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ORIGINAL ARTICLE

A comparison of hydrological impacts from two ensembles of regional climate projections with a range of climate sensitivities

Alison Lindsey Kay[1]

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Abstract
Understanding the range of potential impacts of climate change is crucial for appropriate adaptation planning, especially for floods and water resources. Driving hydrological models with data from climate models provides important information, but can be limited by availability and useability of appropriate climate ensembles for the region of interest. Here, a recently re-processed multi-model ensemble of regional climate projections, derived from Euro-CORDEX, has been used alongside a regional perturbed parameter ensemble, from UK Climate Projections 2018, to drive a national-scale grid-based hydrological model, to assess future impacts on river flows across Great Britain. The results show relatively consistent increases in GB-median winter flows and 5-year return period high flows, but the magnitude of GB-median decreases in summer flows is more different between the two ensembles, as are reductions in 5-year return period low flows. The signs of GB-median changes in spring and autumn flows are inconsistent. Spatial patterns of change also show significant differences between ensemble members. Assuming the climate model results are all plausible, adaptation planning for Britain should take account of impacts from a range of climate models to enable more robust long-term decision-making for water management. Flow changes assessed using fixed baseline and future time-slices differ from those using time-slices derived by model-based global temperature change from the pre-industrial period; the latter removes some uncertainty related to choice of emissions scenario and improves comparability between different climate models, but the preferred approach may depend on the application.

Keywords Climate change · Seasonal mean flow · Flood frequency, Low flow frequency · UKCP18 · EuroCORDEX-UK

Introduction

Understanding the range of potential impacts of climate change is crucial to enable appropriate adaptation planning for a wide range of sectors (Martinich and Crimmins 2019), with the impacts on hydrology, including floods, droughts and water resources, a particular concern (Caretta et al. 2022). Outputs from global or regional climate models are often used to drive hydrological or river routing models to investigate potential impacts on flows at global or large scales (e.g. Müller et al. 2024; Thompson et al. 2021; Marx et al. 2018) or at national or catchment scales (e.g. Krysanova et al. 2017; Sperna Weiland et al. 2021). For Britain, finer resolution regional, rather than global, climate model data is generally considered necessary, particularly for high flow simulation and for all but the largest catchments. Thus, river flow projections for Britain are limited by the availability and useability of appropriate climate ensembles.

Several generations of climate projections for the UK have been specifically produced by the UK Met Office (Hulme et al. 2002, Murphy et al. 2009, 2018), funded by the UK Government to help decision-makers assess climate hazard and risk. These have enabled hydrological impact studies using products ranging from probabilistic projections to Global Climate Model (GCM) and Regional Climate Model (RCM) data (e.g. Reynard et al. 2003; Arnell 2004; Fowler et al. 2007; Christierson et al. 2012; Kay and Jones 2012b; Prudhomme et al. 2012; Sanderson et al. 2012). The latest generation, UK Climate Projections 2018 (UKCP18; Lowe et al. 2018), provides similar products to those provided previously, including ~ 12 km RCM data (UKCP18 Regional). These products have similarly been used to investigate potential hydrological impacts across Britain (e.g. Kay

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✉ Alison Lindsey Kay
alkay@ceh.ac.uk

[1] UK Centre for Ecology & Hydrology, Wallingford OX10 8BB, UK

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et al. 2021b; Lane et al. 2022; Smith et al. 2024). However, the RCM projections are solely based on the Met Office Hadley Centre climate model, albeit using a perturbed parameter ensemble (PPE). They have a tendency to be hotter and drier in summer than those from other GCMs (Murphy et al. 2018; Fig. 5.1), so may not fully represent the potential range.

The CORDEX (Coordinated Regional Climate Downscaling Experiment) initiative (cordex.org/) aims to advance regional climate model applications globally. The European branch of CORDEX, Euro-CORDEX (euro-cordex.net/), provides outputs covering Europe from a multi-model ensemble (MME) using a range of GCM/RCM combinations with ~ 12 km resolution (Jacob et al. 2014). To enhance useability of these projections alongside UKCP18, a project was funded by the UK Climate Resilience Programme to convert Euro-CORDEX data to the grid used for the UKCP18 Regional ensemble, with the same naming conventions (EuroCORDEX-UK; Barnes et al. 2024, ucl.ac.uk/statistics/research/eurocordex-uk).

The aim here is to compare future impacts on river flows from use of the EuroCORDEX-UK MME and the previously applied UKCP18 Regional PPE, when used to drive a grid-based hydrological model for Great Britain. Specifically, changes in seasonal mean flows, high flows and low flows are compared, to assess the extent to which use of the UKCP18 Regional ensemble alone may give an incomplete picture of potential future changes in rivers flows across GB. Flow changes are also assessed using both fixed baseline and future time-slices, and time-slices derived by GCM-based levels of change in global temperature from the pre-industrial period.

Methods

Hydrological model

The Grid-to-Grid (G2G) is a national-scale runoff-production and routing model for Great Britain operating on a 1 km grid at a 15-min time-step (Bell et al. 2009), with an optional temperature-based snow module (Bell et al. 2016). It is mainly parameterised using spatial datasets (e.g. soil types) rather than calibration (Bell et al. 2009) and is driven by 1 km gridded time-series of precipitation and potential evaporation (PE), plus temperature for the snow module. It performs well for flow simulation in a wide range of catchments (Bell et al. 2009, 2016; Rudd et al. 2017; Formetta et al. 2018), particularly where the regime is relatively natural. The inclusion of artificial influences (abstractions and discharges) has been shown to improve performance in affected catchments (Rameshwaran et al. 2022), but limited temporal and spatial data availability means that these factors are not included here.

Climate change projections and their application

UKCP18 Regional

UKCP18 provides information on potential changes in UK climate over the twenty-first century via several products (Murphy et al. 2018), including the UKCP18 Regional (12 km) projections (Met Office Hadley Centre 2018). These comprise a 12-member PPE of the Hadley Centre RCM nested in an equivalent GCM PPE, covering Dec 1980–Nov 2080 under RCP8.5 emissions (Riahi et al. 2011). The data are available re-projected from the native rotated lat-lon grid to a 12 km grid aligned with the GB national grid; the re-projected data are used here. All ensemble members use a 360-day year. Further detail on the prior use of UKCP18 Regional data to drive G2G, for GB and Northen Ireland, is provided by Kay et al. (2023a).

EuroCORDEX-UK

Data from the Euro-CORDEX MME are available re-projected from the individual model grids to the 12 km grid used for UKCP18 Regional (Barnes 2023; Barnes et al. 2024), also covering Dec 1980–Nov 2080 under RCP8.5 emissions. Data are available for 64 GCM/RCM combinations (6 distinct GCMs and 10 RCMs), although not all combinations are included (Table 1). Two GCMs have multiple realisations; only the one used for the most RCMs has been applied here. Two RCMs could not be applied due to issues with orography data (Supp. Section 1). This left 42 GCM/RCM combinations (hereafter 'EC-UK'). Ensemble members use different length years; standard 365/366-day, fixed 365-day (i.e. no leap years) or 360-day. The hydrological model has been coded to use the different year length options as appropriate.

Applying the climate data

For each GCM/RCM combination, re-projected daily precipitation and min/max temperature data are directly available to drive G2G (including the snow module). PE is not directly available so has been estimated from other re-projected daily climate variables using the Hydro-PE method of Robinson et al. (2023), which is based on Penman–Monteith and includes interception.

As in prior applications of G2G with UKCP18 Regional data (e.g. Kay 2021), simple grids of monthly correction factors have been applied to precipitation, aiming to correct coarse monthly/seasonal mean biases. The precipitation are then spatially downscaled from 12 to 1 km using spatial weights derived from 1 km patterns of standard average annual

Table 1 Combinations of GCM and RCM available within EuroCORDEX-UK, with corresponding ensemble member numbering

RCM \ GCM	CNRM-CM5 r1i1p1	EC-EARTH r12i1p1	EC-EARTH r1i1p1	EC-EARTH r3i1p1	IPSL-CM5A-MR r1i1p1	MOHC-HadGEM2-ES r1i1p1	MPI-M-ESM-LR r1i1p1	MPI-M-ESM-LR r2i1p1	MPI-M-ESM-LR r3i1p1	NorESM1-M r1i1p1
ALADIN63	100					132	142			156
CCLM4-8-17	101	110				133	143			
COSMO-crCLIM-v1-1	102	111	112	113		134	144	145	146	157
HadREM3-GA7-05	103	114				135	147			158
HIRHAM5	104	115	116	117	127	136	148			159
RACMO22E	105	118	119	120	128	137	149			160
RCA4	106	121	122	123	129	138	150	151	152	161
RegCM4-6	107	125				139	153			162
REMO2015	108	124			130	140			154	163
WRF381P	109	126			131	141	(155)			164

Blue shading indicates the 42 combinations applied here, while grey shading indicates combinations that were not or could not be applied. The EC-EARTH and MPI GCMs have multiple realisations (r_i_p_ indications by the GCM name); only the realisation used for the most RCMs has been applied here, to avoid skewing overall results to those GCMs. Issues with availability of orography data for the ALADIN and WRF RCMs meant they could not be used here

rainfall (SAAR; Kay et al. 2023b), and the daily totals are spread equally over the G2G model time-steps in each 24-h period. The daily PE data are copied down from 12 to 1 km and also spread equally through the 24-h period. The daily min/max temperature data are downscaled from 12 to 1 km using a lapse rate with elevation, and interpolated through the day using a sine curve (Bell et al. 2016).

Each RCM-based G2G simulation was initialised in Dec 1980 using a states file produced at the end of an observation-based simulation for Jan 1970–Nov 1980 (as Kay 2021), and run through to Nov 2080. Model outputs include 1 km gridded time-series of monthly mean river flows, annual maxima (AMAX) of daily mean river flows for water years (October–September), and annual minima (AMIN) of 7-day mean river flows for years spanning December–November. AMAX extraction uses water years to avoid taking the same event from consecutive years. AMIN extraction would usually use calendar years for the same reason, but December–November is used here to match the climate model data (Dec 1980–Nov 2080). The flows (m^3/s) are output for all non-sea and non-tidal 1 km cells with a catchment drainage area of at least 50 km^2 (hereafter 'river pixels').

Analysis of simulated flows

Time-slices

Previously, standard practice when investigating impacts of climate change was to select fixed reference and future time-slices (typically 30-year periods) and look at changes between them, under one or more emissions scenarios. More recently, motivated by the requirements of policy-makers and public communications (James et al. 2017), studies have used time-slices derived by levels of change in global mean surface temperature (GMST) from the pre-industrial period (e.g. Arnell et al. 2021; Rudd et al. 2023; Smith et al. 2024). Such studies aim to encourage action on both mitigation (to limit emissions to avoid more severe impacts) and adaptation (to reduce the societal and environmental impacts of changes that may be inevitable). This also reduces the focus on emissions scenarios, some of which may be seen as unlikely, and can provide more balanced comparisons between different climate models, which can have very different climate sensitivities (Barnes et al. 2024). Remaining differences between models are then due to (i) differences in local, rather than global, response and (ii) natural variability.

Here, changes are assessed between the following time-slice pairs:

- 1° and 2° GMST change from pre-industrial ('1 deg-2 deg');
- 1° and 3° GMST change from pre-industrial ('1 deg-3 deg'); and
- Fixed 30-year baseline (1980–2010) and far-future (2050–2080) ('Fixed').

The time-slices for 1°, 2° and 3° GMST change from pre-industrial were derived by Barnes et al. (2024) as the 30-year period centred on the year in which the GMST change in the driving GCM exceeds the threshold of interest (github-pages.ucl.ac.uk/EuroCORDEX-UK-plot-explorer/#/time-help). The time-slices vary for each GCM used in EC-UK but also for each UKCP18 PPE member despite them using the same GCM (Fig. 1); the latter differ because variations of RCP8.5 emissions were applied in the UKCP18 PPE to reflect carbon cycle uncertainties (Murphy et al. 2018 Section 1.4).

The reference period is a 1° GMST change, rather than a fixed 30-year period, for the first two options as different climate models have also warmed by differing amounts prior to the fixed baseline (1980–2010); using the 1° time-slice as reference allows for this. For two GCMs (CNRM and

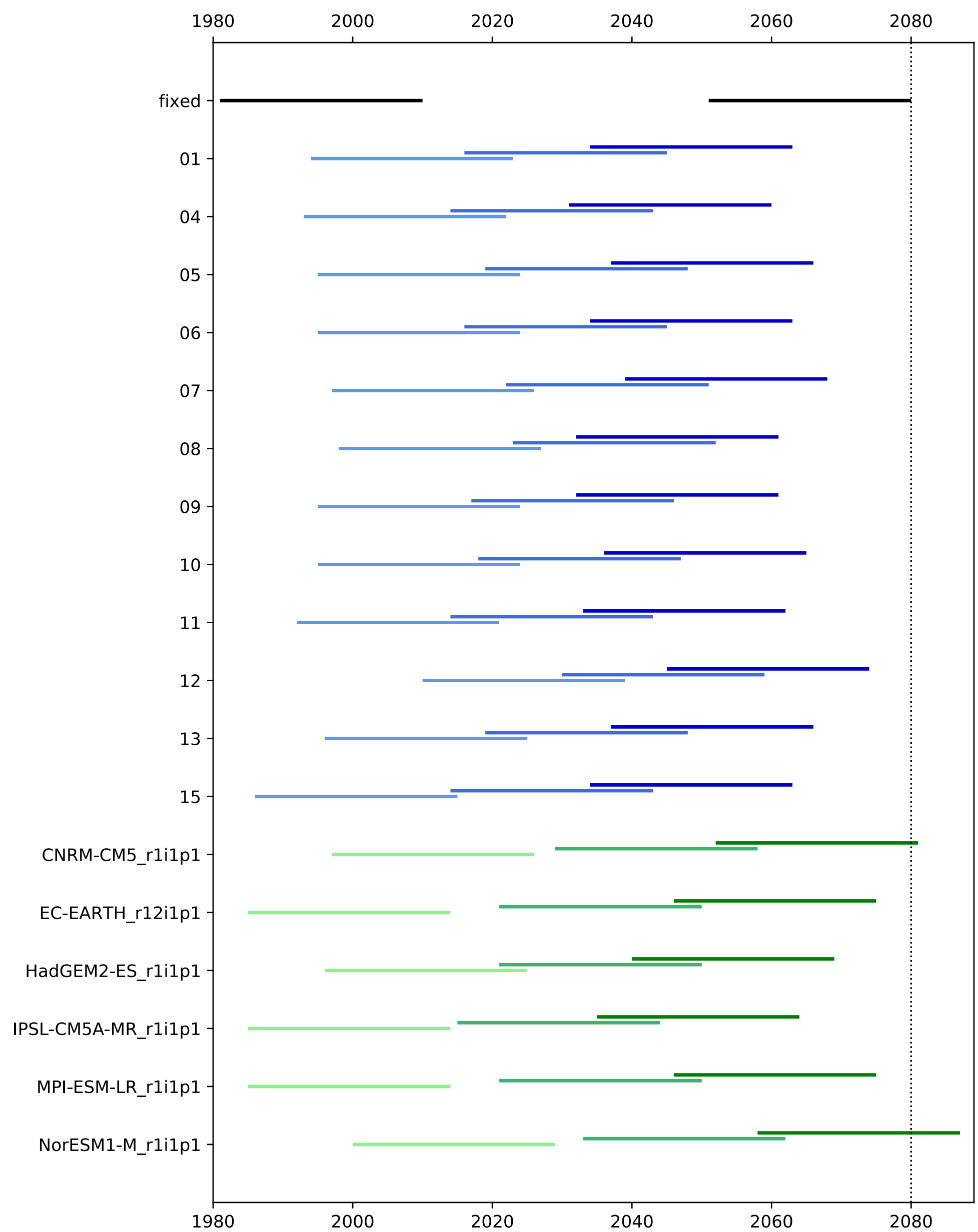


Fig. 1 The 1°, 2° and 3° GMST change 30-year time-slices for each UKCP18 Regional ensemble member (shades of blue) and each EC-UK GCM (shades of green), compared to the fixed baseline and far-future time-slices (black)

NorESM), the 30-year period for a 3° GMST change goes beyond 2080 (Fig. 1). The length of the period (and its corresponding reference period) is thus reduced to fit the end year of 2080 (but it is still centred on the required year so years are removed from the start as well as the end). Thus, the '1 deg-3 deg' time-slices use 26 years for the CNRM GCM and only 14 years for the NorESM GCM.

In all cases, the 1° time-slice is later than the fixed baseline time-slice, and in most cases the 3° time-slice is earlier than the fixed far-future time-slice, so (assuming impacts increase over time) it may be expected that the impacts for a given ensemble member for '1 deg-3 deg' would be less than those for 'Fixed', and the impacts for '1 deg-2 deg' would be less again.

Seasonal mean flow changes

For each G2G run, the 1 km gridded time-series of monthly mean flows are used to derive 1 km grids of seasonal mean flows for each time-slice, using the standard seasons (winter: Dec–Feb, spring: Mar–May, summer: Jun–Aug, autumn: Sep–Nov) (as Kay 2021). Changes in seasonal mean flows for time-slice pairs are then investigated.

High and low flow changes

For each G2G run and each river pixel, flood frequency curves are derived by fitting a generalised logistic distribution to the AMAX for each time-slice, and low flow frequency curves are derived by fitting a generalised extreme value distribution to the AMIN for each time-slice (as Lane and Kay 2021). Changes in high and low flows for time-slice pairs are then calculated for selected return periods. Results here focus on the 5-year return period; longer return periods (rarer events) are avoided due to the short time-slice length for some GCMs ('Time-slices' section).

There are minor differences between time-slices applied for high and low flows, due to use of water years (Oct–Sep) for high flows versus Dec–Nov years for low flows (and seasonal mean flows).

Results

Seasonal mean flow changes

Looking at the GB-median (average across river pixels), the ensemble mean flow change simulated using UKCP18 is lower than the ensemble mean flow change from EC-UK for all seasons and all time-slice pairs (Fig. 2). In winter, this means that the overall EC-UK ensemble gives larger increases in flows than UKCP18 (although some EC-UK GCM-based sub-ensembles show mean decreases in flows), while in summer, the EC-UK ensemble gives lesser decreases in flows than UKCP18 (and some EC-UK GCM-based sub-ensembles show mean increases in flows). In spring and autumn, the EC-UK and UKCP18 ensembles often give different signs of ensemble mean flow change.

For the UKCP18 ensemble, there is generally a worsening of impacts (higher magnitude increases in winter or decreases in spring/summer/autumn flows) when moving from 1 deg-2 deg to 1 deg-3 deg to Fixed time-slice pairs (although in spring, the changes for 1 deg-3 deg and Fixed are very similar), as might be expected given the increasing gaps between the first and second time-slice of each pair ('Time-slices' section). While this monotonic change across time-slice pairs also holds for the overall EC-UK ensemble, it is less clear than for UKCP18 (e.g. in summer, the overall EC-UK mean changes for 1 deg-3 deg and Fixed are very similar), and it does not hold for all GCM-based sub-ensembles (sets of runs driven by the same GCM but with different RCMs).

Perhaps unsurprisingly, the EC-UK sub-ensembles involving the Hadley GCM (EC_HadGEM) or RCM (EC_HadREM) are typically most similar to UKCP18 (a PPE using only HadGEM and HadREM), especially for the 1 deg-2 deg and 1 deg-3 deg time-slice pairs. However, there can still be large differences, indicating the influence of other RCMs used with the Hadley GCM or other GCMs with the Hadley RCM. This is particularly the case for the Fixed time-slice pair due to the different warming rates of different GCMs.

Differences in spatial patterns of change in seasonal mean flows between ensemble members are summarised in Taylor diagrams for the Fixed time-slice pair (Fig. 3) with the corresponding maps in Figs. 4, 5, 6, and 7. The Taylor diagrams show each map's standard deviation and its correlation with a reference map (the UKCP18 ensemble mean change for each season). For all four seasons, the Taylor diagrams show that most members of the EC-UK ensemble have lower correlations with the reference map than the UKCP18 ensemble members.

For winter flows (Fig. 4), UKCP18 mostly gives decreases in the southeast and increases in the northwest, whereas many EC-UK ensemble members give increases over large areas, with limited areas showing decreases. Correspondingly, Taylor diagrams (Fig. 3a) show many EC-UK ensemble members with a standard deviation lower than the UKCP18 ensemble mean, although few are negatively correlated, indicating similar spatial gradients for the two ensembles.

For spring flows (Fig. 5), many EC-UK ensemble members give increases in the southeast, whereas UKCP18 ensemble members mostly only give increases in the west. Correspondingly, Taylor diagrams (Fig. 3b) show many EC-UK ensemble members with a negative correlation to

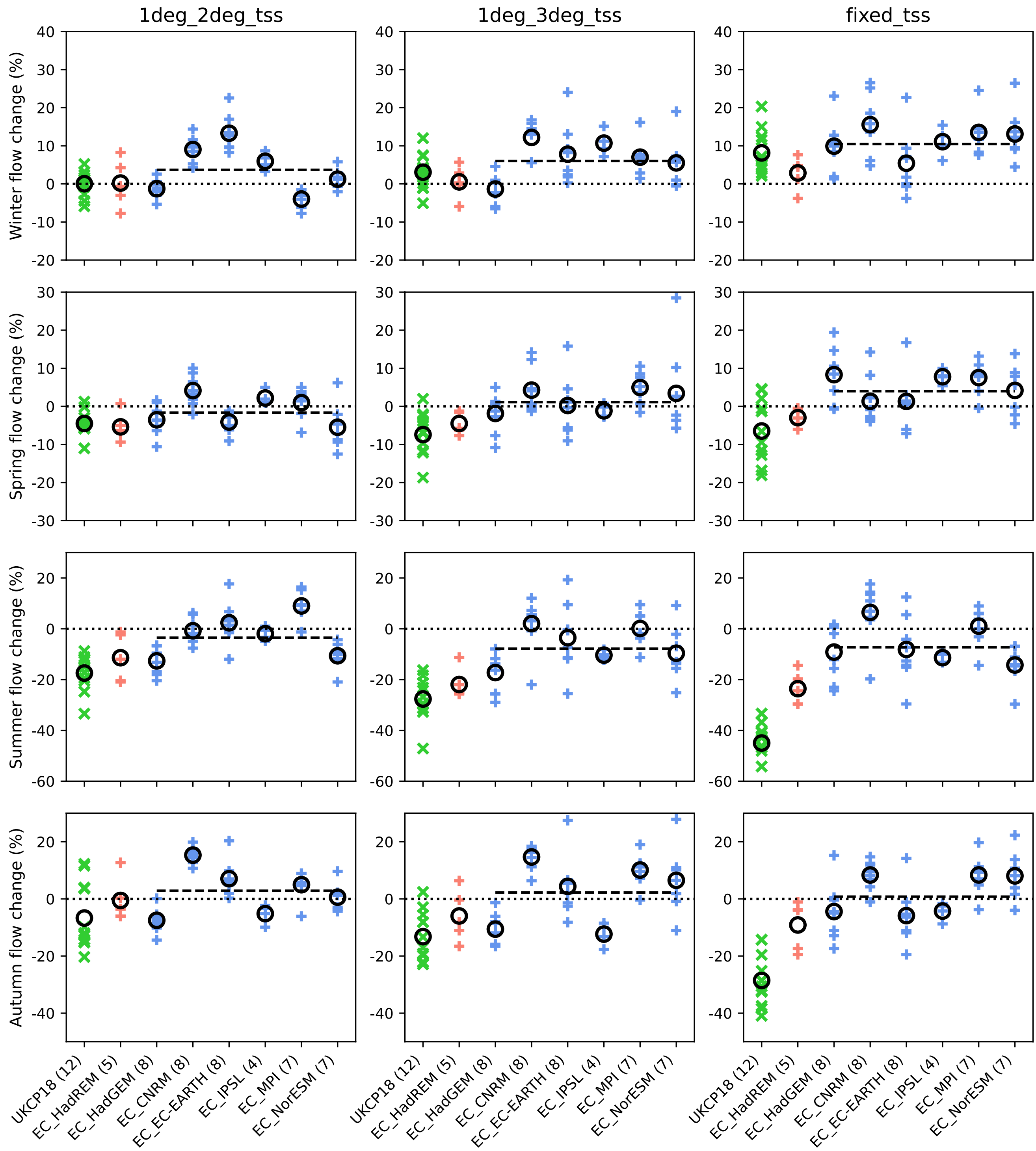


Fig. 2 The GB-median change in river flows for each time-slice pair (1 deg-2 deg, 1 deg-3 deg, Fixed; left to right) for each season (top to bottom), for the UKCP18 ensemble (green crosses) and EC-UK ensemble (blue plus signs). The EC-UK ensemble is split by driving GCM (HadGEM, CNRM, EC-EARTH, IPSL, MPI and NorESM), and the subset using the Hadley RCM is also plotted for comparison (red plus signs). For each sub-ensemble, the mean is shown (black circle), and the number of sub-ensemble members is given in brackets. The overall EC-UK ensemble mean is also shown (black dashed horizontal line)

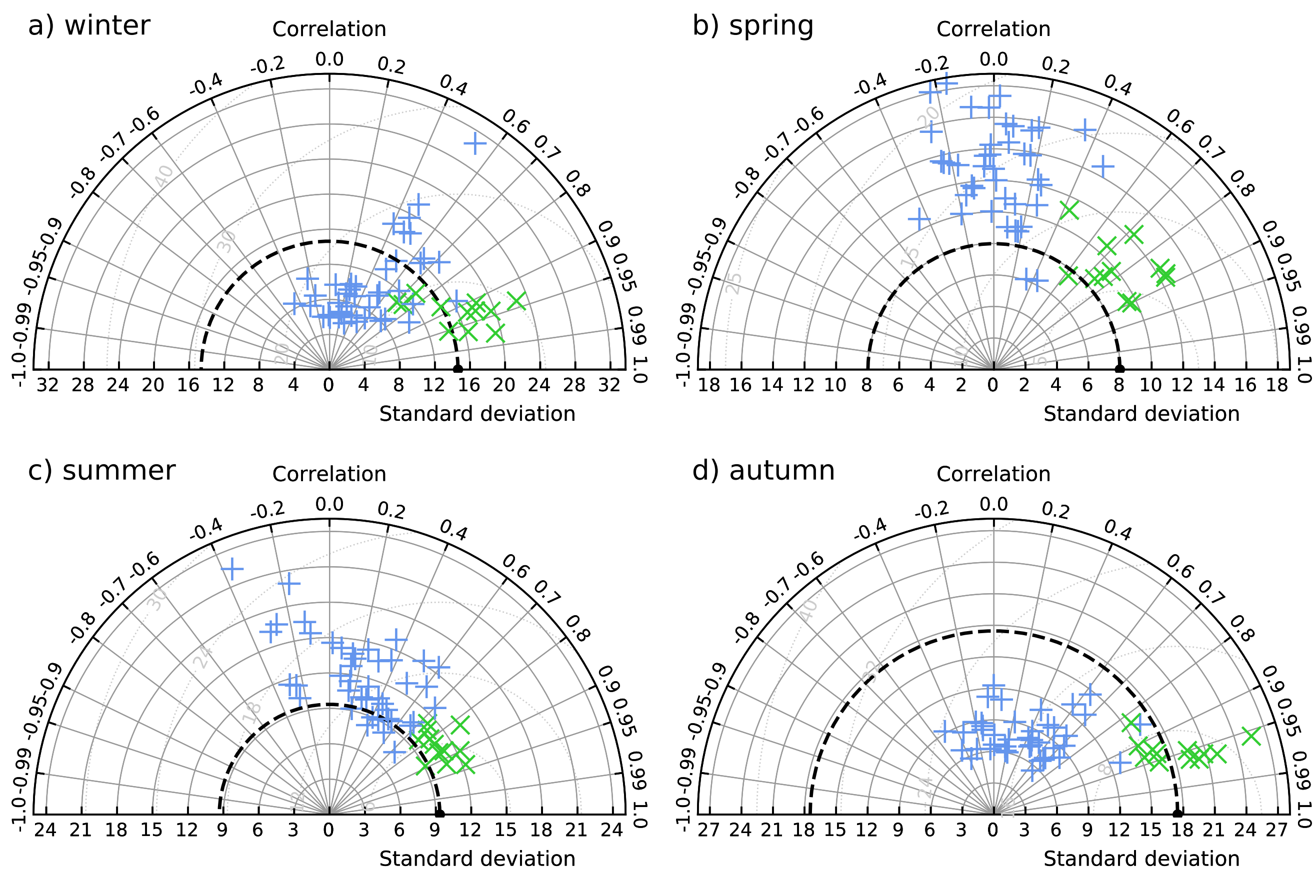


Fig. 3 Taylor diagrams comparing the spatial patterns of change in seasonal mean flows across GB for the UKCP18 ensemble (green crosses) and EC-UK ensemble (blue plus signs) for the Fixed time-slice pair. The reference pattern is taken as the UKCP18 ensemble mean (black circle on the x-axis)

the UKCP18 ensemble mean, indicating different spatial patterns of change. The standard deviations of the EC-UK ensemble cover a broader range than the UKCP18 ensemble, indicating greater differences in spatial variation.

For summer flows (Fig. 6), UKCP18 gives large decreases almost everywhere, whereas some EC-UK ensemble members give increases, especially to the southeast. Correspondingly, Taylor diagrams (Fig. 3c) show some EC-UK ensemble members with a negative correlation to the UKCP18 ensemble mean, although not as many as for spring flows. The standard deviations of the EC-UK ensemble mostly cover a similar range to the UKCP18 ensemble.

For autumn flows (Fig. 7), UKCP18 mostly only gives large decreases (apart from relatively small areas to the northwest), whereas some EC-UK ensemble members give increases across large areas. Correspondingly, Taylor diagrams (Fig. 3d) show some EC-UK ensemble members with a negative correlation to the UKCP18 ensemble mean, although again not as many as for spring flows. The standard deviations of the EC-UK ensemble are almost all lower than for the UKCP18 ensemble.

Taylor diagrams and maps for the 1 deg-3 deg time-slice pair are given in Supp. Section 2 (Supp. Figs. 1–5) for comparison—they show relatively similar patterns to those for the Fixed time-slice, but changes are generally lower.

High and low flow changes

Figure 8 shows the change in 5-year return period high and low flows as the median across all GB river pixels, for each time-slice pair and each model run. For low flows, for all time-slice pairs, the mean change from the UKCP18 ensemble is lower than the mean change from the EC-UK ensemble (and indeed lower than the mean from each GCM-based sub-ensemble), although all are negative. This means that the UKCP18 ensemble gives worse decreases in low flows than EC-UK. Both ensembles show worsening impacts when moving from 1 deg-2 deg to 1 deg-3 deg to Fixed time-slice pairs, although the differences for the EC-UK ensemble are much smaller than for UKCP18.

For high flows, the mean changes from the UKCP18 ensemble and the EC-UK ensemble are positive for all time-slice pairs, indicating worsening flood peaks. However, the

Fig. 4 Maps of percentage change in winter flows for the UKCP18 (top) and EC-UK (bottom) ensembles, between the fixed baseline and far-future time-slices

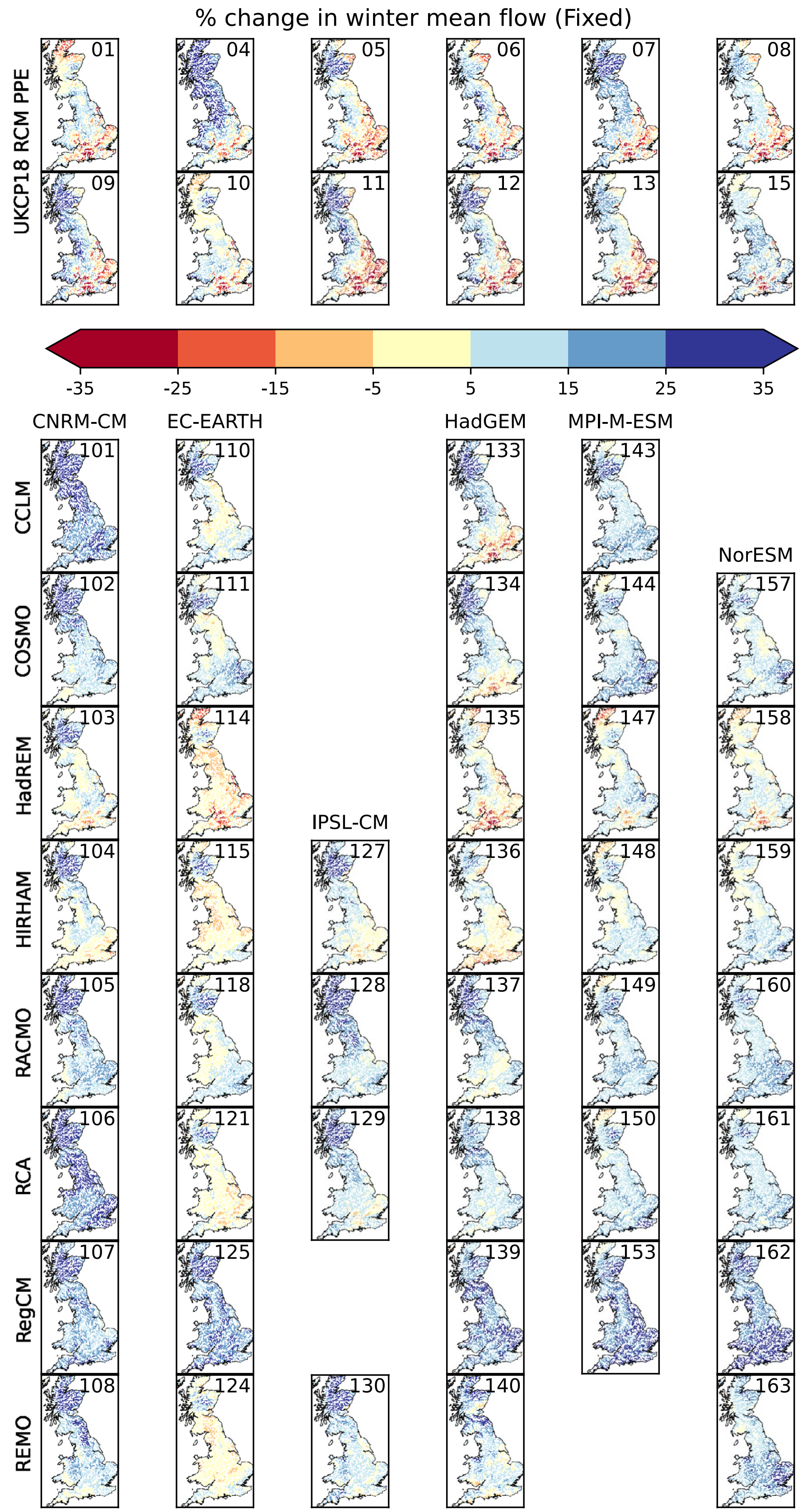


Fig. 5 As Fig. 4 but for change in spring flows

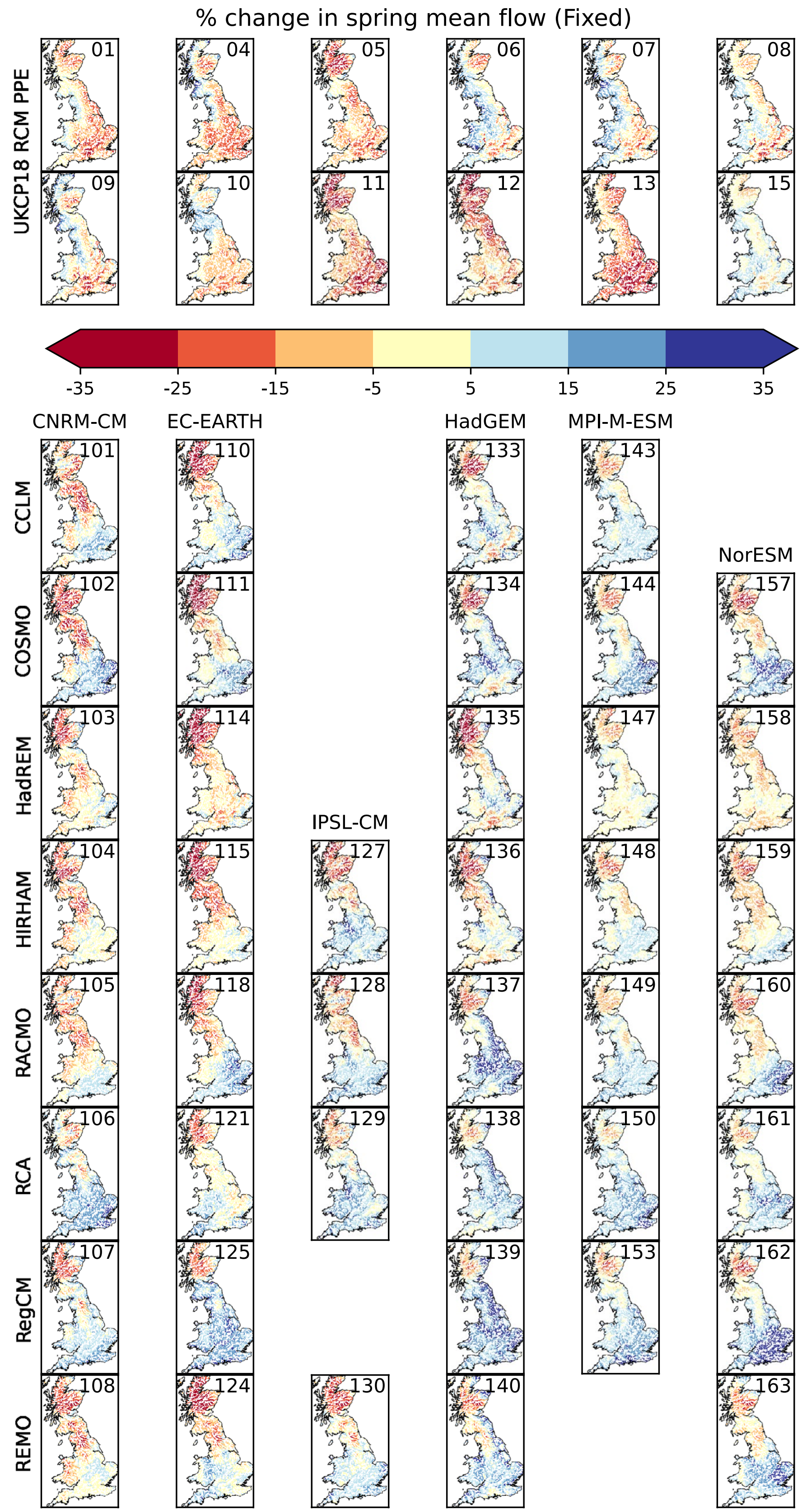


Fig. 6 As Fig. 4 but for change in summer flows

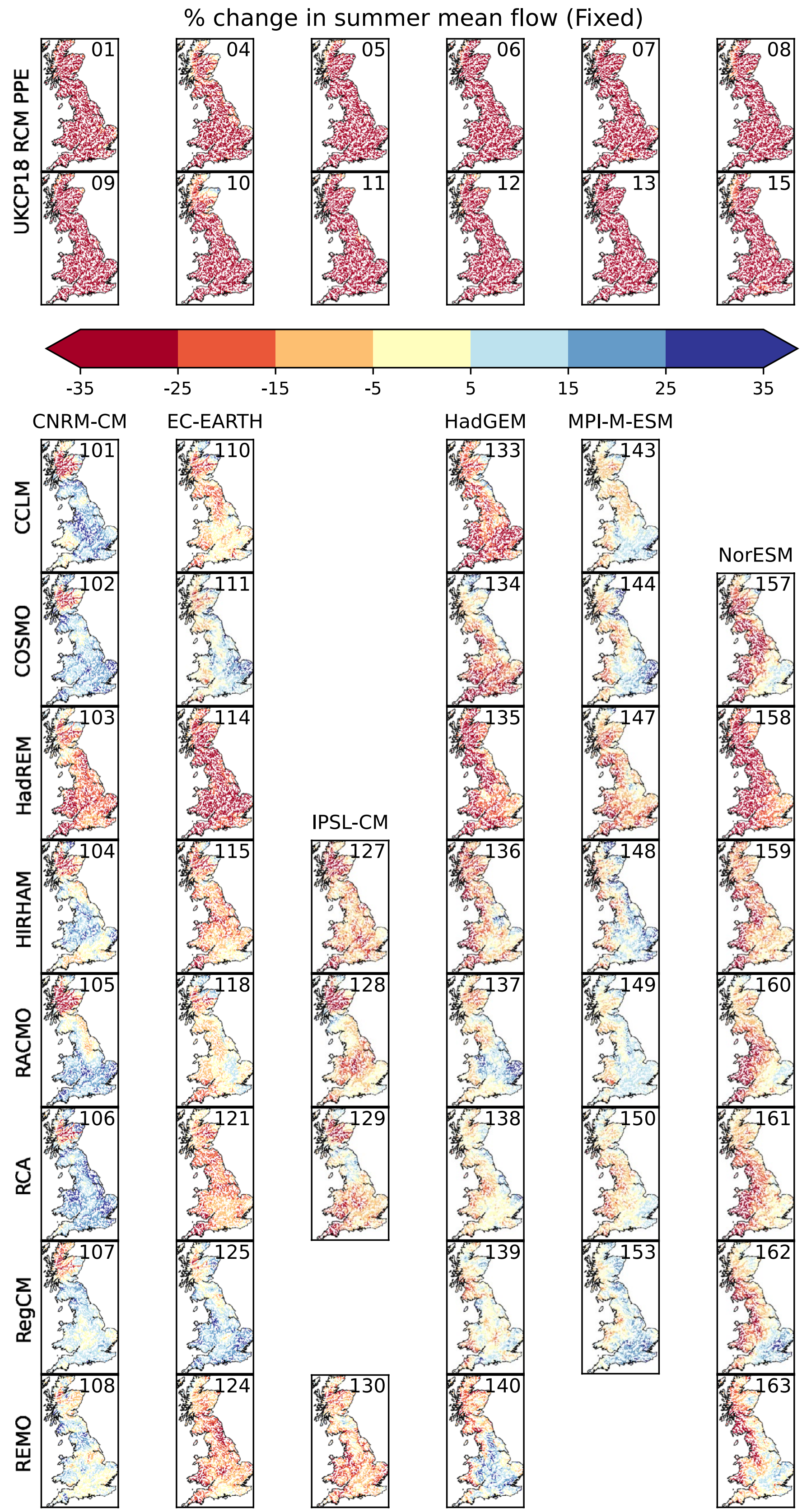
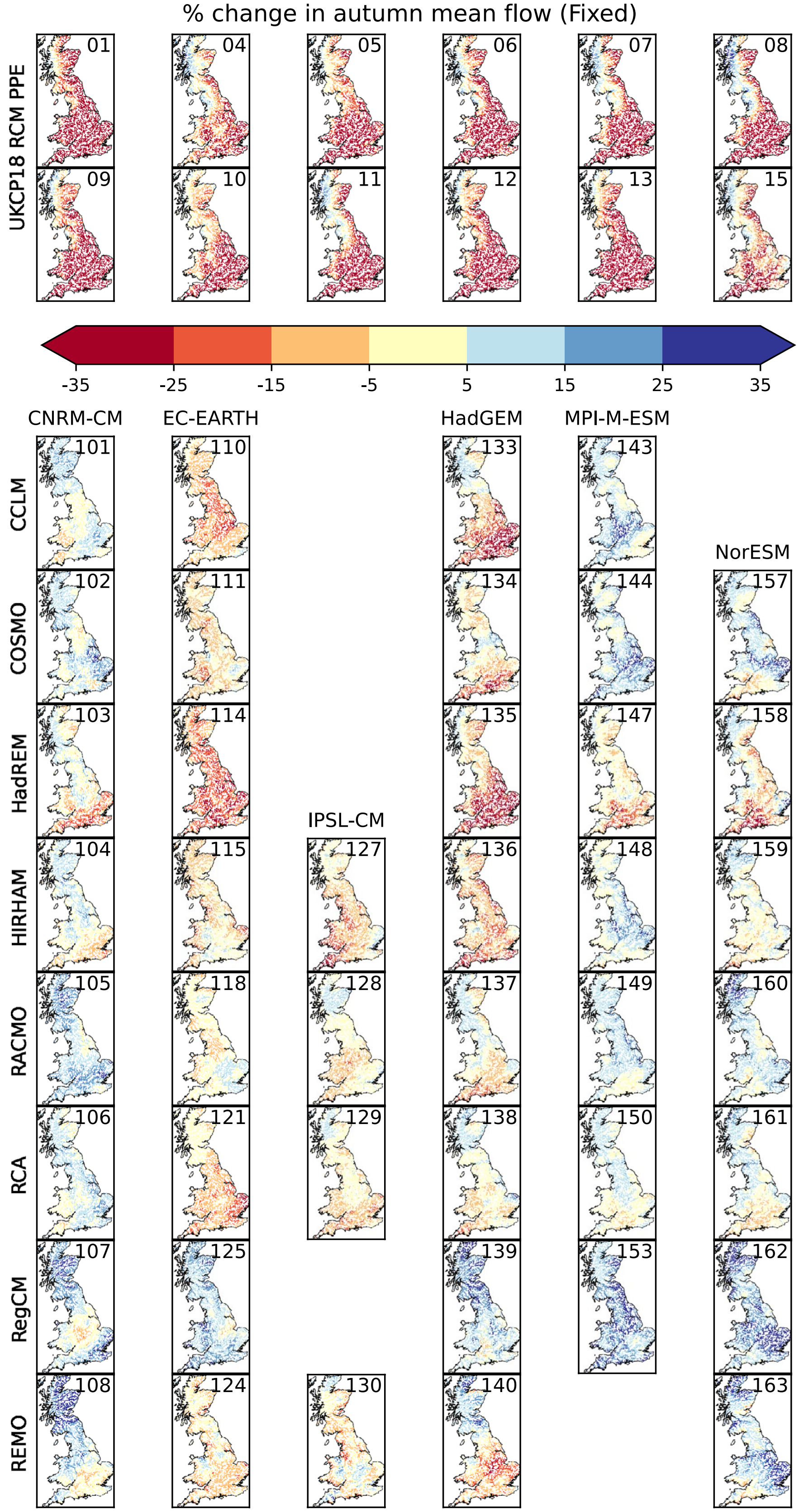


Fig. 7 As Fig. 4 but for change in autumn flows



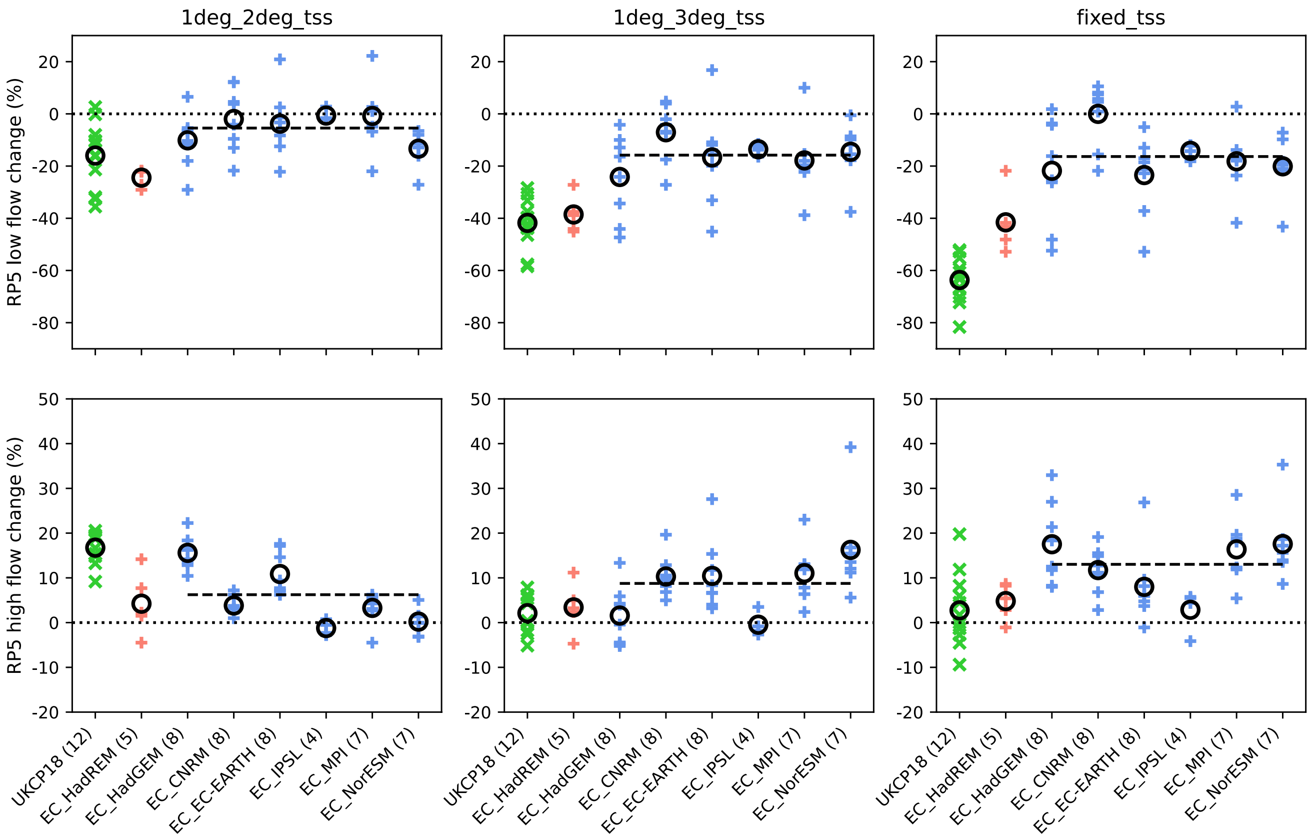


Fig. 8 As Fig. 2 but showing the GB-median change in 5-year return period low flows (top) and 5-year return period high flows (bottom)

overall EC-UK ensemble mean gives a monotonic increase moving from 1 deg-2 deg to 1 deg-3 deg to Fixed time-slice pairs, while UKCP18 gives the highest increase (higher than EC-UK) for the 1 deg-2 deg pair and lower increases (lower than for EC-UK) for the 1 deg-3 deg and Fixed time-slice pairs.

As for seasonal mean flow changes, the EC-UK subsets involving the Hadley GCM or RCM are typically most similar to UKCP18, especially for the 1 deg-2 deg and 1 deg-3 deg time-slice pairs, but some larger differences, especially for the Fixed time-slice pair, indicate the influence of other RCMs/GCMs when used with the Hadley GCM/RCM.

Taylor diagrams (Fig. 9) show that most members of the EC-UK ensemble have lower correlations with the reference map (the UKCP18 ensemble mean) than the UKCP18 members, for changes in both low flows and high flows. For a substantial proportion of the EC-UK ensemble, the correlations are negative, indicating different spatial patterns of change.

Low flow changes (Fig. 10) are relatively similar to summer flow changes (Fig. 6), which is perhaps unsurprising as river flows and soil moisture levels are typically at their lowest in summer in GB (Kay et al. 2023a). UKCP18 gives large decreases almost everywhere, whereas some EC-UK ensemble members give increases, especially to the southeast. Correspondingly, Taylor diagrams (Fig. 9a) show some EC-UK ensemble members with a negative correlation to the UKCP18 ensemble mean. The standard deviations of the EC-UK ensemble cover a similar range to the UKCP18 ensemble.

High flow changes (Fig. 11) are relatively similar to winter flow changes (Fig. 4), which is again perhaps unsurprising as river flows and soil moisture levels are typically at their highest in winter in GB (Kay et al. 2023a). Some UKCP18 ensemble members give decreases in the southeast and increases in the northwest (although patterns are very mixed), whereas many EC-UK ensemble members give increases over larger areas, with more limited areas showing decreases. Correspondingly, Taylor diagrams (Fig. 9b) show many EC-UK ensemble members with lower standard deviations than the UKCP18 ensemble, and many EC-UK ensemble members have a negative correlation to the UKCP18 ensemble mean.

Again, Taylor diagrams and maps for the 1 deg-3 deg time-slice pair (Supp. Figs. 6–8) show relatively similar patterns to those for the Fixed time-slice but changes are generally lower.

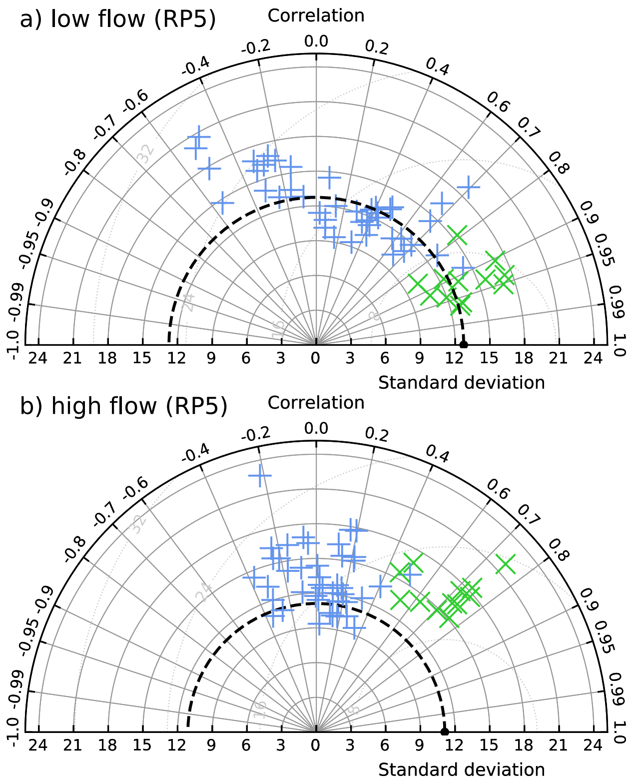


Fig. 9 Taylor diagrams comparing the spatial patterns of change in 5-year return period **a** low flows and **b** high flows across GB for the UKCP18 ensemble (green crosses) and EC-UK ensemble (blue plus signs) for the Fixed time-slice pair. The reference pattern is taken as the UKCP18 ensemble mean (black circle on the x-axis)

Discussion

Projected flow changes across GB are likely to be predominantly driven by precipitation changes, but PE changes are also important (e.g. Kay and Davies 2008), and in some upland areas, temperature increases can also affect flows via snow (e.g. Bell et al. 2016). Potential large-scale changes in antecedent soil moisture conditions are particularly important for changes in seasonal and low river flow, since soil moisture deficits strongly control surface runoff (Robock 2003; Moore 2007), and can be important for flood occurrence and magnitude (e.g. Berghuijs, et al. 2019, Bennett et al. 2018). Additional smaller-scale spatial variation in responses is likely due to catchment properties, particularly the influence of slower-responding groundwater stores in southern England (e.g. Kay et al. 2021a).

For the fixed baseline and far-future time-slices, the GB-median increases in winter flows and decreases in summer flows for both the EC-UK and UKCP18 ensembles (Fig. 2) are consistent with the meteorological analysis of Barnes et al. (2024; Fig. 9), which shows clear increases in winter precipitation and decreases in summer precipitation for both ensembles (Supp. Fig. 9a,c). For both precipitation and flows, the summer decreases from UKCP18 are much larger than those from EC-UK, and a small number of EC-UK ensemble members (especially from the CNRM GCM) show summer increases.

Barnes et al. (2024) do not show spring or autumn precipitation, but plots were obtained from their Plot Explorer tool. For spring (Supp. Fig. 9b), these show similar changes for UKCP18 and EC-UK, with ensemble median increases but decreases for several members. For autumn (Supp. Fig. 9d), there is more difference between the two ensembles, with median increases for EC-UK but decreases for UKCP18, although both have several ensemble members showing the opposite change. This mixed picture of spring and autumn precipitation changes carries through to flows, except for consistent decreases in autumn flows from UKCP18, likely due to the persistence of the much greater summer decreases. When using 1 deg-2 deg time-slices, the precipitation analysis of Barnes et al. (2024) shows more consistency in changes for the EC-UK and UKCP18 ensembles, especially for summer, as does the seasonal flow analysis here.

Robinson et al. (2023) show large PE increases for the UKCP18 ensemble; these are not shown by the EC-UK ensemble (Supp. Fig. 10). This likely contributes to the flow differences, particularly the reduced impacts on summer and low flows for EC-UK compared to UKCP18. Supp. Fig. 10 also shows that a small number of EC-UK ensemble members give consistently higher PE than the rest; these all use the RegCM RCM. Further investigation is required to assess why, but flow simulations using this RCM should perhaps be excluded from further GB analyses if some of the meteorological variables going into the PE estimation are unrealistic.

The GB-median increases in 5-year return period high flows for the EC-UK ensemble (Fig. 8, Fig. 11) are consistent with the European-scale modelling of Di Sante et al. (2021). They use Euro-CORDEX runoff with a routing model to produce river flow, and investigate future changes in annual mean, peak (AMAX) and 100-year return period flood flows. For the far-future under RCP8.5, they find statistically significant increases in peak flow over much of England and Wales and similar areas of southern England show robust increases in floods.

Sperna Weiland et al. (2021) use Euro-CORDEX climate variables to drive three hydrological models for nine catchments across Europe, including the Severn in GB. They apply two performance-based weighting schemes to combine the ensemble members, to provide ‘more confident’ future flow projections. Both weighted and unweighted results show increases in annual mean flow, 7-day AMIN flow and AMAX flow for the Severn (with ensemble ranges encompassing decreases). The increases in AMAX are consistent with changes in high flows here (Fig. 11), but the increases in 7-day AMIN may be less consistent with changes in low flows here, which tend towards decreases (Fig. 10). Previous

Fig. 10 As Fig. 4 but for change in 5-year return period low flows

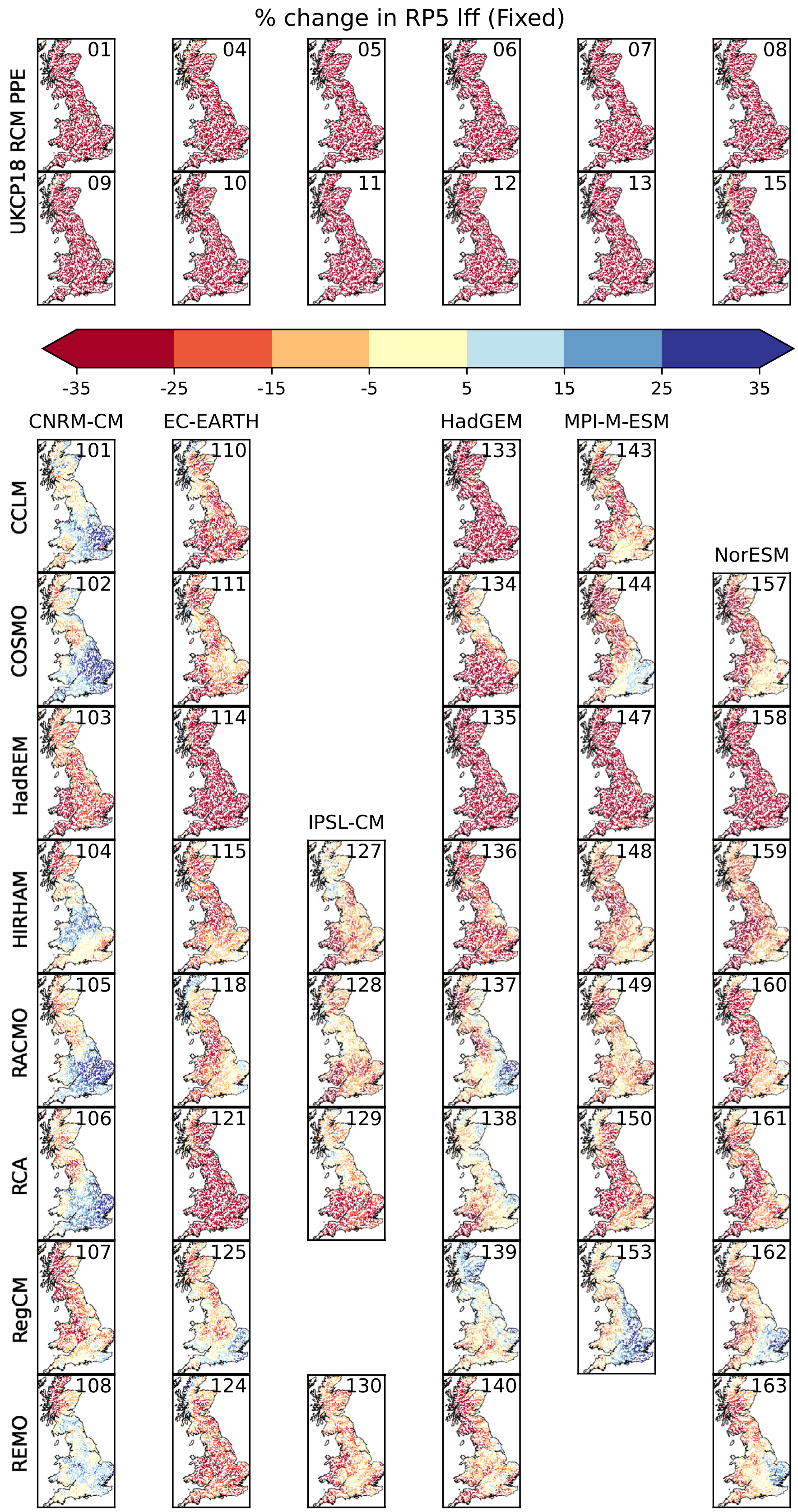
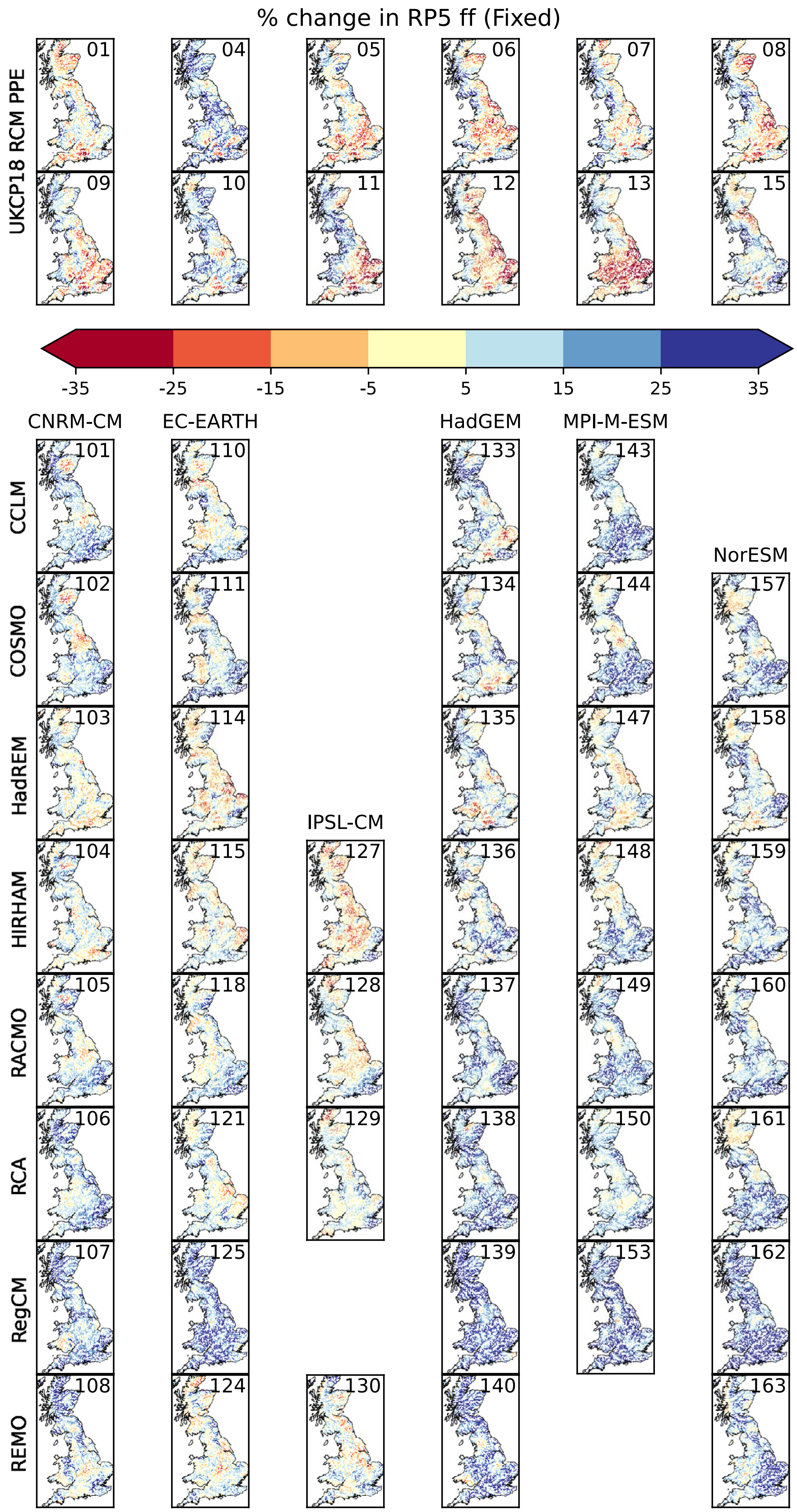


Fig. 11 As Fig. 4 but for change in 5-year return period high flows



studies have suggested that low flow changes are more likely to be affected by hydrological model choice than high flows (e.g. Giuntoli et al. 2015).

When using a large ensemble such as EC-UK, it is tempting to summarise results via, for example, maps of the ensemble mean. Such maps are not shown here since they could mask large differences between members and may not well-represent the spatial pattern of any individual member(s). This is highlighted by the Taylor diagram for changes in high flow (Fig. 9b), where the standard deviations for the individual UKCP18 ensemble members are all higher than that for the ensemble mean used as the reference map. Furthermore, the EC-UK ensemble is an ‘ensemble of opportunity’; it is not designed to represent the full range of uncertainty, and some models are over-/under-represented due to missing GCM/RCM combinations (Evin et al. 2021). Also, climate models can share components; assuming independence can give over-confident projections (Pennell and Reichler 2011). One of the weighting schemes of Sperna Weiland et al. (2021) aimed to account for climate model dependence alongside meteorological performance. This gives much greater weight to the EC-EARTH GCM (0.46) and low weights to the CNRM and IPSL GCMs (0.05 and 0.06), with similar weights (0.11–0.14) for each of the HadGEM, MPI and NorESM GCMs, although it is not clear how much this is from performance vs independence. Sperna Weiland et al. (2021) note that “high weights obtained through past good performance can provide deviating projections for the future”. So while information about individual model performance may help in the interpretation of results from multi-model ensemble members, it is not typically a useful way of combining those results.

The spatial resolution of the climate model data here is 12 km. Recent work using 5 km convection-permitting model (CPM) data showed future flow changes from the CPM were almost always higher than from the equivalent RCM (Kay 2022). Recent analysis of the first multi-model ensemble of CPMs showed improved representation of precipitation over the Alpine region of Europe (Pichelli et al. 2021). Such an ensemble combined with hydrological modelling could provide improved flow projections, particularly for high flows, assuming reliability of the climate simulations at much finer scales. The analysis of Barnes et al. (2024) indicates that the choice of GCM is a more important control on simulated precipitation changes than the (12 km) RCM; whether this holds for finer resolution CPMs would need to be assessed.

Another key source of uncertainty in climate projections is natural internal climate variability (Deser 2020), “which can result in apparent decadal trends that may be greater or lower than the long-term underlying anthropogenic climate change trend” (Martel et al. 2018). Subsequent hydrological projections will be affected, particularly for extremes (Gu et al. 2019, Kay and Jones 2012a). This may be one reason for the flow impacts not always changing monotonically given expanding gaps between time-slices, although another factor could be nonlinear effects from combined changes in precipitation and PE. The effect of natural variability could be investigated by using the other realisations available for some EuroCORDEX-UK GCM/RCM combinations (Table 1), although large initial-condition ensembles are required for a proper assessment (Deser 2020; Jain et al. 2023).

Conclusions

Two very different ensembles of relatively high-resolution climate change projections for Britain, one a perturbed parameter ensemble from a single GCM/RCM combination (from UKCP18) and one a multi-model ensemble of various combinations of GCM and RCM (from Euro-CORDEX), have been used to drive a national-scale grid-based hydrological model (Grid-to-Grid). The simulated impacts on seasonal mean flows and 5-year return period low and high flows have been assessed. There are relatively consistent increases in GB-median winter flows and high flows, but the magnitude of GB-median decreases in summer flows is more different between the two ensembles, as are reductions in low flows. The signs of GB-median changes in spring and autumn flows are less consistent. Spatial patterns of change also show clear differences between ensemble members.

Flow changes assessed using fixed baseline and future time-slices also differ from those using time-slices derived by GCM-based levels of change in GMST from the pre-industrial period. Which approach is preferred may depend on the application. Direct adaptation planning (e.g. designing flood defences) may still prefer to use fixed time-slices (depending on the planning horizon) with an ‘appropriate’ emissions scenario (often one considered precautionary). In contrast, studies aiming to assess the impacts avoided by keeping GMST lower are clearly simplified by use of time-slices based on warming levels, thus removing some of the uncertainties around choice of emissions scenario and improving comparability between different climate models.

Assuming the results from all models are plausible, adaptation planning for Britain should take account of impacts from a range of climate models. However, Barnes et al. (2024) note that “…neither the EuroCORDEX ensemble nor the combined EuroCORDEX-UKCP regional ensemble systematically samples a range of climate sensitivities, so neither should be interpreted as representative of the possible distribution of future scenarios, although the two ensembles taken together are arguably more representative than either one in isolation”. Ideally, hydrological model uncertainty would also be included, particularly for low flows. In addition, analyses using CPM-based MMEs could enable improved flood adaptation, and application of large initial-condition ensembles can support more robust adaptation decision-making for water management than MMEs alone (Mankin et al. 2020).

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Data availability The river flows simulated using the UKCP18 Regional ensemble are available from EIDC (https://doi.org/10.5285/18be3704-0a6d-4917-aa2e-bf38927321c5), while those simulated using the EC-UK ensemble are available from the author upon reasonable request.

Declarations

Competing interests None.

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