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The impact of climate change on UK river flows: a preliminary comparison of two generations of probabilistic climate projections

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Abstract

The impacts of climate change on future river flows are a growing concern. Typically, impacts are simulated by driving hydrological models with climate model ensemble data. The UK Climate Projections 2009 (UKCP09) provided probabilistic projections, enabling a risk-based approach to decision-making under climate change. Recently, an update was released - UKCP18 - so there is a need for information on how impacts may differ. The probabilistic projections from UKCP18 and UKCP09 are here applied using the change factor method with catchment-based hydrological modelling for 10 catchments across England. Projections of changes in median, mean, high and low flows are made for the 2050s, using the A1B emissions scenario from UKCP09 and UKCP18 as well as the RCP4.5 and RCP8.5 emissions scenarios from UCKP18. The results show that, in all catchments for all flow measures, the central estimate of change under UKCP18 is similar to that from UKCP09 (A1B emissions). However the probabilistic uncertainty ranges from UKCP18 are, in all cases, greater than from UKCP09, despite UKCP18 having a smaller ensemble size than UKCP09. Although there are differences between the central estimates of change using UKCP18 RCP4.5, RCP8.5 and A1B emissions, there is considerable overlap in the uncertainty ranges. The results suggest that existing assessments of hydrological impacts remain relevant, though it will be necessary to evaluate sensitive decisions using the latest projections. The analysis will aid development of advice to users of current guidance based on UKCP09, and help make decisions about the prioritisation of further hydrological impacts work using UKCP18, which should also apply other products from UKCP18 like the 12km regional data.

Keywords

Climate change; hydrological impacts; rainfall-runoff; probabilistic projections; UK Climate Projections 2018; UKCP09; UKCP18

1 Introduction

The impacts of climate change on future river flows are of global concern, not just because of possible increases in the frequency and magnitude of floods and droughts, but also the impact of changes in the flow regime on river water quality, erosion, morphology and ecology.

In Britain, the UK Climate Projections 2009 (UKCP09; Murphy et al 2009) produced a step change compared to previous projections, because as well as providing a 12-

member perturbed physics ensemble of a Regional Climate Model (RCM) nested in a Global Climate Model (GCM), it provided probabilistic projections, enabling a risk-based approach to decision-making under climate change. The UKCP09 probabilistic projections have been used in a number of studies of the impacts of climate changes on river flows in Britain, including assessing changes in average, low and high river flow (Charlton and Arnell 2014), investigating impacts on floods (Kay and Jones 2012a, Kay et al. 2014), and investigating the implications for water resources (Christierson et al. 2012, Harris et al. 2013), as well as water-related problems like subsidence (Pritchard et al. 2015) and sediment yield (Coulthard et al. 2012).

The UK Climate Projections 2018 (UKCP18; Lowe et al. 2018), update UKCP09, again including probabilistic projections. Many users of climate impact information want to know how impacts simulated using UKCP18 compare with UKCP09. The work presented here provides early information on the potential scale of differences in impacts on river flows, to aid the development of advice to users of current policy guidance based on the UKCP09 projections.

The probabilistic projections from both UKCP18 and UKCP09 are applied using catchment-based hydrological modelling for 10 catchments across England. The simulated river flows are compared to flows simulated using observed climate data for a baseline period, to look at modelled changes in flow. The analysis considers changes in mean and median flow (Q_{mean} and Q50), as well as changes in measures of high and low flow (Q5 and Q95, the flows exceeded 5% and 95% of the time respectively). Details of the catchments, models and methods are provided in Section 2, with results in Section 3, discussion in Section 4 and conclusions in Section 5.

2 Method

2.1 Hydrological modelling

The 10 catchments were selected to provide good spatial coverage of England and to cover a range of catchment properties (Figure 1 and Supplementary Table 1). The hydrological model applied for each catchment was either the PDM (Moore 2007), a lumped model typically used for smaller catchments, or CLASSIC (Crooks and Naden 2007), a semi-distributed model better for larger catchments (see Supp. Section 1.2 for further detail). Both models are run here at a daily time-step.

Both hydrological models require daily time-series of precipitation and potential evaporation (PE), plus daily minimum and maximum temperature for the common snow module. The precipitation data are from CEH-GEAR (Tanguy et al. 2016), the PE data are from MORECS (Hough and Jones 1997), and the temperature data are from Met Office (Perry et al. 2009). See Supp. Section 1.3 for further detail on the driving data, all of which are available for the baseline period 1961-2001.

While calibrations for both models were available from previous work (Reynard et al. 2009), the PDM was re-calibrated for this study as the previous calibrations prioritised performance for flood peaks whereas this work covers the whole flow regime. Existing calibrations were used for CLASSIC, as only the two routing parameters within CLASSIC are specifically calibrated against flow data and these already considered the whole flow regime.

2.2 Climate change projections and their application

Both UKCP09 and UKCP18 provide probabilistic projections consisting of *N* sets of changes in a number of climate variables, where *N* is 10,000 for UKCP09 and 3,000 for UKCP18. The UKCP09 projections are available as monthly changes from a baseline 30-year time-slice (1961-1990) to a number of future 30-year time-slices under three emissions scenarios (equivalent to SRES B1, A1B and A1F1; IPCC 2000), on a 25 km grid over the UK or for 23 river-basin regions. The UKCP18 projections are similarly available on a 25 km grid or for river-basin regions (Met Office Hadley Centre 2018b) but under four representative concentration pathways (RCP2.6, 4.5, 6.0, 8.5; van Vuuren et al. 2011) as well as SRES A1B emissions (which lies between RCP6.0 and RCP8.5 in terms of temperature projections; Met Office Hadley Centre 2018a). However, the UKCP18 projections are available as time-slice mean changes from three different baseline periods, and as time-series of anomalies.

The UKCP18 30-year time-slice mean changes from the 1961-1990 baseline are applied here, since they are equivalent to the UKCP09 projections. The river-basin region data are used as they are consistent across any given river catchment; modelling for each catchment uses probabilistic projection data from the river-basin region within which it is located. The 2050s (2040-2069) future time-slice is used with the A1B emissions scenario for both UKCP09 and UKCP18, to allow direct comparison between the old and new projections, and for UKCP18 two of the newer RCPs are also used (RCP4.5 and RCP8.5). The 2050s time-slice is used, rather than a later time-slice, as it is has greater relevance for current planning horizons in the water sector.

The probabilistic projections provide monthly changes in precipitation and temperature, but not PE. For each catchment, the required sets of monthly changes in PE are derived from the corresponding sets of monthly temperature changes using a baseline temperature time-series for the catchment and the temperature-based PE formula of Oudin et al. (2005) (as Kay and Jones 2012a). Plots of seasonal changes in precipitation and PE for each set of probabilistic projections, for each of the 10 catchments, are given in Supp. Section 1.6.

The probabilistic projections are applied for each catchment using the change factor method, which involves the application of monthly changes to a baseline time series for that variable (Kay and Jones 2012a). The adjusted climate time-series are then used to drive the hydrological model for each catchment. In each case, the river flows simulated with the adjusted climate time-series are compared to those simulated using the original climate data, to look at modelled changes in Q_{mean}, Q50, Q5 and Q95.

3 Results

Notched boxplots show the range of percentage changes in each flow measure by the 2050s, for each set of probabilistic projections and each catchment for mean and median flow (Q_{mean} and Q50; Figure 2) and high and low flow (Q5 and Q95; Figure 3).

Under A1B emissions, for all four flow measures in all 10 catchments, the central estimate of change from the UKCP18 probabilistic projections is similar to that from the UKCP09 projections (Supp. Table 3). However, the 10^{th}-90^{th} percentile range (and 25th-75th range) from the UKCP18 projections is greater than that from the UKCP09 projections, despite UKCP18 having a smaller ensemble size than UKCP09. For Q_{mean}, the size of the 10th-90th percentile range averaged across the 10 catchments is 22.8% for UKCP09 but 28.7% for UKCP18, with the average ranges for Q50 being 22.1% for UKCP09 and 27.7% for UKCP18 (Supp. Table 4). For Q5, the differences under UKCP09 and UKCP18 are similar to those for Q_{mean} and Q50, with average ranges of 28.0% for UKCP09 and 34.6% for UKCP18, but for Q95 the differences are typically less, with average ranges of 22.9% for UKCP09 but 26.1% for UKCP18 (Supp. Table 4).

The central estimates of change using UKCP18 RCP4.5 and RCP8.5 emissions are typically shifted slightly to either side of the central estimate of change for A1B emissions, but there is still considerable overlap in the uncertainty ranges (Figure 2 and Figure 3).

4 Discussion

4.1 Flow changes

For all four flow measures in all 10 catchments, the central estimate of change under A1B emissions from the UKCP18 probabilistic projections is similar to that from the UKCP09 projections. The differences are small - never less than -2% or greater than 4% (Supp. Table 3) - but in many cases (about 27 out of 40) they are statistically significant as the notches in the boxplots do not overlap, which means there is 95% confidence that the medians differ. The differences between the central estimates of change under UKCP18 and UKCP09 are typically greater for Q95 and Q50 than for Q_{mean} and Q5.

The central estimates of the changes in Q95, Q50 and Q_{mean} flows are generally negative (i.e. indicate decreases in low and mid-range flows in most cases), but under UKCP18 they are often less severe (i.e. typically indicate smaller decreases) than those from UKCP09 (Supp. Table 3). The central estimates of change in Q5 are positive (i.e. indicate increases in high flows) for 7 out of 10 catchments, and the increases under UKCP18 are greater than those from UKCP09 for 3 catchments (Supp. Table 3). In most cases (33 out of 40) the central estimates of change under RCP8.5 emissions are more extreme (i.e. suggest greater magnitude increases or decreases) than the change under RCP4.5 emissions, especially for changes in Q5 and Q95.

Flow changes vary between catchments, partly because of spatial differences in the climatic changes but also because of differences in the response of catchments with different physical properties. For example, there are differences in the response of catchments 43005 and 47007, especially for Q95 (where the reductions for 47007 are double those for 43005; Figure 3 and Supp. Table 3), despite both being in the SW England region. Similarly, there are differences in the response of catchments 38003 and 39001, which are both in the Thames region. Catchment characteristics (for example soils, geology and topography), which influence the response of the catchment to climatic inputs and thus lead to different model parameterisations, are the main reason for such differences.

4.2 Linking flow changes to climatic changes

The differences between changes in flows using UKCP18 and UKCP09 projections are generally consistent with expectations given differences between UKCP18 and UKCP09 climatic changes (see Supp. Section 1.6):

- For low and mid-range flows, typical flow decreases are smaller using UKCP18 than UKCP09. This is consistent with smaller decreases in summer precipitation and smaller increases in summer PE in UKCP18 compared to UKCP09.
- For high flows, typical flow increases are often greater using UKCP18 than UKCP09, which is again consistent with smaller decreases in summer precipitation and smaller increases in summer PE in UKCP18 compared to UKCP09, as soil moisture deficits at the end of summer are likely to be lower. This, together with often higher increases in autumn precipitation in UKCP18 than UKCP09, leads to greater potential for higher winter flows in UKCP18. This is despite there being slightly smaller increases in winter precipitation in UKCP18 than UKCP09, although the latter probably contributes to there being less difference between UKCP18 and UKCP09 for high flows than for low/mid-range flows.
- The uncertainty ranges of the flow changes are wider using UKCP18 projections than UKCP09 projections, probably because the same is true for the precipitation projections.

4.3 Implications for plans and guidance

Typically water plans deal with weather uncertainty by planning for an extreme event of specified probability. For example, flood design often considers an event with an annual probability of occurrence of 1% (often referred to as a 100-year return period). In a non-stationary climate, new approaches to water planning are required (Milly et al. 2008). However, practitioners often find these approaches difficult to use, usually because they require large ensembles of simulations that are difficult to perform using the tools available, most of which were designed for single deterministic simulations. For this reason, UK regulators have developed guidance on climate change flood allowances (Environment Agency 2019) and on simplified approaches to estimating river flows for water resources simulations (Environment Agency 2017).

The small differences indicated by this study between flow changes simulated using UKCP09 and UKCP18 suggest that current allowances and guidance remain valid, and that screening based on UKCP09 remains a useful guide to climate change over the next 30 years. Similarly, more detailed studies based on UKCP09 are likely to show changes of the same direction and similar magnitude to those that would be derived using UKCP18. However, the increase in Q5 compared to UKCP09 may be important in some applications, and the wider range of possible changes may also be important for decisions where risk tolerance is low. It will be necessary to review current guidance in the light of UKCP18, making full use of the range of new information available, to ensure that risks are managed appropriately. Where investment decisions are sensitive to small changes in climate, further more detailed analysis will always be necessary, and there is scope for improved decision-making using approaches that expose risk tolerances more fully by considering a fuller range of future climate (e.g. Hall et al. 2019).

4.4 Sources of uncertainty

The probabilistic projections are applied here using the change factor method. The advantage of this method is that it is easy to apply, but the disadvantage is that it does not allow for future changes in the variability or sequencing of events (Cloke et al. 2013, Vormoor et al. 2017). Kay and Jones (2012a) investigated the use of alternative UKCP09 products (probabilistic projections, RCM data and weather generator data) to model the impacts of climate change on flood peaks for a small number of catchment across GB. Their results showed that, while there was relatively good agreement between the median impacts from each product, the use of time-series generally led to a wider range of impact uncertainty than the use of probabilistic projections. This could also be the case for other parts of the flow regime.

Due to limitations with both baseline datasets and variables available in the probabilistic projections, changes in PE could not be estimated using the physically-based Penman-Monteith formula (Monteith 1965). Instead, changes in PE were estimated using a purely temperature-based formula and these changes were applied to baseline observation-based PE from MORECS, which does use the Penman-Monteith formula. This is not ideal, though temperature-based PE changes may be more reliable (Kay et al. 2013) because of biases in energy balance and wind estimates in RCMs. Another question is whether future PE estimates should allow for increased stomatal closure under higher atmospheric CO_2 concentrations (Rudd and Kay 2016), which reduces future increases in PE and has been shown to influence the simulated impacts of climate change on low flows (Kay et al. 2018). Like most hydrological studies, this work assumes that catchment response to rainfall and evapotranspiration is essentially stationary: more work is needed to understand how catchment response will change in response to a changing climate.

While climate models may be the main source of uncertainty in hydrological projections (e.g. Vetter et al. 2017, Roudier et al. 2016, Gosling et al. 2011), uncertainty from hydrological models (both model structure and parameterisation) may be important, especially for low flows (Vetter et al. 2017, Giuntoli et al. 2015), and different sources of uncertainty can combine to produce greater overall uncertainty (Vaghefi et al. 2019). Further work using an ensemble of hydrological models and calibrations would be expected to provide more confidence. The use of a single future time-slice and the 1961-1990 baseline period also introduces an element of uncertainty in resulting impacts, due to natural climate variability (e.g. Kay and Jones 2012b).

5 Conclusions

Currently, much of the available information and guidance on the potential impacts of climate change in Britain is based on the UK Climate Projections 2009, including most of the information on river flows (e.g. Kay et al. 2014, Prudhomme et al. 2012, Christierson et al. 2012, Bell et al. 2012). The recent release of updated climate projections, UK Climate Projections 2018, means it may be necessary to update existing guidance, but full updates will take time to produce, often requiring substantial amounts of new modelling to be performed. By producing some early information on the potential scale of differences in impacts on river flows between UKCP09 and UKCP18 (albeit only for four flow measures using one UKCP18 product for one future time-slice), the work presented here aids the development of advice to users of current policy guidance based on the UKCP09 projections, and helps with decisions about the prioritisation of further hydrological impacts work based on UKCP18. The limitations of this approach, particularly in assuming stationarity in catchment response, highlight the need for further work to understand how catchments may change over the coming decades.

The results show that existing plans and guidance based on UKCP09 are likely to remain valid, though detailed planning or investment should be updated using the new projections, especially where significant investment is necessary. Ideally, such indicative results would be available at the launch of new climate projections. End users are often unable to process climate change information: paradoxically, the availability of new projections – intended to improve the response to climate change – may slow or halt adaptation action, with users reluctant to follow old plans in case they are wrong, but unable to formulate new approaches. Consistent, salient indicators, for example of changes in river flow, would help users to evaluate the impact of new climate science on current plans.

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Data availability

Data available from the authors upon reasonable request.

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Figures

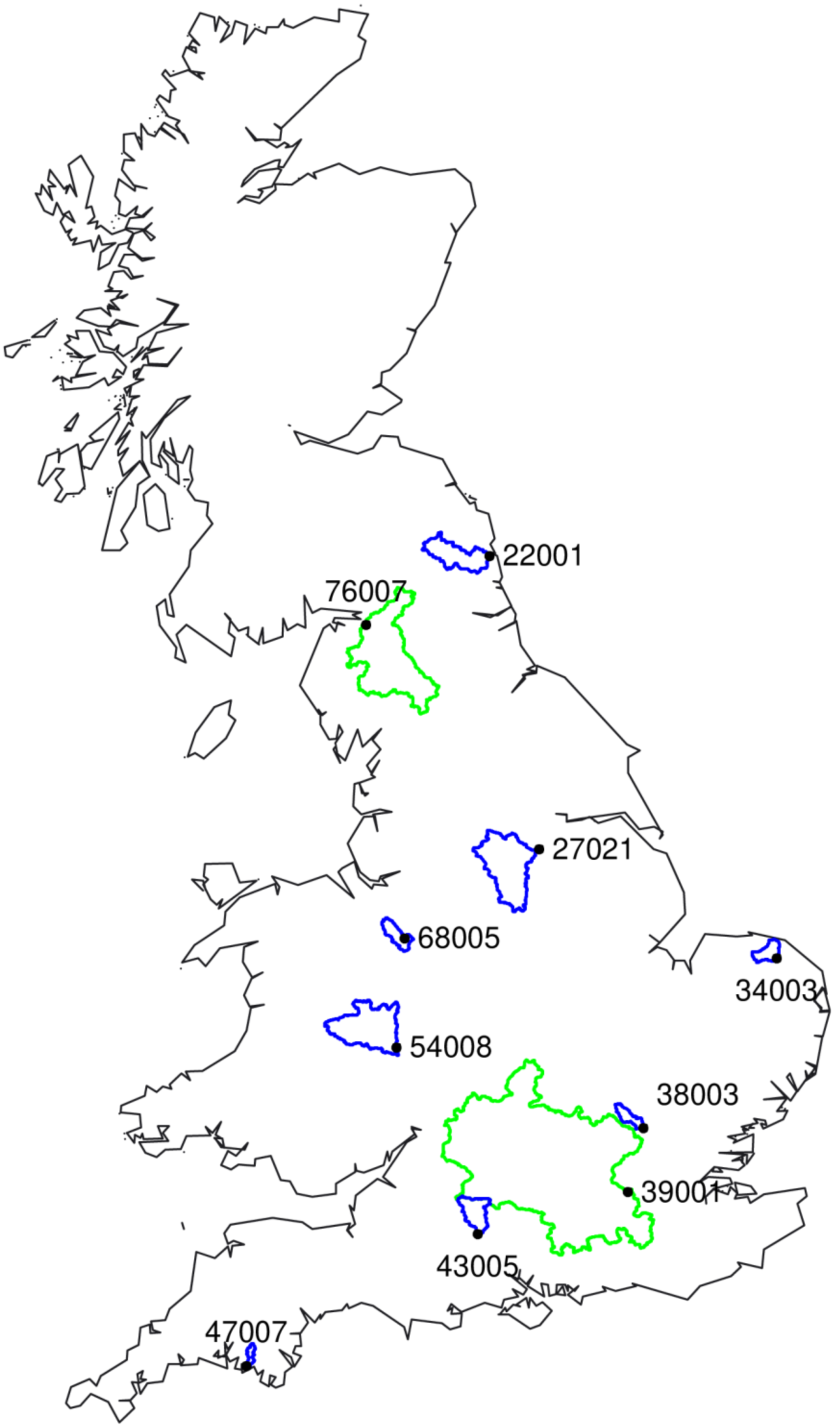

Figure 1 Locations of the study catchments.

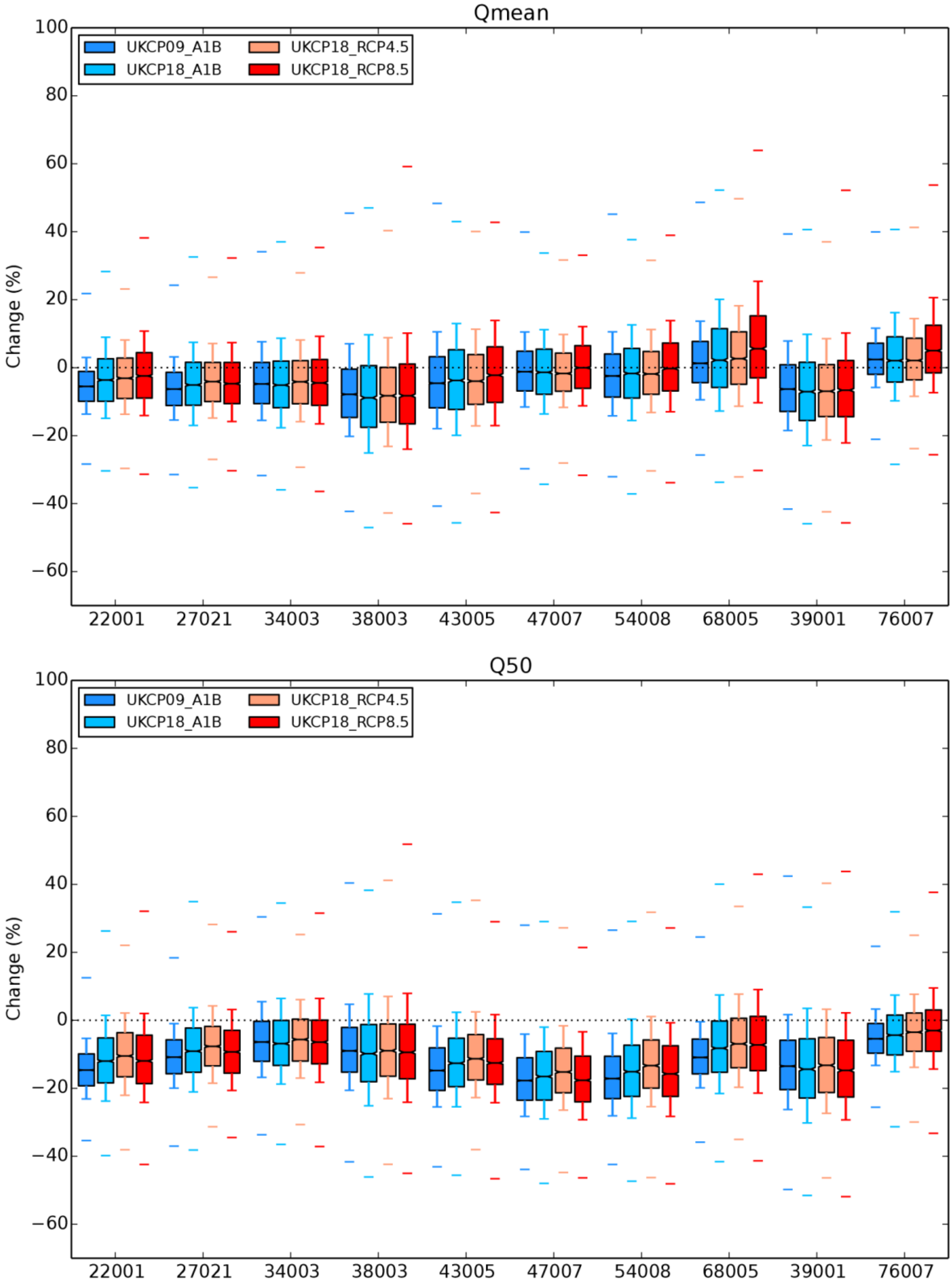

Figure 2 Range of percentage changes in mean flow (top) and median flow (bottom) for the 10 catchments, using UKCP09 and UKCP18 probabilistic projections for the 2050s (2040-2069). Each box shows the 25th-75th percentile range, with the 50th percentile shown by the black line and notches in the box. The whiskers show the 10th-90th percentile range, with markers beyond the whiskers showing the overall min and max (if within the plotted range). Note that there is an ensemble of 10,000 probabilistic projections for UKCP09 and 3,000 for UKCP18.

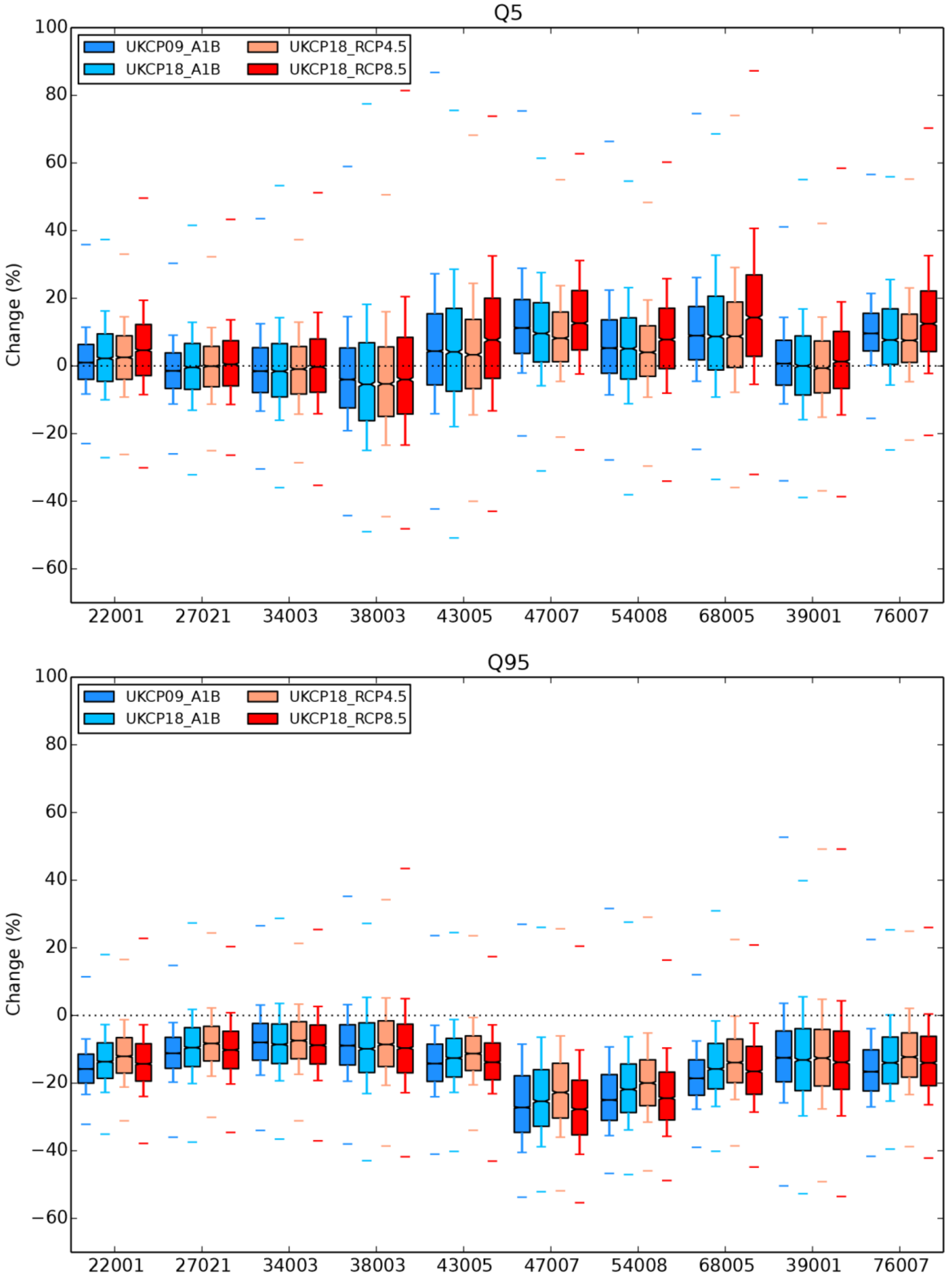

Figure 3 As Figure 2 but for percentage changes in measures of high flow (Q5, the flow exceeded 5% of the time; top) and low flow (Q95, the flow exceeded 95% of the time; bottom).

The impact of climate change on UK river flows: a preliminary comparison of two generations of probabilistic climate projections

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Supplementary Material

1 Methodology

1.1 Catchments

Table 1 provides details of the 10 catchments modelled, including selected catchment properties, the hydrological model applied (Section 1.2) and the UKCP18 river-basin region within which each catchment is contained.

Table 1 Details of the study catchments, the hydrological model used for each, and the UKCP18 river-basin region with which each is contained.

Catchment number	River name	Location	Area (km^2)	SAAR (mm)	BFI (-)	Model	UKCP18 river-basin region
22001	Coquet	Morwick	569.8	850	0.45	PDM	Northumbria
27021	Don	Doncaster	1256.2	799	0.56	PDM	Humber
34003	Bure	Ingworth	164.7	669	0.83	PDM	Anglian
38003	Mimram	Panshanger Park	133.9	656	0.94	PDM	Thames
43005	Avon	Amesbury	323.7	745	0.91	PDM	SW England
47007	Yealm	Puslinch	54.9	1410	0.56	PDM	SW England
54008	Teme	Tenbury	1134.4	841	0.57	PDM	Severn
68005	Weaver	Audlem	207.0	719	0.50	PDM	NW England
39001	Thames	Kingston	9948.0	719	0.64	CLASSIC	Thames
76007	Eden	Sheepmount	2286.5	1214	0.49	CLASSIC	Solway

SAAR is Standard Average Annual Rainfall for 1961-1990; BFI is Base Flow Index

1.2 Hydrological models

Two different hydrological models are used; the Probability Distributed Model (PDM; Moore 1985, 2007), which is a lumped model typically used for smaller catchments, and the Climate and LAnd use Scenario Simulation In Catchments model (CLASSIC; Crooks and Naden 2007), which is a semi-distributed model better for larger catchments.

The PDM model structure invoked here is a reduced-parameter form of the full model. It assumes that water storage capacity across the catchment is probability-distributed following a uniform distribution. Capacities vary from zero to a maximum value c_{max}, and have equal frequency of occurrence $1/c_{max}$ over the range. A splitting function partitions the saturation-excess direct runoff from this probability-distributed storage into two parallel fast and slow pathways, with fractions α and 1-α respectively. The fast pathway ("surface storage") is represented by a single linear store while the slow pathway ("groundwater storage") is represented by a cubic store. The sum of water flows from the two pathways gives the river flow at the catchment outlet. The model thus employs five parameters: the rainfall factor f_c (accounting for rainfall representativeness and abstraction/return/transfer effects on the catchment water balance), the maximum water storage capacity c_{max}, the time constants of the surface and groundwater storage functions (k_1 and k_b), and the splitting fraction α. The exponent b_e in the evaporation function relating actual evaporation to potential evaporation (PE) and soil moisture deficit (Moore 2007) is included as a further parameter.

CLASSIC was developed for estimating the impacts of climate and land use change in large catchments. The model comprises three component modules and is applied on a (typically 10km) grid framework with climatic inputs of rainfall and PE to each grid square. The components are a soil water balance module, a drainage module, and a simple channel routing module. The soil water balance module operates as a soil moisture accounting system characterised by two parameters, the total depth of water available to vegetation and the percentage of this depth from which evaporation occurs at the potential rate. When the soil moisture deficit (SMD) exceeds this depth, loss of water is determined by an exponential relationship between PE and SMD. The hydrologically effective rainfall generated by the soil water balance module forms the input to the drainage module in which the water is held in storage reservoirs. Soils overlying permeable substrata are modelled with a one-component store, outflow from which is determined by a time parameter; soils overlying substrata with no significant underlying aquifer are modelled with two component stores, representing quick and slow flow, operating in parallel. These stores each have time parameters to determine their rates of outflow, with a further parameter determining the proportion through the quick store. Urban areas have a separate water balance and drainage module, and the total grid square outflow is given by the sum of the outflows from each storage reservoir operating within a particular grid square. The routing module convolves the grid square outflow with a measure of the catchment channel network (the network width function) determined from a DTM. This is further convolved with a routing function with two parameters, for wave velocity and a coefficient of diffusion. Individually routed grid square flows are summed to provide the total flow at the simulation site, normally a flow gauging station.

1.3 Baseline data

The precipitation data are derived from CEH Gridded Estimates of Areal Rainfall (CEH-GEAR; Tanguy et al. 2016, Keller et al. 2015), which provides 1km gridded daily rainfall data for the UK. The PE data are derived from the Met Office Rainfall and Evaporation Calculation System (MORECS; Hough and Jones 1997), which provides 40km monthly estimates of short grass PE based on the Penman-Monteith formulation (Monteith 1965). The monthly PE are divided equally over each day in the month. The temperature data are taken from 5km daily min and max data (Perry et al. 2009). For each PDM catchment, data from the 5km grid box containing the catchment centroid are used, along with the grid box centre altitude at which the temperature applies. For each CLASSIC catchment, temperature (and corresponding altitude) data for each 10km model grid box are derived using weighted averages of the relevant 5km grid boxes. Within the snow module, the temperature data are applied to elevation zones within each catchment (PDM) or 10km grid box (CLASSIC), using a lapse rate (0.0059°C/m) and 50m elevation data (Morris and Flavin 1990).

Table 2 gives the start and end dates of the observed flow data (nrfa.ceh.ac.uk) used for model calibration and performance assessment, and the percentage of missing data in the baseline period (1961-2001). Naturalised flows are only available for catchment 39001, and were used for the existing CLASSIC calibration for that catchment; otherwise gauged flows were used.

Table 2 The start and end years of daily mean flow data used for model calibration and performance assessment, and the percentage of missing daily mean flow data in the baseline period (1961-2001).

Catchment number	Start year	End year	% missing data (1961-2001)
22001	1963	2001	6.97
27021	1961	2001	5.14
34003	1961	2001	0.49
38003	1961	2001	0.01
43005	1965	2001	9.96
47007	1963	2001	7.57
54008	1961	2001	0.00
68005	1961	2001	3.16
39001	1961	2001	0.00
76007	1967	2001	16.49

1.4 PDM calibration

As in a previous application of this form of the PDM (Reynard et al. 2009), the splitting parameter *α is set as 1-BFIHOST*, where *BFIHOST* is an estimate of the base-flow index derived from HOST soil types (Boorman et al. 1995).

The model parameters were calibrated separately for each catchment using a combination of automatic optimisation (minimisation of suitably chosen objective functions) along with manual parameter adjustment based on visual inspection of the hydrographs. The automatic calibration uses a modified form of the simplex direct search method (Nelder and Mead 1965; Gill et al. 1981). It is carried out in two stages for each catchment:

1. The long-term base-flow response is first calibrated by varying the parameters c_{max}, k_b, b_e, (with $f_c = 1$) and minimising the RMSE of natural log errors over the full baseline period. Employing logarithmic errors increases the sensitivity to errors in lower flows.
2. The parameters dominating the fast response (f_c, c_{max}, k_1) are calibrated next, by minimising the RMSE of the square roots of the errors over a six-month flood-rich period. Square roots are used to prevent applying greater weight to either high or low flows.

1.5 Model performance in the baseline period

The performance of the models is evaluated for each catchment against available observed flow data over the baseline period, leaving off the first year of each run (1961) as a spin-up period. The assessment concentrates on the percentage errors in the four specific flow measures of interest (Q_{mean}, Q50, Q5 and Q95).

Figure 1 shows the model performance in terms of percentage errors in the four specific flow measures. Each shows relatively good performance, with the magnitude of errors generally less than 10%. Only Q95 (the low flow measure) has errors greater than 10%, for just two catchments – the Mimram (38003) and the Teme (54008). The Mimram has significant export of water via groundwater abstraction (Marsh and Hannaford 2008), which is likely to affect the base-flow and lead to larger percentage errors in modelled low flows than for other parts of the flow regime. In the Teme, upstream shoaling may lead to the rating for low flows varying from year to year (Marsh and Hannaford 2008), resulting in errors in gauged low flows.

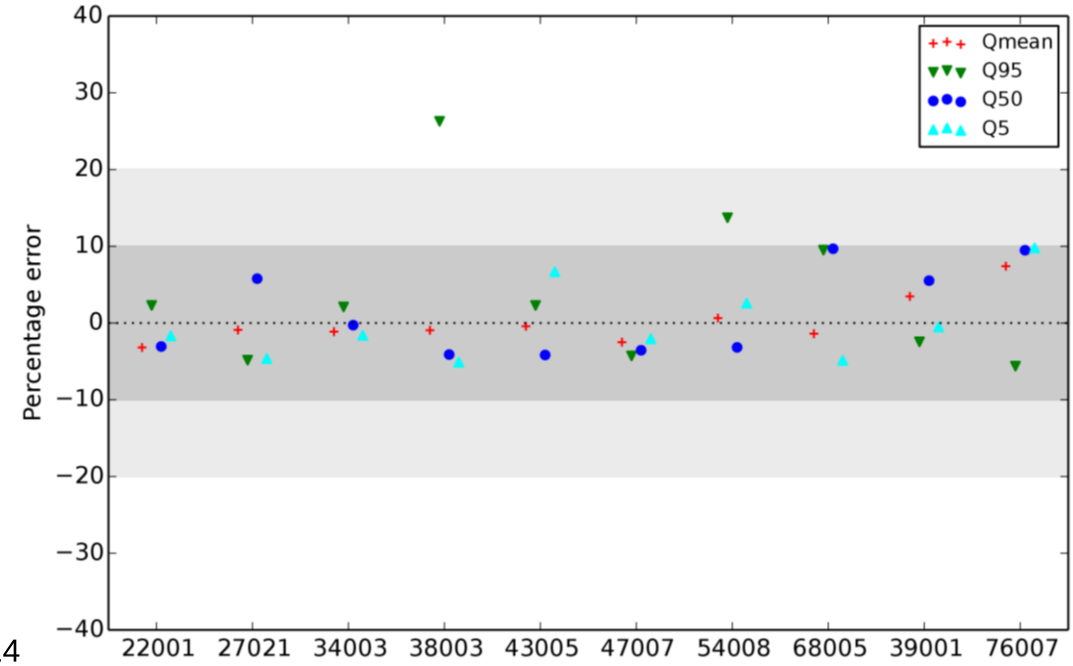

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Figure 1 Model performance for the 10 catchments, in terms of percentage errors in four flow measures; Q_{mean}, Q95, Q50 and Q5.

1.6 Climate change projections

The seasonal changes in inputs from each set of probabilistic projections, for each of the 10 catchments, are shown in Figure 2 (precipitation) and Figure 3 (PE).

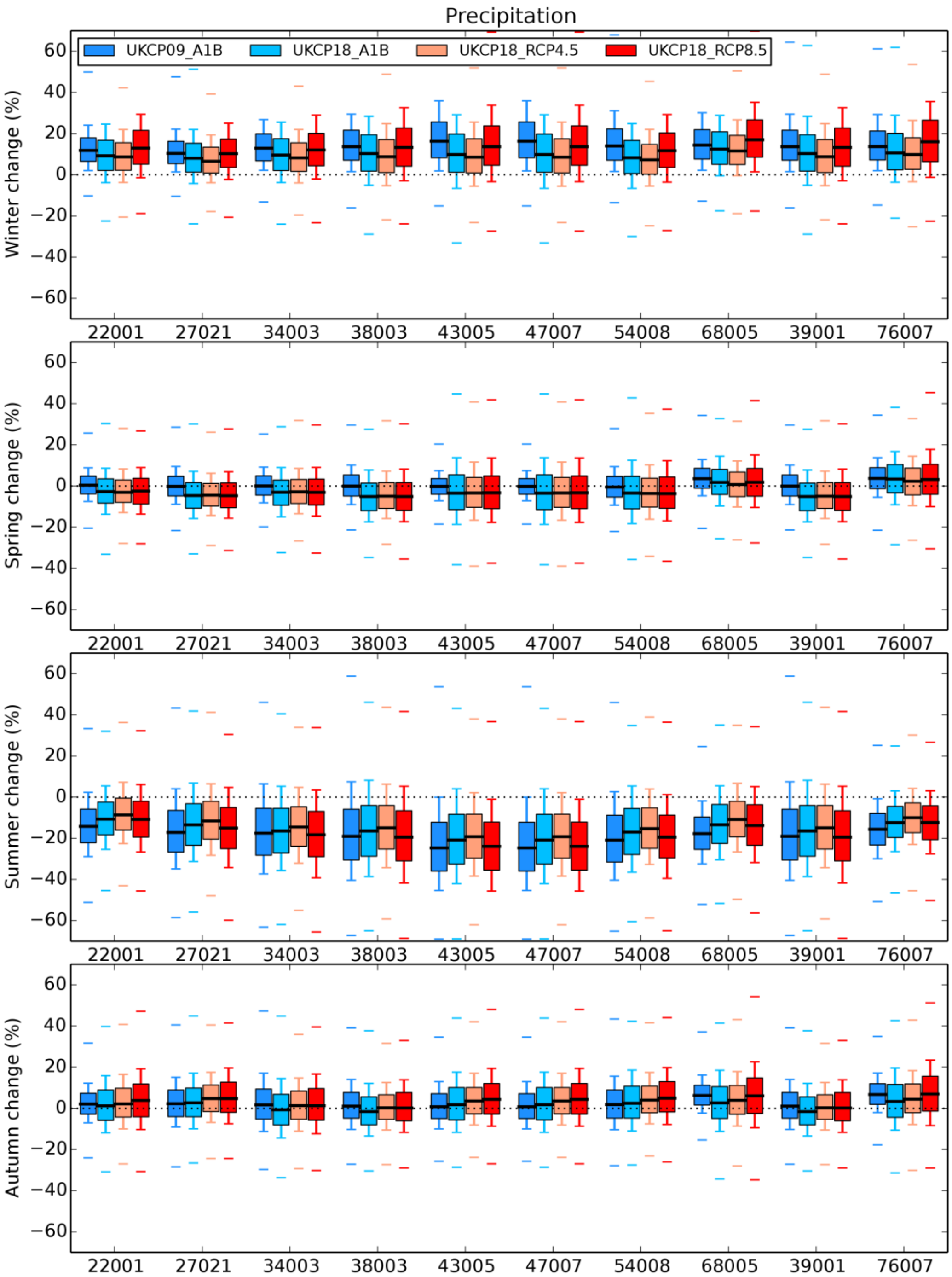

Figure 2 Range of percentage changes in seasonal precipitation for the 10 catchments, using UKCP09 and UKCP18 probabilistic projections for the 2050s (2040-2069). Each box shows the 25th-75th percentile range, with the 50th percentile shown by the black line across the box. The whiskers show the 10th-90th percentile range, with markers beyond the whiskers showing the overall min and max (if within the plotted range). Note that the changes in each season are calculated here by averaging the changes for the three standard months in each season; this may not be completely consistent with the directly available seasonal probabilistic projections, but uses the monthly data applied for the flow modelling.

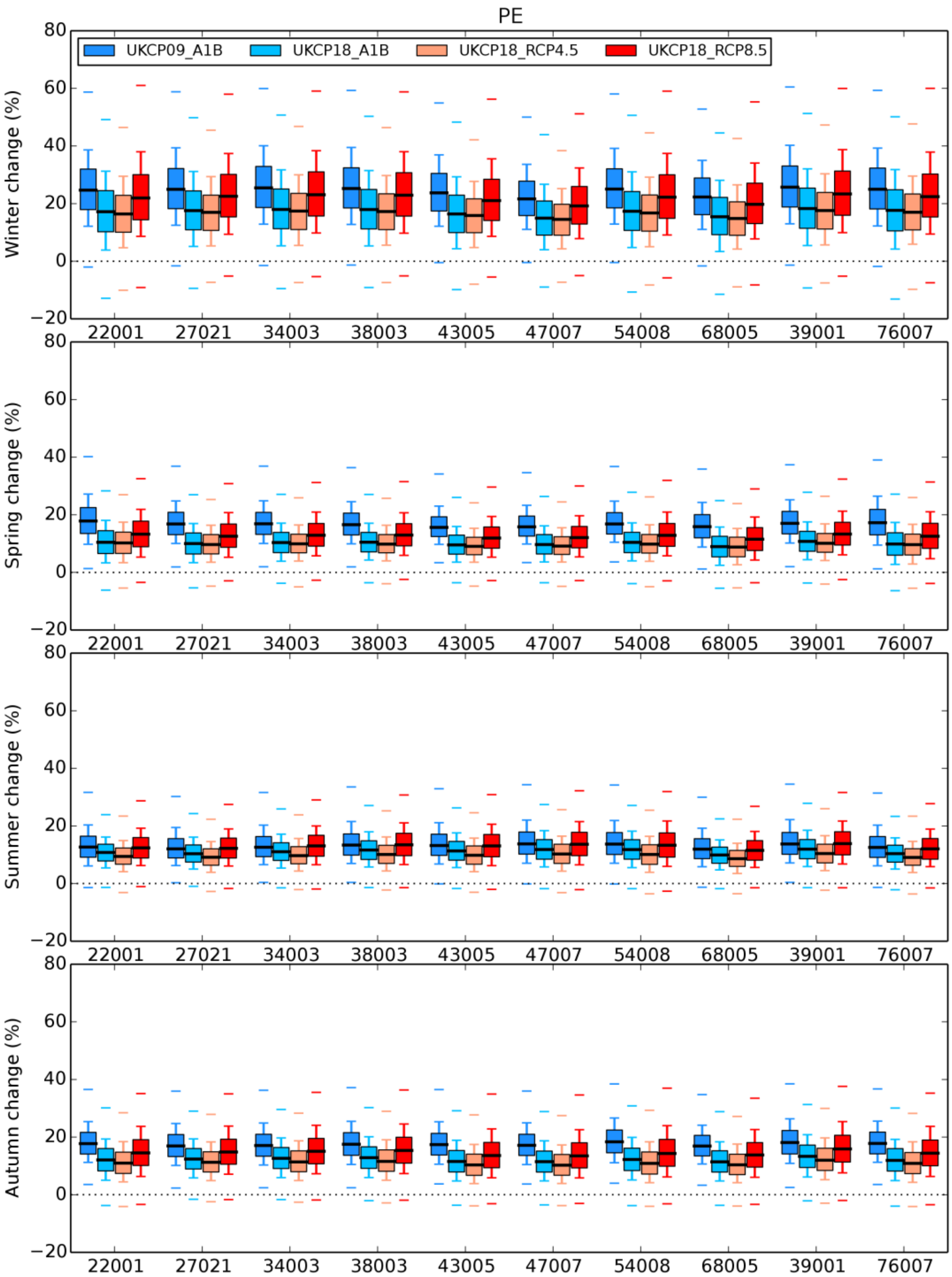

Figure 3 As Figure 2 but for the range of percentage changes in PE.

2 Results

Table 3 compares the median change in each flow measure in each catchment, under the UKCP09 and UKCP18 probabilistic projections, while Table 4 compares the 10th-90th percentile range in each case.

Table 3 The median change in Q_{mean}, Q50, Q95 and Q5 in each catchment, using the UKCP09 and UKCP18 probabilistic projections for the 2050s (A1B emissions). Also shown are the differences in each case (UKCP18-UKCP09).

	UKCP09				UKCP18				Differences			
	Q_{mean}	Q50	Q95	Q5	Q_{mean}	Q50	Q95	Q5	Q_{mean}	Q50	Q95	Q5
22001	-5.5	-14.6	-15.8	1.0	-3.6	-12.0	-13.7	2.2	1.9	2.6	2.1	1.2
27021	-6.3	-10.8	-11.2	-1.5	-5.1	-9.1	-9.5	-0.4	1.2	1.7	1.7	1.1
34003	-4.8	-6.4	-8.0	-1.5	-5.1	-6.9	-8.6	-1.6	-0.3	-0.5	-0.6	-0.1
38003	-7.8	-9.0	-8.9	-4.0	-8.9	-9.8	-9.9	-5.4	-1.1	-0.8	-1.0	-1.4
43005	-4.6	-14.8	-14.2	4.4	-3.8	-12.6	-12.6	4.2	0.8	2.2	1.6	-0.2
47007	-1.2	-17.7	-27.2	11.2	-1.4	-16.5	-25.4	9.6	-0.2	1.2	1.8	-1.6
54008	-2.4	-17.1	-25.0	5.3	-1.7	-15.1	-21.8	5.1	0.7	2.0	3.2	-0.2
68005	1.3	-10.9	-18.6	9.0	2.2	-8.2	-15.8	8.7	0.9	2.7	2.8	-0.3
39001	-6.3	-13.5	-12.5	0.7	-7.1	-14.4	-13.1	0.0	-0.8	-0.9	-0.6	-0.7
76007	2.4	-5.4	-16.6	9.6	2.1	-4.4	-14.0	7.7	-0.3	1.0	2.6	-1.9
Average	-3.5	-12.0	-15.8	3.4	-3.2	-10.9	-14.4	3.0	0.3	1.1	1.4	-0.4

Table 4 The size of the 10th-90th percentile range for the change in Q_{mean}, Q50, Q95 and Q5 in each catchment, using the UKCP09 and UKCP18 probabilistic projections for the 2050s (A1B emissions). Also shown are the differences in each case (UKCP18-UKCP09).

	UKCP09				UKCP18				Differences			
	Q_{mean}	Q50	Q95	Q5	Q_{mean}	Q50	Q95	Q5	Q_{mean}	Q50	Q95	Q5
22001	16.6	17.8	16.5	19.7	23.9	25.3	20.0	26.3	7.3	7.5	3.5	6.6
27021	18.6	19.0	17.6	20.4	24.5	24.8	21.9	26.0	5.9	5.8	4.3	5.6
34003	23.1	22.3	20.7	25.9	26.3	25.1	22.9	30.3	3.2	2.8	2.2	4.4
38003	27.2	25.3	22.6	33.8	34.8	32.9	28.5	43.2	7.6	7.6	5.9	9.4
43005	28.5	23.8	21.1	41.3	32.9	27.9	21.5	46.5	4.4	4.1	0.4	5.2
47007	22.0	24.3	32.0	31.0	24.8	27.0	32.4	33.5	2.8	2.7	0.4	2.5
54008	24.7	24.2	26.2	31.0	28.1	29.1	27.6	34.4	3.4	4.9	1.4	3.4
68005	23.2	19.5	20.2	30.6	32.8	29.0	25.3	41.9	9.6	9.5	5.1	11.3
39001	26.3	27.9	29.4	25.5	32.7	33.7	35.2	32.7	6.4	5.8	5.8	7.2
76007	17.4	16.6	23.1	21.2	25.9	22.5	25.5	31.1	8.5	5.9	2.4	9.9
Average	22.8	22.1	22.9	28.0	28.7	27.7	26.1	34.6	5.9	5.7	3.1	6.6

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