional has been widely applied for UK hydrological impact studies as it was the first UK climate product to provide an ensemble of high-resolution (12 km), spatially coherent projections covering the UK (Hannaford et al., 2022; Kay et al., 2023a; Lane et al., 2022; Smith et al., 2024). An additional four ensemble members have since been added to UKCP18 Regional (Short et al., 2024)– but here we focus on the original 12 ensemble members which have been widely applied in previous studies (hereafter referred to as UKCP18-Reg).

2.1.2. EuroCORDEX-UK

Climate data from the European CoOrdinated Regional Downscaling EXperiment (EuroCORDEX) have recently been released reprojected onto the same 12 km grid as UKCP18 Regional (Barnes, 2023; Barnes et al., 2024). These EuroCORDEX-UK projections also cover Dec 1980 – Nov 2080 under RCP 8.5 emissions scenario. The full dataset includes 64 GCM/RCM combinations, however issues with orography data for 2 RCMs and multiple realisations of some GCMs led to 42 GCM/RCM combinations (6 GCMs, 8 RCMs) being used here (hereafter referred to as EC-UK). A model list is given in Table 1, with full details on the processing of EuroCORDEX-UK data for G2G supplied in Kay (2025).

Table 1

Time slices used for each GCM/RCM combination in this study. All 30-year time slices start on 1st December in the given year. For the 1 °C, 2 °C and 3 °C global warming time-slices, the respective global warming level is first exceeded in the centre of the 30-year period. For UKCP18-Reg, ensemble member numbers are given in brackets following the start years. Dates marked with * indicate simulations that didn't reach 3 °C warming by Dec 2050 and therefore the final available 30-year time slice has been used.

GCM reference	Number of RCMs	Start date of 30-year time slice				
		Fixed baseline	1 °C GWL	2 °C GWL	3 °C GWL	Fixed future
UKCP18	12 (PPE)	1980	1986 (15)	2014 (4)	2031 (4)	2050
			1992 (11)	2014 (11)	2032 (8)	
			1993 (4)	2014 (15)	2032 (9)	
			1994 (1)	2016 (1)	2033 (11)	
			1995 (5)	2016 (6)	2034 (1)	
			1995 (6)	2017 (9)	2034 (6)	
			1995 (9)	2018 (10)	2034 (15)	
			1995 (10)	2019 (5)	2036 (10)	
			1996 (13)	2019 (13)	2037 (5)	
			1997 (7)	2022 (7)	2037 (13)	
			1998 (8)	2023 (8)	2039 (7)	
			2010 (12)	2030 (12)	2045 (12)	
EC_CNRM	8	1980	1997	2029	2050*	2050
EC_EC-EARTH	8	1980	1985	2021	2046	2050
EC_IPSL	4	1980	1985	2015	2035	2050
EC_HadGEM	8	1980	1996	2021	2040	2050
EC_MPI	7	1980	1985	2021	2046	2050
EC_NorESM	7	1980	2000	2033	2050*	2050

2.1.3. Representation of key hydroclimatic variables in UKCP18 Regional vs EuroCORDEX-UK

A full evaluation of historical biases and projected changes in UK temperature and precipitation from the UKCP18 Regional and EuroCORDEX-UK ensembles is given in Barnes et al., (2024), with plots for a wide range of variables available via their plot explorer tool (https://github-pages.ucl.ac.uk/EuroCORDEX-UK-plot-explorer/). Here, we summarise their key findings for UK temperature and precipitation, with further plots given in the supplementary information.

For average winter and summer temperatures, there is much overlap across the two ensembles for the historical period (1989–2008), but the EuroCORDEX ensemble has a larger spread including some ensemble members with particularly low average winter temperatures (<2 °C). Compared to HadUK-Grid observations, both ensembles show negative biases (i.e. cold bias) for summer and winter temperatures across the UK, but these biases are larger for the EuroCORDEX ensemble (mean bias of −1.1 °C in Summer and −0.6 °C in winter) compared to the UKCP18 Regional ensemble (mean bias of −0.6 °C in winter and −0.4 °C in summer), likely due to the wider ensemble spread. Future changes in temperature show more discrepancies between the ensembles, particularly when focusing on summer temperatures. UKCP18 Regional includes members showing larger changes in winter air temperature by 2050–2079 (up to ~2.5 °C in EuroCORDEX vs 3.3 °C in UKCP18 Regional), and much larger changes in summer air temperatures (+1.3–3.3 °C in EuroCORDEX vs +2.8–4.3 °C in UKCP18 Regional). Greater temperature increases by 2050–2079 in UKCP18 Regional could be attributed to greater climate sensitivity in the ensemble members and CO_2 pathways that tend to lie above the standard RCP8.5 scenario (Barnes et al., 2024; Yamazaki et al., 2021). However, even when comparing changes between 1 °C and 2 °C warming, the UKCP18 Regional ensemble indicates increased summer warming compared to EuroCORDEX.

For precipitation, the EuroCORDEX ensemble members cover a wider range of UK-average values over the historical period (precipitation rate 2.3–5.7 mm/day) than UKCP18 Regional (precipitation rate 4–5.1 mm/day). Compared to HadUK-Grid observations, overall bias values are similar between the EuroCORDEX and UKCP18 Regional ensembles, but EuroCORDEX tends to underestimate precipitation over upland areas in western GB and overestimate elsewhere whereas UKCP18 Regional has larger overestimations in winter and smaller overall biases in the summer. By the future 2050–2079 time period, while both EuroCORDEX and UKCP18 Regional ensemble members indicate increasing UK-average winter precipitation and decreasing summer precipitation, these changes are more consistent and pronounced across the UKCP18 Regional ensemble (winter changes of −5 to +22% vs 7–20% and summer changes of +8 to −23% vs −10 to −38% in the EuroCORDEX-UK and UKCP18 Regional ensembles respectively).

2.1.4. Application of climate data

The hydrological model requires 1 km input grids for precipitation, potential evapotranspiration (PE) and min/max temperature. Daily precipitation and min/max temperature were available at 12 km from both UKCP18-Reg and EC-UK RCMs, while PE had to be estimated from other climate outputs. The climate data processing steps were kept consistent with previous studies (Hannaford et al., 2022; Kay, 2025; Lane and Kay, 2021), as outlined below.

Precipitation data were first bias-corrected before being downscaled to 1 km, as they showed substantial biases compared to observations over the historical period. Bias correction was carried out using a relatively simple monthly-mean correction against CEH-GEAR observations over the period 1981–2010 (Tanguy et al., 2019), aiming to correct for coarse monthly/seasonal mean biases (as in Kay, 2021). Bias-corrected precipitation was downscaled to 1 km based on the distribution of the Standard-period Average Annual Rainfall (SAAR) and divided equally down to the 15-min model time-step (as in Kay et al., 2023b).

PE was estimated using the Hydro-PE method (including interception) of Robinson et al., (2023), using a range of climate model outputs including the bias-corrected precipitation. The 12 km PE grids were copied down to 1 km and spread equally throughout the day. Min/max temperature data were downscaled to 1 km using a lapse rate with elevation, and varied throughout the day using a sine curve (as in Bell et al., 2016).

It is important to note that there are many bias correction methods available, including linear scaling, local intensity scaling of precipitation, non-parametric quantile mapping, and parametric quantile mapping, with some methods specifically designed to be trend preserving (Spuler et al., 2024; Teutschbein and Seibert, 2012). The choice of bias correction method can be an important source of uncertainty in hydrological climate impact studies, although for low flows it is generally a smaller source of uncertainty than the selection of climate model/ hydrological model (De Niel et al., 2019). Here, we were focused on estimating droughts from monthly mean river flows, and therefore linear scaling of monthly mean precipitation was considered sufficient. The bias correction has been applied separately to each ensemble member, treating them each independently; this will reduce the variability within/between the ensembles during the historical period.

2.2. Hydrological modelling

Grid-to-Grid (G2G) is a distributed hydrological model that has been used to investigate the impact of climate change on river flows, floods and droughts at catchment, regional and national scales (Bell et al., 2016, 2009; Kay et al., 2023a, 2018; Lane and Kay, 2021; Rudd et al., 2019). G2G runs on a 1 km grid across Great Britain and can therefore provide simulations of natural river flows as a grid or as time-series for a particular location (gauged or ungauged). G2G is configured using spatial datasets of landscape properties such as soil type and drainage network, together with a few nationally-applied model parameters (Bell et al., 2009). The parameters used here are the same as those used in previous studies (Bell et al., 2009; Rudd et al., 2019), and the optional snow module was also applied (Bell et al., 2016).

For all RCM-driven simulations, the hydrological model was run continuously through Dec 1980 – Nov 2080, with states initialised in Dec 1980 from an observation-driven run (as in Kay, 2025). G2G was adjusted to expect different numbers of days in a year from different ensemble members, as the climate output included standard 365/366-day, fixed 365-day and 360-day years from different

GCM/RCM combinations. Monthly mean river flows (m^3s^{-1}) were extracted for each river pixel, here defined as a non-sea and non-tidal 1 km grid cells that have a drainage area of at least 50 km^2.

2.3. Selection of time slices

Drought characteristics were calculated for five 30-year time slices (see Table 1). These included time slices at set global warming levels (GWLs) where dates differed between ensemble members, alongside a fixed baseline period (Dec 1980 – Nov 2010) and fixed future period (Dec 2050 – Nov 2080). The advantage of using GWLs is that it allows for a fairer comparison between ensemble members, removing the effect of the different rates of warming between climate models and instead focusing on regional variations and natural variability.

Dates for the 30-year time slices relating to 1 °C, 2 °C and 3 °C GWLs were supplied by (Barnes et al., 2024) (github-pages.ucl.ac.uk/EuroCORDEX-UK-plot-explorer/#/time-help). These time slices are centred around the year each ensemble member first exceeds global mean surface temperatures (GMSTs) of 1 °C, 2 °C and 3 °C change from pre-industrial. Time slice dates varied between the driving GCMs but also between each UKCP18-Reg ensemble member due to differences in the RCP8.5 emissions scenarios applied. The time-period covered by 1 °C ranges from 1985 to 2040 in the climate models and so can broadly be considered as reflective of current conditions, with recent observations indicating that the calendar year of 2024 was the first to exceed 1.5 °C above pre-industrial levels (Bevacqua et al., 2025). Further analysis therefore uses 1 °C as a baseline when calculating changes by 2 °C and 3 °C warming.

The EC_CNRM and EC_NorESM reached 3 °C in time periods starting 2053 and 2059 respectively. To keep a consistent 30-year drought identification period, the 3 °C time slice for these models was selected to be the final 30 years of the simulation (Dec 2050– Nov 2080).

2.4. Drought identification

Droughts were identified from simulated monthly mean river flows using a threshold approach, following Rudd et al., (2017). Generally, threshold approaches compare a time-series of river flows against a threshold, with periods when river flows fall below the threshold being defined as drought events. The threshold can be fixed or varying, with no standard definition. Here, we apply a variable threshold of monthly-mean flow, as thisapproach successfully identified historic drought periods in a previous study using G2G simulated river flows (Rudd et al., 2017).

The drought identification and classification procedure was carried out for each river pixel and 30-year time slice as follows. First, standardised flow anomalies were calculated using

$$standardised\ flow\ anomaly = \frac{X - X_{mon}}{\sigma_{mon}},$$

Where X is the monthly mean time series, X_{mon} is the long term (Dec 1980-Nov 2010) monthly mean flow and σ_{mon} is the long term (Dec 1980-Nov 2010) monthly standard deviation. This uses a variable threshold of the long-term monthly mean flow for drought events to remove seasonality in hydrological response, and the long-term standard deviation to standardise metrics and enable comparison between rivers.

Second, each period where the anomaly was negative (i.e. a deficit) for at least two months was classed as a drought event, and the following characteristics were calculated:

i. Standardised drought intensity - the maximum deficit;
ii. Drought duration - the length of time in deficit (months);
iii. Standardised drought severity - duration multiplied by the mean deficit.

Any event with a standardised drought severity less than four was excluded from the subsequent analysis, following Rudd et al. (2017) who identified that this gave a good match between simulated droughts and observations of notable drought periods. It ensured that minor events were excluded, as mean-monthly flow is a relatively lenient drought threshold compared to other approaches in the literature (Chan et al., 2023; Van Loon and Laaha, 2015). Droughts extending beyond the time-slice were assumed to end immediately after the final month of the time-slice. The average drought severity, intensity and duration were then calculated for each pixel and each time-slice, by taking the mean values across all included drought events.

Extreme droughts were then identified (those with a standardised severity >8), following thresholds identified in previous studies (Rudd et al., 2019, 2017). The frequency of extreme droughts was calculated for each pixel and time-slice:

iv. Extreme drought frequency – count of droughts with standardised severity > 8,

Finally, the number of times each month was in drought conditions within the 30-year time slice was calculated as an indication of drought seasonality.

There are many different indexes used to characterise drought, including standardised indicators such as the standardised streamflow index (SSI) and a range of different threshold methods, with no recognised ‘correct’ approach (Beyene et al., 2014). An advantage of the threshold approach used here is that there is no fixed time interval (for example, the 6-month,12-month or 24-month

SSI) and we can therefore explore multi-year droughts in a flexible way.

3. Results

3.1. Drought characteristics at 1 °C warming

When looking at GB-average drought characteristics at 1 °C GMST warming (Fig. 1), there is much overlap between UKCP18-Reg and EC-UK ensemble members. Ensemble mean values are shown as black circles to highlight how use of different ensembles may result in different conclusions, although here we focus on the ensemble spread and individual members (green crosses and blue plusses) which are more meaningful.

Most ensemble members show GB-mean standardised drought severities in the range of 6.5–9 (UKCP18-Reg 6.9–9.2, EC-UK 6.4–8.5), drought intensities of 1.4–1.6 standard deviations below the monthly average flow (UKCP18-Reg 1.36–1.61, EC-UK 1.40–1.60), drought durations of 7–10 months (UKCP18-Reg 8–10, EC-UK 7–9), and between 1 and 4 extreme droughts (severity > 8) within the 30-year period (UKCP18-Reg 1.9–4.1, EC-UK 1.0–3.9). The UKCP18-Reg ensemble tends towards droughts with a longer duration and thus higher severity than simulated using EC-UK. However, the ensemble spread of GB-average drought intensities simulated with UKCP18-Reg encompasses the EC-UK ensemble members.

There are also similar spatial patterns in drought severity and duration simulated by UKCP18-Reg and EC-UK ensemble members at 1 °C GMST warming. Fig. 2 shows maps of drought characteristics at 1 °C GWL for each GCM. Only one example ensemble member is shown for UKCP18-Reg and each EC-UK GCM to highlight the key patterns, with maps for all ensemble members given in the Supplementary Information. Simulations from all GCMs agree that droughts are most severe and of the longest duration in southeast England. There is a band of the most severe droughts aligning with the location of chalk aquifers across south/eastern England in all simulations. While the UKCP18-Reg ensemble member shown in Fig. 2 shows relatively modest drought durations, other ensemble members have high drought durations (exceeding 10–12 months) over larger areas of southern and eastern England (see supplementary information). Southern England also tends to have the largest number of extreme droughts for most ensemble members.

There is less agreement between ensemble members in spatial patterns of drought intensity. Some ensemble members (e.g. CNRM+HadREM3 and IPSL+HadREM3) show a stronger east/west divide with less intense droughts over central and eastern England, and more intense droughts along the west coast. Other GCMs show less regional variation in drought intensity (e.g. HadGEM+HadREM3 and EC-EARTH+HadREM3).

Any differences between ensemble members could be the result of natural variability as well as due to variations in climate model structure. Some similarity between the ensembles may be due to precipitation bias correction being applied over the baseline period, which in some cases overlaps with the 1 °C warming period. However, the bias adjustment only corrects for monthly mean precipitation, and not the precipitation variability, sequencing of wet/dry months or the distribution of precipitation within the month which will all have an impact on the simulated droughts.

3.2. GB-average changes in drought characteristics

Fig. 3 shows the change in GB-mean drought characteristics as GWLs exceed 1 °C and between fixed baseline and future time slices (values for each period are plotted in the supplementary information Figure S7). Between 1 °C warming and 3 °C warming, all but one of the UKCP18-Reg projections show a worsening of drought severity, characterised by increased drought intensity and duration. All of the UKCP18-Reg ensemble members show an increase in the number of extreme droughts. Conversely, the EC-UK ensemble shows little overall change in drought severity between 1 °C and 3 °C warming, with some tendency towards more intense droughts offset by

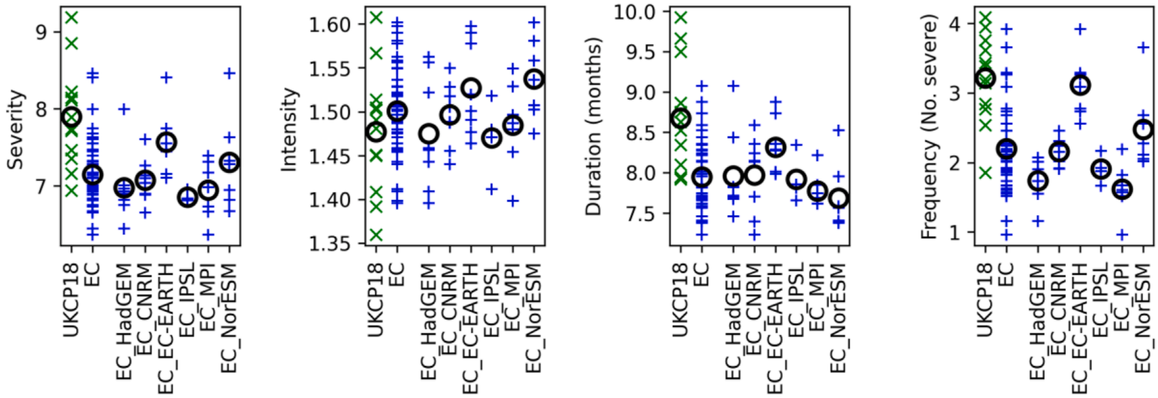

Fig. 1. Drought characteristics across Great Britain at 1 °C GMST warming. GB-mean values are given for drought severity, intensity, duration and number of extreme events, for all UKCP18-Reg (green crosses) and EC-UK (blue plus signs) ensemble members. The second column of each subplot (EC) shows all EC-UK members, while columns 3–8 show each EC-UK GCM individually. Black circles show the mean values for each set of ensemble members.

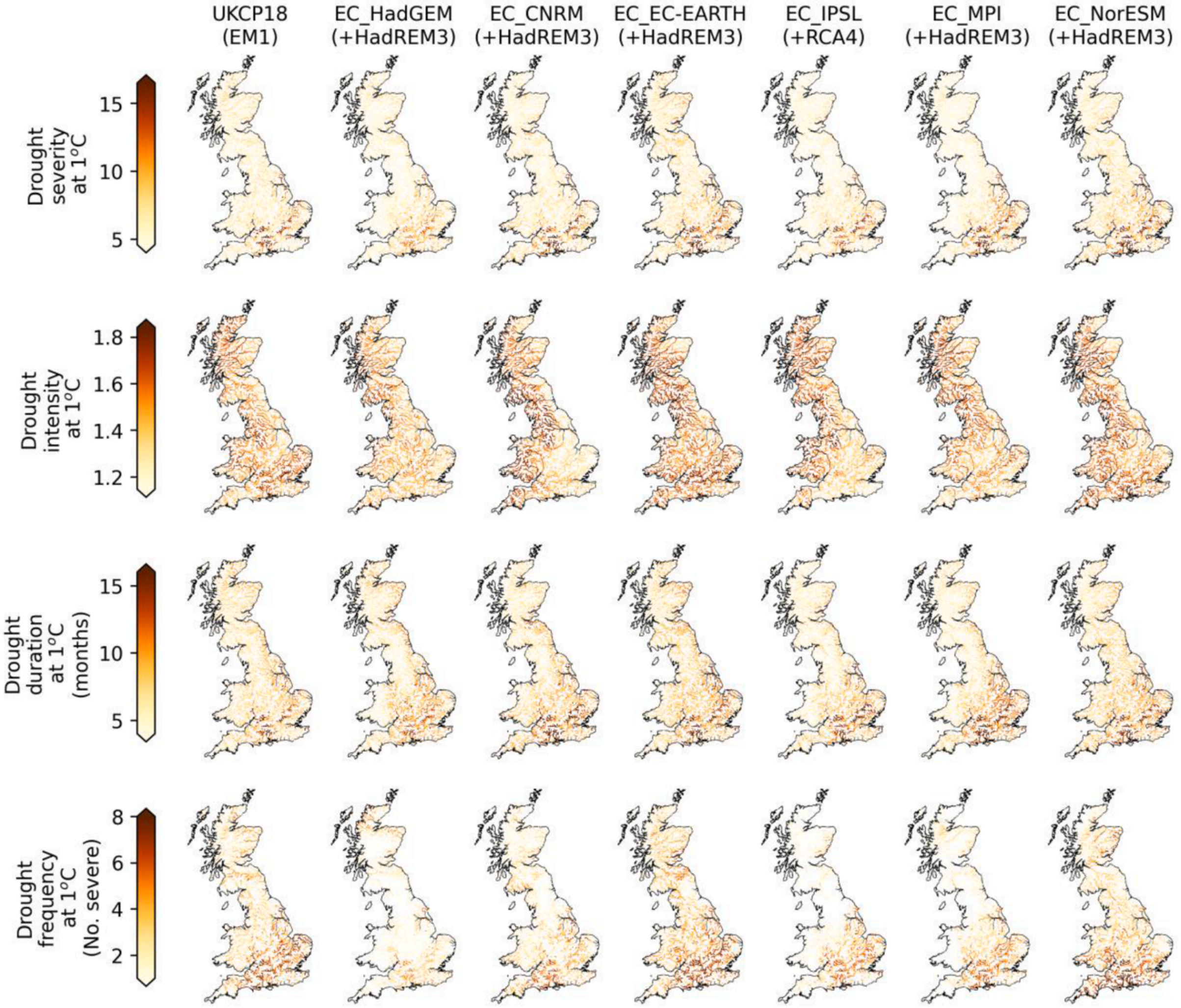

Fig. 2. Maps of drought characteristics across GB at 1 °C GMST warming. These are given for a sample of ensemble members: UKCP18-Reg ensemble member 01 (left column), and each EC-UK GCM (right columns) with HadREM3 RCM where available (see titles for GCM/RCM combinations). Maps for all GCM/RCM combinations are given in the supplementary information.

shorter drought durations.

In terms of percentage changes in drought characteristics between 1 °C and 3 °C GWL, the UKCP18-Reg (and EC-UK) ensemble ranges are −13 to + 73% (-19 to +33%) for drought severity, −4 to + 15% (-5 to +12%) for intensity, and −12 to + 33% (-23 to +19%) for duration (see supplementary information for plots of % change Figure S8). The ensemble mean changes in drought severity are + 33% for UKCP18-Reg compared to + 1% for EC-UK: while use of an ensemble mean is not advised, this demonstrates how different conclusions can be drawn based on drought projections from the different ensembles.

The disparity between the UKCP18-Reg and EC-UK projections is most pronounced when looking at changes between the fixed baseline and future periods (Fig. 3). Nearly all UKCP18-Reg ensemble members show relatively large increases in drought severity, intensity, and the number of extreme droughts, while EC-UK ensemble members do not indicate any consistent increases in drought severity or duration. This is likely in part due to differences in climate sensitivities, with the UKCP18-Reg ensemble members generally showing a faster rate of warming than the EC-UK ensemble (as seen in Table 1).

There is a single UKCP18-Reg ensemble member (EM15) which shows a reduction in drought severity, intensity and duration, both for 1 °C to 3 °C GWLs and for the baseline to future time slice. This means that the UKCP18-Reg ensemble spread almost encompasses the EC-UK ensemble spread for changes in GB-average drought characteristics, despite different conclusions being drawn from the ensemble mean projections.

The more extreme drought projections from UKCP18-Reg compared to EC-UK link to regional differences in temperature and precipitation changes. Overall, UKCP18-Reg projections indicate greater drying (greater decreases in summer precipitation, smaller increases in winter precipitation) and larger increases to summer temperatures (and thus PE) between 1 °C and 2 °C than EC-UK (see Supp Figure S1 and Supp. Figure S2).

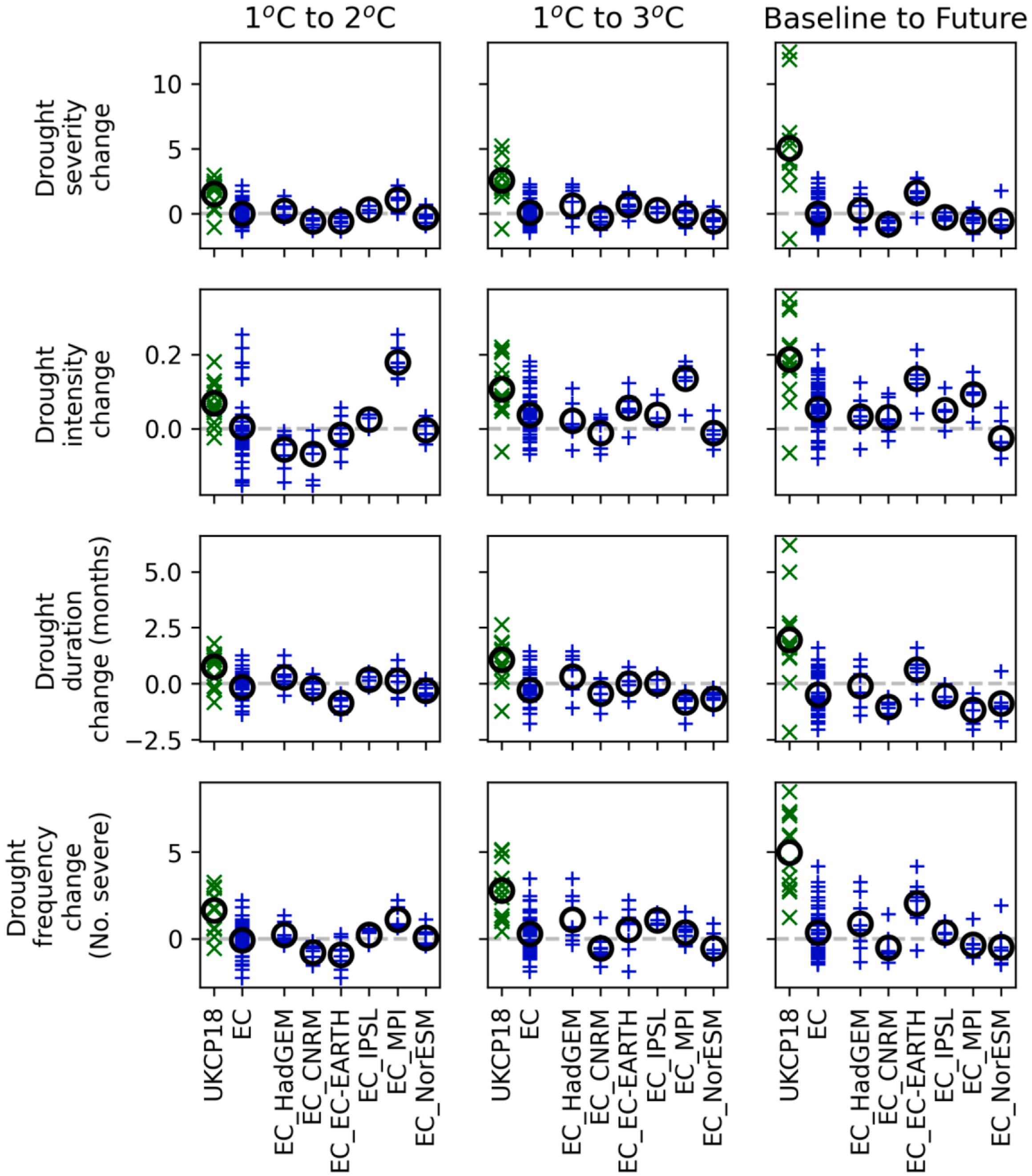

Fig. 3. Changes in GB-mean drought characteristics across the UKCP18-Reg and EC-UK ensembles and for each EC-UK GCM. As indicated by the x axis labels, columns show the range across the UKCP18-Reg ensemble (column 1), the EC-UK ensemble (column 2) and each EC-UK GCM (columns 3 onwards). Green x's show UKCP18-Reg ensemble members, blue + 's show EC-UK ensemble members, and black circles show the mean for each column. Row subplots show changes in standardised drought severity, standardised drought intensity, drought duration (months) and number of extreme drought events respectively. Column subplots show changes between periods associated with a 1 °C to 2 °C GMST warming, a 1 °C to 3 °C GMST warming, and fixed baseline (1980–2010) to future (1950–1980) time slice respectively.

Impact ratios for all drought characteristics are given in Fig. 4 to show how drought characteristics are projected to change with increased warming. These show GB-average drought characteristics at each GWL relative to 1 °C GWL (e.g. a value of 2 indicates a doubling or 100% increase in that drought characteristic compared to the value at 1 °C GWL). The UKCP18-Reg projections tend to show a fairly consistent pattern of more severe, intense and long-lasting droughts at higher levels of global warming across GB. However, many of the EC-UK simulations do not show such consistent changes with increased global warming. For example, MPI shows a large increase in drought intensities between 1 °C and 2 °C warming, but drought intensities then reduce by 3 °C warming.

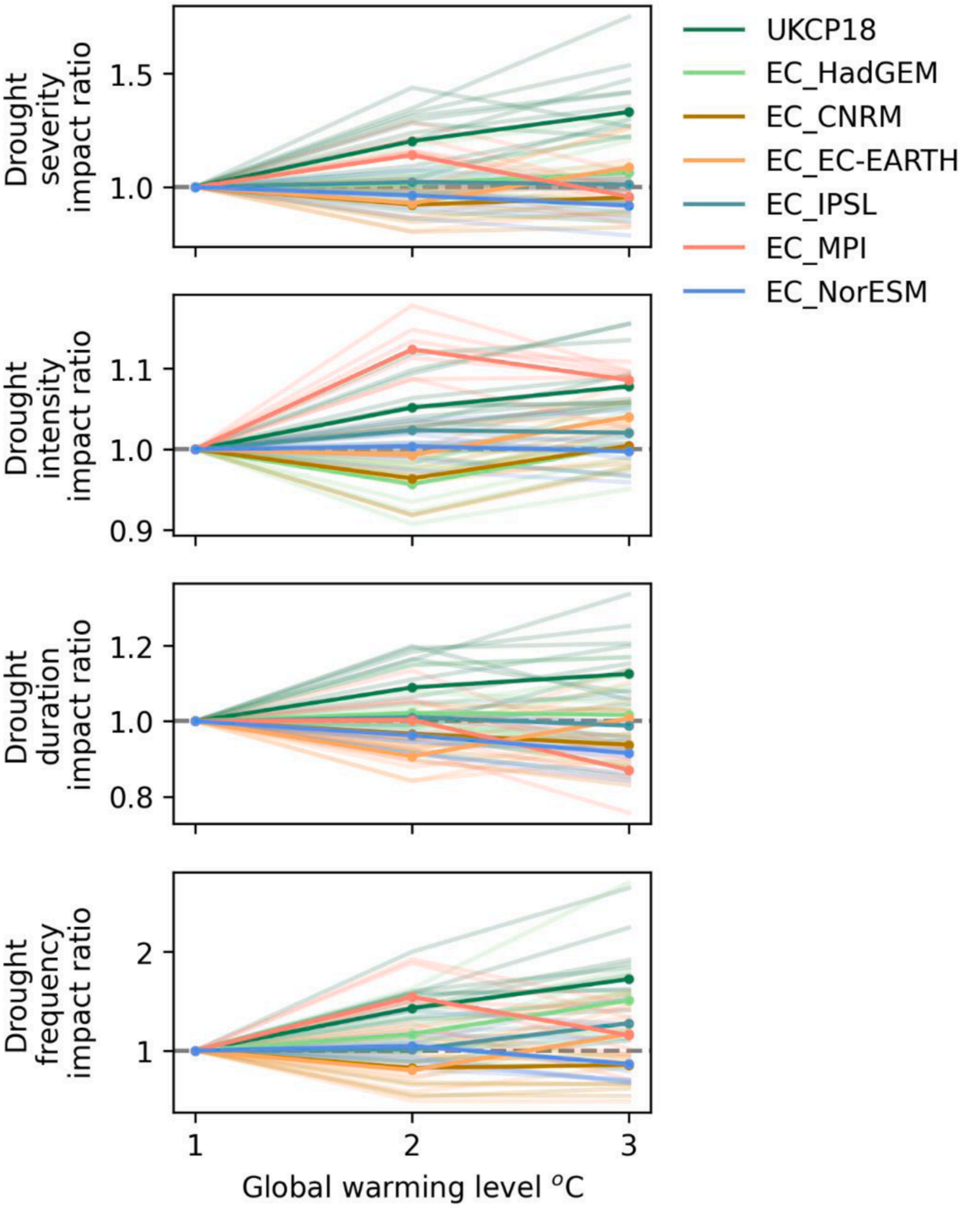

Fig. 4. Impact ratios showing how GB-average drought characteristics change with different GWLs, as a fraction of their values at 1 °C GWL. Lines are shown for each ensemble member, coloured by driving GCM. Bold lines give the ensemble mean for that GCM, while thinner lines show each ensemble member.

Conversely, EC-EARTH shows a reduction in drought durations between 1 °C and 2 °C, which then increase again between 2 °C and 3 °C global warming. We have not carried out any tests to confirm whether these non-monotonic changes are statistically significant, but it is likely that these fluctuations over time are due to internal variability rather than reflecting the long-term climate trend.

3.3. Regional variation in drought changes

Regional changes in drought characteristics between 1 °C and 3 °C GWLs are summarised across all ensemble members in Fig. 5. There is a strong spatial pattern to drought severity change in the UKCP18-Reg projections, with most ensemble members showing the largest increases in drought severity across the southeast (Anglian, Thames and SE England river basin regions). This spatial pattern is echoed in a few of the EC-UK ensemble members, although there is much variation with some ensemble members indicating reductions to drought severity in the southeast and others indicating little spatial variation in future drought changes. Again, there is a single UKCP18-Reg ensemble member (EM15) that contrasts with the rest of the UKCP18-Reg ensemble, and shows reductions in drought

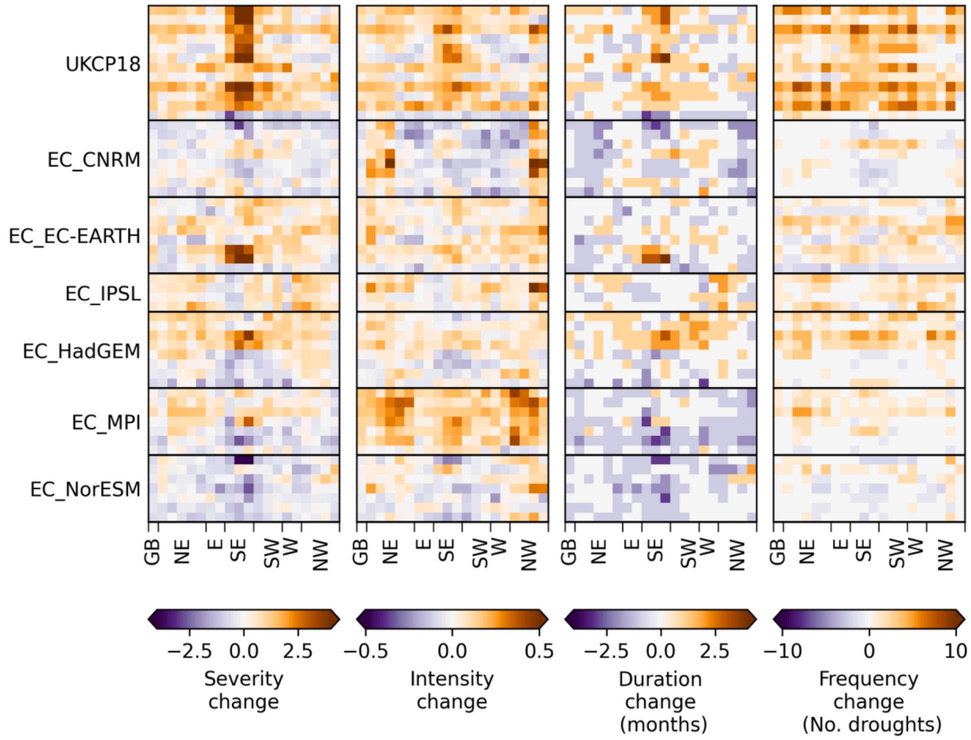

Fig. 5. Heatmaps of changes in drought severity, intensity, duration (months) and number of extreme droughts between 1 °C and 3 °C GWLs, comparing projections from all 12 UKCP18-Reg and 42 EC-UK ensemble members. Within each heatmap, each row is a different ensemble member (GCMs are identified on the left) and each column is changes averaged over a different region (broad locations within GB are identified on the x axis). Column 1 is the whole of GB, the subsequent columns are NE (North Highlands, NE Scotland, Tay, Forth, Tweed), E (Northumbria, Humber), SE (Anglian, Thames, SE England), SW (SW England, Severn, W Wales), W (Dee, NW England), NW (Solway, Clyde, Argyll and West Highlands) river basin regions respectively.

severity across the southeast.

Many ensemble members show large increases in drought intensity in northern regions (North Highlands, NE Scotland, Tay, Argyll and West Highlands river basin regions), with most UKCP18-Reg and MPI ensemble members also indicating increasing drought intensities in the southeast. Changes in drought duration are mixed, with many ensemble members showing shorter droughts across all regions, while others show a trend towards longer droughts especially across the southeast.

Changes in the number of extreme droughts do not show any consistent spatial patterns. Maps of changes to drought characteristics are given in the supplementary information (Figures S9 – S12).

3.4. GB-average changes in drought seasonality

Fig. 6 looks at the seasonality of drought across GB, by showing the proportion of time each month of the year is under drought conditions and the change in the number of droughts occurring within each month with increased warming. This shows the UKCP18-Reg ensemble deviating from the EC-UK ensemble as GWLs rise from 1 °C to 3 °C. In general, the UKCP18-Reg ensemble members show increases in drought occurrence for all months, but especially over the summer (May-Sept). Most EC-UK ensemble members have a less pronounced increase in drought occurrence over the summer, and generally decreasing drought occurrence over the winter (Nov-March). However, within the EC-UK ensemble spread there are some members that show year-round reductions in drought occurrence.

4. Discussion

4.1. UKCP18 Regional projections in context

The few previous studies evaluating climate change impacts for hydrological drought nationally across Great Britain generally indicated an increase in drought severity with climate change (Arnell et al., 2021; Dobson et al., 2020; Parry et al., 2024; Rudd et al., 2019; Smith et al., 2024). Using the weather@home simulations, Rudd et al. (2019) found nationwide increases in drought severity and extent, and Dobson et al. (2020) found a worsening of extreme streamflow droughts across all modelled catchments. Using the UKCP18 Regional projections, Parry et al. (2024) similarly found increases in drought severities across over 90% of 200 simulated UK catchments, and Smith et al., (2024) found increases in drought duration which were particularly pronounced in east / south-east

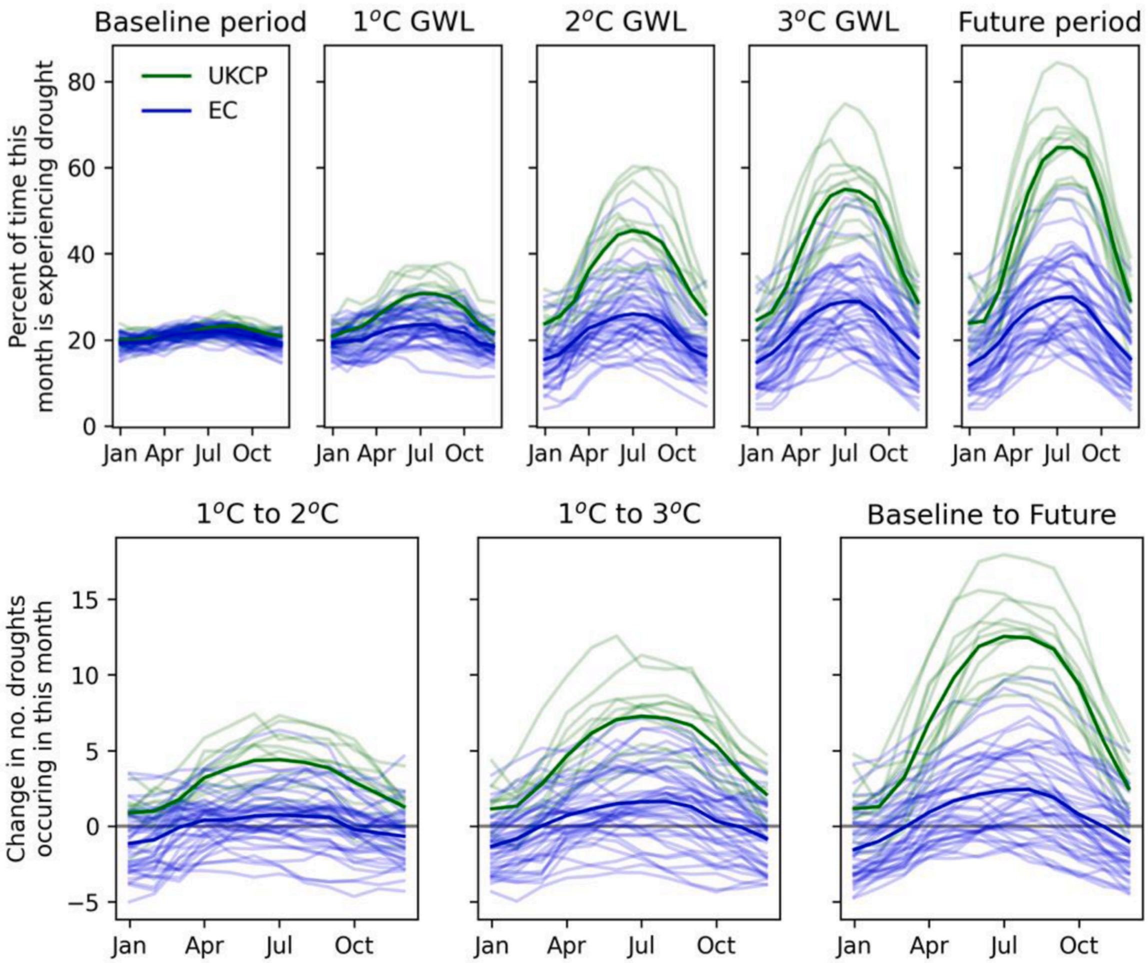

Fig. 6. GB-average drought seasonality and relative changes in seasonality as simulated by UKCP18-Reg (green) ensemble members and EC-UK (blue) ensemble members, with bold lines showing ensemble means. Top row shows drought seasonality (expressed as the percentage of time each month is in drought conditions) for each of the 30-year time slices. The bottom row highlights changes in the number of droughts in each month over the 30-year period, from left to right: between 1 °C and 2 °C GWL, between 1 °C and 3 °C GWL, and between the baseline (1980–2010) and future (2050–2080) time slices respectively.

England. Most previous GB-wide studies were based on the Hadley Centre climate model which underpinned weather@home and UKCP18 Regional climate products.

The large GCM/RCM ensemble presented here gives context to previous UK drought impact literature. Here, we show that the UKCP18-Reg ensemble projections are generally on the more extreme end for future drought impacts for severity, although other climate models indicate potentially larger increases to drought intensities and different spatial patterns of future drought changes. While UKCP18-Reg projections indicated increasing drought severity, intensity, duration and frequency with increased global warming, projections underpinned by EC-UK showed little overall change in drought severity, especially when focusing on the ensemble mean.

Our results are in agreement with previous studies that have used alternative climate projections alongside the Hadley Centre model (Arnell et al., 2021; Kay, 2025; Wittekind, 2023). For example, Arnell et al., (2021) applied the UKCP18 Global projections for future droughts, finding that while simulations underpinned by the Hadley Centre GCM showed substantial increases in time under drought conditions, CMIP5-driven simulations showed little change. Similarly, Kay, (2025) found much larger and more consistent reductions in summer flows over the UKCP18 Regional ensemble compared to EuroCORDEX-UK.

There is a single UKCP18 Regional ensemble member (EM15) projecting less severe drought impacts, resulting in the UKCP18-Reg ensemble spread better reflecting the wider range of potential impacts from the EC-UK projections. This highlights the importance of considering the ensemble range when making water management decisions, rather than focusing on an ensemble-median or mean which can be heavily influenced by ensemble member selection and may not be representative of many (or any) individual ensemble members.

4.2. Implications for water resource management

A key challenge for future water resource management is dealing with the uncertainties in future projections. Here, we highlight that use of UKCP18-Reg projections does not fully capture the uncertainties in drought impacts, but does include many of the more extreme scenarios. We highlight the particularly large uncertainties for drought impacts in south-east England, where some of the largest changes (both increases or decreases depending on the ensemble member) in drought severity and duration are projected. The SE has previously been highlighted as an area vulnerable to some of the greatest decrease in low flows, and increasing drought severity due to climate change (Lane and Kay, 2021; Parry et al., 2024; Smith et al., 2024). The more groundwater dominated catchments in the south-east tend to experience longer duration multi-year droughts, while flashier catchments in north and west England are more susceptible to shorter, more intense events (Barker et al., 2024).

Changes in drought seasonality may present further challenges for water resource management. An amplification of drought seasonality can be seen across both the UKCP18 Regional and EC-UK ensembles, with droughts generally occurring more frequently over the summer (May-Sept). An increase in summer droughts, when river levels are already at their lowest, could have many negative impacts. For example, fish kills, algal blooms, water pollution and hampered navigation were all observed during the 2022 summer drought (Barker et al., 2024). Furthermore, dry weather in spring/summer could result in a greater demand on farm irrigation reservoirs and possible water supply issues, with knock-on effects for crop growth and the livestock sector.

One potentially surprising finding is that there isn't a consistently monotonic relationship between changes in drought characteristics and global warming level for all the ensemble members. A common assumption may be that climate change impacts will intensify as global warming levels rise. While this was the case for many regions, in some areas impacts were found to be worse at 2 °C than 3 °C. This could be due to natural variability causing extended wetter/drier periods, alongside non-linear effects from precipitation and PE changes over time. Natural variability is a particular issue when looking at climate change extremes such as droughts; a 30-year period may only contain one or two severe events and thus a single severe drought occurring in an earlier time period may obscure the underlying climate change trend. The difficulty of identifying trends in drought events given internal variability was demonstrated by Chan et al. (2025), who found that droughts are highly sensitive to multi-annual and multi-decadal variability in a study using a single model initial condition large ensemble.

Our lack of a monotonic change in droughts with increased warming contrasts with Arnell et al., (2021) who found a generally consistent increase in the proportion of time under drought conditions with level of warming. This paper used climate projections in a different way – applying delta changes to observed input data – which may explain the different findings. Our results also contrast with studies looking at low flow changes over time, which generally report larger decreases in low flows for projections further into the future (Charlton and Arnell, 2014; Kay et al., 2021, 2018). This highlights the importance of a precautionary approach to future drought planning, as we can't assume that planning for a higher global warming level change will automatically cover all the possible impacts for lower global warming level changes.

4.3. Limitations and recommendations for future research

We used a single hydrological model for this study as the focus was on differences between UKCP18 Regional and EC-UK projections. However, hydrological model structure and parameterisation can be a considerable source of uncertainty in climate impact studies, particularly for low flows (Chegwidden et al., 2019; De Niel et al., 2019; Lane et al., 2022; Meresa and Romanowicz, 2017; Visser-Quinn et al., 2019). Previous studies have explored hydrological model differences for low flow/drought impacts in the UK (Parry et al., 2024; Tanguy et al., 2023). Parry et al. (2024) evaluated climate change impacts on drought from UKCP18 Regional driven simulations using G2G and three other hydrological models. They found that all models agreed droughts were likely to become more prolonged and severe, but projections using G2G often differed from the three catchment calibrated models. This was most noticeable in south-east England where G2G showed some of the steepest reductions in Q90 over time. Therefore, our use of G2G may result in drought impacts that are more severe than would be projected by other hydrological models.

The two large ensembles used here summarise plausible future changes to drought but are not designed to represent the full uncertainty range. We do not attempt to capture possible high impact but low likelihood events that could be particularly damaging and therefore of interest for planning purposes. Other techniques such as storylines showing how past droughts could have unfolded differently giving even worse impacts (Chan et al., 2022; Shepherd et al., 2018; van der Wiel et al., 2021), or the use of very large ensembles from Single Model perturbed-Initial condition Large Ensembles (SMILES) could be used as complementary approaches to explore these unlikely extremes alongside the overview presented here (Chan et al., 2025; Kay et al., 2024; Maher et al., 2021). Furthermore, SMILES can be used to distinguish climate-driven trends from natural variability, and establish when statistically significant changes in hydrological extremes may emerge (Chan et al., 2025).

5. Summary and conclusions

This study modelled climate change impacts for hydrological droughts across Great Britain, using data from two large climate ensembles (the UKCP18 Regional perturbed-parameter ensemble and the EuroCORDEX-UK multi-model ensemble) as input to a national hydrological model. The results highlighted that the choice of climate model structure can substantially change conclusions regarding climate change impacts for droughts. The UKCP18 Regional PPE indicated substantial increases in hydrological drought severity, intensity and duration across Great Britain, with increasing drought frequency across all seasons. In contrast, the EuroCORDEX-UK MME indicated little change in GB-average drought severity, with a reduced chance of droughts during the wetter winters. The spatial pattern of drought changes also differed between the ensembles: most UKCP18 Regional projections highlighted the southeast as particularly vulnerable to increases in drought severity, while the EuroCORDEX-UK projections covered a wider range of possibilities. There was a single UKCP18 Regional ensemble member projecting more modest changes to droughts that brought the spread of UKCP18 Regional projections in line with the EuroCORDEX-UK MME, highlighting the importance of considering the full ensemble spread. These results give context to previous UK drought impact studies based on UKCP18 Regional, showing that they are potentially sampling the more extreme range of future drought impacts.

Author Contributions

RL, AK and AR were involved in the initial conceptualisation, methodology and data analysis. AK ran the model simulations. RL carried out the analysis and data visualisation. RL wrote the manuscript with input from co-authors.

CRediT authorship contribution statement

Alison C Rudd: Writing – original draft, Conceptualization. **Lane Rosanna A.:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Alison L Kay:** Writing – review & editing, Methodology, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Rosanna Lane reports financial support was provided by UK Research and Innovation Natural Environment Research Council. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2026.103417.

Data availability

Data will be made available on request.

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