



Supplement of

A large-sample investigation into uncertain climate change impacts on high flows across Great Britain

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S1 Biases in RCM projections

An evaluation of the biases in the UKCP18 RCM projections relative to observed data was carried out to inform selection of an appropriate bias correction technique. This focused on biases in daily and seasonal precipitation/ PET, heavy precipitation, and PET quantiles, as these were considered most important for the median and higher flow statistics used in the main paper.

S1.1 Mean daily rainfall bias

Figure S1 gives the observed mean daily precipitation across Great Britain, as a reference. There is a west-east gradient in mean daily rainfall, with generally reduced rainfall as you move east across the country. The highest daily rainfall can be seen in western Scotland. Figure S2 and Figure S3 show the biases in UKCP18 projections for mean daily precipitation over the baseline period. It can be seen that there is a general trend to smooth the pattern of precipitation – with RCMs underpredicting mean precipitation in the wettest areas (west Scotland, and in some cases south-west England and Wales) and overpredicting in the driest areas (along the east coast and south-east England). Most RCMs show a similar spatial pattern of bias, although there are clear differences between RCM runs. There is a general trend towards all RCMs overpredicting mean annual rainfall by around 3 – 35% (the median across all catchments in Figure S3).

On average the RCMS overpredict the number of wet days in a year (Figure S4), with the majority of grid cells receiving an extra 0 - 55 (0 - 30%) wet days per year. RCM number 10 stands out as showing less bias than the other ensemble members.

S1.2 Seasonal rainfall bias

Figure S5 shows the percentage changes in seasonal rainfall. Figure S6 highlights the month of the year with the largest biases from each of the UKCP18 ensemble members. The figures show that RCMs tend to overpredict rainfall in winter and Spring across most of Great Britain, except for west Scotland where rainfall is generally underpredicted. A more complex pattern of bias is seen for Summer and Autumn rainfall. In the summer there is an overall trend towards overprediction in Scotland, with a more mixed picture for England and Wales. Autumn rainfall biases tend to be smaller, and spatial patterns of bias differ between the RCMs.

S1.3 Heavy rainfall bias

Biases in RCM projections of heavy rainfall percentiles (80th percentile rainfall – 99th percentile rainfall) are given in Figure S7 and Figure S8. The RCMs tend to overestimate rainfall generally, with the tendency to underpredict in areas of high rainfall (east Scotland and east Wales). Across Great Britain, biases in projections of the 80th percentile rainfall are around -40 to 75%, whilst biases in projections of the 99th percentile rainfall tend to be smaller at around -40 to 40%.

S1.4 Mean daily PET bias

Figure S9 shows the distribution of PET over GB for each RCM, compared to observed. Figure S10 shows maps of the percentage bias in PET for each RCM. The RCMs produce a much larger spread in PET than is seen for the observed data. The RCMs tend to overestimate PET in the southeast, where observed PET is high, and underestimate PET in Scotland, where observed PET is lower. Biases in mean daily PET are in the region of -20% to +40%.

S1.5 Seasonal PET bias

Plots showing PET biases split by season are given in Figure S11. These continue the pattern of the RCMs overestimating PET variability. Summer PET is generally overestimated (up to $\sim +40\%$), Winter PET is generally underestimated (in some areas by up to 100%). The same spatial pattern of RCMs underestimating PET in the north and underestimating in the southeast persists through all seasons.

S1.6 Quantiles

Figure S12 shows bias in RCM PET quantiles. Low quantiles are underpredicted, higher PET quantiles are more likely to be overpredicted.



Figure S1. Observed mean daily precipitation over the baseline period across Great Britain.

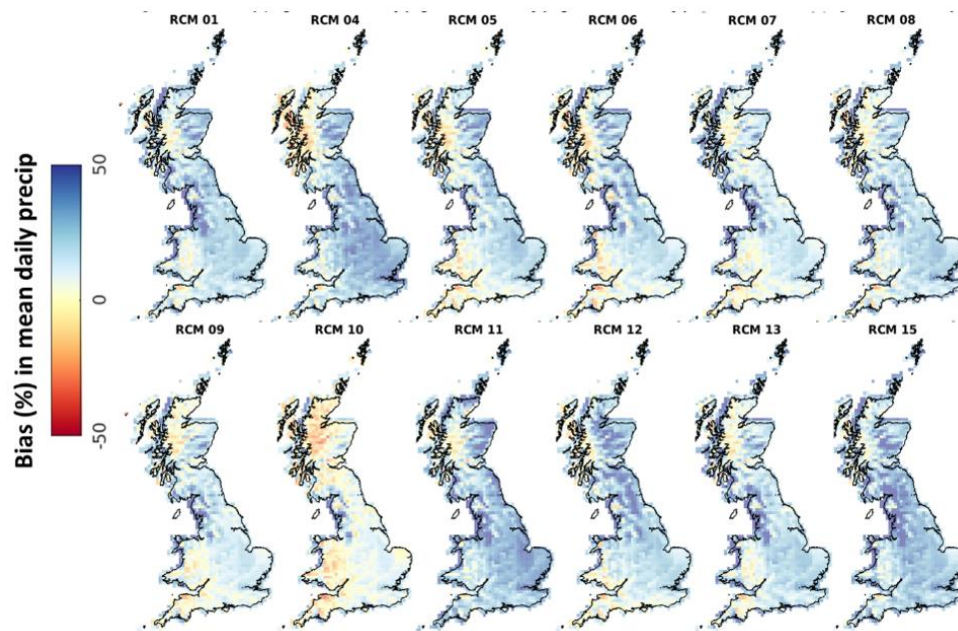


Figure S2. Percentage difference in mean daily rainfall between observations and each ensemble member of UKCP18.

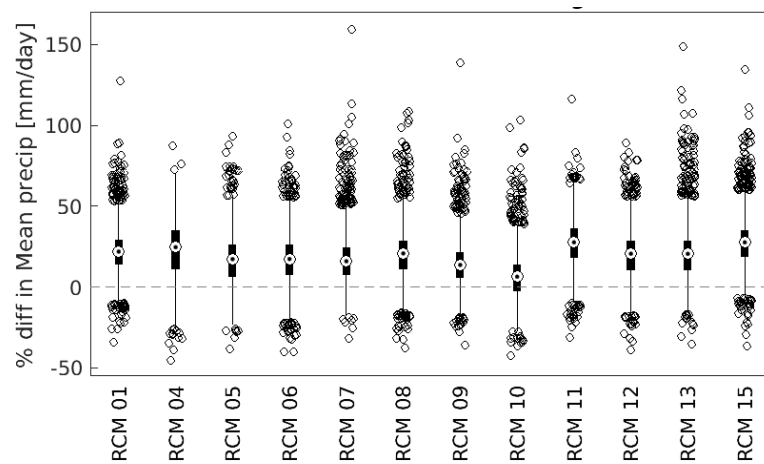


Figure S3. Percentage difference in mean daily rainfall between observations and each ensemble member of UKCP18.

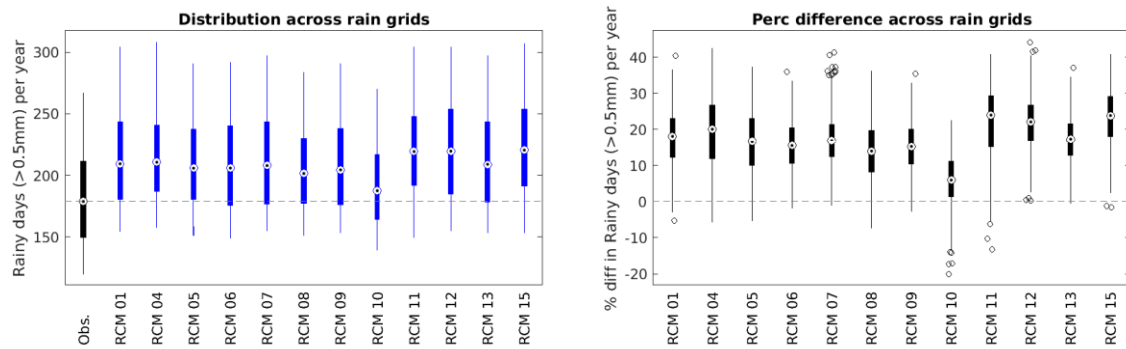


Figure S4. Bias in number of rainy days (defined as a day with at least 0.5mm of rainfall). Left: distribution in number of rain days across Great Britain, from the observed rainfall data and 12 UKCP18 ensemble members. Right: percentage difference in number of rain days between each ensemble member and the observed data over the baseline period.

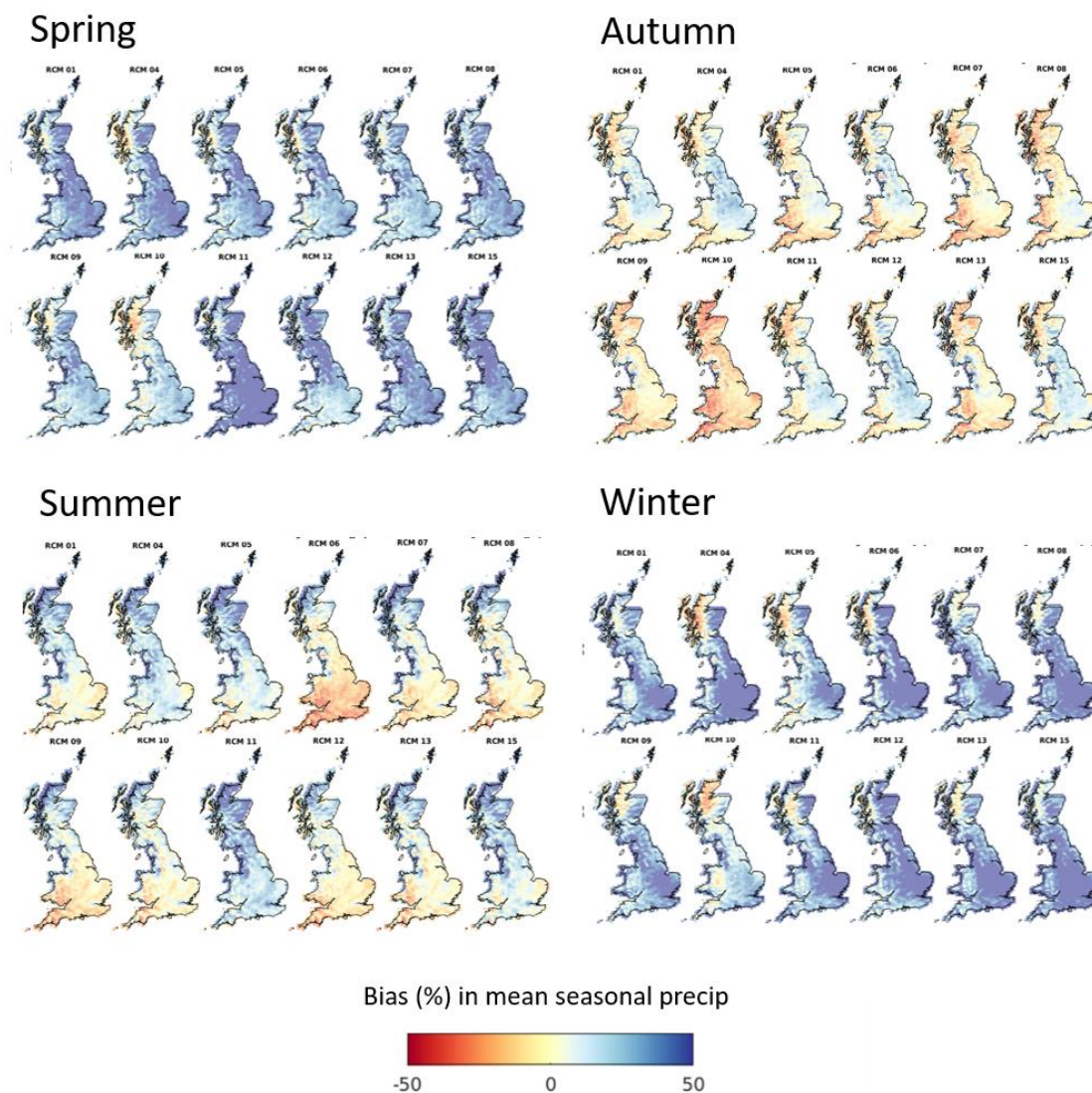


Figure S5. Seasonal rainfall biases. Each plot shows the percentage difference in seasonal average rainfall between a UKCP18 ensemble member and observations over the baseline period.

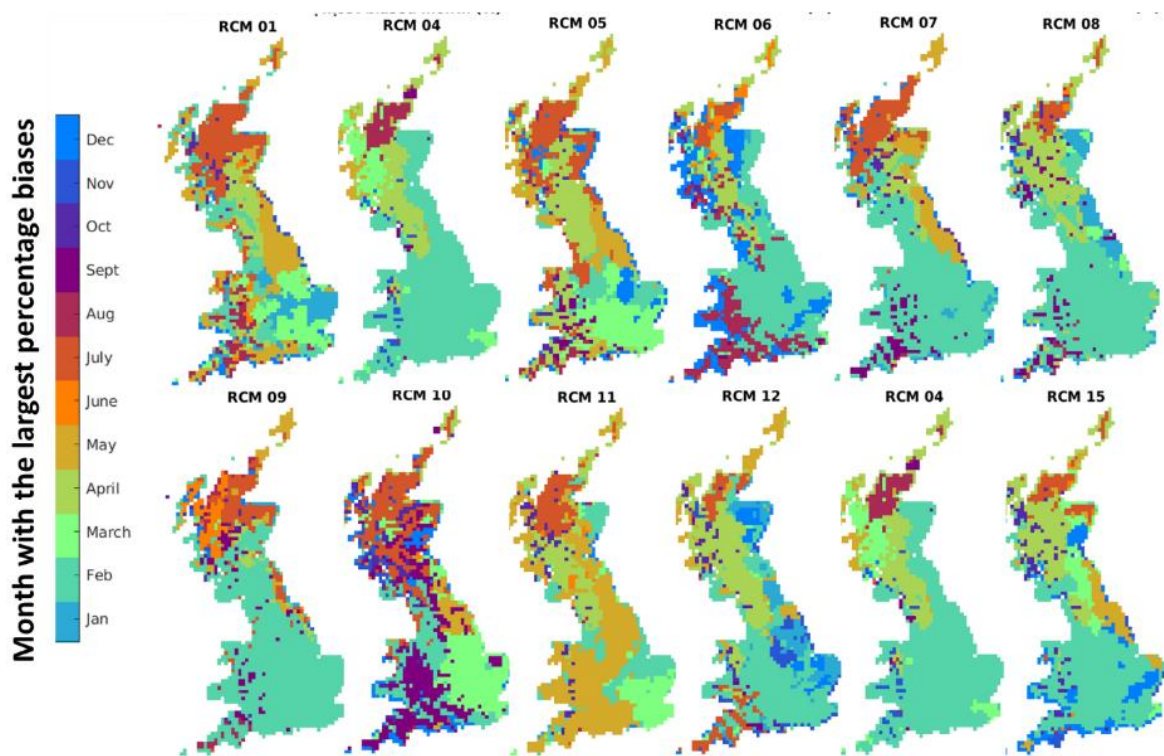


Figure S6. Month with the largest rainfall biases. Each plot shows the month with the largest percentage difference in rainfall between a UKCP18 ensemble member and observations over the baseline period.

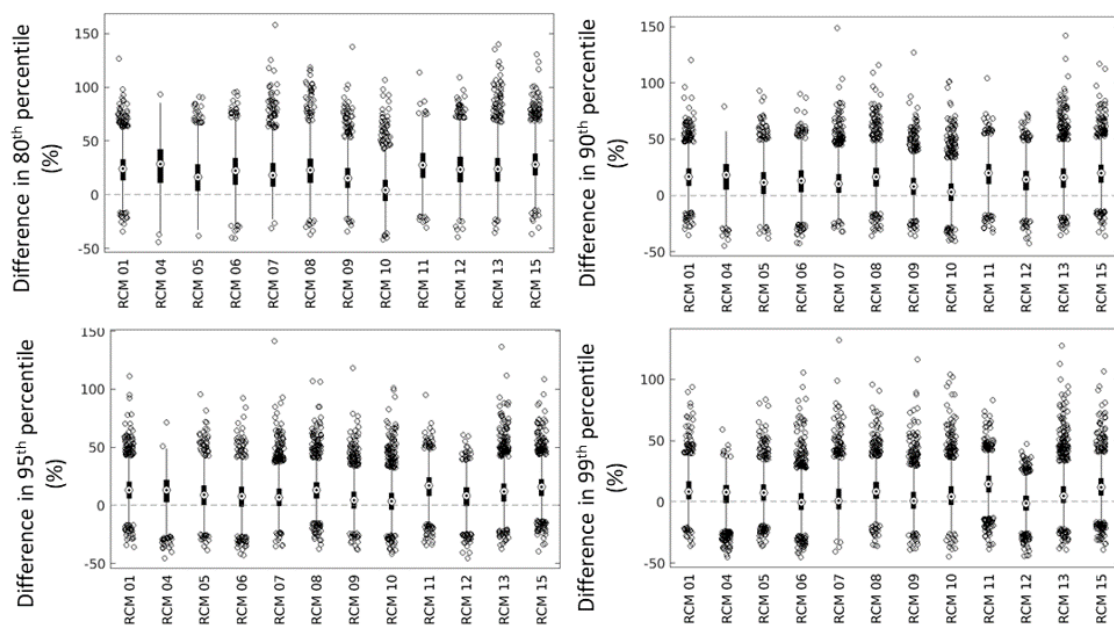


Figure S7. Boxplots showing rainfall biases for 80th percentile rainfall (top left), 90th percentile rainfall (top right), 95th percentile rainfall (bottom left) and 99th percentile rainfall (bottom right).

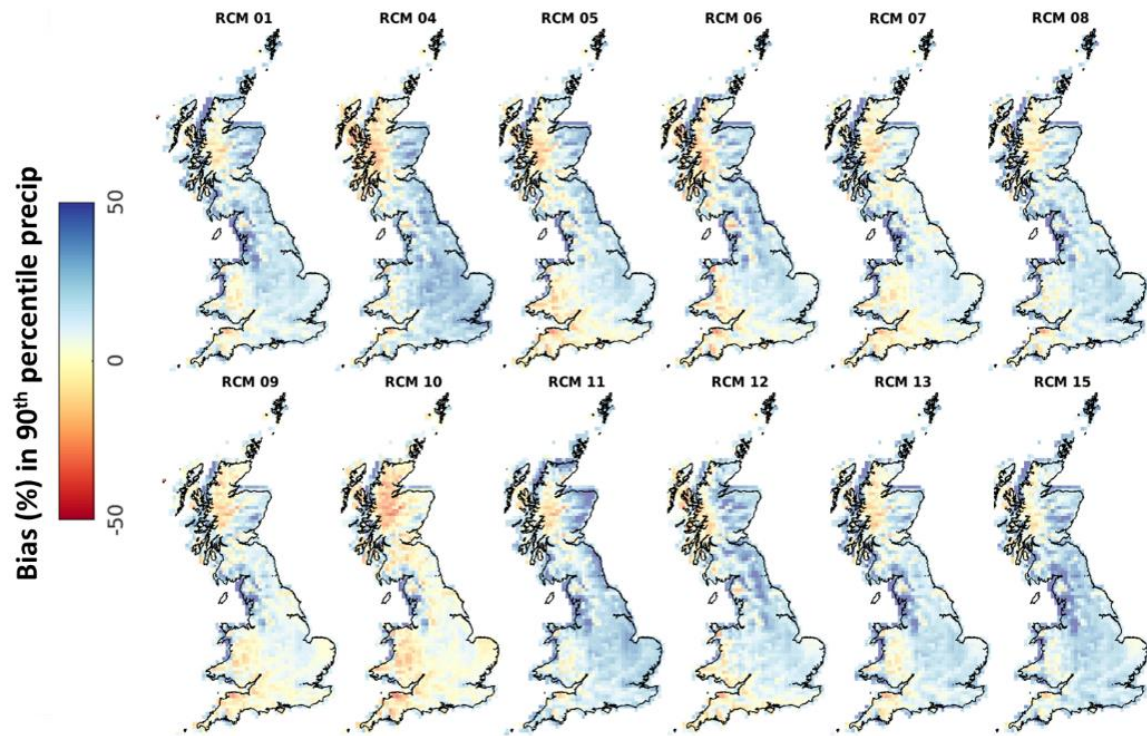


Figure S8. Rainfall biases for the 90th percentile rainfall value. Each plot shows the percentage difference in 90th percentile rainfall between a UKCP18 ensemble member and observations over the baseline period.

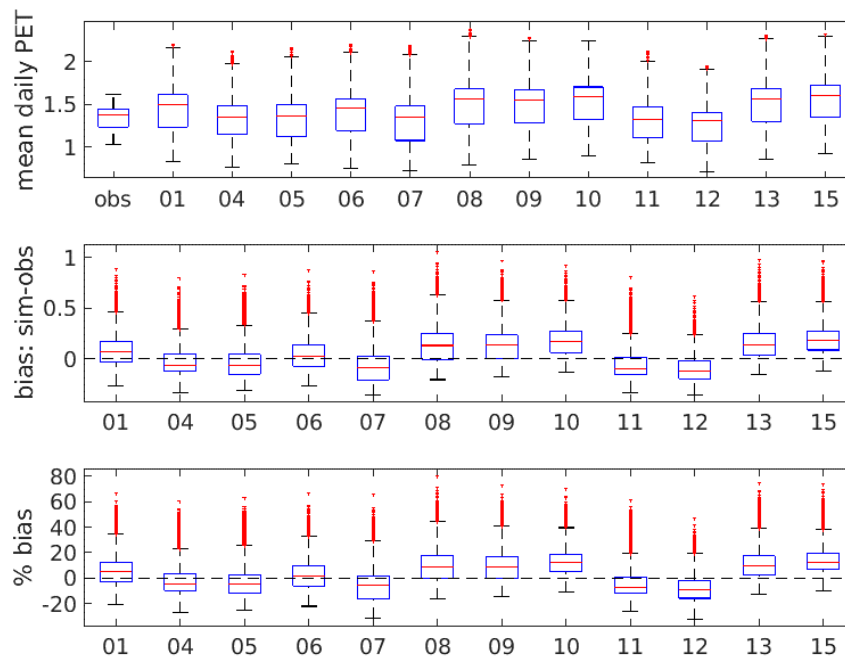


Figure S9. Boxplots show distribution of observed and simulated mean daily PET across Great Britain. Top: mean daily PET distributions from the observed data and 12 RCMs. Middle: distributions of difference between observed

and each RCM. Bottom: distribution of difference between observed and simulated PET, as a percentage of the observed value.

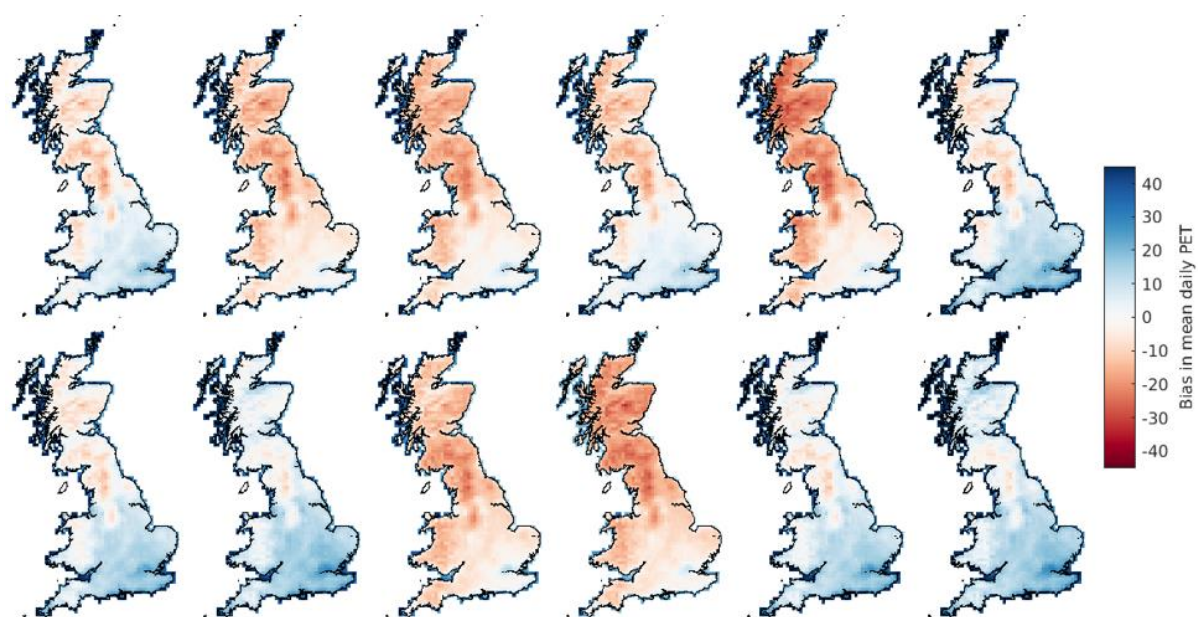


Figure S10. Percentage bias in mean daily PET for each ensemble member. The ordering of RCM ensemble members is consistent with Figure S8.

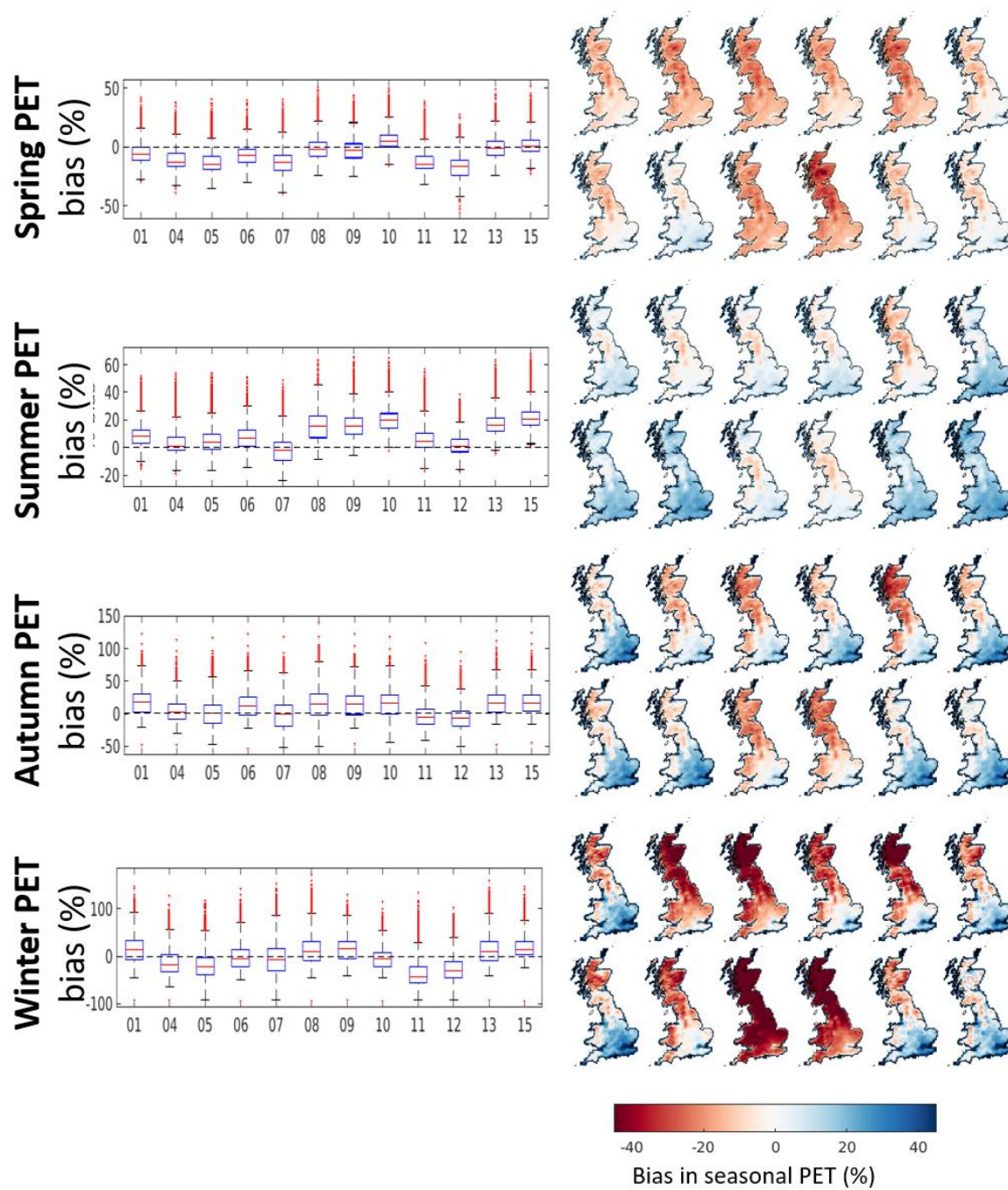


Figure S11. Percentage biases in RCM PET data compared to an observed PET product. Results are split by seasons, from top row to bottom Spring (March-May), Summer (June-August), Autumn (September-November) and Winter (December-February). Left column gives boxplots showing the distribution across GB, right column shows maps of % bias for each RCM and each season. The ordering of RCM ensemble members is consistent with Figure S8.

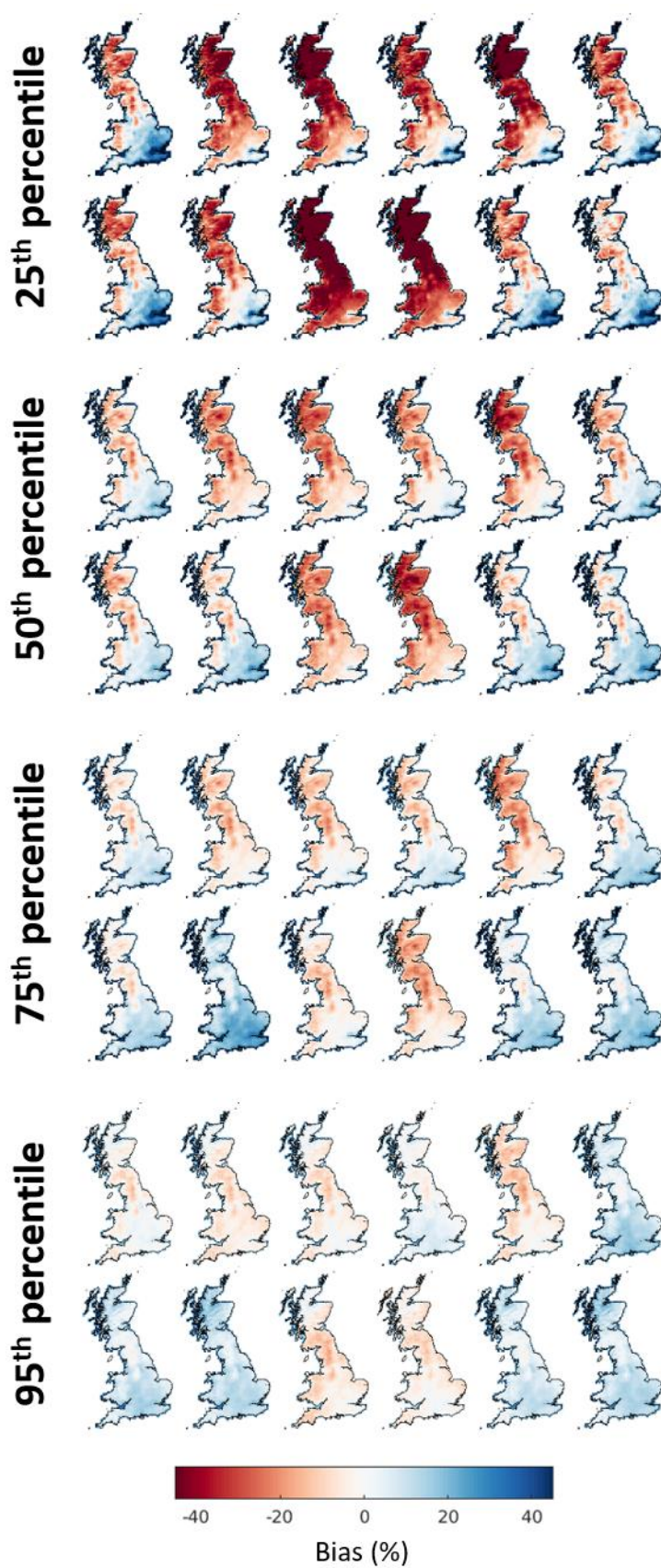


Figure S12. Percentage bias in PET quantiles from each ensemble member. The ordering of RCM ensemble members is consistent with Figure S8.

S2 The impact of reservoirs on model performance

In the main text we evaluated the performance of the RCM-hydrological modelling chain. Catchments where runoff was affected by reservoirs or heavily regulated flows were excluded from this analysis, as the model does not simulate these processes and so errors in these catchments would likely not be due to the RCM data. Catchments impacted by reservoirs/regulated flows were identified using the factors affecting runoff (FAR) from the UK Hydrometric Register (Centre for Ecology and Hydrology, 2008). Here, we explore whether the presence of reservoirs/ heavily regulated flows has a large impact on model performance.

Of the 346 catchments included in this study, the majority (60%) have no reservoirs in the catchment. 71 gauges (20%) have 1-5 reservoirs upstream, and 20% of gauges have more than 5 reservoirs upstream. While 40% of gauges do have a reservoir in the catchment, the capacity of the reservoirs is an additional important indicator of its impact on the flow time series as many of these reservoirs have a small capacity relative to the average precipitation and flow at the gauge. Of the 346 gauges, only 20 (5%) had a capacity greater than 10% of mean annual rainfall.

Figure S13 shows the percentage error in RCM-driven simulations over the observed period. Catchments have been split into those with reservoirs/regulated flows (red) and those without (blue). When looking at median flows (Q50) there is no discernible difference in performance between catchments with and without reservoirs/ regulated flows. Surprisingly, when looking at high flows (Q10, Q1 and AMAX) the catchments with reservoirs or regulated flow regimes tend to have lower percentage errors. This could be due to their location in the country, with reservoirs often in wetter areas and therefore smaller percentage errors. Overall, these plots show that including catchments with reservoirs/ regulated flows would not have reduced the model performance presented in the main paper.

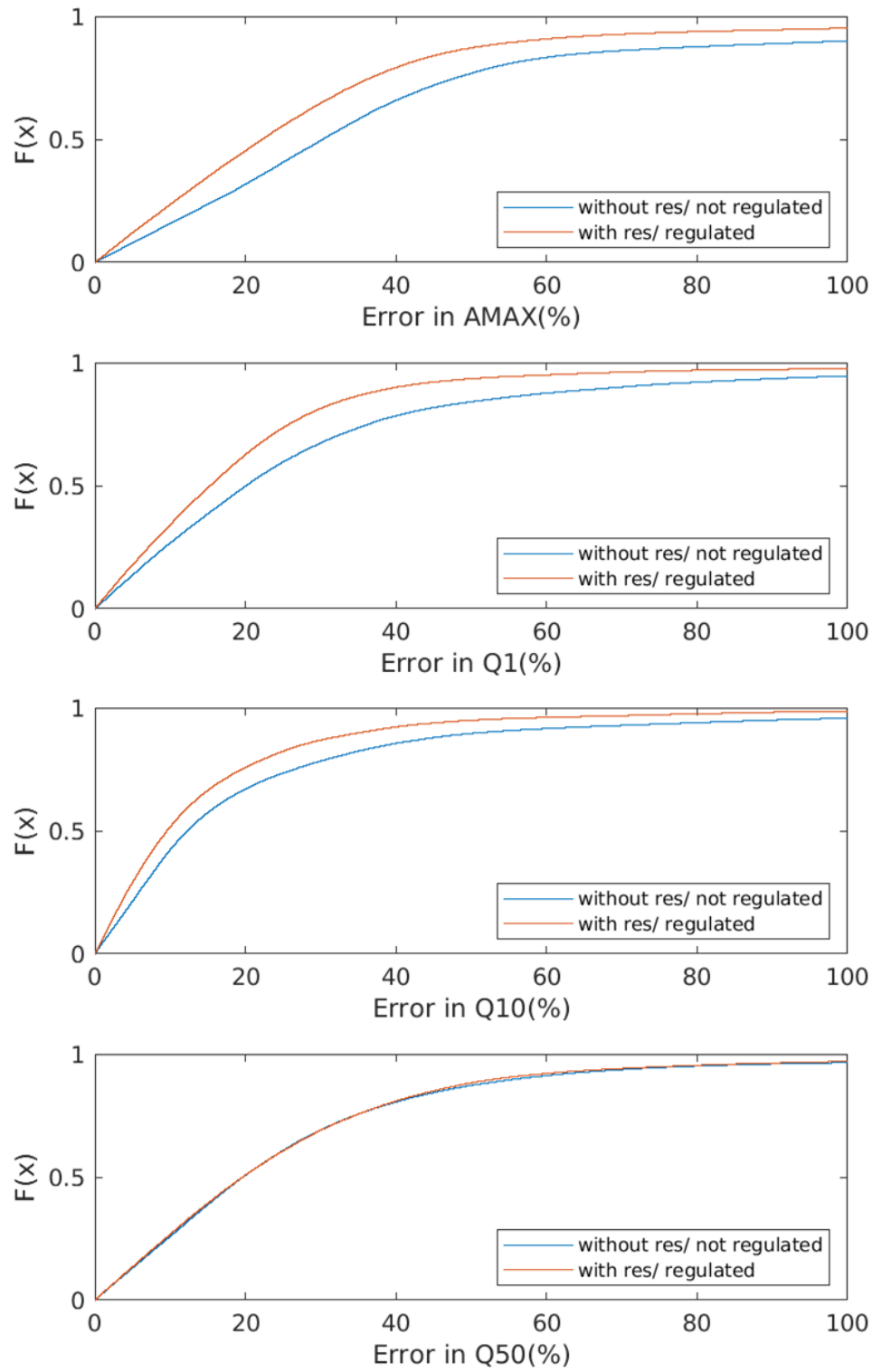


Figure S13. CDF plots showing the percentage error in RCM-driven simulations compared to observations (as in Figure 2 of the main manuscript). The CDF plots include all 12 RCM runs and 30 parameter set runs, for all unregulated catchments (blue) and catchments with reservoirs or regulated flow regimes (red).

S3 Additional maps of modelled baseline and changing high flows

In the main text we presented spatial maps showing percentage change in high flows across Great Britain. We only showed 3 out of the 360 modelled future scenarios, which were selected as they represented the minimum, median and maximum GB-wide change in Q10 from the full ensemble of projections and thus gave an overview of the possible range in future changes. However, the full range of changes for individual catchments is likely to be greater than shown in these figures, and it is possible that the spatial pattern of change could be different for other scenarios. There are also limitations to using percentage change to indicate where the largest changes to high flows occur, as use of percentages may overemphasize changes in areas where simulated flows are lowest. In this supplement we therefore show additional plots to help aid this analysis. These additional plots include:

1. An additional 24 modelled scenarios of climate change impact on median and higher flows (Q50, Q10, Q1 and AMAX).
2. For each of these 24 scenarios, maps of baseline values and absolute change are given to help interpretation of the percentage changes.
3. Maps showing the total ensemble range in high flow changes for each catchment. Unlike the scenario maps these are not spatially coherent (as values have been averaged over all climate and hydrological model simulations). These should therefore only be interpreted for specific catchments and should not be viewed as a consistent future projection for GB.

The additional 24 scenarios were selected to demonstrate further variation in the modelled results. We present results for all 12 RCM ensemble members, and 2 hydrological model parameter sets. The RCM ensemble members result in the largest difference between the simulations, and therefore it was considered important to present results from all ensemble members. To show difference between hydrological model parameter sets, two sets were chosen which often produced contrasting percentage changes in high flows. Set 15 consistently resulted in lower changes to high flows (when evaluating the GB-wide percentage change in AMAX, Q1, Q10 and Q50), and whilst no hydrological model parameter set consistently produced higher percentage changes across all high flow metrics, set 12 produced the highest GB-wide changes to AMAX and Q1.

Figure S13 to Figure S16 demonstrate that when analysing a larger number of scenarios, the same key features emerge that are presented in the main text. Mainly, the higher percentage changes in AMAX and Q1 flows seen along the west coast, the general reductions or small changes in Q1 and Q10 flows seen in the southeast, and a reduction in Q50 across GB. These features can also be seen in the plots of the full ensemble spread (Figure S17 and Figure S18).

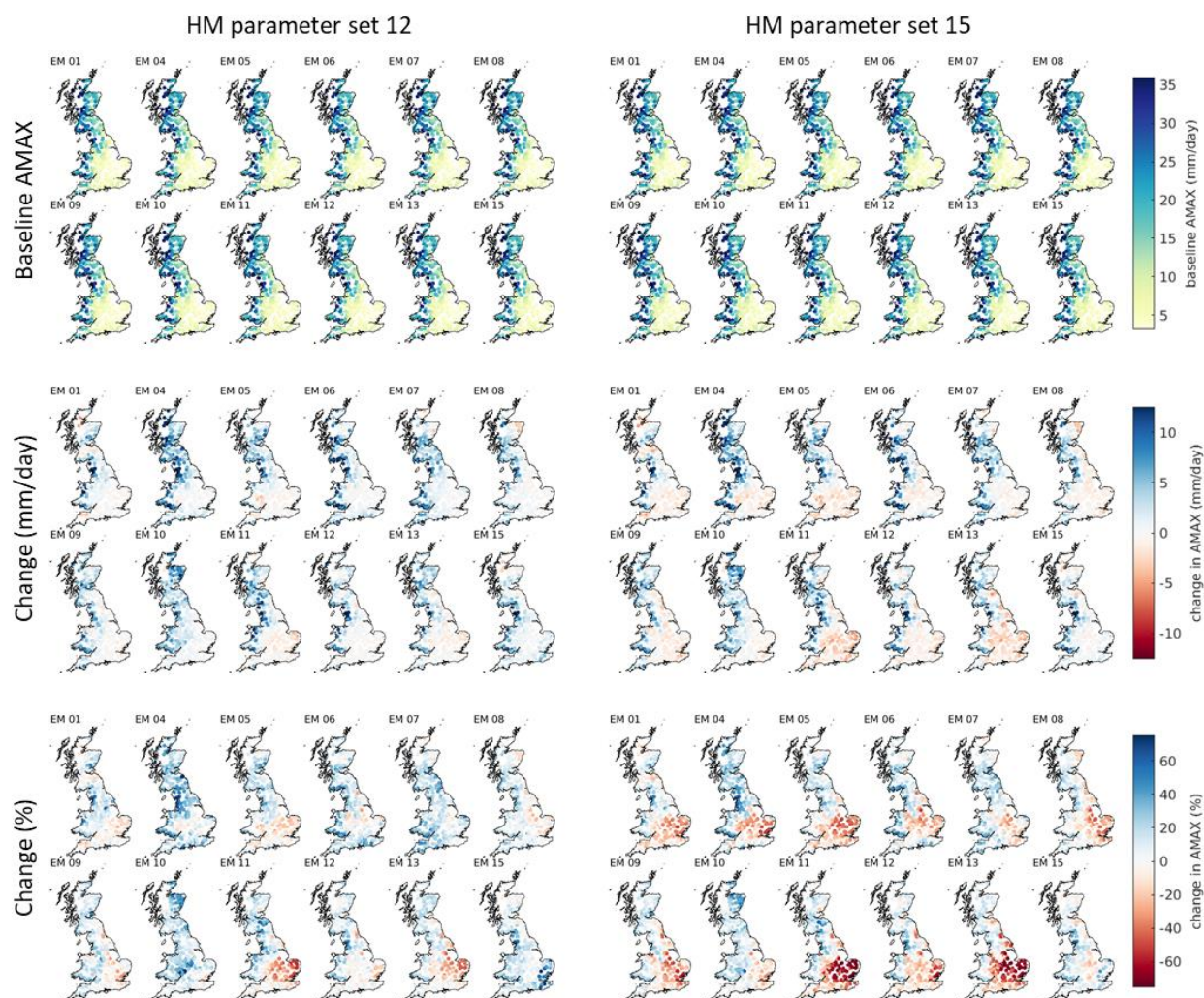


Figure S14 . Maps showing changes in the magnitude of AMAX flows between the baseline and future periods for 24 example simulations. Each map shows a nationally coherent projection. Plots on the left show results from all RCM ensemble members when using hydrological model parameter set 12, whilst plots on the right show results using hydrological model parameter set 15. Rows show data over the baseline period (top), absolute change between the baseline and future (middle), and percentage change between the baseline and future (bottom). These plots complement Figure S4 in the main text by providing additional modelled scenarios, and expanding on the percentage change maps by also showing baseline values and absolute changes.

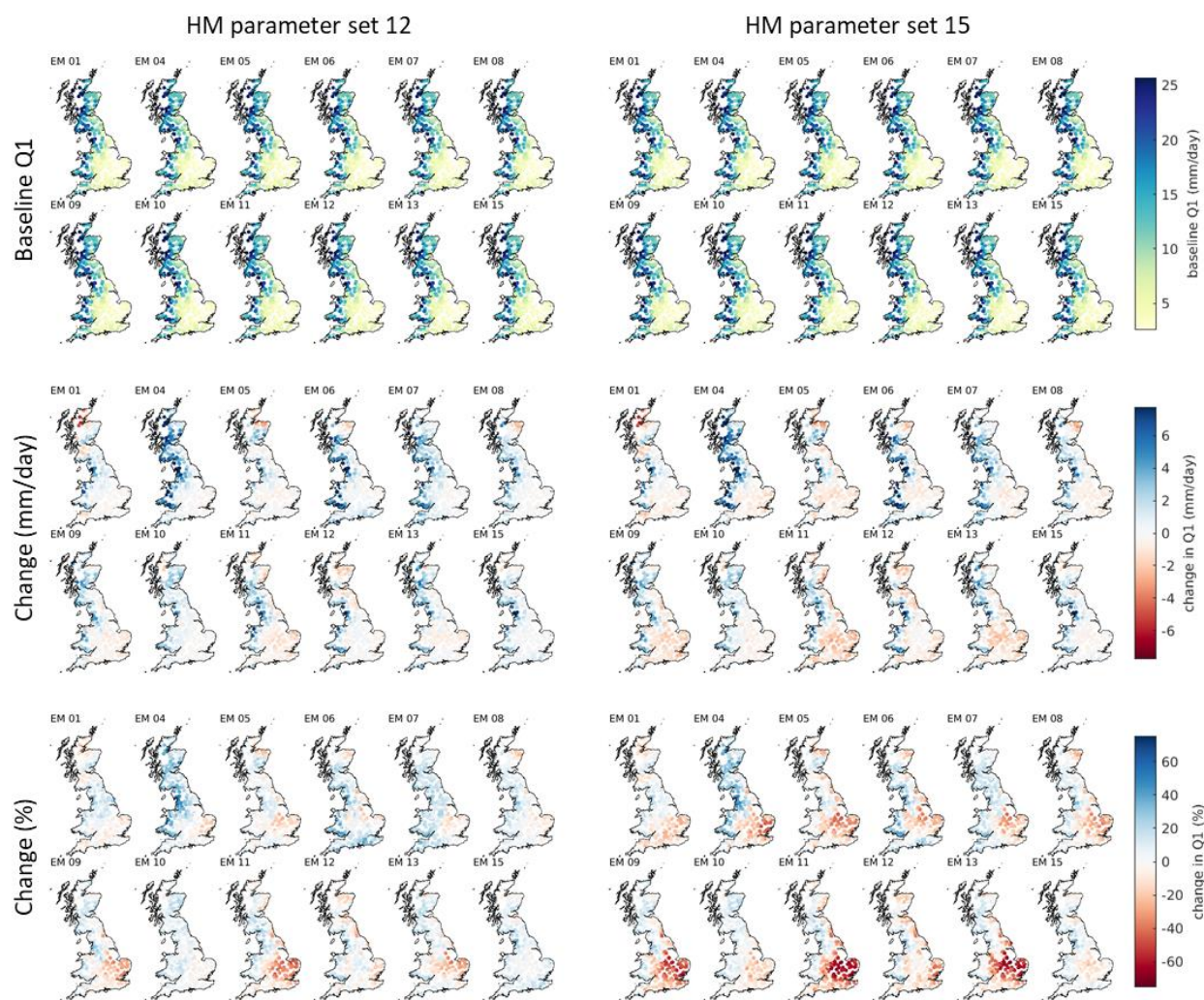


Figure S15 . As for Figure S13, but showing results for Q1.

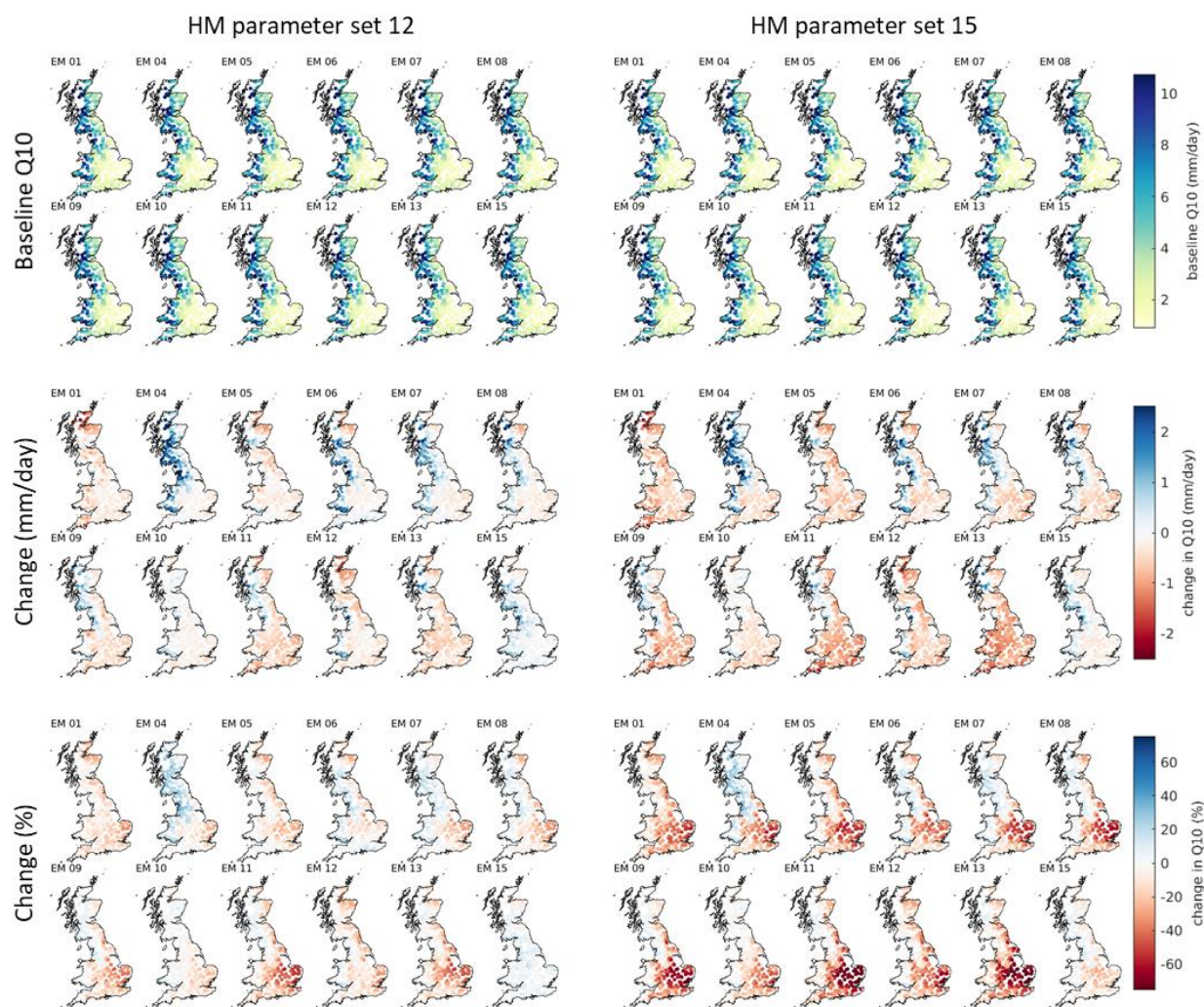


Figure S16 . As for Figure S13, but showing results for Q10.

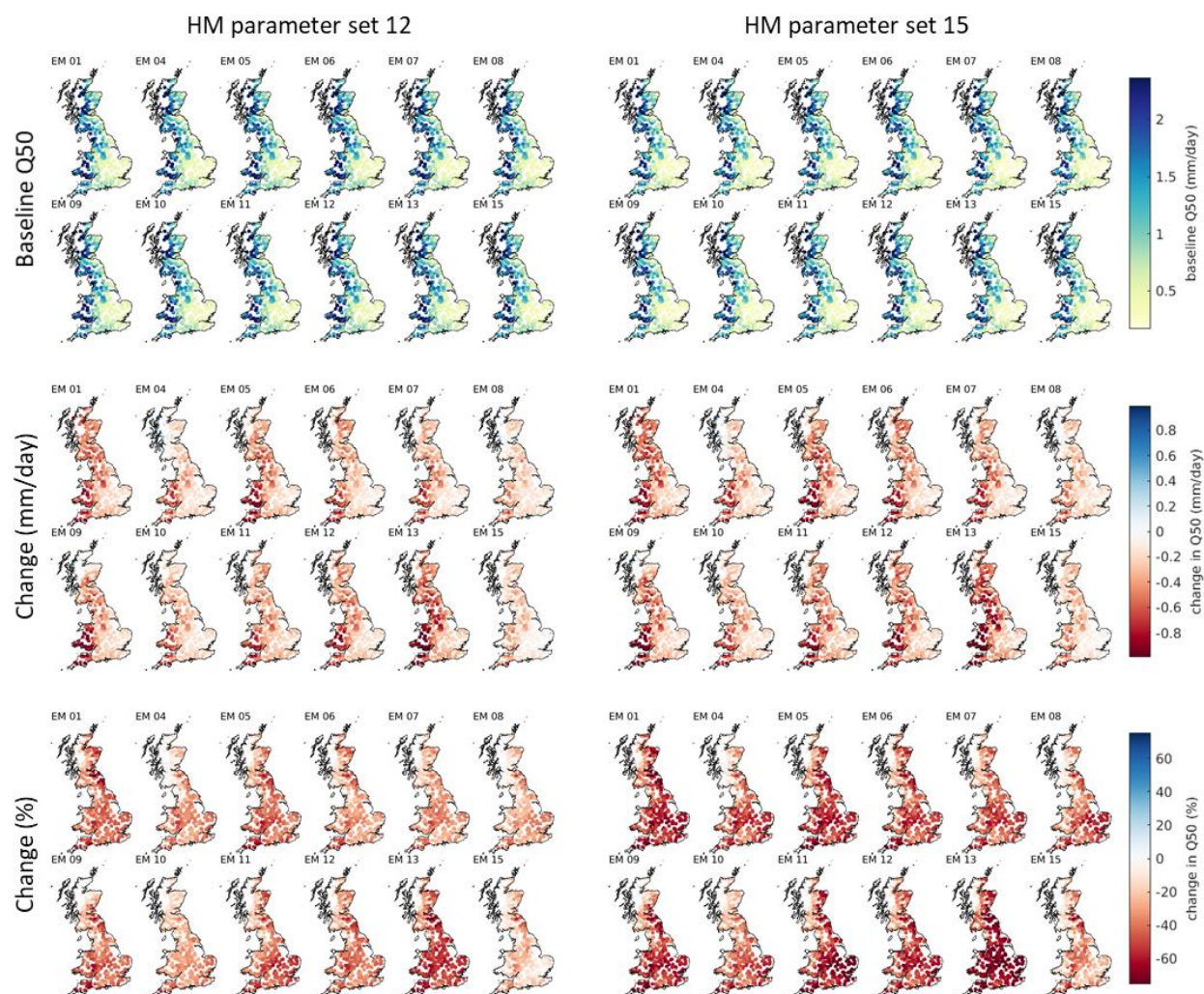


Figure S17 . As for Figure S13, but showing results for Q50.

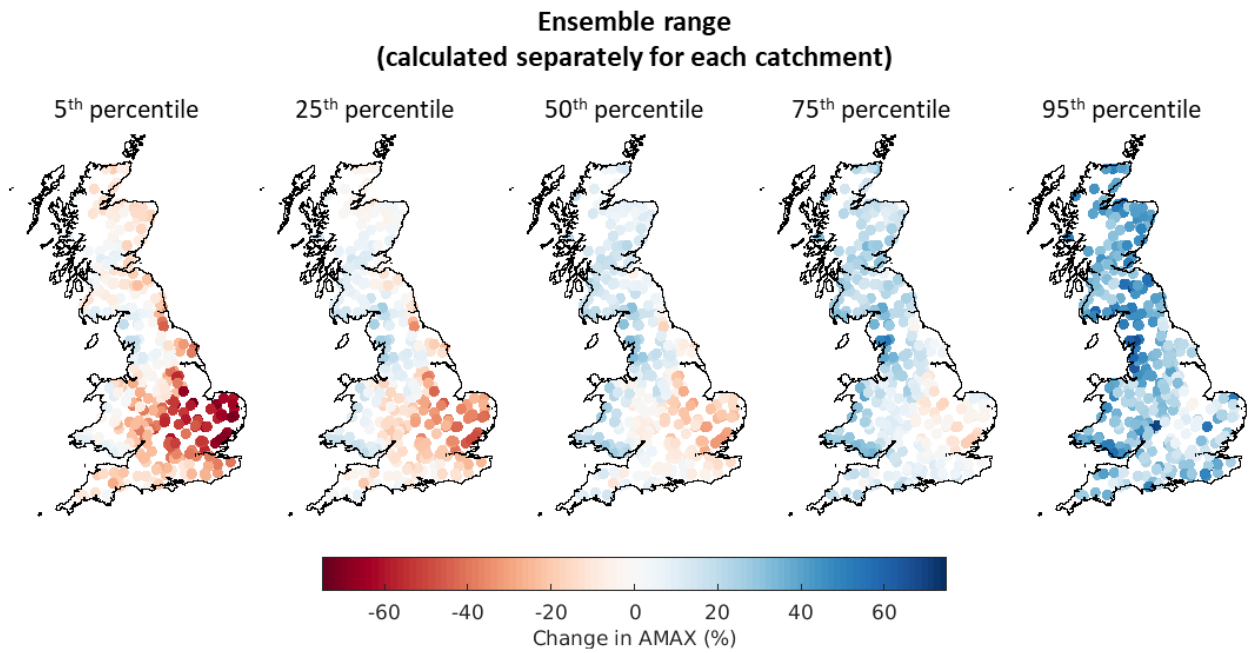


Figure S18 . Maps summarising the ensemble range in AMAX changes between the baseline and future period. From left to right these show the 5th, 25th, 50th, 75th and 95th percentile of change from the 360 modelled scenarios (12 RCMs and 30 hydrological model parameter sets). These values were calculated individually for each catchment, and therefore do not represent possible GB scenarios but instead should be interpreted for individual catchments.

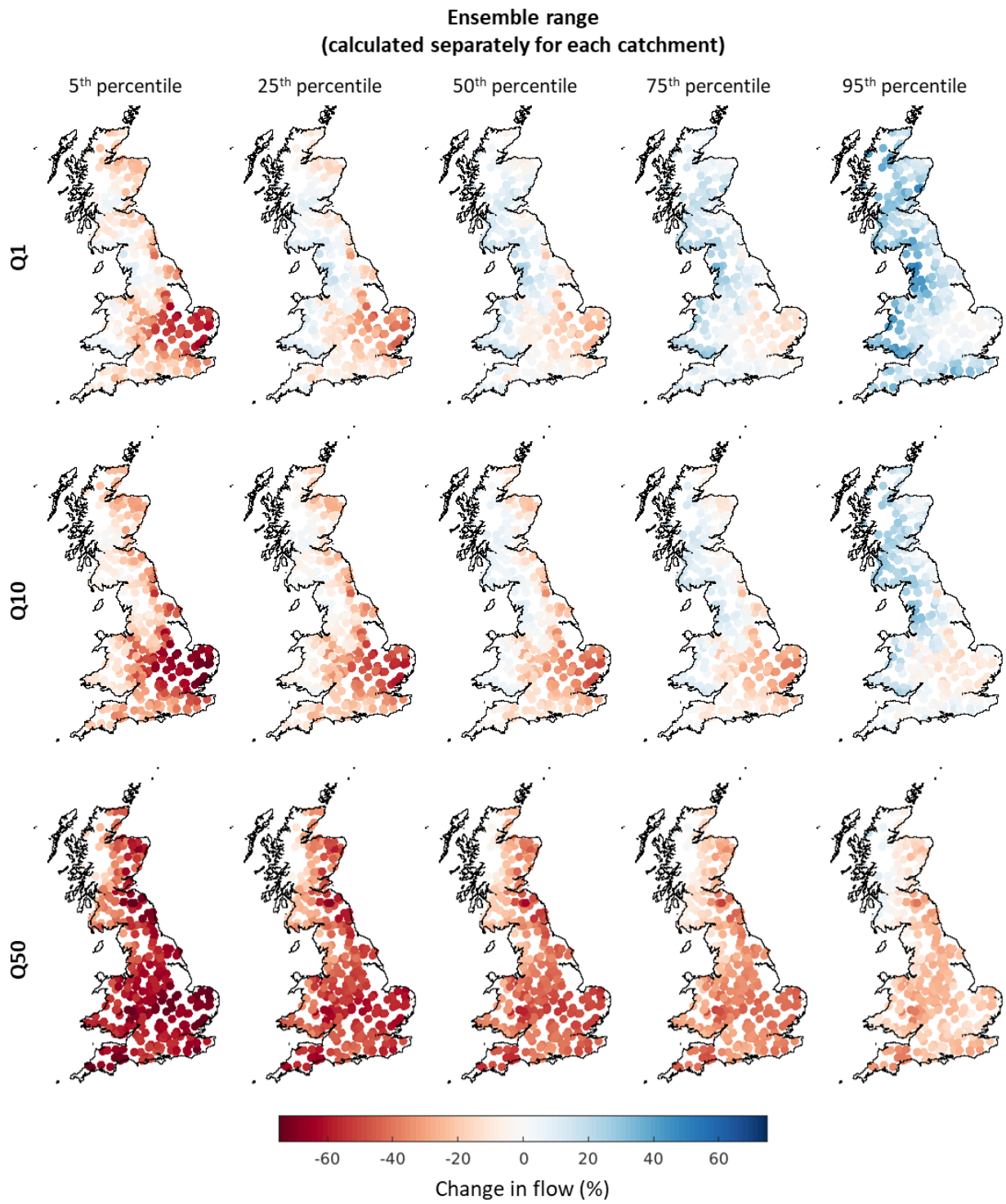


Figure S19. As for Figure S17, but showing results for Q1, Q10 and Q50.

S4 Additional heatmaps of region-average changes

In the main text we presented a heatmap showing the region-average change in Q10 flow magnitude between the baseline and future periods, showing the range in projections between RCM and hydrological model parameters. Here, similar maps are given for all flow metrics. Note, plots are all given on the same colour scale (ranging from -70% to +70% changes), so can be compared between flow metrics.

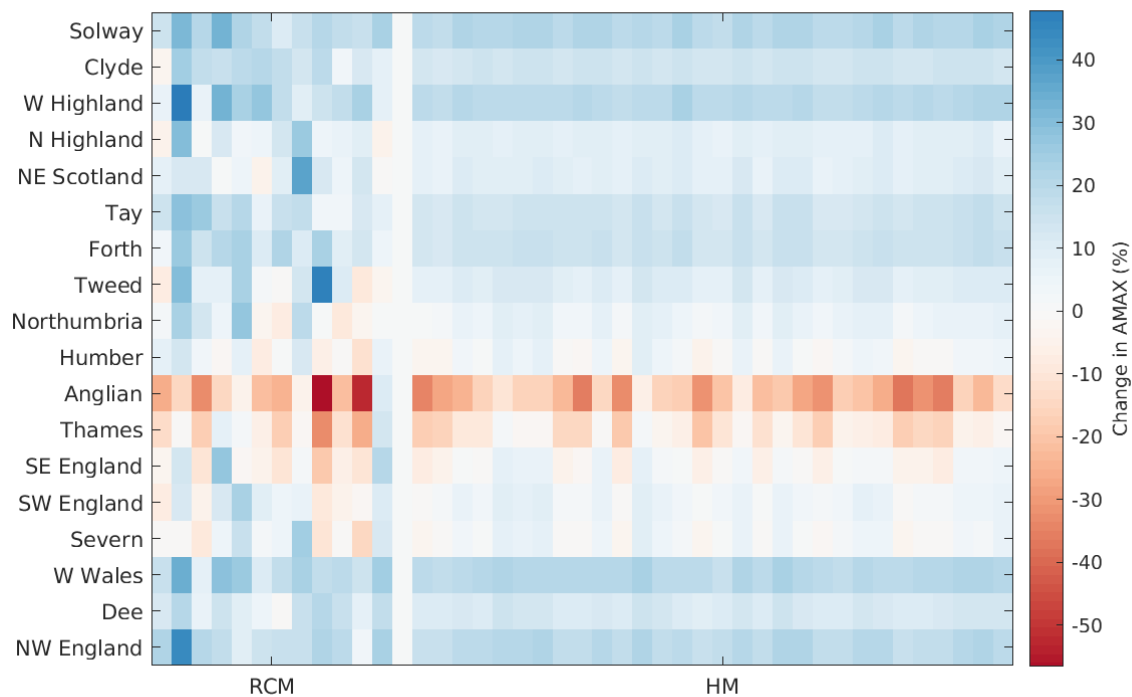


Figure S20. Heatmap showing region-average changes in AMAX flow magnitude between the baseline and future periods. The 12 columns on the left focus on the difference between RCM parameterisations, using the median flow value from all hydrological model parameter sets. The 30 columns on the right focus on the difference between hydrological model parameterisations, using the median flow value from all RCMs. Regions have been ordered by location, with the relative position within GB given on the left.

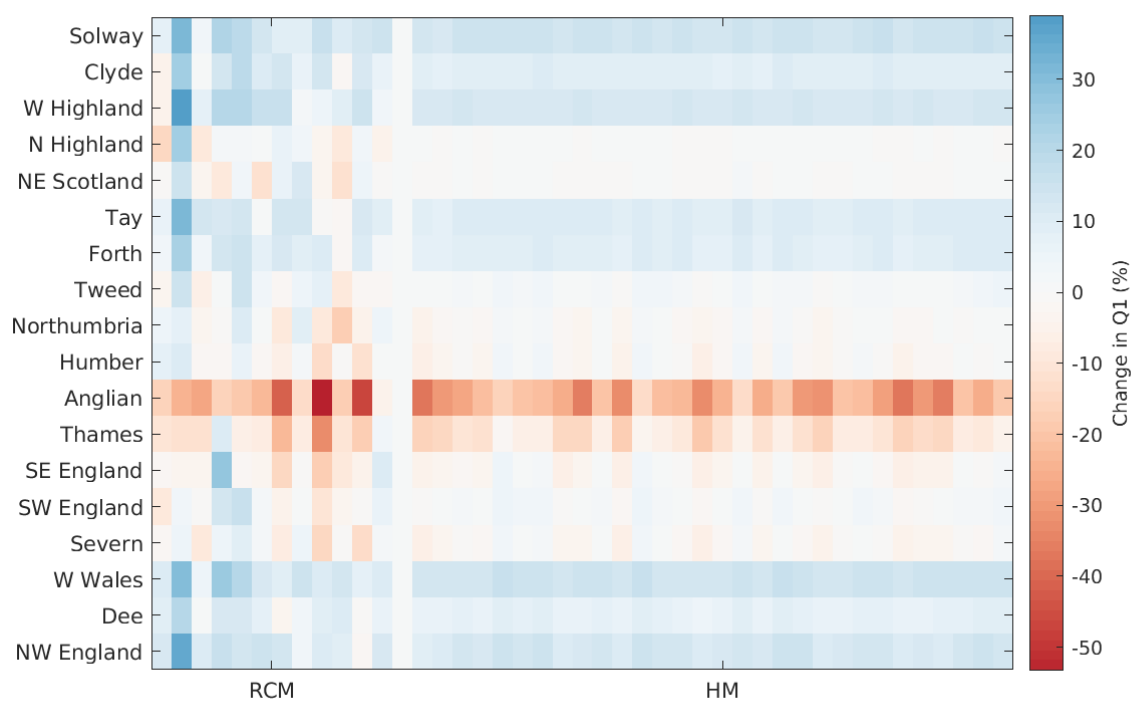


Figure S21. As for Figure S20, but showing change in Q1.

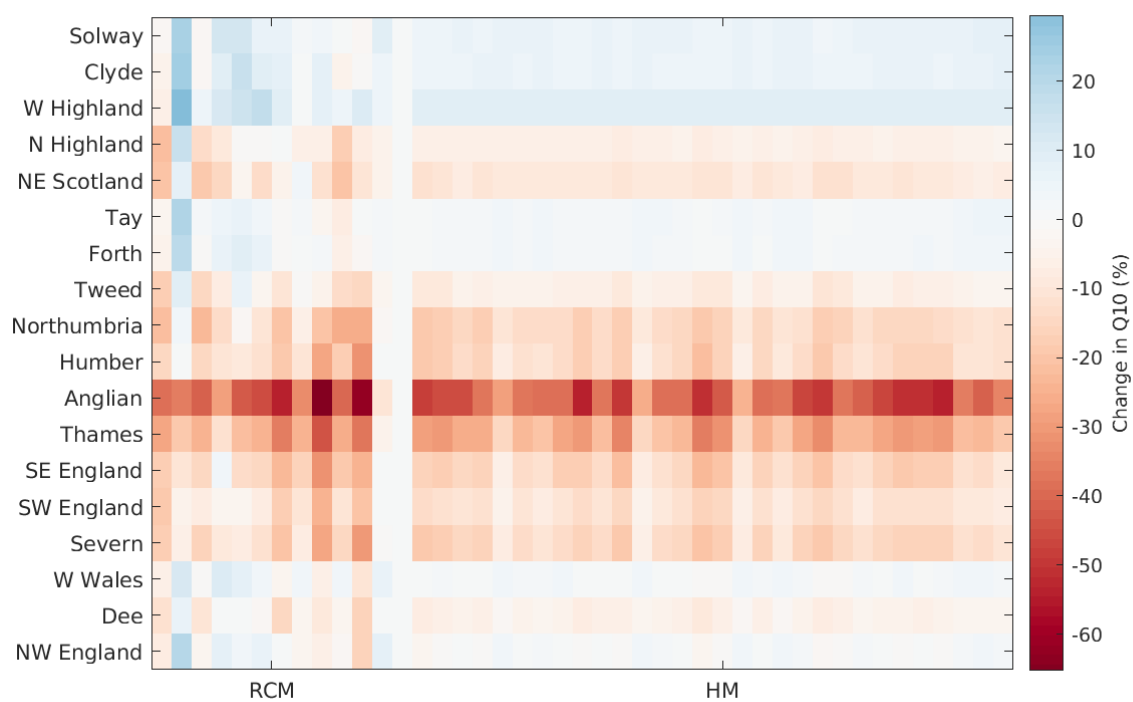


Figure S22. As for Figure S20, but showing change in Q10.

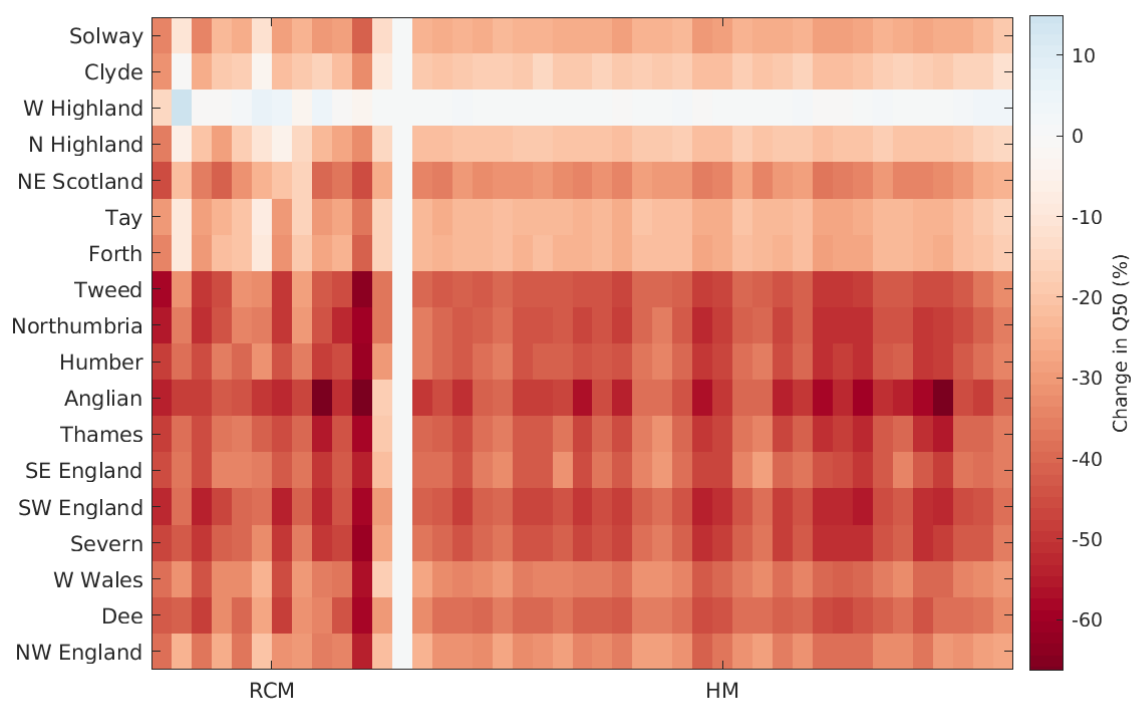


Figure S23. As for Figure S20, but showing change in Q50.

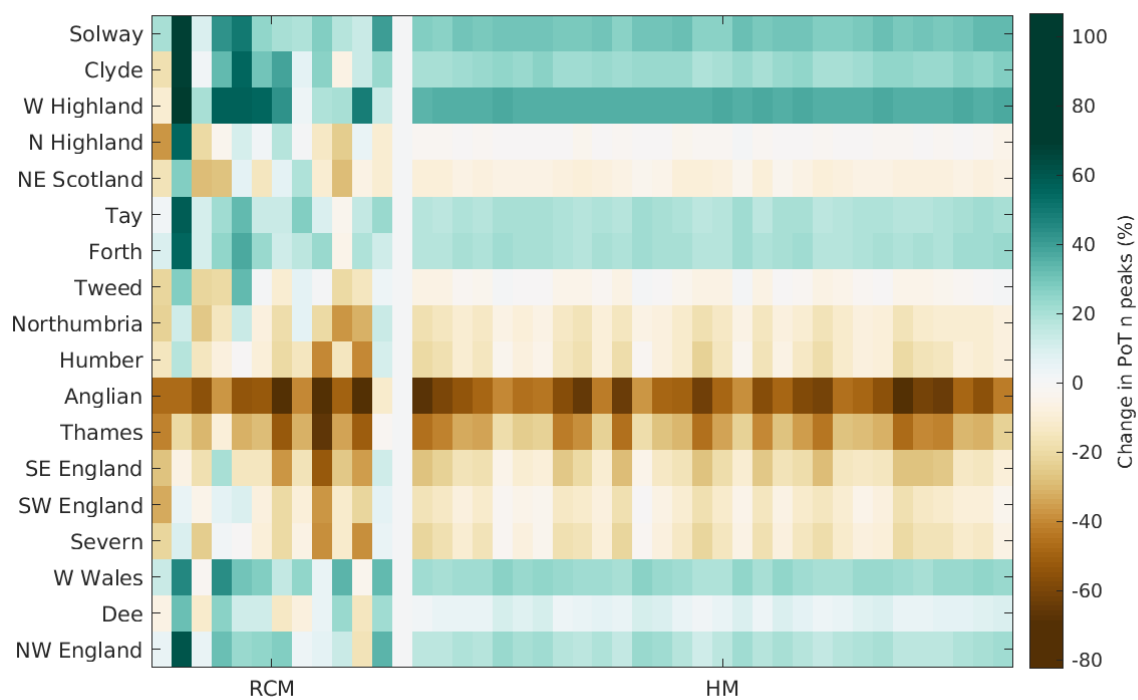


Figure S24. As for Figure S20, but showing change in the number of PoT peak events.

S5 Additional plots showing the relationship between changes in precipitation and changes in flow

In the main paper we explored the relationship between 95th percentile precipitation change and Q1 change across all catchments, showing only the median of all hydrological parameter sets. Here we present additional plots looking at the relationship between changes in precipitation and changes in river flows for other precipitation quantiles (Figure S25), flow quantiles (Figure S25) and hydrological model parameter sets (Figure S26).

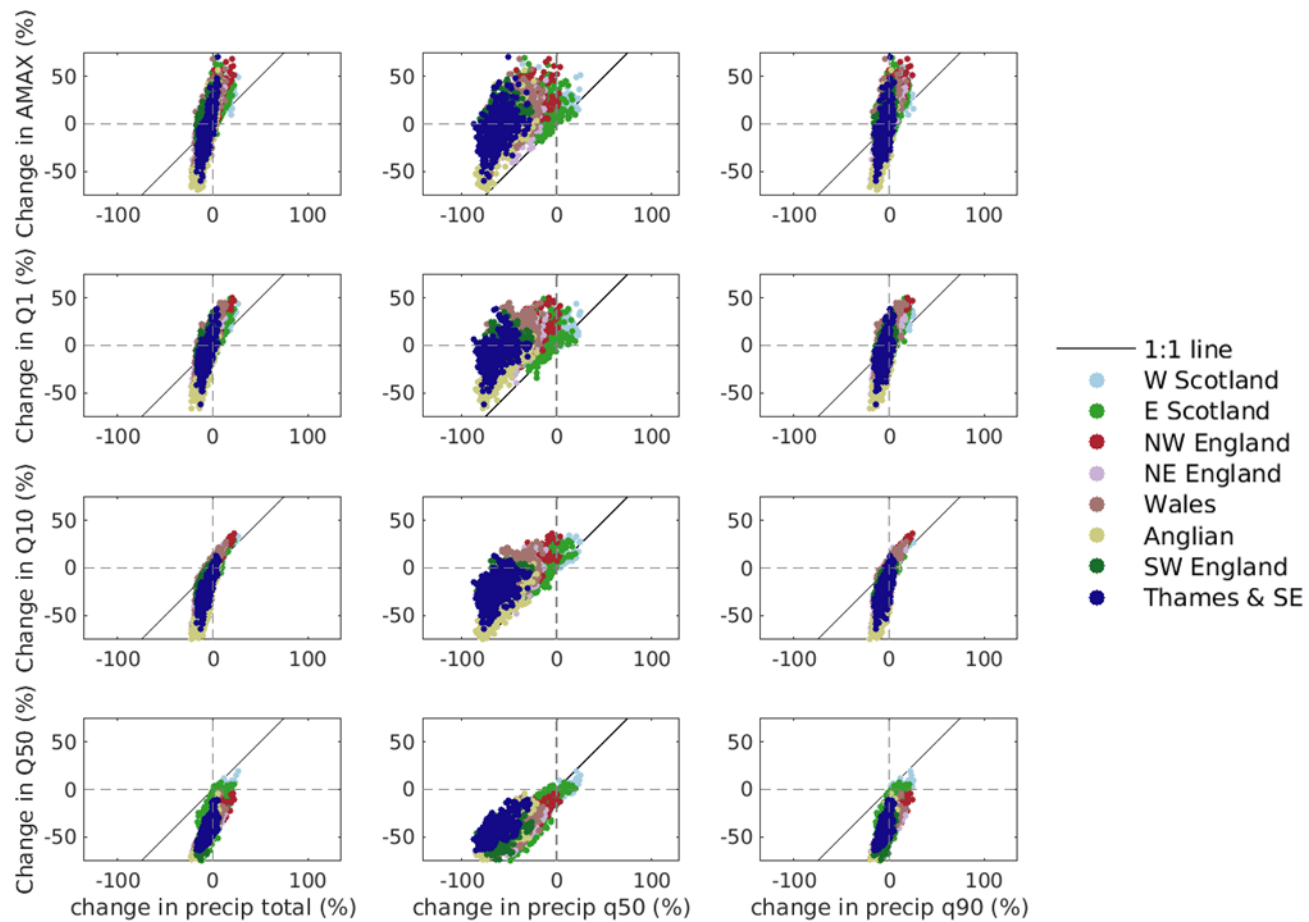


Figure S25. Relationship between precipitation change and flow changes, focusing on different precipitation and flow metrics. Results are presented for all RCMs and all catchments using the median of all hydrological model parameter sets. Each row shows changes in a different flow metric, and each column shows changes in a different precipitation metric.

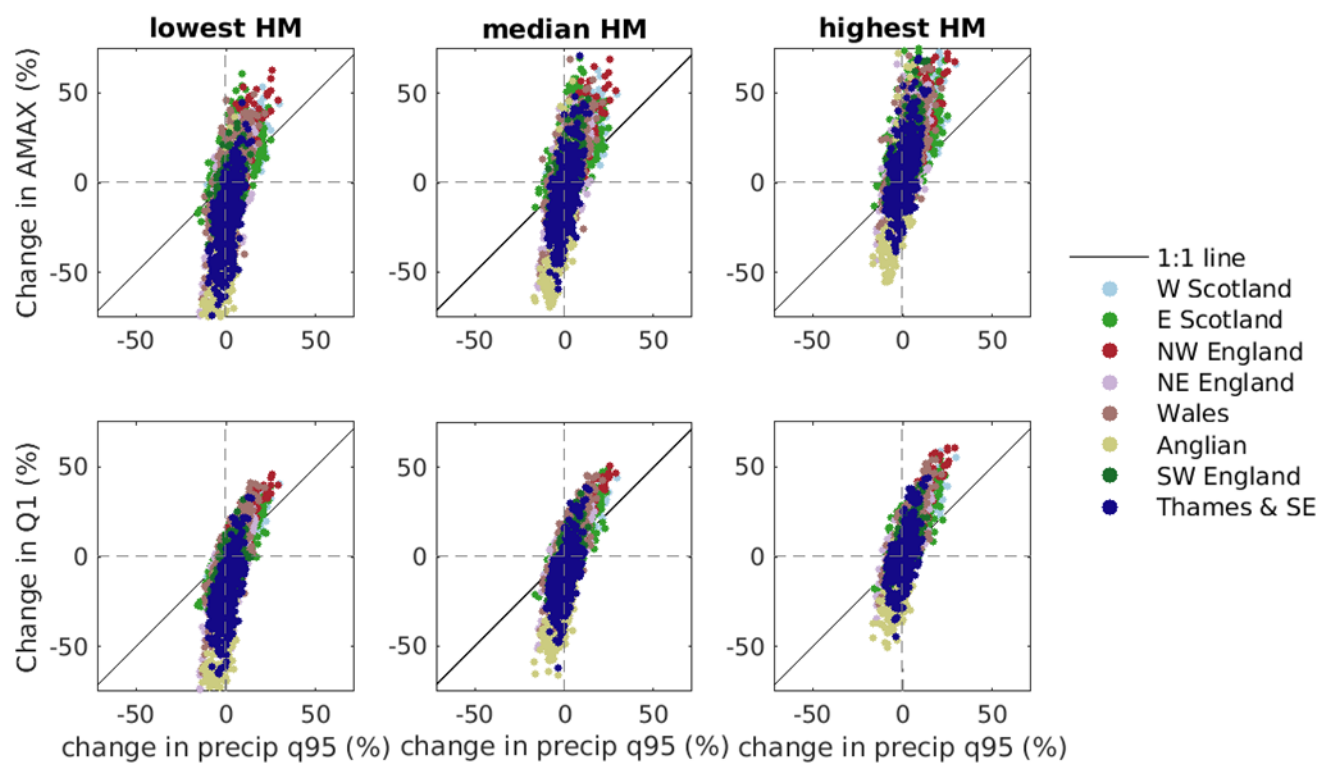


Figure S26. Relationship between precipitation change and flow changes when using different hydrological model parameter sets. Results are presented for all RCMs and all catchments, using the hydrological model parameter set that resulted in the lowest flow changes (left column), median of all parameter sets (middle column) and highest parameter set (right column). Results are presented for two different flow metrics, change in AMAX flows (top row) and change in Q1 (bottom row).