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# The relationship between climate forcing and hydrological response in UK catchments

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Received: 11 August 2010 – Accepted: 12 August 2010 – Published: 4 October 2010

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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## Abstract

This paper assesses the relationship between amount of climate forcing – as indexed by global mean temperature change – and hydrological response in a sample of UK catchments. It constructs climate scenarios representing different changes in global mean temperature from an ensemble of 21 climate models assessed in the IPCC AR4. The results show a considerable range in impact between the 21 climate models, with – for example – change in summer runoff at a 2 °C increase in global mean temperature varying between –40% and +20%. There is evidence of clustering in the results, particularly in projected changes in summer runoff and indicators of low flows, implying that the ensemble mean is not an appropriate generalised indicator of impact, and that the standard deviation of responses does not adequately characterise uncertainty. The uncertainty in hydrological impact is therefore best characterised by considering the shape of the distribution of responses across multiple climate scenarios. For some climate model patterns, and some catchments, there is also evidence that linear climate change forcings produce non-linear hydrological impacts. For most variables and catchments, the effects of climate change are apparent above the effects of natural multi-decadal variability with an increase in global mean temperature above 1 °C, but there are differences between catchments. Based on the scenarios represented in the ensemble, it is likely that the effect of climate change in northern upland catchments will be seen soonest in indicators of high flows, but in southern catchments effects will be apparent soonest in measures of summer and low flows. The uncertainty in response between different climate model patterns is considerably greater than the range due to uncertainty in hydrological model parameterisation.

## 1 Introduction

The literature now contains hundreds of examples of the potential impact of future climate change on hydrological regimes, in an increasingly wide variety of environments

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(see Kundzewicz et al., 2007 and Bates et al., 2008 for reviews of some of these studies). The vast majority of these studies apply a set of climate scenarios to an observed baseline climatology, and simulate hydrological regimes under baseline and future climates using a catchment hydrological model. Most scenarios are defined for a specific emissions scenario (studies increasingly use the IPCC SRES scenarios) and time horizon (typically the 2050s); most also construct scenarios from only a small number of climate models. This makes it difficult to compare results from different studies or to infer impacts under different emissions scenarios. It also makes it difficult to assess the relationship between rate of climate forcing and rate of hydrological response, and identify potential critical thresholds or non-linear responses to change.

The aim of this paper is to examine the relationship between climate forcing – as indexed by change in global average temperature – and hydrological response, using six case study catchments representing different hydrological characteristics in the UK, and multiple climate scenarios derived from the climate models evaluated in the IPCC's Fourth Assessment Report (IPCC, 2007). These scenarios are scaled to represent prescribed changes in global average temperature ranging from 0.5 °C (above 1961–1990) to 6 °C. The changes in indicators of hydrological regime, and the variation between the 18 climate models, are compared with the effects of “natural” multi-decadal climatic variability with no climate change, and with the effects of uncertainty in hydrological model parameterisation. The paper complements papers in this special issue which follow the same basic methodology (Todd et al., 2010).

## 2 Methodology

### 2.1 Introduction

The basic methodology applies climate scenarios representing prescribed changes in global average temperature to observed baseline climate data in six case study catchments, and simulates river flows using a catchment hydrological model. This

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section first introduces the case study catchments, then describes the hydrological model and its performance in the study catchments, before describing how the climate scenarios are defined and applied.

## 2.2 Case study catchments

The case study catchments are the same as used in earlier impact assessments by Arnell (2003a, 2004). Figure 1 shows the locations of the catchments, together with baseline (1961–1990) mean monthly runoff. Table 1 summarises catchment characteristics and the baseline annual water balance. The Greta and Eden catchments both drain relatively impervious upland catchments, and some winter precipitation in each currently falls as snow; snow storage and snowmelt peaks, however, are not a major feature of the hydrological regime in either catchment. The Harper’s Brook and Teme catchments both lie in the English midlands, and drain lowland catchments with relatively limited relief. Both have mixed land covers and geological characteristics. The Lambourn and Medway catchments are both in Southern England. The Medway is largely underlain by relatively impermeable clays but some portions of the catchment are underlain by chalk, which is highly permeable. In contrast, the Lambourn catchment is almost entirely underlain by chalk. In this catchment, virtually all of the river flows derive from groundwater storage replenished by recharge during winter. All of the catchments are largely rural, with mixed agricultural land covers.

## 2.3 The hydrological model

The model used in this study (and used in Arnell and Reynard, 1996; Arnell, 2003a, 2004) is a daily conceptual water balance model with lumped inputs assumed constant across the catchment, and with a soil moisture storage capacity that varies statistically across the catchment. The model derives from Moore’s (1985; 2007) probability-distributed model (PDM), and a macro-scale version has been used across the global

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domain (Arnell, 2003b; Gosling and Arnell, 2010). Three model parameters essentially partition rainfall into evaporation and streamflow, and two parameters route streamflow out of fast and slow stores to the catchment outlet. For the catchments in which snow occurs, precipitation is assumed to fall as snow when temperature is below 0 °C, and snow melts once temperatures rise above 0 °C in a two-stage process. Potential evaporation is calculated using the Penman-Monteith formula. The five model parameters were estimated by manual calibration over the period 1980–1983, and validated using data from 1983–1989 (Arnell and Reynard, 1996). Table 2 shows model bias and Nash-Sutcliffe efficiency over the calibration and validation periods. It is assumed that model parameters do not change as climate changes.

The model is run in each catchment with 30 years of daily precipitation, potential evaporation and, for the upland catchments, temperature, spanning the period 1961–1990. Potential evaporation data were taken from the MORECS data set.

This paper concentrates on average annual monthly and seasonal runoff, and on flows exceeded 5% (“high flows”) and 95% (“low flows”) of the time.

The effect of uncertainty in model parameterisation on the estimated impacts of climate change were determined (for just the Harper’s Brook catchment) by defining 100 sets of random variations around the calibrated parameter set. Each parameter was allowed to vary by up to plus or minus 10%, and each of the 100 parameter sets sampled within this range. Table 3 summarises bias and Nash-Sutcliffe efficiency across the 100 variants, over the calibration and validation periods. Note that none of the perturbed parameter sets produced particularly poor representations of observed flows, so all were used in the uncertainty analysis.

## 2.4 Climate scenarios

Climate scenarios were derived from 21 of the climate models used in the Coupled Climate Model Intercomparison Project phase 3 (CMIP3: Table 4) and subsequently reviewed in the IPCC (Meehl et al., 2007; IPCC, 2007). One was omitted because it

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is not recommended for use in impact assessments due to large biases in mid- and high-latitudes. Note that the 21 climate models do not represent a set of independent models.

A pattern-scaling approach was used to define scenarios from each model representing prescribed changes in global mean annual temperature (see Mitchell and Osborn, 2005 for details). For each climate variable (defined below), month, model grid cell and climate model, change per degree of global mean annual temperature change was determined from regression relationships between that variable and global mean annual temperature (Mitchell and Osborn, 2005). The regression relationships were developed from the CMIP3 A2 simulations, where available, and validated by comparing rescaled patterns with changes simulated by the same model under A1 emissions (Mitchell and Osborn, 2005). The pattern-scaling approach assumes that each climate variable responds linearly to changing global mean annual temperature. Whilst this has been shown to be a reasonable assumption for moderate amounts of climate change (Mitchell and Osborn, 2005; Mitchell, 2003), it may not hold for high changes, and is unlikely to hold where the rate of temperature change slows or even reverses.

Climate patterns were defined for change in mean monthly precipitation, mean monthly temperature, mean monthly vapour pressure and mean monthly cloud cover (from which change in mean monthly net radiation was determined). The patterns also include change in the parameters of the gamma distribution of monthly rainfall (Mitchell and Osborn, 2005), from which it is possible to derive change in the year to year distribution of monthly rainfall (as characterised by the coefficient of variation of monthly rainfall). The scenarios do not include change in windspeed, so it was assumed that baseline windspeed remained unchanged. Scenarios representing a prescribed change in global mean temperature were constructed by scaling the patterns to that temperature. Scenarios are then downscaled from the original climate model resolution to  $0.5 \times 0.5^\circ$  by simple interpolation (Mitchell and Osborn, 2005).

The scenarios were applied to the case study catchments by first identifying the appropriate  $0.5 \times 0.5^\circ$  grid square and subsequently perturbing the catchment 1961–

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1990 daily rainfall, temperature and potential evaporation data by the mean monthly changes to create new 30-year daily time series. The variability in monthly precipitation from year to year was altered by rescaling anomalies from the mean to produce a time series with altered coefficient of variation (as also done by Arnell, 2003a).

5 Figure 2 summarises the climate scenarios for each catchment, showing change in mean annual temperature, mean winter rainfall, mean summer rainfall and mean summer potential evaporation for a 2 °C change in global mean average temperature. Most of the climate scenarios project an increase in temperature at the study sites slightly below the global average, although one consistently projects a slightly larger than average rise in temperature across the UK. The climate models consistently project an increase in mean winter rainfall, with magnitudes varying between models, and virtually all project a decrease in mean summer rainfall. One climate model projects an increase in summer rainfall across the whole of the UK; one more projects very small changes. Summer potential evaporation increases under all but one of the projections, but the magnitude of change varies considerably between climate models. The increase is broadly related to temperature change, but is influenced by the change in relative humidity and, to a lesser extent, net radiation. For example, the model which projects a decrease in summer potential evaporation has a relatively high increase in summer temperature, but combines this with a large increase in relative humidity and a reduction in net radiation so potential evaporation actually falls. This variation between models in their projected change in evaporation has also been identified by Boe and Terray (2008), who showed that the differences were related to the way the models represented the respective roles of soil moisture and radiative energy at the surface on evaporation; these differences led in turn to differences in summer rainfall and temperature response.

25 Scenarios characterising the effect of “natural” multi-decadal variability, in the absence of climate change, were taken from the UKCIP98 scenario set (Hulme and Jenkins, 1998) as used in Arnell (2003a). These scenarios were ultimately derived from a long unforced control run of HadCM2, and represent seven separate 30-year

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periods, each expressed as a change relative to 1961–1990. Average annual temperature differs from the 1961–1990 average by between  $-0.29$  and  $+0.21$  °C in the seven multi-decadal variability scenarios, and mean monthly rainfall typically varies by between 5 and 10%.

## 3 Results

### 3.1 Seasonal changes in monthly flow regimes

Figure 3 shows the mean monthly flow regimes for the six catchments, with a 2 °C change in global mean temperature. In each case, seven climate models are highlighted to allow comparison with similar figures in the papers in this special issue; the other 14 climate model results are shown as thin dashed lines.

Qualitatively, the patterns of change in runoff through the year in the study catchments shown in Fig. 3 are similar to the patterns simulated in the same catchments under earlier scenarios (Arnell, 2003a; 2004); there is a strong tendency towards increased runoff in winter and reduced runoff in summer, with geographical variations between the different catchments. Quantitatively, the changes projected under the UK-CIP02 scenarios (Arnell, 2004) are, for a similar change in global mean temperature, towards the bottom end of the changes shown in Fig. 3 (relatively small increases in winter runoff and relatively large decreases in summer runoff).

### 3.2 Hydrological response to forcing

Figure 4 shows the response of mean winter runoff, mean summer runoff,  $Q_5$  (high flow) and  $Q_{95}$  (low flow) in each of the six case study catchments, for global average temperatures from 0.5 to 6 °C above the 1961–1990 mean. For each catchment, two features are immediately apparent. First, whilst there may be a consistent direction of change for each hydrological indicator, there is considerable variability around

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the magnitude of change at each temperature increase. For example, summer runoff changes by between +18% and -42% in the Harper's Brook catchment for a 2°C increase in global mean temperature. Second, for some hydrological indicators and climate models, the relationship between global forcing and hydrological response is non-linear. In some cases the rate of change of indicator declines with increase in temperature; in a few other cases the indicator increases at relatively low temperature increases before decreasing with higher temperature increases. This arises because of changes in the relative importance of changes in rainfall and potential evaporation. In the Harper's Brook catchment, for example,  $Q_{95}$  increases with temperature for one climate model (MRI232) until global mean temperature increases above 2°C before declining because the effect of increased potential evaporation outweighs the effect of increased rainfall.

In some catchments – Harper's Brook, Medway and Teme – the different climate models produce “clusters” of change in summer runoff, with some models producing a large reduction in runoff, some a moderate reduction, and some an increase. This clustering can be attributed largely to clusters in change in summer potential evaporation (as seen in Fig. 2), which are in turn largely related to clusters in change in summer temperature. This suggests that it is reasonable to expect a multi-modal response to climate change: Brekke et al. (2008) also noted multi-modal responses with the CMIP3 set in California.

Much of the difference between the catchments relates to the difference between climate scenarios across the UK, but some of the differences are due to differences in catchment physical characteristics. Most obviously, there is a clear difference in winter runoff change in the Lambourn catchment and the other two southern catchments (Harper's Brook and Medway), which have very similar changes in climate. Most scenarios project a decrease in winter runoff in the Lambourn, despite an increase in winter rainfall. This happens because runoff in the Lambourn is almost entirely generated from groundwater recharge during winter; although winter rainfall is projected to increase, the duration of the season over which recharge occurs reduces because

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of higher evaporation in autumn and spring, so total recharge is reduced. In the other catchments, winter runoff is generated from winter rainfall through quickflow processes.

### 3.3 Climate change and natural multi-decadal variability

Figure 4 also shows (as horizontal lines) the range in change in hydrological indicator due to natural multi-decadal variability in the absence of climate change. The relative effect of climate change and natural variability varies between indicators and catchments. For example, the climate change signal is much stronger than the effect of variability in the Greta catchment for winter runoff than for summer runoff; the effect on winter runoff is smaller in the Greta than in Harper's Brook. Figure 5 shows the proportion of climate model projections of change of each hydrological indicator that exceed the standard deviation of that indicator due to natural multi-decadal variability. Note that the proportions should not be interpreted as likelihoods of climate change signal exceeding natural variability, although they do give an indication of the strength of climate change signal. The clear difference between northern and southern catchments is apparent (climate change effect large in winter in the north and in summer in the south). A majority of climate models project changes greater than the standard deviation due to natural multi-decadal variability for increases in global temperature of less than 1 °C either in winter (in the north) or in summer (in the south). In Southern England, the climate change effects on summer runoff, relative to the effects of natural variability, are larger in the impermeable catchments (Harper's Brook and Medway) than the permeable catchment (Lambourn).

### 3.4 Relative magnitude of climate forcing and hydrological model uncertainty

Figure 6 shows the change in mean seasonal runoff in the Harper's Brook catchment for a 1 and 2 °C global mean warming and the HadCM3 climate model pattern, with river flows simulated with the original hydrological model parameters and the set of 100 perturbed parameters. Hydrological model parameter uncertainty has negligible effect on

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the change in mean winter and spring runoff, but relatively more effect on mean summer and, particularly, autumn runoff. This is largely because the different parameter sets produce greater differences in absolute runoff during summer and autumn than in other times of the year, and therefore the seasonal water balance (and hence sensitivity to change) is different. The range in change between different hydrological model parameterisations, however, is considerably smaller than the range in change between different climate models. The effect of hydrological model parameter uncertainty in this study is slightly smaller than found in Irish catchments by Steele-Dunn et al. (2008) and for the Thames by Wilby (2005).

Figure 7 plots change in mean summer runoff, for a 2°C change in global mean temperature, against hydrological model bias in the calibration and validation periods. There is a clear relationship between bias and projected change in summer runoff, with the smallest changes occurring with hydrological model parameterisations which lead to underestimates of annual runoff. Removing the model fits with the greatest bias leads to a reduction in the effect of hydrological model parameter uncertainty on estimated change in runoff. For example, removing all model runs with a bias in the validation period of greater than 15% leads to a reduction in the range in reduction in summer runoff from -30 to -45% to -35 to -45% (a 10 percentage-point range rather than a 15 percentage-point range).

### 3.5 Representing the effects of climate model uncertainty

Figure 4 shows that there is a considerable range in the potential impact of climate change on hydrological regimes in UK catchments amongst the 21 climate scenarios considered. This leads to two (related) questions:

- (i) How can this information be synthesised or summarised?
- (ii) Can the different climate model projections be treated differently?

Papers in the climate literature summarising the results of multiple climate model runs typically present the mean change, and use the standard deviation of change across

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model runs as an indication of uncertainty. However, this assumes that the changes are normally distributed; evidence from Fig. 4 suggests that hydrological changes are not necessarily normally distributed, and are not necessarily even uni-modal. The ensemble mean is therefore not necessarily an appropriate indication of “typical” change, and the standard deviation is not a good measure of uncertainty. Another approach is to fit an empirical distribution function to the changes and use a particular inter-quantile range (e.g. the range between the 10 and 90% quantiles) to characterise uncertainty. Whilst this accounts for non-normality, it does not address multi-modal outcomes. Perhaps a more satisfactory – but graphical – approach is to construct a histogram of potential changes.

The most simple calculation of an ensemble mean or the construction of a histogram of impacts assumes that all climate model projections are equally credible. An increasing literature has explored methods of weighting different model projections in order to produce either weighted ensemble mean estimates of impact or weighted probability distributions and histograms (e.g., Tebaldi et al., 2005; Moise and Hudson, 2008), or to cull “poorly-performing” models from the analysis. There are however, both practical and conceptual challenges to this approach. On the practical level, it is not clear how to calculate model weights. Ability to simulate past behaviour is not necessarily a good guide to a model’s ability to project future changes, and there are many potential indicators of model skill (Gleckler et al., 2008). On a conceptual level, it has been argued that, because of deep and structural uncertainty, it is not appropriate to seek to estimate the relative weight of different climate models, and to do so would lead to significant over-interpretation of model-based scenarios (Stainforth et al., 2007): all models are only partial representations of a complex world, and miss important processes. In practice, studies that have examined the effects of weighting models differently or culling “poor” models have shown that the weighting or culling has relatively little effect on the estimated range of climate change impacts (Brekke et al., 2008; Chiew et al., 2009).

No attempt has therefore been made to weight the different trajectories of change shown for the different climate models in Fig. 4, or to cull trajectories based on model

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performance (although it should be noted that one climate model was eliminated before the analysis was undertaken, on the recommendation of the CMIP3 website). The most appropriate way of representing the effect of model uncertainty is therefore to consider all model simulations separately – as shown by the different lines in Fig. 4 – and summarise model spread through histograms. Figure 8, for example, shows change in  $Q_{95}$  in each catchment with a 2 °C change in global mean temperature. The multi-modal nature of some of the distributions is clear.

## 4 Conclusions

This paper has examined the effect of climate change on river flow characteristics in a sample of UK catchments, using a large number of climate scenarios (based on 21 climate models) scaled to represent progressively increasing amounts of climate change. This approach allows an assessment of the relationship between climate forcing and hydrological response, and also facilitates comparisons between climate model scenarios in order to characterise uncertainty. There are, of course, several key caveats with the analysis. It is assumed that catchment properties do not change over time, and more specifically that hydrological model parameters derived from the recent past continue to apply as climate changes. It is assumed that the pattern-scaling approach used to construct consistent scenarios representing progressive increases in global mean temperature is appropriate; this may not be the case for the highest increases in global mean temperature considered here. Finally, the climate scenarios represent just changes in mean monthly climate, together with changes in year-to-year variability in rainfall, but do not characterise potential changes in, for example, the relative amounts of rain falling in different intensity events, or changes in the structure of year-to-year variability in weather. It is therefore likely that the results underestimate potential changes in hydrological characteristics. Despite these caveats, it is possible to draw a number of conclusions.

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There is a large spread in hydrological response to projected climate change, driven largely but not entirely by differences in projected change in rainfall with the 21 climate models. Differences in projected summer potential evaporation also affect substantially projections of change in summer runoff and indicators of low flow. Percentage changes in runoff tend to be greatest in late summer and early autumn. With an increase in global mean temperature of 2 °C (above the 1961–1990 mean), the percentage change in summer runoff typically varies between –40% and +20%, in the six study catchments.

There is some evidence of multi-modal response to climate change across the 21 climate models, with changes in summer runoff and indicators of low flows falling into clusters. This is largely driven by differences in climate model projections of summer evaporation change – itself influenced by different climate model formulations. This implies that it is inappropriate to characterise the impacts of climate change by the ensemble mean impact, or represent uncertainty by simple measures such as the standard deviation of response.

For most of the hydrological indicators considered, and most catchments, the effect of climate change begins to exceed that of multi-decadal variability once the increase in global mean temperature exceeds 1 °C.

There is evidence of non-linear hydrological response to a linear climate change forcing in some catchments, with some climate scenarios. This reflects changes in the relative importance of precipitation and potential evaporation change with increasing global mean temperature.

The difference in impact between climate scenarios is considerably larger than the effect of hydrological model parameter uncertainty on the estimated impact of climate change.

There is evidence that the different catchments respond in slightly different ways to the same climate scenario, partly depending on their geographical location and partly determined by their catchment physical characteristics (specifically volume of storage). For example, the analysis suggests that the climate change signal, relative to natural

variability, is likely to be most readily detected in winter runoff and indicators of high flows in Northern UK, and in summer runoff and indicators of low flow in Southern UK.

The study explicitly did not seek to weight the different climate models used to construct the scenarios, largely on conceptual grounds. The diversity in hydrological response to climate change illustrated by this analysis suggests that assessments of the range of potential impacts need to consider the full range of climate models available.

*Acknowledgement.* The research presented in this paper was conducted as part of the QUEST-GSI project, funded by the UK Natural Environment Research Council (NERC) under the QUEST programme (grant number NE/E001890/1). The climate scenarios were produced by Simon Gosling (Walker Institute) using the ClimGen software package, produced by Tim Osborn, University of East Anglia.

## References

- Arnell, N. W.: Relative effects of multi-decadal climatic variability and changes in the mean and variability of climate due to global warming: future streamflows in Britain, *J. Hydrol.*, 270, 195–213, 2003a.
- Arnell, N. W.: Effects of IPCC SRES emissions scenarios on river runoff: a global perspective, *Hydrol. Earth Syst. Sci.*, 7, 619–641, doi:10.5194/hess-7-619-2003, 2003b.
- Arnell, N. W.: Climate change impacts on river flows in Britain: the UKCIP02 scenarios, *J. Chart. Inst. Water. E.*, 18, 112–117, 2004.
- Arnell, N. W. and Reynard, N. S.: The effects of climate change due to global warming on river flows in Great Britain, *J. Hydrol.*, 183, 397–424, 1996.
- Bates, B. C., Kundzewicz, Z., Wu, S., and Palutikof, J. (eds): *Climate Change and Water*, Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp., 2008.
- Boe, J. and Terray, L.: Uncertainties in summer evapotranspiration changes over Europe and implications for regional climate change, *Geophys. Res. Lett.*, 35, L05702, doi:10.1029/2007GL032417, 2008.

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- Chiew, F. H. S., Teng, J., Vaze, J., and Kirono, D. G. C.: Influence of global climate model selection on runoff impact assessments, *J. Hydrol.*, 379, 172–180, 2009.
- Gleckler, P. J., Taylor, K. E., and Doutriaux, C.: Performance metrics for climate models, *J. Geophys. Res.*, 113, D06104, doi:10.1029/2007/JK008972, 2008.
- Gosling, S. N. and Arnell, N. W.: Simulating current global river runoff with a global hydrological model: model revisions, validation and sensitivity analysis, *Hydrol. Process.*, doi:10.1002/hyp.7727, 2010.
- Hulme, M. and Jenkins, G.: Climate change scenarios for the United Kingdom: scientific report, UKCIP Technical Report No. 1, Climatic Research Unit, University of East Anglia, 1998.
- IPCC: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Cambridge University Press, Cambridge, 996 pp., 2007.
- Kundzewicz, Z. W., Mata, L. J., Arnell, N. W., et al.: Freshwater resources and their management, in: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by: Parry, M. L., Canziani, O. F., Palutikof, J. P. et al., Cambridge University Press, Cambridge, 173–210, 2007.
- Meehl, G. A., Covey, C., Delworth, T. et al.: The WRCM CMIP3 multimodel dataset – a new era in climate change research, *B. Am. Meteorol. Soc.*, 88, 1383–1394, 2007.
- Mitchell, T. D.: Pattern scaling – an examination of the accuracy of the technique for describing future climates, *Clim. Change*, 60, 217–242, 2003.
- Mitchell, T. D. and Osborn, T. J.: *ClimGen: a flexible tool for generating monthly climate data sets and scenarios*, Tyndall Centre for Climate Change Research Working Paper, 2005.
- Noise, A. F. and Hudson, D. A.: Probabilistic prediction of climate change for Australia and Southern Africa using the reliability ensemble average of IPCC CMIP3 model simulations, *J. Geophys. Res.*, 113, D15113, doi:10.1029/2007JD009250, 2008.
- Moore, R. J.: The probability-distributed principle and runoff production at point and basin scales, *Hydrol. Sci. J.*, 30, 273–297, 1985.
- Moore, R. J.: The PDM rainfall-runoff model, *Hydrol. Earth Syst. Sci.*, 11, 483–499,

doi:10.5194/hess-11-483-2007, 2007.

Stainforth, D. A., Allen, M. R., Tredger, E. R., and Smith, L. A.: Confidence, uncertainty and decision-support relevance in climate prediction, *Philos. T. R. Soc. A*, 365, 2145–2161, 2007.

5 Steele-Dunne, S., Lynch, P., McGrath, R. et al.: The impacts of climate change on hydrology in Ireland, *J. Hydrol.*, 356, 28–45, 2008.

Tebaldi, C., Smith, R. L., Nychka, D., and Mearns, L. O.: Quantifying uncertainty in projections of regional climate change: A Bayesian approach to the analysis of multimodel ensembles, *J. Climate*, 18, 1524–1540, 2005.

10 Todd, M. C., Taylor, R. G., Osborn, T., Kingston, D. G., Arnell, N. W., and Gosling, S. N.: Quantifying the impact of climate change on water resources at the basin scale on five continents—a unified approach, *Hydrol. Earth Syst. Sci. Discuss.*, in press, 2010.

Wilby, R. L.: Uncertainty in water resource model parameters used for climate change impact assessment, *Hydrol. Process.*, 19, 3201–3219, 2005.

# HESSD

7, 7633–7667, 2010

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**Table 2.** Model performance.

	Calibration (1980–1983)		Validation (1983–1989)	
	Bias (%)	Nash-Sutcliffe	Bias (%)	Nash-Sutcliffe
Greta	–2.4	0.596	–3.4	0.543
Harper's Brook	–1.9	0.66	–6.8	0.581
Lambourn	–3.2	0.815	–1.5	0.752
Medway	0.1	0.712	–10.1	0.747
Teme	–12.1	0.548	–2.4	0.626
Eden	11.4	0.444	10.5	0.451

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**Table 3.** Model performance in the Harper’s Brook catchment, with 100 sets of perturbed parameters.

	Calibration (1980–1983)		Validation (1983–1989)	
	Bias (%)	Nash-Sutcliffe	Bias (%)	Nash-Sutcliffe
Original	–1.9	0.66	–6.8	0.581
Minimum	–8.6	0.62	–19.2	0.398
Maximum	6.1	0.68	4.6	0.615

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**Table 4.** CMIP3 models used to define climate projections (see Meehl et al., 2007 for full references).

IPCC I.D.	Centre and location
BCCR-BCM2.0	Bjerknes Centre for Climate Research (Norway)
CGCM3.1 (T47)	Canadian Centre for Climate Modelling and Analysis (Canada)
CGCM3.1 (T63)	Canadian Centre for Climate Modelling and Analysis (Canada)
CSIRO-Mk3.0	CSIRO Atmospheric Research (Australia)
CSIRO-Mk3.5	CSIRO Atmospheric Research (Australia)
CNRM-CM3	Météo-France, Centre National de Recherches Météorologiques (France)
GFDL-CM2.0	Geophysical Fluid Dynamics Laboratory (USA)
GFDL-CM2.1	Geophysical Fluid Dynamics Laboratory (USA)
GISS-AOM	NASA/Goddard Institute for Space Studies (USA)
GISS-EH	NASA/Goddard Institute for Space Studies (USA)
GISS-ER	NASA/Goddard Institute for Space Studies (USA)
INM-CM3.0	Institute for Numerical Mathematics (Russia)
IPSL-CM4	Institut Pierre Simon Laplace (France)
MIROC3.2 (medres)	Centre for Climate System Research, National Institute for Environmental Studies, Frontier Research Center for Global Change (Japan)
MIROC3.2 (hires)	Centre for Climate System Research, National Institute for Environmental Studies, Frontier Research Center for Global Change (Japan)
MRI-CGCM2.3.2	Meteorological Research Institute (Japan)
ECHAM5/MPI-OM	Max Planck Institute for Meteorology (Germany)
CCSM3	National Center for Atmospheric Research (USA)
PCM	National Center for Atmospheric Research (USA)
UKMO-HadCM3	Hadley Centre for Climate Prediction and Research (UK)
UKMO-HadGEM1	Hadley Centre for Climate Prediction and Research (UK)

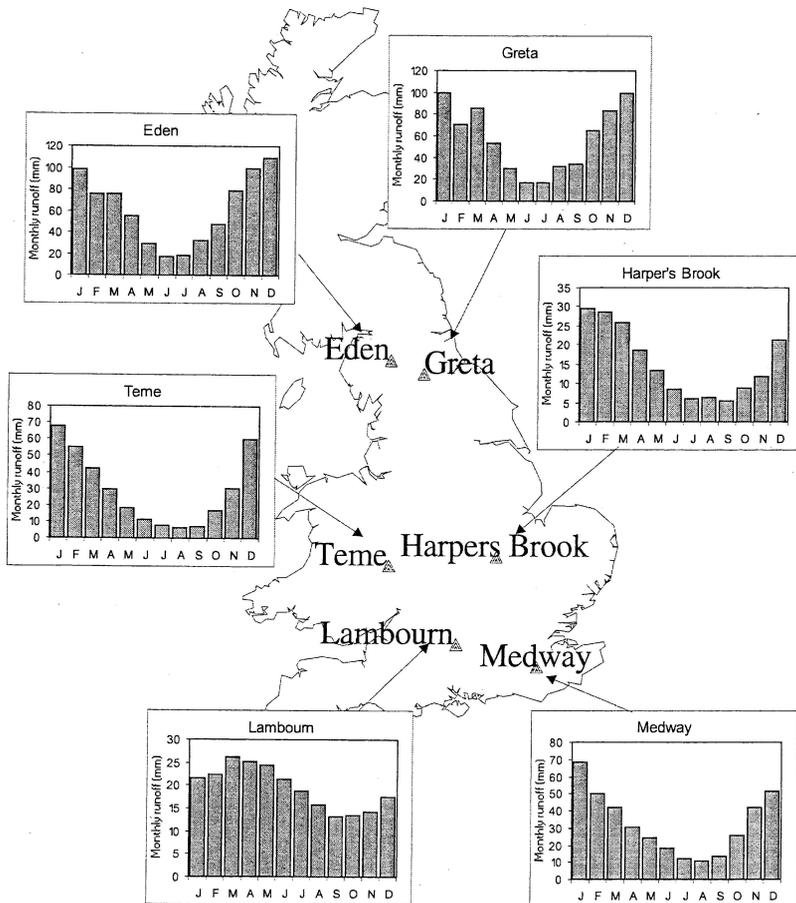


Fig. 1. Catchment locations (Arnell, 2003a).

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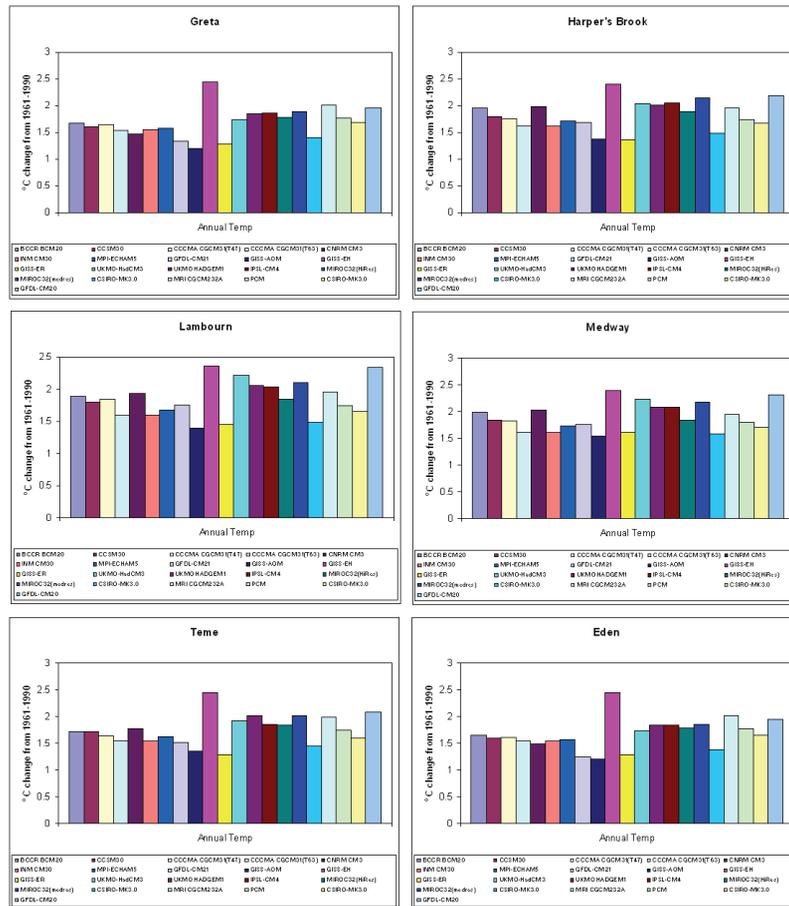
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**Fig. 2.** Climate scenarios for each catchment, for a 2°C rise in global mean temperature. **(a)** Catchment average annual temperature. **(b)** Potential evaporation and rainfall.

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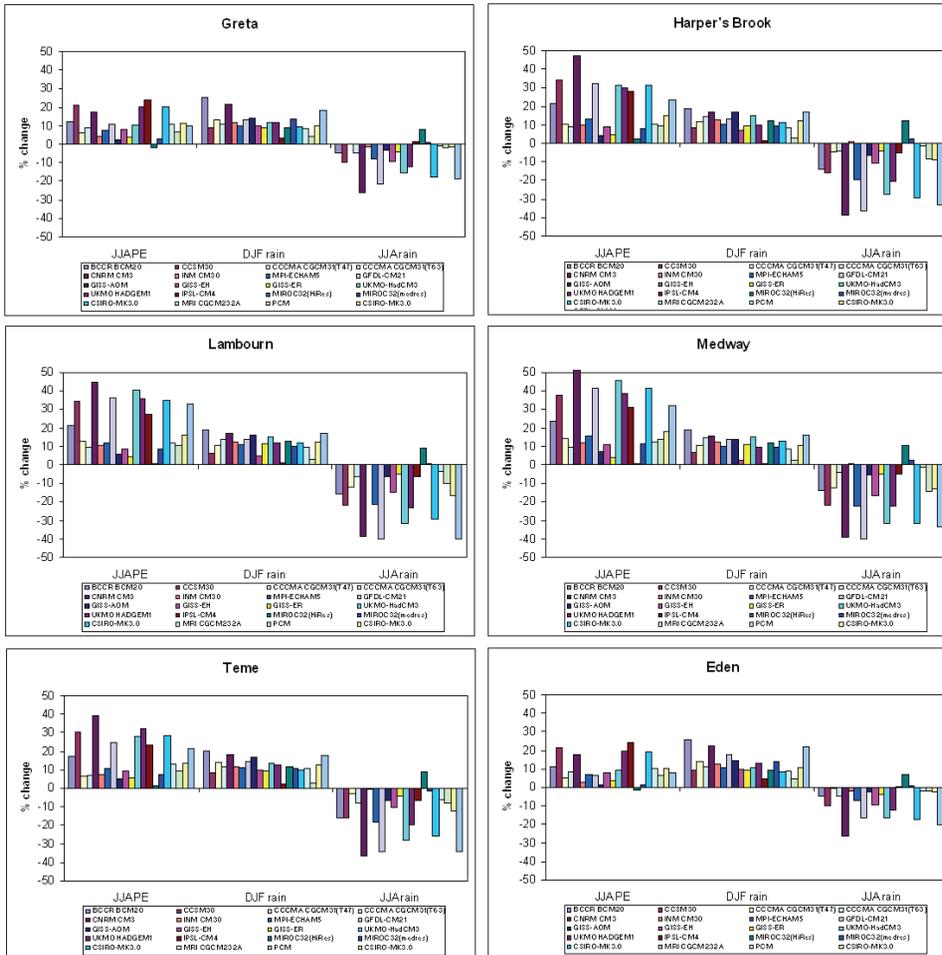
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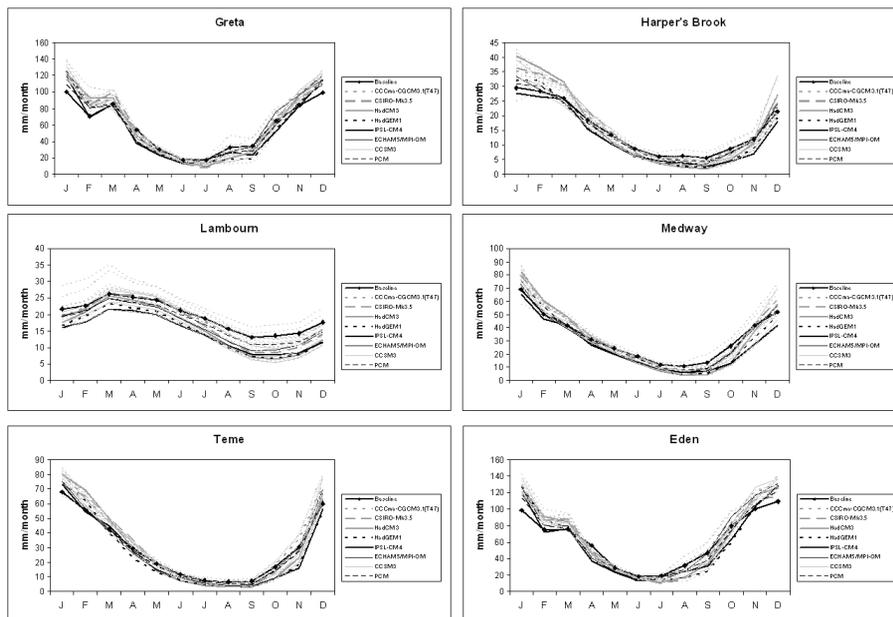


(b)

Fig. 2. Continued.

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**Fig. 3.** Mean monthly runoff for each catchment, under the baseline climate and with a 2°C rise in global mean temperature. Seven climate models are highlighted (for comparison with Todd et al., 2010), and the rest are indicated by dotted lines.

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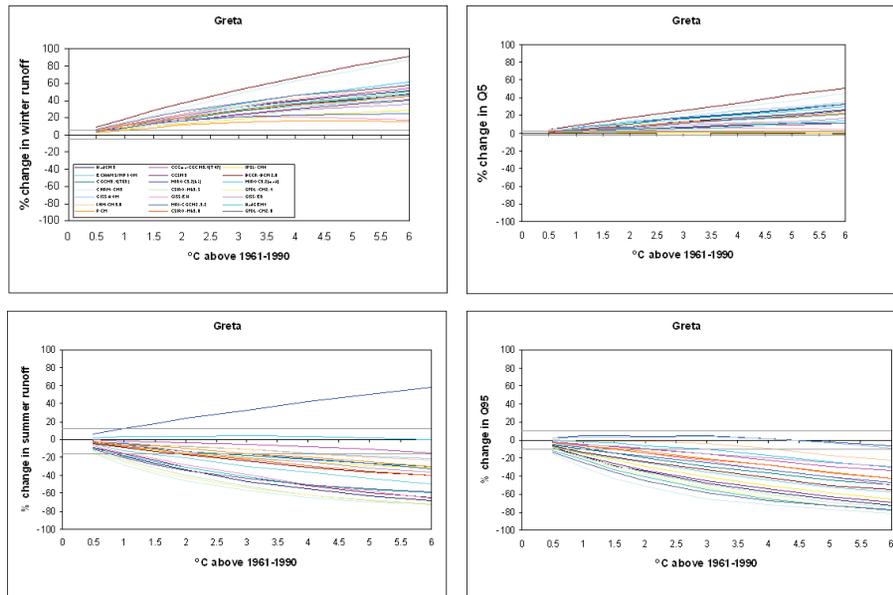


Fig. 4. Change in mean winter runoff, mean summer runoff,  $Q_{95}$  and  $Q_5$  in each catchment.

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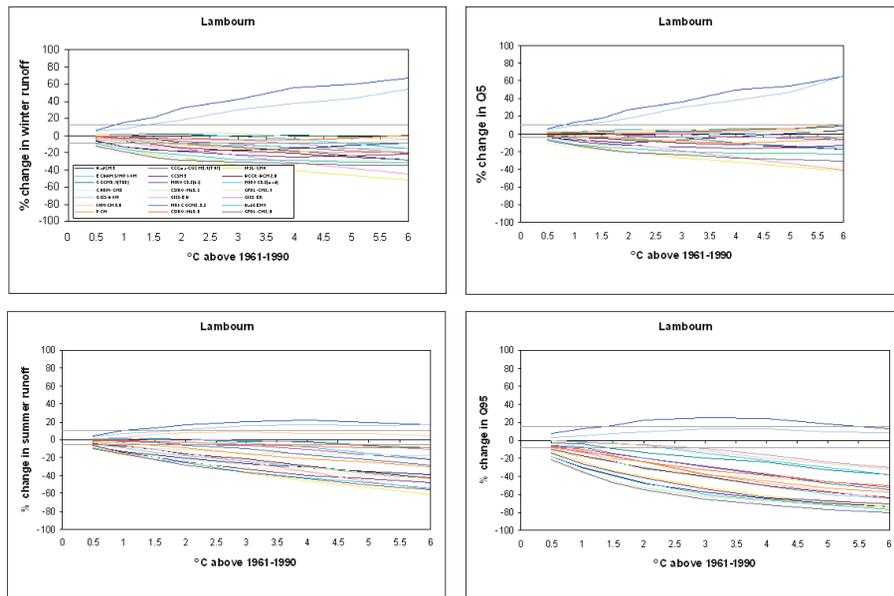


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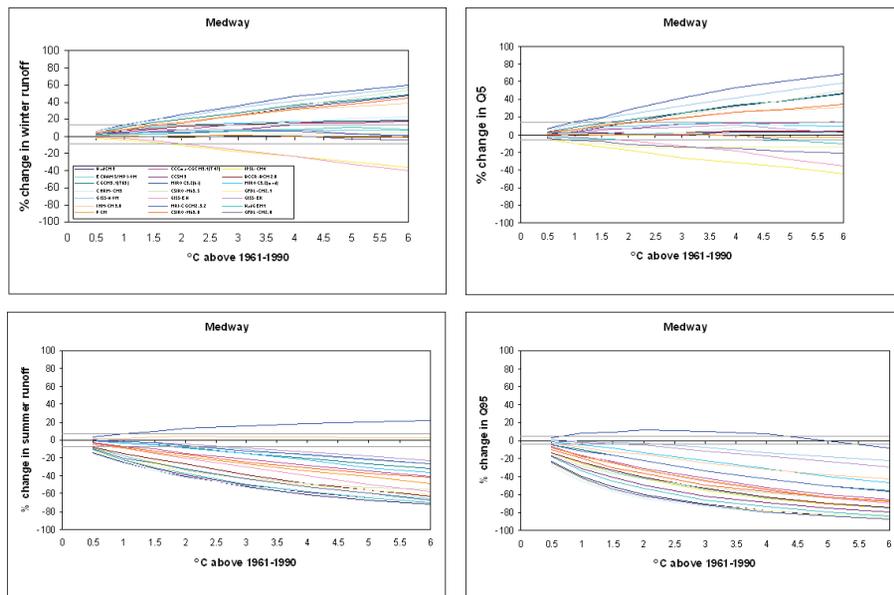


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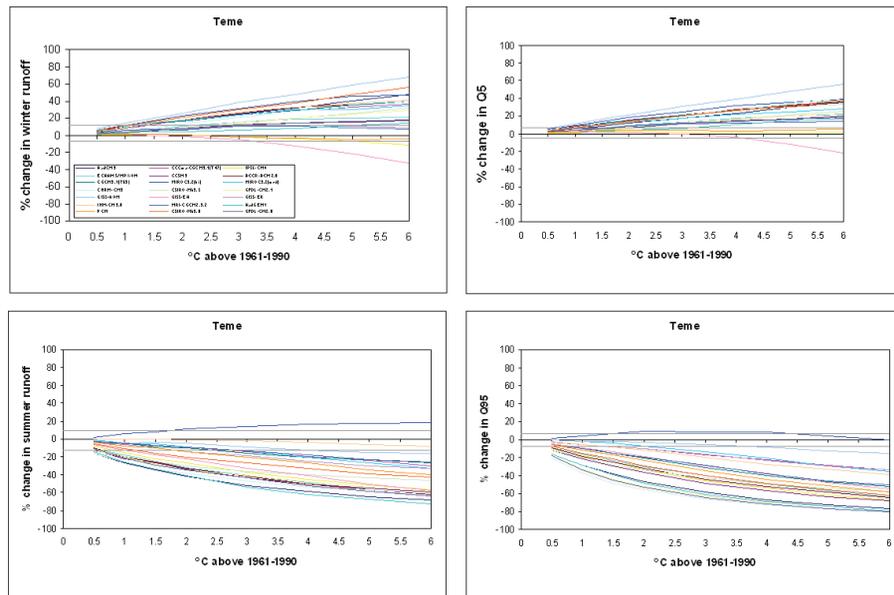


Fig. 4. Continued.

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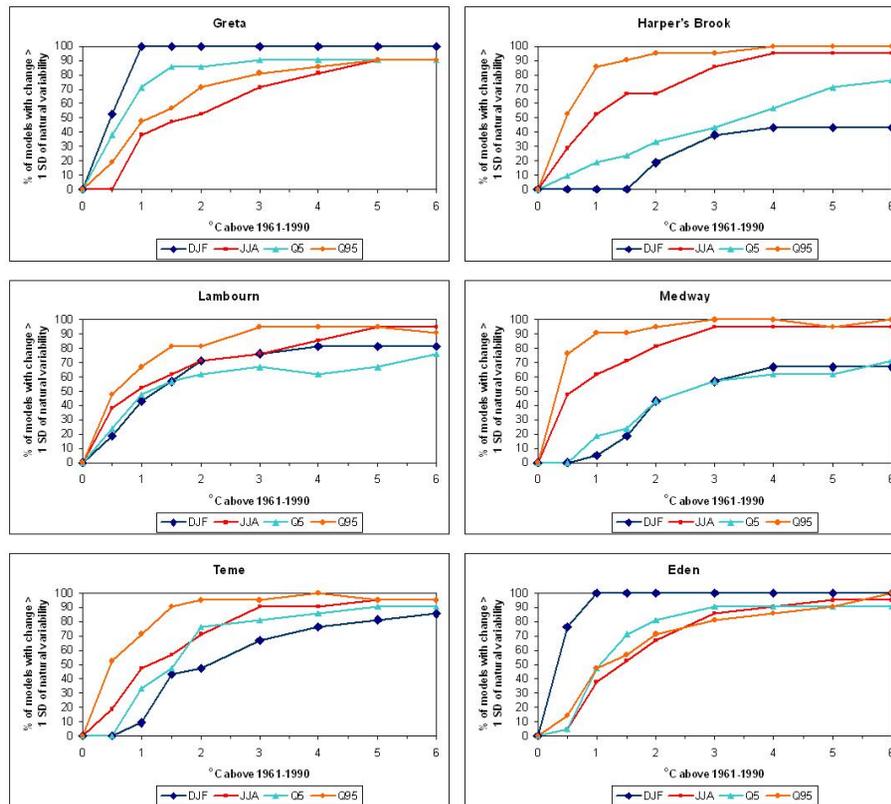
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**Fig. 5.** Proportion of climate scenarios where change in runoff exceeds the standard deviation due to climatic variability.

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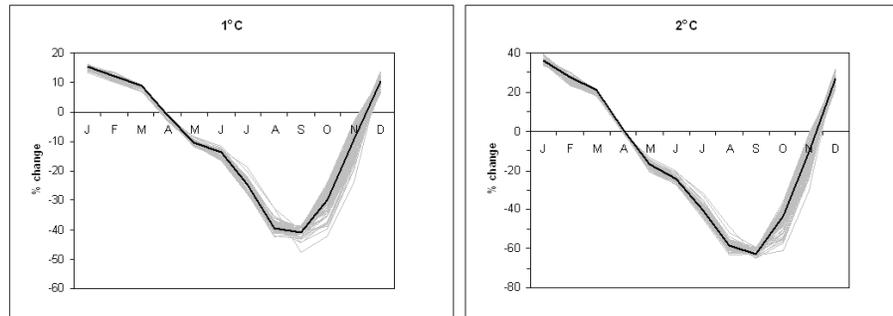
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**Fig. 6.** Change in mean monthly runoff for the Harper's Brook catchment under the HadCM3 climate scenario, for a 1°C and 2°C rise in global mean temperature, with the original hydrological model parameter set and the perturbed parameter set.

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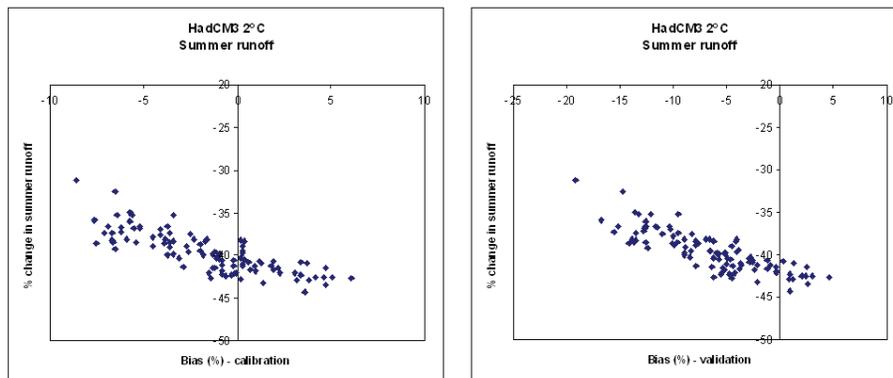
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**Fig. 7.** Effect of hydrological model bias on change in mean summer runoff in the Harper's Brook: HadCM3 climate scenario and a 2°C rise in global mean temperature.

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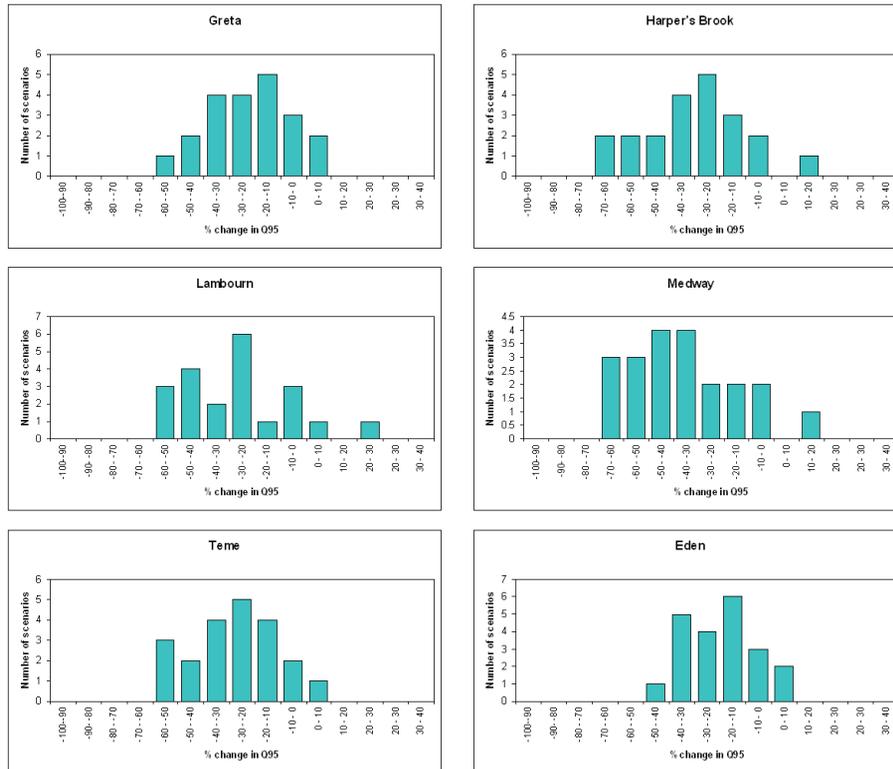
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**Fig. 8.** Histograms of change in  $Q_{95}$  with a  $2^{\circ}\text{C}$  rise in global mean temperature.

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