# Impacts of Climate Change on Surface Water in the Onkaparinga Catchment

## Final Report Volume 3: Impacts of Climate Change on Runoff

Westra, S., Thyer, M., Leonard, M. & Lambert, M.

Goyder Institute for Water Research

Technical Report Series No. 14/27

www.goyderinstitute.org

**Goyder Institute for Water Research Technical Report Series ISSN: 1839-2725**

The Goyder Institute for Water Research is a partnership between the South Australian Government through the Department of Environment, Water and Natural Resources, CSIRO, Flinders University, the University of Adelaide and the University of South Australia. The Institute will enhance the South Australian Government's capacity to develop and deliver science-based policy solutions in water management. It brings together the best scientists and researchers across Australia to provide expert and independent scientific advice to inform good government water policy and identify future threats and opportunities to water security.

The following Associate organisations contributed to this report:

Enquires should be addressed to: Goyder Institute for Water Research
Level 1, Torrens Building
220 Victoria Square, Adelaide, SA, 5000
tel: 08-8303 8952
e-mail: enquiries@goyderinstitute.org

**Citation**

Westra, S., Thyer, M., Leonard, M. & Lambert, M., 2014, *Impacts of Climate Change on Surface Water in the Onkaparinga Catchment – Volume 3: Impact of Climate Change on Runoff in the Onkaparinga Catchment,* Goyder Institute for Water Research Technical Report Series No. 14/27, Adelaide, South Australia.

**Copyright**



**Disclaimer**

## Table of Contents

## List of Figures

# Executive Summary

This is the third in a series of three final reports describing the University of Adelaide component of *Task 4: Application Test Bed*, which builds on the development and evaluation of the hydrological models (report one) and an evaluation of the downscaling approach (report two). This report provides flow projections for three sub-catchments of the Onkaparinga catchment (Scott Creek, Echunga Creek and Houlgrave Weir), based on non-homogenous hidden Markov model (NHMM) simulations of rainfall and potential evapotranspiration from 15 global climate models (GCMs) and two representative concentration pathways (RCPs) that describe possible future atmospheric greenhouse gas emission and concentration scenarios. The results are assessed using the following flow metrics: (a) mean annual flows; (b) low annual flows (lowest 10th percentile annual flows); (c) low daily flows (lowest 10th percentile daily flows); and (d) high daily flows (95th and 99th percentile daily and annual maximum flows).

The percentage change in mean annual flow for four future time horizons is presented in the figure below relative to the 1976-2005 baseline. The results are presented as a cumulative distribution function (CDF), and combines the uncertainty in the RCPs, GCMs and hydrological models, as well as the stochastic uncertainty from 100 NHMM simulations of each model combination.

The results indicate potentially significant changes in mean annual flows, with median changes of -14% (2016-2045), -24% (2036-2065), -33% (2056-2085) and -37% (2071-2100). The projections have large uncertainties, with the 90 percent uncertainty intervals ranging from -33% to +5% (2016-2045) to -70% to -8% (2071-2100). Despite this uncertainty, the probability of a decrease in mean annual flow significantly outweighs the probability of an increase: 88% of simulations show a decrease by 2016-2045, and 98% show a decrease by 2071-2100.

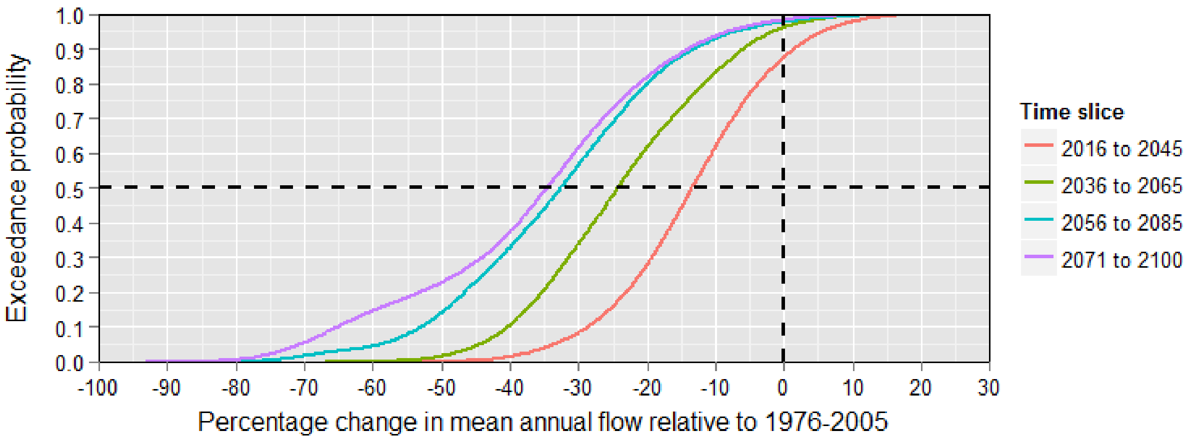



**Figure E1: Projected changes in mean annual streamflow relative to 1976-2005**

Most of the uncertainty comes from the GCMs, and, particularly in the second half of the twenty-first century, from the RCPs. In contrast, the hydrological models contributed only a small portion of overall uncertainty. The difference between RCPs becomes particularly notable in the second half of the 21st century, with projections for 2071-2100 of an average decrease of 25% for RCP 4.5 (a concentration pathway that assumes some level of technological and/or behavioural change to reduce greenhouse gas emissions), compared to a decrease of 48% for RCP 8.5 (a concentration pathway that does not account for possible efforts to constrain greenhouse gas emissions).

Using changes in mean annual flows as a benchmark, results for other flow metrics and seasons are as follows:

- Of the two highest-flow seasons (winter and spring), the larger flow decreases occur in spring. For example, mean seasonal flows decrease by an average of 44% by 2071-2100 in spring, compared to 32% in winter. Results in summer and autumn were similar to changes in spring, but the contribution of total annual flow from these seasons was small.
- Scott Creek results were generally consistent with Houlgrave Weir, whereas changes in Echunga Creek were much greater. The catchment 'elasticity' (the percentage change in annual average runoff for each percentage change in annual average rainfall) was 2.50 for Houlgrave Weir, 2.53 for Scott Creek and 2.72 for Echunga Creek, highlighting Echunga Creek's greater sensitivity to changes in rainfall.
- Low annual flows exhibited a greater decrease than the mean annual flows with an average decrease of 47% for 2071-2100 for Houlgrave Weir.
- For low daily flows the reductions were slightly lower than for mean annual flows (for example a reduction of 29% for 2071-2100, compared to 37% for mean annual flows). Much stronger declines were observed in spring (44% for 2071-2100), which was also consistent with the mean annual flow results. Interestingly, for this flow metric Houlgrave Weir and Echunga Creek exhibited similar sensitivities, whereas Scott Creek is much more sensitive to changes in rainfall.
- For the high daily flows, projections for the 95th percentile daily flow are similar to the mean annual flow projections. In contrast, the projected reductions are lower for the 99th percentile, and even lower for the annual maximum results. This can be understood with reference to the changes in the flow duration curve, which shows smaller changes for the largest flows, and the rainfall exceedance probability plot, which shows that the most intense rainfall events are expected to experience relatively small decreases relative to more moderate events. However it should be noted that GR4J is not a flood model and is not designed nor calibrated to simulate rare high flows; therefore the high daily flow results should be interpreted with caution.

These results are summarised for Houlgrave Weir in the table below for the 2016-2045 and 2071-2100 time slices. Similar results were found for the other two catchments. The main differences were that Echunga Creek experienced greater sensitivity to changes compared to Scott Creek, except for low flows where Scott Creek was the most sensitive.

To facilitate more in-depth exploration of the results, a software package has been developed in the R statistical computing language. This package is able to produce a range of plots describing results from the different RCPs, GCMs, hydrological models, NHMM simulations and flow metrics.

A practical implication arising from the research is that South Australian water resource planners need to account for the possibility of a significantly drier flow regime in the future. Water supplies are likely to be particularly vulnerable, as the low annual flows associated with droughts appear to be more sensitive to changes in rainfall compared to the other flow metrics. Flow metrics associated with environmental flow requirements and water allocations are likely to reduce at similar rate to the mean annual flows. High flow events are not likely to reduce as dramatically as annual and low flows, although further research is needed to verify this result.

**Table E1: Median changes in flow metrics for Houlgrave Weir**

| Flow Metric | Practical Impact | 2016-2045 | 2071-2100 |
|---|---|---|---|
| Mean flow<br>-Annual<br>-Spring | Water Resources | <br>-14%<br>-19% | <br>-37%<br>-44% |
| Low annual flows (10th percentile) | Droughts | -20% | -47% |
| Low daily flows (10th percentile) | Environmental Flows, Water Allocation | -13% | -29% |
| High daily flows<br>- 99th percentile<br>- Annual maximum flow | Floods | <br>-10%<br>-8% | <br>-31%<br>-27% |

# 1 Introduction

This is the third of three final reports describing the University of Adelaide component of *Task 4: Application Test Bed* for the Goyder Climate Change project. The aim of the Goyder Climate Change project is to develop a benchmark suite of downscaled climate projections and climate variable time series for South Australia. The contribution of Task 4 is to apply the downscaled data in a series of hydrology test cases to provide iterative feedback on the overall downscaling activity throughout the project lifecycle.

The Onkaparinga catchment has been identified as the case study location for this project. The catchment was selected because of the availability and quality of observational data and its importance as a water supply catchment for the Adelaide region. The University of Adelaide component of Task 4 involves applying the rainfall-runoff model 'GR4J' [*Perrin et al.*, 2003] to three sub-catchments in the Onkaparinga: Houlgrave Weir, Echunga Creek and Scott Creek. Each of these sub-catchments has long records of historical daily flows, and collectively they represent the majority of the flow volume in the Onkaparinga catchment upstream of the Happy Valley diversion. This enables the downscaled hydrometeorological forcing variables (rainfall, temperature, radiation, humidity and pressure) to be tested by comparing simulated flows obtained from historically-forced GCMs with flows obtained from instrumental records of rainfall and potential evapotranspiration (PET). The implications of future climate change on flows in the three sub-catchments can then be evaluated.

The work has been divided into the following three reports:

> **Report 1:** *Hydrological Model Development and Sources of Uncertainty*. This report focuses on assessing the relative contribution of the principal sources of hydrological model uncertainty: input errors, output errors and model structural errors. The Bayesian Total Error Analysis methodology is used as the basis of the analysis. Findings are used to improve the model structure, and develop a set of models that can be used to produce the climate projections.
>
> The outcome was the development of a set of non-stationary hydrological model structures that led to improvements in the prediction of flows during a drier confirmatory period.
>
> **Report 2:** *Hydrological* e*valuation of the CMIP3 and CMIP5 GCMs and the Non-homogenous Hidden Markov Model (NHMM)*. This report describes the comparison of historical flows in three sub-catchments of the Onkaparinga. Estimated flows are obtained by passing the NHMM projections of rainfall and other meteorological variables through a calibrated hydrological model. A total of five General Circulation Models (GCMs) from the Coupled Model Intercomparison Project Phase 3 (CMIP3) archive, 15 GCMs from the CMIP5 archive and a reanalysis model run are evaluated.
>
> The outcome was a comprehensive evaluation of the NHMM model, which indicated a consistent underestimation of high flows and annual flow volumes, and an overestimation of low flows. This motivated the use of a relative change approach for Report 3.
>
> **Report 3 (this report):** *Impact of climate change on runoff.* Using the hydrological models developed in Report 1, and the downscaling approach evaluated in Report 2, this report

outlines projections for future flows in the Onkaparinga catchment using the 15 CMIP5 GCMs, for four 30-year future time slices: 2016-2045; 2036-2065; 2056-2085 and 2071-2100. Attributes of future flows include aggregate annual and seasonal flow patterns, low flows and peak high flows.

# 2 Overview of this Report

This report provides hydrological model projections for three sub-catchments of the Onkaparinga catchment (Scott Creek, Echunga Creek and Houlgrave Weir), based on NHMM simulations of rainfall and potential evapotranspiration from 15 general circulation models (GCMs) and two representative concentration pathways (RCPs). The results use the non-homogenous hidden Markov model (NHMM) outputs provided by CSIRO that have been provided as part of *Task 3: Downscaling and climate change projections for South Australia* of the Goyder Climate Change project.

In Section 3, an overview is provided of the climate change scenarios used for this analysis, including a detailed overview of the RCPs, GCMs and hydrological models that collectively are designed to represent model uncertainty. This is followed by a discussion of the mean annual flow results in Section 4, low annual flow results in Section 5, low daily flow results in Section 6 and high daily flow results in Section 7. These results are synthesised in the context of changes to the full flow duration curve in Section 8. A software package has been developed to facilitate more in-depth exploration of results in terms of RCPs, GCMs, hydrological models, seasons and flow metrics, and this is described in Section 9. Conclusions are given in Section 10. Finally, the question of whether it is possible to use only a subset of NHMM simulations rather than using the full suite of 100 simulations for a particular impact study is discussed in Appendix 1.

# 3 Climate Change Scenarios

## 3.1 Overview of scenarios

This report describes future climate change projections for three subcatchments in the Onkaparinga catchment based on an ensemble of GCMs, RCPs and hydrological models for four time slices over the 21st century. The models and subcatchment are summarised below:

- Two RCPs: RCP4.5 and RCP8.5 (see Section 3.2);
- 15 GCMs from the CMIP5 archive (see Section 3.3);
- Four hydrological models (see Section 3.4);
- Three subcatchments: Houlgrave Weir, Scott Creek and Echunga Creek. These represent well-instrumented catchments that capture the majority of the flow upstream of Clarendon Weir (the offtake for the Happy Valley reservoir).
- 100 realisations from the NHMM algorithm as provided in Task3; and

This combination of GCMs, RCPs, hydrological models, subcatchments and NHMM replicates leads to 36,000 daily time series to be analysed. These simulations collectively seek to capture the dominant sources of uncertainty associated with future climate change projections: greenhouse gas emissions uncertainty, climate model uncertainty, stochastic downscaling uncertainty and hydrological model uncertainty. Notwithstanding the simplifications of the hydrological processes embedded in the selected GR4J models and its calibration as discussed in Report 1 and the biases that have been identified in the NHMM downscaling as discussed in Report 2.

The projections are assessed over four 30-year future time horizons: 2016-2045; 2036-2065; 2056-2085 and 2071-2100, with all the results presented relative to a 1976-2005 historical climate baseline. Furthermore, flows are described using a range of flow metrics at daily, seasonal[1] and annual timescales, as summarised in Table 1. Further details on the GCMs, RCPs and hydrological models are provided in the sections below.

**Table 1: Flow metrics used in this report.**

| **Metric** | **Practical Applications** |
|---|---|
| Mean annual flow | A range of applications including water balance calculations and water security assessments |
| Low annual flow<br>(10th percentile annual flow) | Drought risk assessments |
| Low daily flow<br>(10th percentile daily flow) | Water allocation and environmental flows |
| High daily flow (95th, 99th percentile daily flows and annual maximum flows) | Flood risk assessment, and various environmental flow applications |

[1] Seasons are defined as Dec-Jan-Feb (DJF), Mar-Apr-May (MAM), Jun-Jul-Aug (JJA) and Sep-Oct-Nov (SON).

## 3.2 Representative greenhouse gas concentration pathways

RCP's represent possible future atmospheric greenhouse gas emission and concentration scenarios, described in terms of the total radiative forcing expected in 2100 and the expected trajectory of greenhouse gas emissions over the 21$^{st}$ century needed to get to that radiative forcing. Two RCPs were provided by CSIRO for investigation: RCPs 4.5 and 8.5, which represent increases in radiative forcing in 2100 relative to preindustrial levels of 4.5 and 8.5 W/m$^2$, respectively.

To put these concentrations into perspective, Figure 1 presents emissions trajectories until 2100 for a variety of emissions pathways. This figure includes "baseline scenarios" (defined as scenarios without explicit additional efforts to constrain emissions) ranging from RCP6.0 to RCP8.5, together with "mitigation pathways" that account for various technological and behavioural changes, and which include forcing levels from RCP2.6 to RCP6.0 [*IPCC*, 2014]. Note also that the $CO_2$eq concentration in 2011 has been estimated to be 430 ppm. Thus, RCP 4.5 represents a mid-range "mitigation pathway" scenario, whereas RCP8.5 represents the upper limit of the "baseline" scenarios.

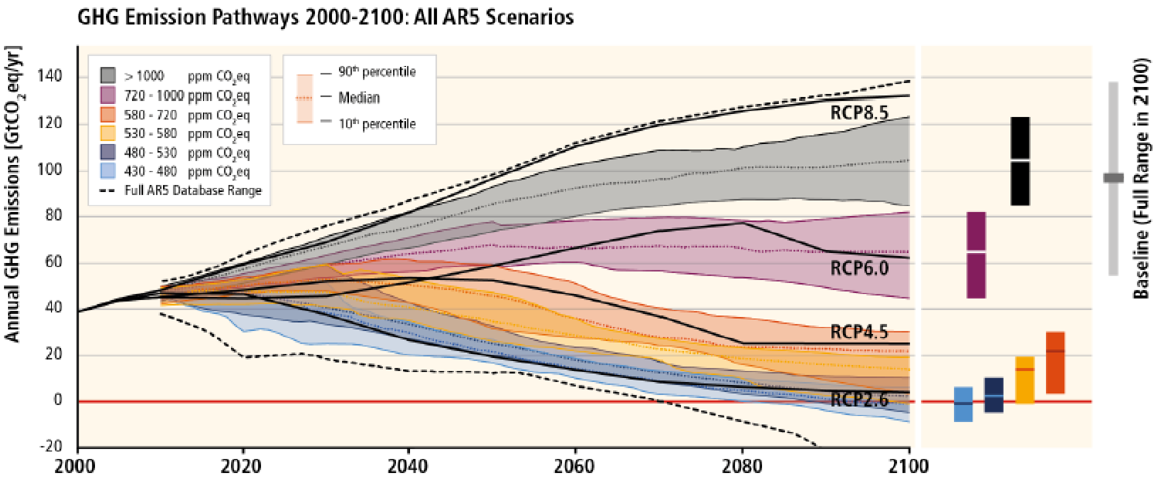



**Figure 1: Pathways of global greenhouse gas emissions ($GtCO_2eq/yr$) in 'baseline' and 'mitigation' scenarios for different long-term concentration levels [*IPCC*, 2014].**

## 3.3 Climate models

GCMs are mathematical models of planetary circulation of the atmosphere and oceans. They are used to assess large-scale changes in energy and water cycles as a result of changes in greenhouse gas emissions and concentrations. For this project, GCM projections were provided from the World Climate Research Program Coupled Model Intercomparison Project Phase 5 (CMIP5) archive, and the 15 models described in Table 2 have been analysed. The model projections are downscaled to catchment-scale estimates of daily rainfall and potential evapotranspiration using the NHMM algorithm and Morton's equation for areal potential evapotranspiration, with further details provided in the first [*Westra et al.*, 2014a] and second [*Westra et al.*, 2014b] volume of this report series.

A detailed review of the performance of the combined GCM and NHMM simulations provided in the second volume of this report series [*Westra et al.*, 2014b] showed that, based on their capacity to simulate the historical climate, it was not possible to identify a subset of GCMs that were able to yield consistently better simulations than the remaining GCMs. Therefore, the full ensemble of 15 CMIP5 models are used in this report, as it is likely to lead to a better assessment of overall projection uncertainty compared to the situation where only a small subset of models is used. This approach is consistent with other studies that have explored the role of GCM choice on overall streamflow predictive uncertainty [*Chiew et al.*, 2009].

**Table 2: CMIP5 GCMs models included in ensemble**

| Climate model ID | Climate modelling group | Country |
|---|---|---|
| ACCESS1-0 | Commonwealth Scientific and Industrial Research Organisation and Bureau of Meteorology | Australia |
| ACCESS1-3 | Commonwealth Scientific and Industrial Research Organisation and Bureau of Meteorology | Australia |
| BCC-CSM1-1-M | Beijing Climate Centre, China Meteorological Administration | China |
| CanESM2 | Canadian Centre for Climate Modelling and Analysis | Canada |
| CNRM-CM5 | Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique | France |
| CSIRO-Mk-3.6 | Commonwealth Scientific and Industrial Research Organisation, Queensland Climate Change Centre of Excellence | Australia |
| GFDL-ESM2G | NOAA Geophysical Fluid Dynamics Laboratory | USA |
| GFDL-ESM2M | NOAA Geophysical Fluid Dynamics Laboratory | USA |
| INM-CM4 | Institute for Numerical Mathematics | Russia |
| IPSL-CM5A-LR | Institut Pierre-Simon Laplace | France |
| IPSL-CM5B-LR | Institut Pierre-Simon Laplace | France |
| MIROC.ESM | Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies | Japan |
| MIROC5 | Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology | Japan |
| MRI-CGCM3 | Meteorological Research Institute | Japan |
| NorES1-M | Norwegian Climate Centre | Norway |

## 3.4 Hydrological models

The first volume of this report series [*Westra et al.*, 2014a] investigated a set of 22 stationary and non-stationary versions of GR4J. Model performance was tested over an independent confirmatory period from 2000 to 2009 that was significantly drier than the period used for parameter estimation. An ensemble of four models was selected from this set as the basis for developing future-climate projections. This selection was based on each model's performance in the historical setting together with the need to select a range of model structures. These models are summarised in Table 3.

**Table 3: Hydrological models included in ensemble**

| Model | Description |
|---|---|
| $g_{1.1}$ | Standard GR4J model, and is used as a benchmark against which other models can be evaluated. |
| $g_{1.8}^*$ | Accounts for non-stationarity due to seasonal variability, the effect of the previous 365-day rainfall and PET, as well as a linear trend in the capacity of the production store. Rather than extrapolate the linear trend into the future, the trend has been fixed to its value at the end of the calibration period (31/12/1999); see volume 1 of this report for details [*Westra et al.*, 2014a]. |
| $g_{2.2}$ | Incorporates an additional parameter to control the portion of rainfall that enters the production store. |
| $g_{3.11}^*$ | Combines the additional parameters used in model $g_{1.8}^*$ with the parameter that controls the portion of rainfall entering the production store as adopted in model $g_{2.2}$. |

# 4 Changes in the Mean Annual Flow

## 4.1 What is the change in mean annual flow for different time slices?

Changes in the mean annual flow rate at Houlgrave Weir are presented relative to the historical climate for all four time slices (Figure 2). These projections encompass variability due to the 15 GCMs, 2 RCPs, 4 hydrological models and 100 NHMM simulations, and are as follows:

- Median percentage change for the four time slices are: -14% (2016-2045), -24% (2036-2065), -33% (2056-2085) and -37% (2071-2100);
- Uncertainties are large, and increase substantially in the second half of the 21st century. The 90 percent probability intervals range from -33% to +5% change (2016-2045), to -70% to -8% (2071-2100).
- The probability of a decrease in mean annual flow significantly outweighs the probability of an increase. The projected probability of decrease is 88% by 2016-2045 and 98% by 2071-2100.

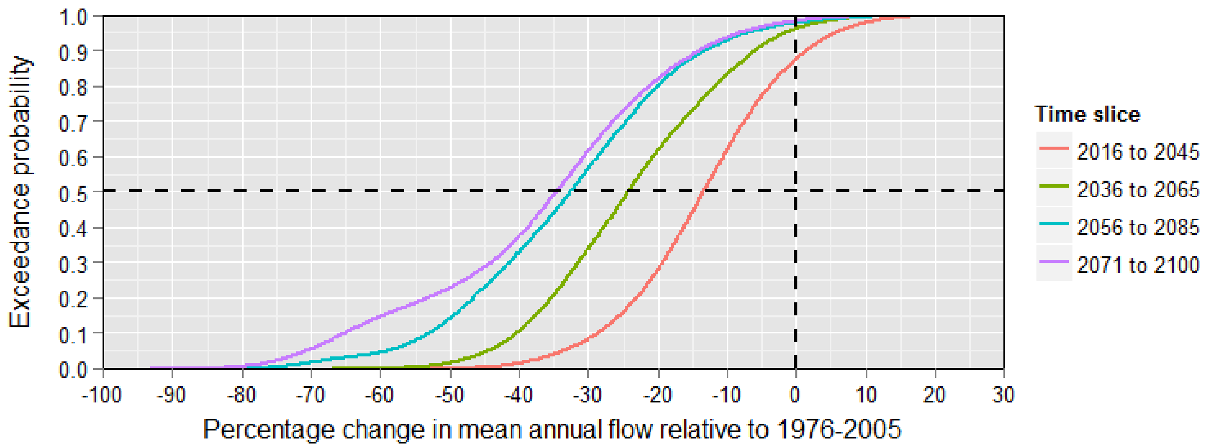



**Figure 2: Cumulative distribution function of the projected change in mean annual flow relative to the 1976 to 2005 baseline, for four future time slices. The plot combines results from all 15 GCMs, 2 RCPs, 4 hydrological models and 100 NHMM simulations.**

## 4.2 What is the range of change in mean annual flow for different RCPs?

Changes in the mean annual flow rate at Houlgrave Weir are presented relative to the historical climate for each RCP and for all four time slices (Figure 3). Projections for RCP 8.5 are always associated with a stronger declines compared to RCP 4.5, although the projections are reasonably similar in the first half of the 21st century. For example the projections for 2016-2045 are for an average of an 11% decrease for RCP 4.5 compared to a 16% decrease for RCP 8.5, whereas for 2071-2100 the projections are for an average of a 25% decrease for RCP 4.5, compared to a 48% decrease for RCP 8.5.

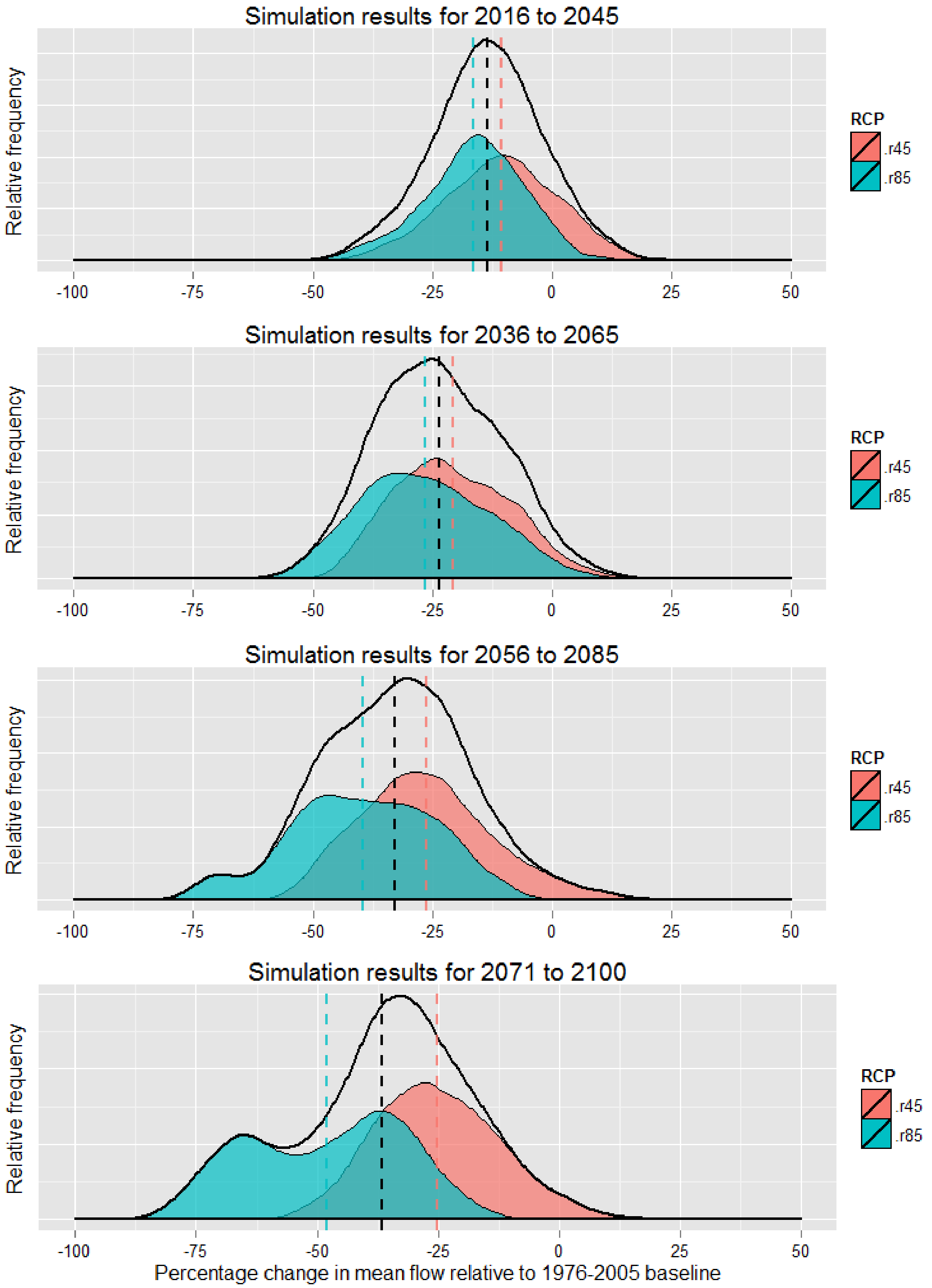



**Figure 3: Percentage change in mean annual flow at Houlgrave Weir for all GCMs and hydrological models, for four time slices. Shaded distributions represent results for different RCPs, while the solid black lines represents the combined projections for both RCPs. Vertical dashed lines represent the mean percentage change.**

## 4.3 What are the dominant contributors to total uncertainty?

The contribution of the different modelling components and assumptions to the overall projection uncertainty are compared for 2071-2100 (Figure 4). The solid black line represents the overall probability distribution after combining uncertainty from the RCPs, GCMs and hydrological models, whereas the shaded distributions represent the GCMs (Figure 4, upper panel) and the hydrological models (Figure 4, lower panel).

As can be seen, the GCMs contribute a significant portion towards the overall predictive uncertainty, whereas the hydrological models each give similar predictions. Whereas significant differences were observed between the stationary and non-stationary hydrological models as described in the first volume of this report series [*Westra et al.*, 2014a], this did not lead to substantial changes in aggregate predictions (when expressed as a percentage change relative to the historical climatological baseline).

The finding that the hydrological models contributed only a small portion of the overall uncertainty was surprising given that the non-stationary hydrological model provides far better predictions of flows in a drier a confirmatory period than the baseline stationary hydrological model. It suggests that improvements to the hydrological model do not have a significant impact on the climate change projections, at least when compared to the significant uncertainty associated with the GCMs and RCPs. It is unclear whether the relatively small contribution of hydrological modelling uncertainty relative to total uncertainty is (1) due to the "relative change" climate change impact assessment approach adopted here (see volume 2 of this report series [*Westra et al.*, 2014b] for further details), (2) a function of the rainfall-runoff response of this catchment, or (3) a function of the class of hydrological models adopted (lumped, conceptual). As part of future research, an improved understanding of the role of the hydrological model in climate change projections is recommended to verify these results, for example using physically-based hydrological modelling approaches in conjunction with conceptual lumped models to more fully explore uncertainty associated with the rainfall-runoff transformation.

The GCM-based results are also presented for the same time slice in Figure 5 as a box and whisker plot, to better show the relative contribution of the GCMs to total uncertainty. The within-GCM stochastic uncertainty (due to multiple NHMM simulations) was generally small compared to the between-GCM uncertainty, highlighting the potential for underrepresenting total uncertainty if only a smaller subset of GCMs were used. Furthermore, significant differences between RCP 4.5 and RCP 8.5 are evident, with much lower estimates of average streamflow for the higher RCP; this is consistent with the conclusions in Section 4.2. With the exception of the CSIRO Mk3.6 model, which showed on average no change in streamflow for RCP 4.5, all the GCMs predicted declining streamflow by 2071 to 2100, with declines of as much as ~80% for RCP 8.5.

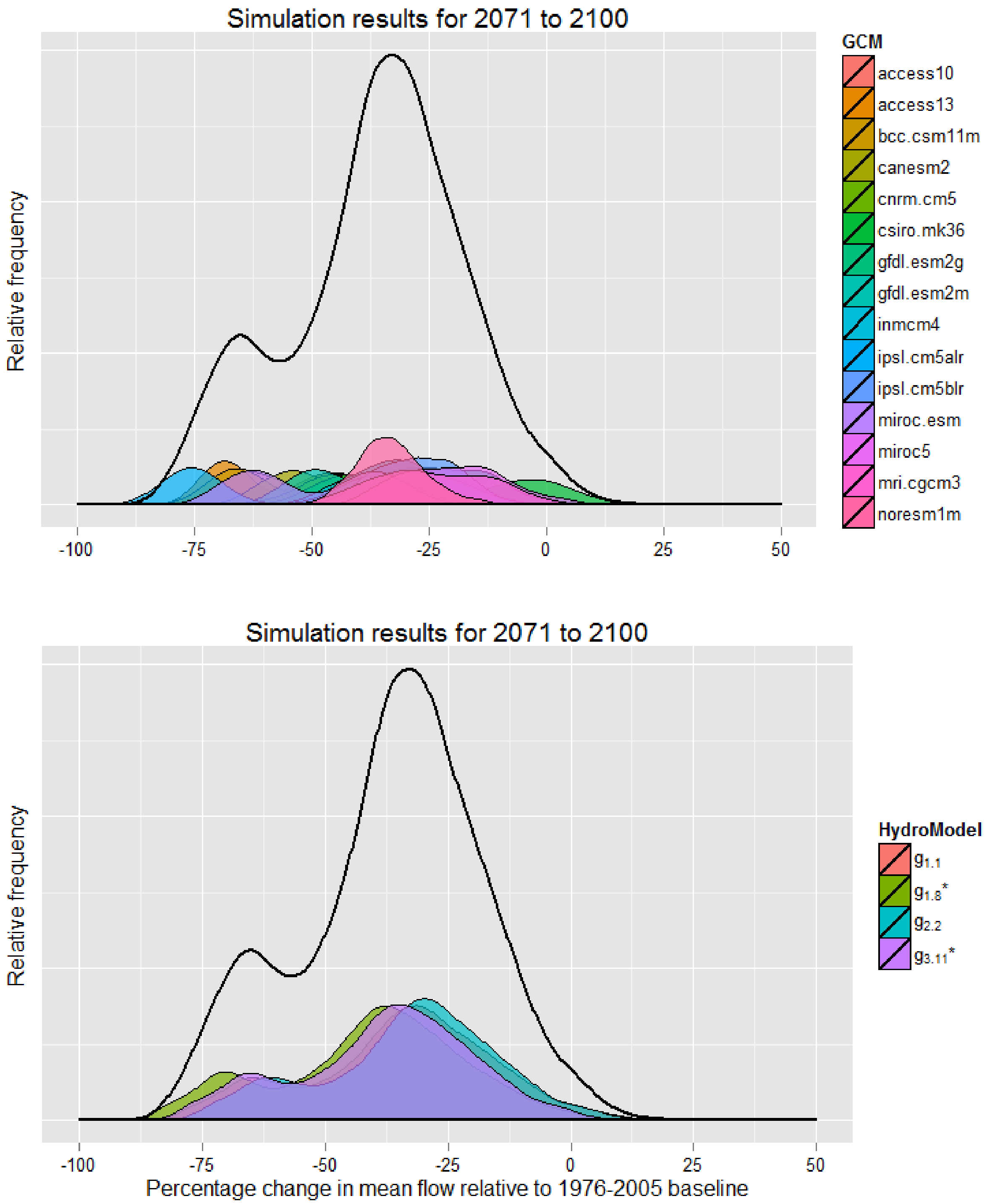



**Figure 4: Percentage change in mean flow at Houlgrave Weir for both RCPs, describing role of GCM uncertainty (upper panel) and hydrological model uncertainty (lower panel).**

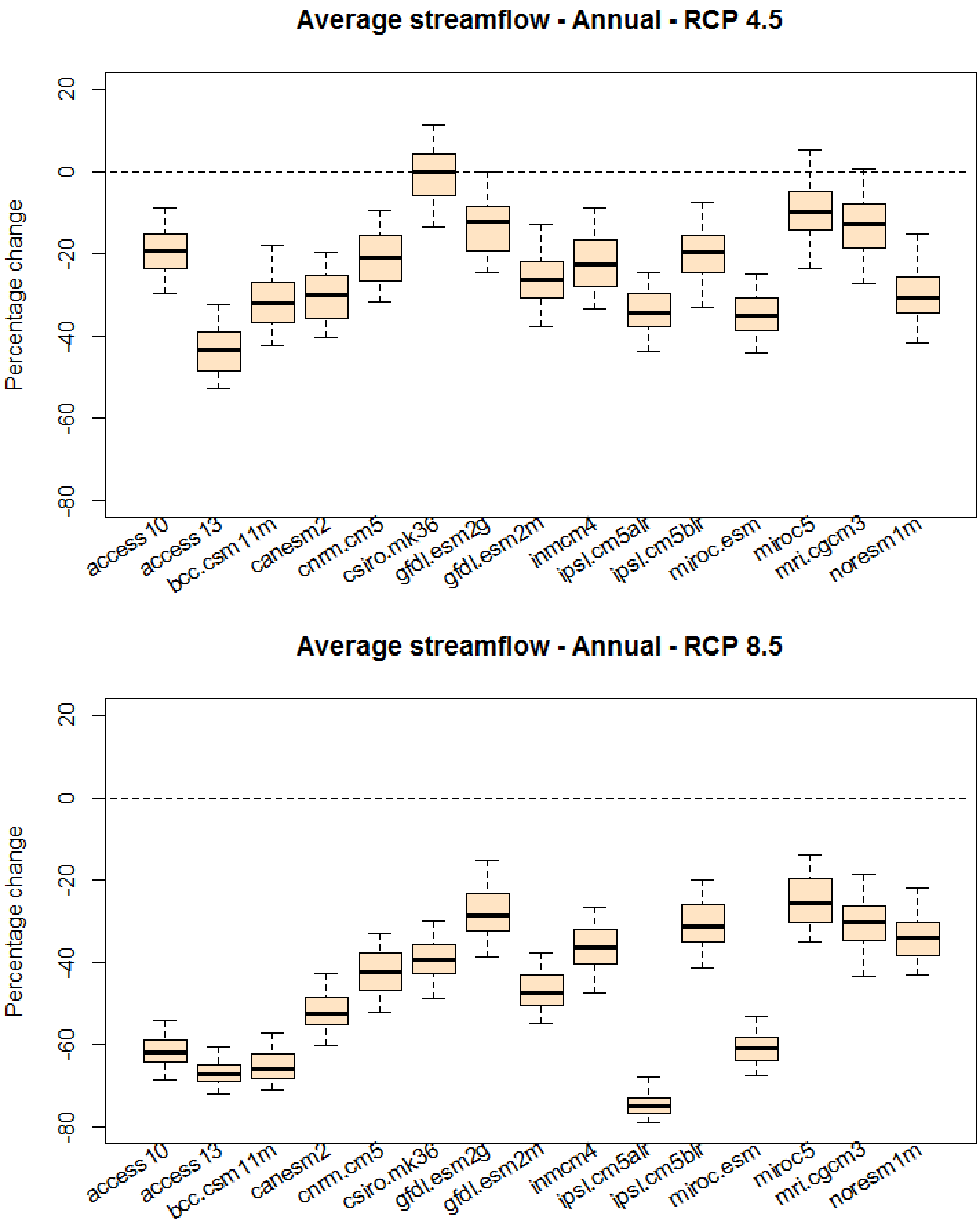



**Figure 5: Changes in annual average streamflow at Houlgrave Weir for the 2071-2100 time slice, for RCP 4.5 (upper panel) and RCP 8.5 (lower panel) for all GCMs.**

## 4.4 Do predictions differ significantly by season?

Results are presented separately for the two highest flow seasons: winter and spring, and for two time slices: 2016-2045 (Figure 6) and 2071-2100 (Figure 7). The largest decreases in the mean flow occur in spring, with an average decrease of 20% for 2016-2045, and 44% for 2071-2100. Results in summer and autumn were more reflective of changes in spring compared to winter (not shown), but the contribution of total annual flow from these seasons is very small (see volume one of this report series [*Westra et al.*, 2014a]).

Rainfall predictions are presented separately for each GCM in winter and spring in Figure 8. The results typically show that the percentage change in rainfall is much greater for spring (average decrease of 28%) compared to winter (average decrease of 11%), although the variability between models was also high. Finally, predictions are shown (Figure 9) for each season and for four representative GCMs (access10, csiro.mk36, gfdl.esm2g and miroc.esm) that spanned the range of projections given in Figure 8. For three of the GCMs, the strongest declines were observed in spring, with the remaining GCM showing the greatest decline in summer.

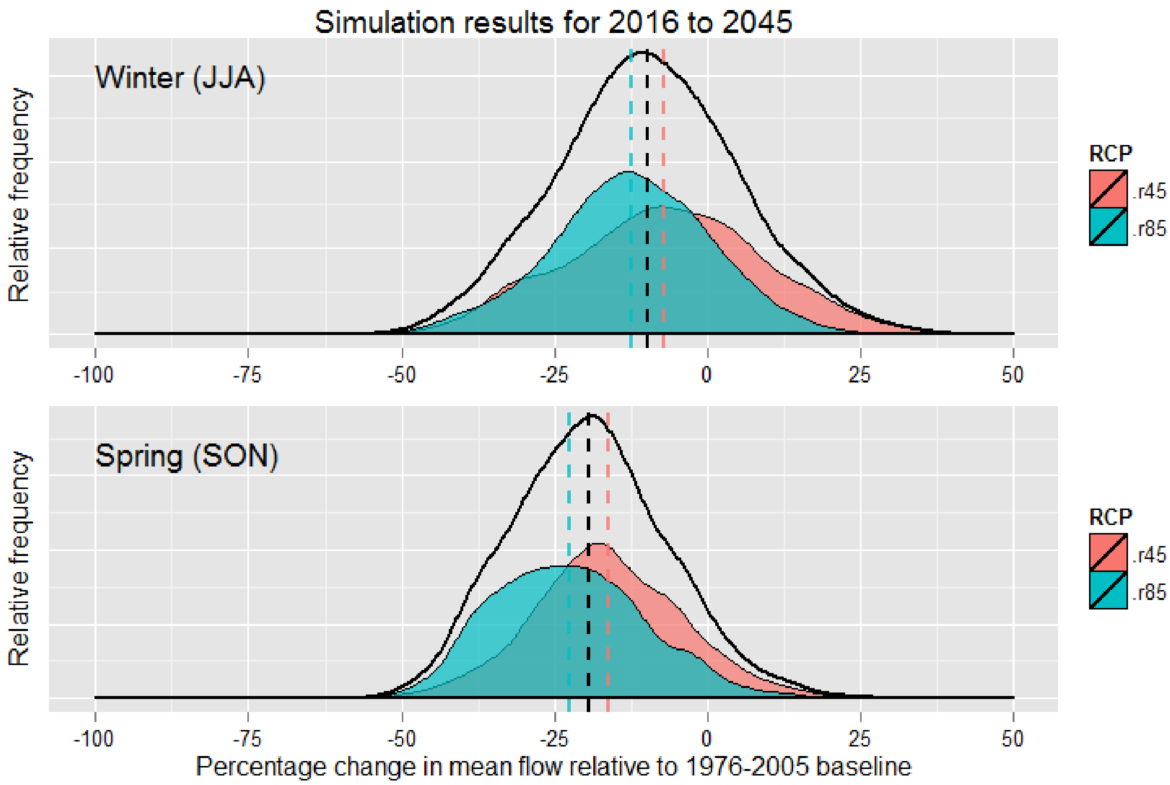



**Figure 6: Percentage change in mean winter and spring flow at Houlgrave Weir for 2016 to 2045 for all GCMs and hydrological models, presented for two RCPs.**

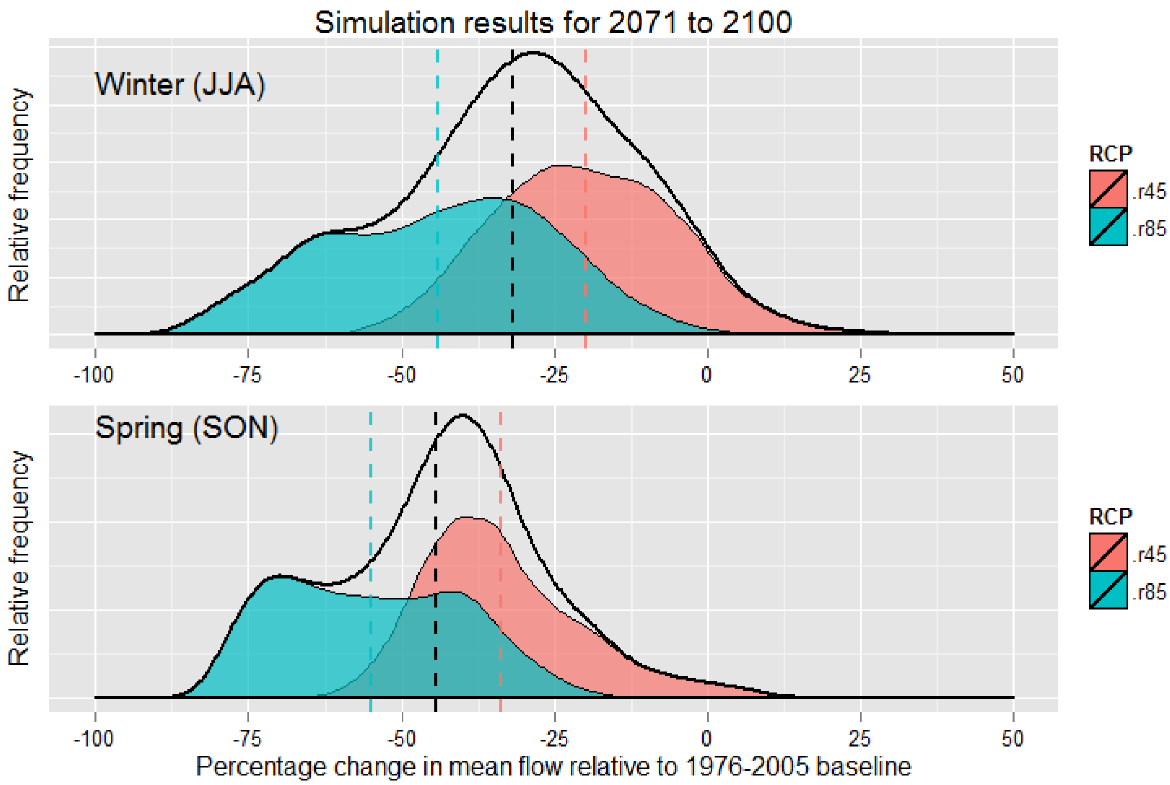



**Figure 7: Percentage change in mean winter and spring flow at Houlgrave Weir for 2071 to 2100 for all GCMs and hydrological models, presented for two RCPs.**

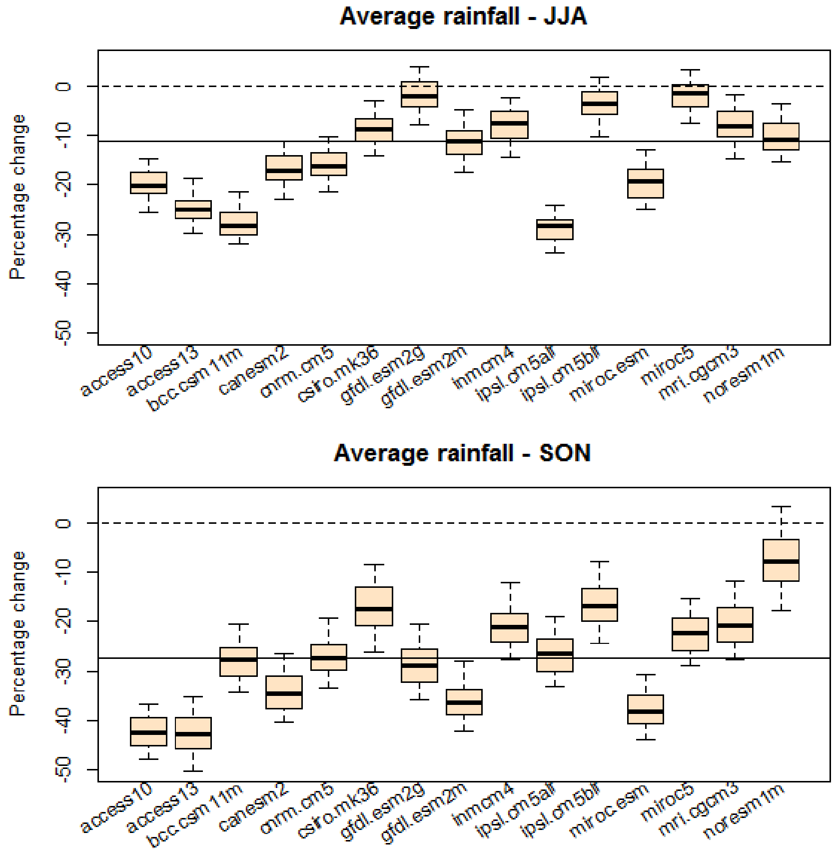



**Figure 8: Changes in seasonal rainfall for the period 2071-2100 relative to the 1976-2005 baseline, for winter (upper panel) and spring (lower panel).**

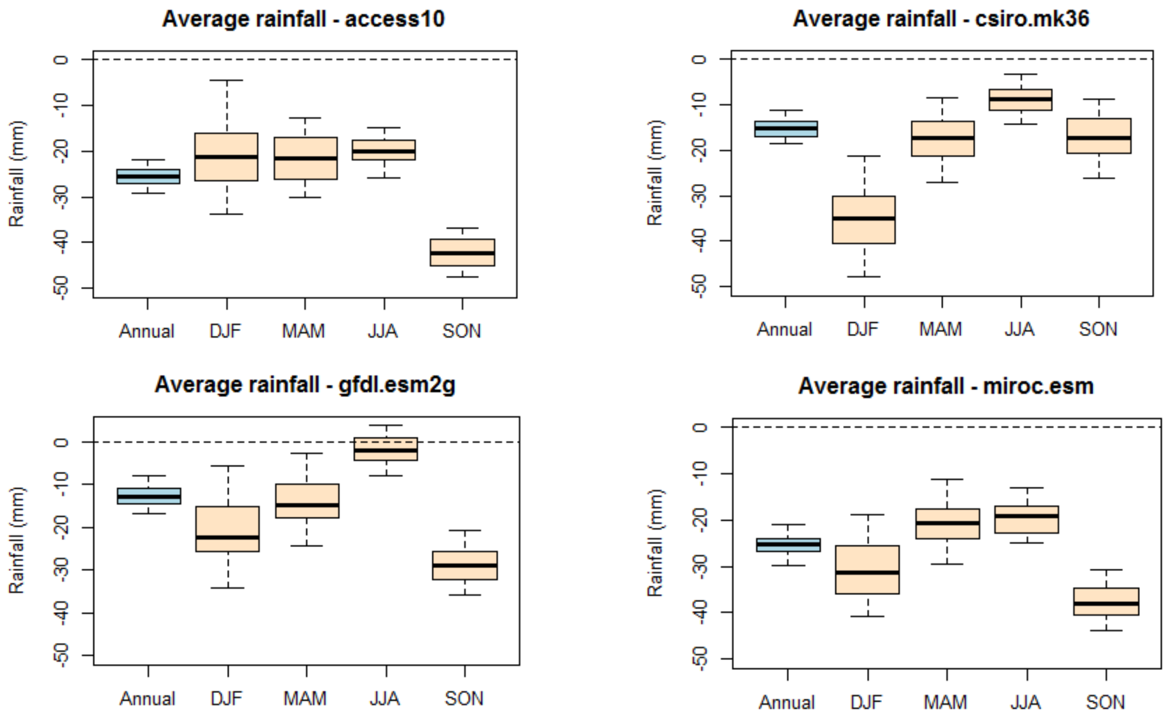



**Figure 9: Changes in annual and seasonal rainfall for the period 2071-2100 relative to the 1976-2005 baseline, for four representative GCMs.**

## 4.5 How do the results differ by catchment?

The results for Scott Creek and Echunga Creek are presented for 2016-2045 (Figure 10), and 2071-2100 (Figure 11). They can be contrasted to the results for Houlgrave Weir in Figure 3. When averaged across RCPs, GCMs and hydrological models, projections for 2016-2045 are for a 13% decline in annual rainfall on average for both Houlgrave Weir and Scott Creek, and 18% decline for Echunga Creek. For 2071-2100, the mean annual flows typically decline by about 35% (Houlgrave Weir), 35% (Scott Creek) and 43% (Echunga Creek). Therefore, the projected declines at Echunga Creek are slightly higher than for the other two sub-catchments.

To better understand the reasons for this, 'elasticity' plots – describing the percentage change in annual average runoff against percentage change in annual average rainfall [e.g. see *Chiew*, 2006] – are presented in Figure 12 for all three sub-catchments. The elasticities are calculated for RCP8.5 using model $g_{1.1}$, based on all GCMs and future time slices. The elasticity values for Houlgrave Weir and Scott Creek are similar (2.50 and 2.53, respectively), whereas the value for Echunga Creek is slightly higher (2.72). The results are generally consistent across GCMs and time slices. The greater sensitivity of Echunga Creek is reflected in a smaller runoff coefficient for this catchment (0.10, compared to 0.14 for Scott Creek and 0.17 for Houlgrave Weir), with lower runoff coefficients generally associated with higher elasticity values across Australia [*Chiew*, 2006].

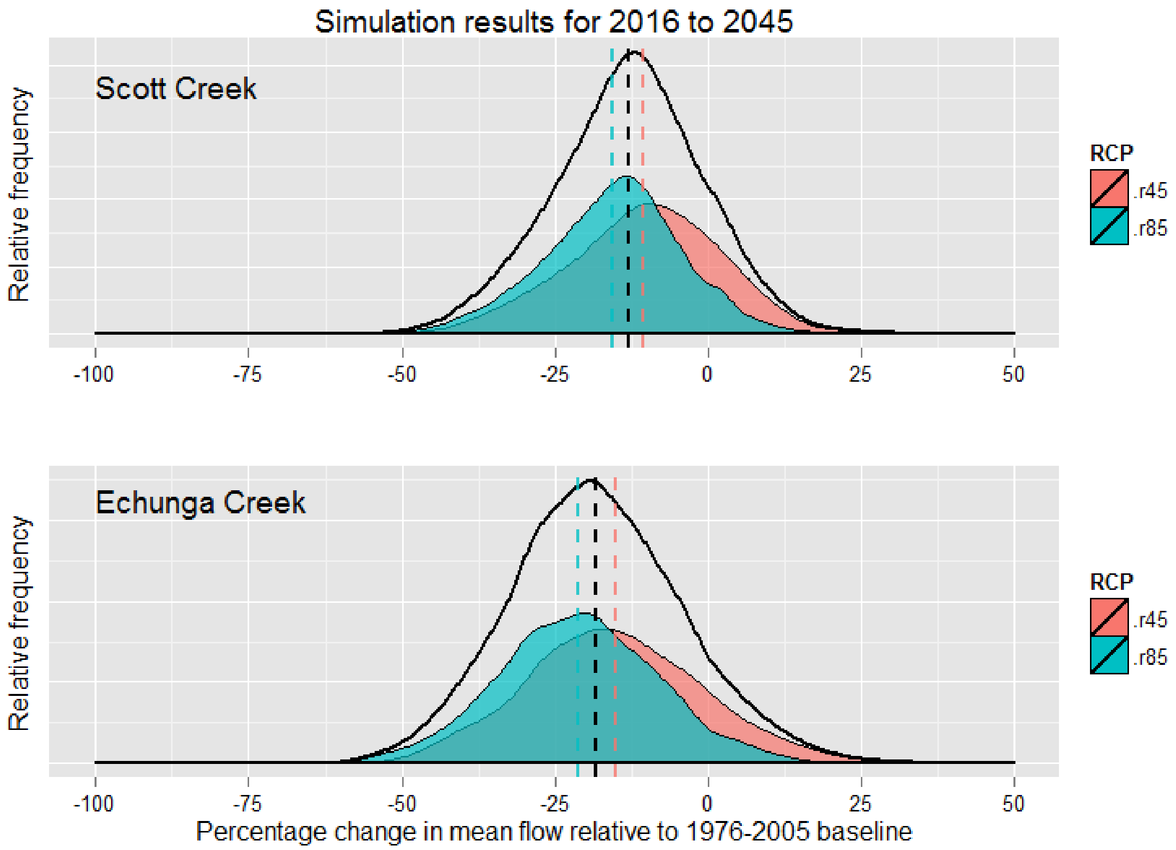



**Figure 10: Percentage change in mean annual flow at Scott Creek and Echunga Creek for all GCMs and hydrological models for 2016 to 2045.**

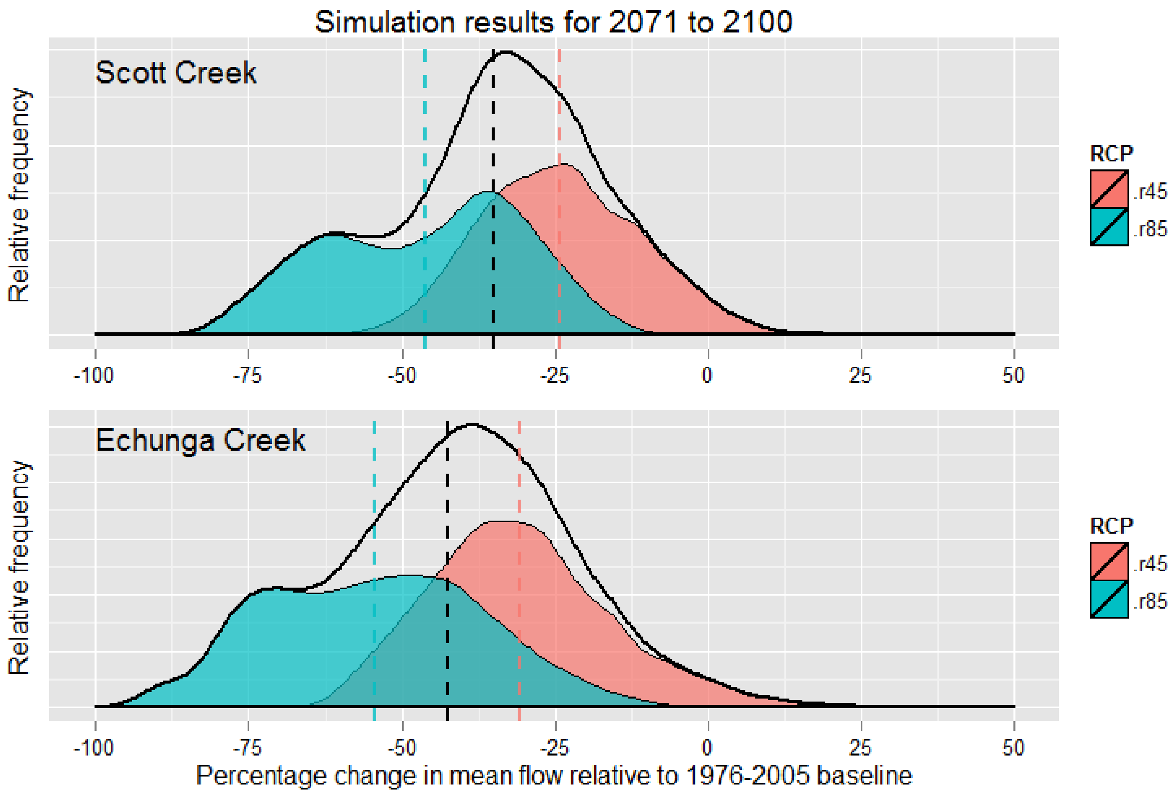



**Figure 11: Percentage change in mean annual flow at Scott Creek and Echunga Creek for all GCMs and hydrological models, for the 2071 to 2100 time slice.**

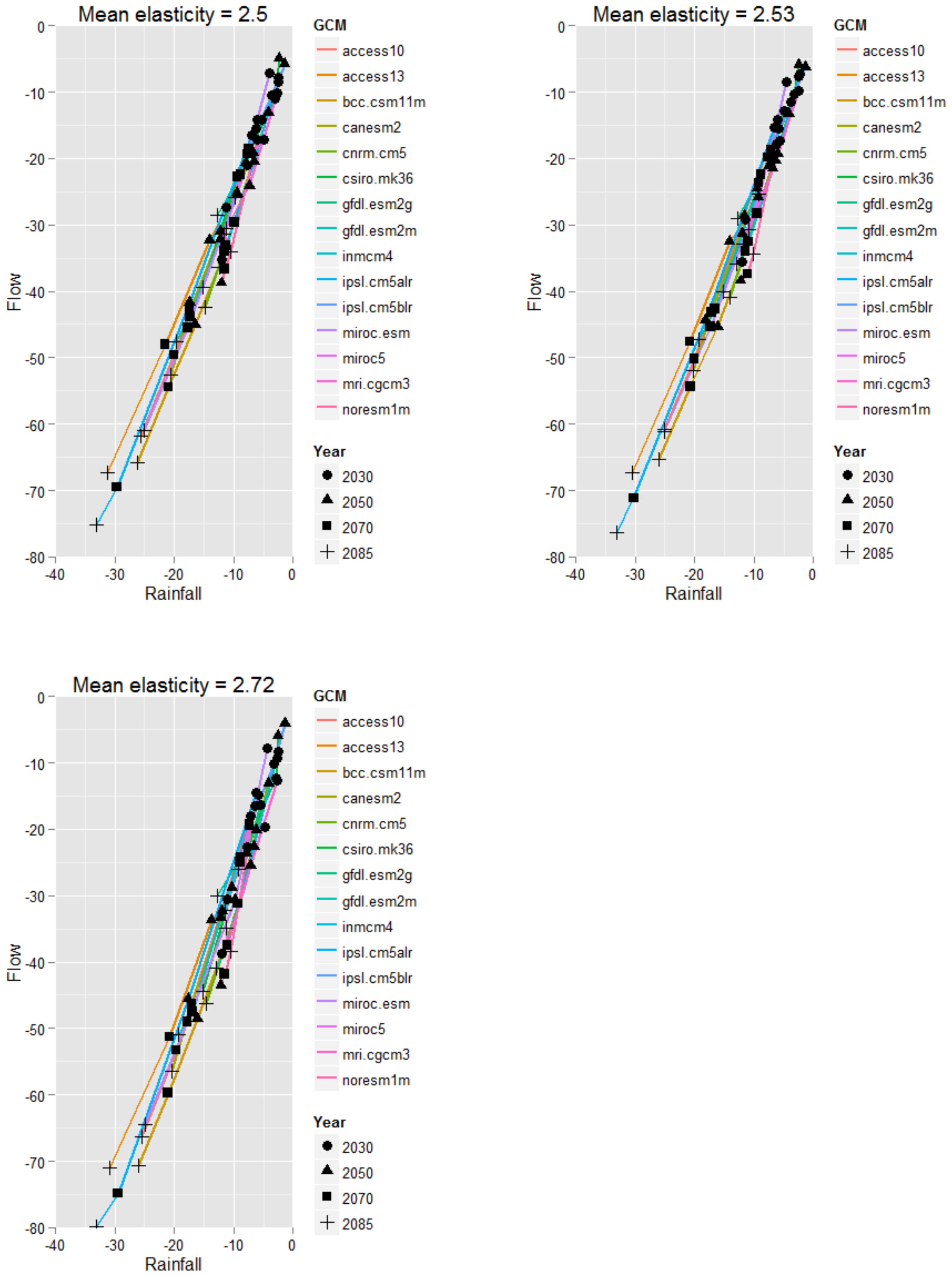



**Figure 12: Elasticity plots representing the percentage change in mean annual flow as a function of percentage change in annual average rainfall, for Houlgrave Weir (upper left), Scott Creek (upper right) and Echunga Creek (lower right).**

# 5 Changes to Low Annual Flow

Low annual flows are defined as the 10th percentile of the annual flow, and are critical for drought risk estimation.

## 5.1 How do to the low annual flow results compare to the mean annual flows?

The projected changes to the 10th percentile of annual flows are presented for Houlgrave Weir for 2016-2045 and 2071-2100 (Figure 13). These results show a reduction in the low flows by approximately 20% for 2016-2045 (compared to a 13% reduction for mean flows), and by 47% for 2071-2100 (compared to a 35% reduction for mean flows). Therefore, low annual flows appear to be more vulnerable to decreases in rainfall than the mean annual flows.


**Figure 13: Percentage change in the 10th percentile of annual flow at Houlgrave Weir for all GCMs and hydrological models, for the 2016 to 2045 and 2071 to 2100 time slices**

## 5.2 How do the low annual flow results compare between catchments?

The elasticity plots for the low annual flows are presented for the three sub-catchments in Figure 14, and can be compared to the elasticity values for mean annual flow in Figure 12. The elasticity values are slightly higher (indicating a higher sensitivity to changes in rainfall) for dry years compared to mean annual flow conditions. Once again, the results for Houlgrave Weir and Scott Creek are similar, whereas Echunga Creek has higher elasticity.

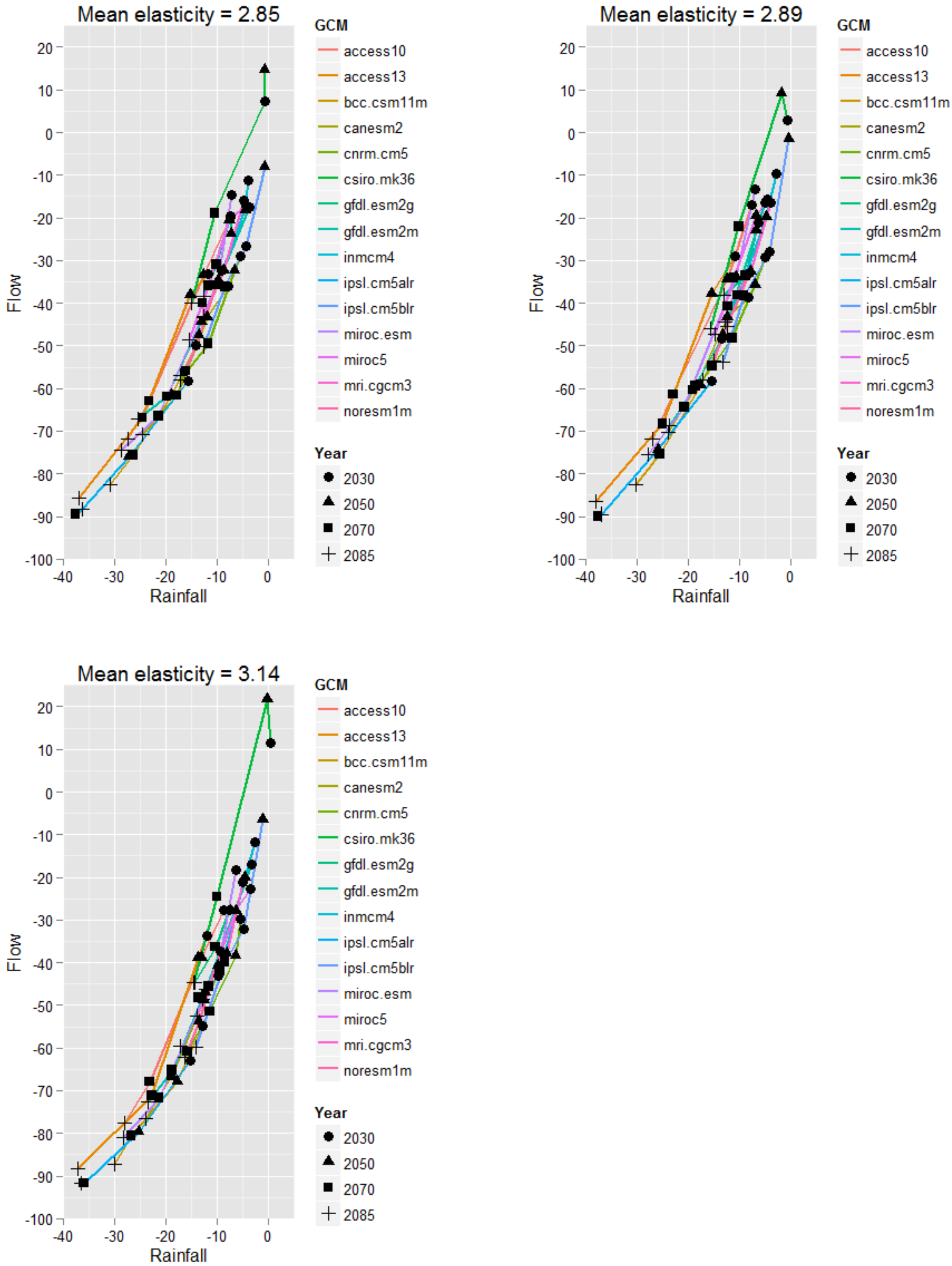



**Figure 14: Elasticity plots, representing the percentage change in the low annual flows as a function of percentage change in annual average rainfall, for Houlgrave Weir (upper left), Scott Creek (upper right) and Echunga Creek (lower right).**

# 6 Changes in Low Daily Flows

Low daily flows are defined as the 10th percentile of the daily flow duration curve, applied to either the entire year (called the annual curve) or separately over each season. This quantity is important for a range of applications, including water allocation and environmental flows.

## 6.1 How do to low daily flow results compare to the mean annual flows?

This section considers the results for the 10th percentile of the daily flows. It is important to emphasize that the daily flow rates in the bottom 10% are extremely low, and contribute only a very small proportion of the total flow volume (e.g. the bottom 55% of flow days contribute only 5% of flow volume).

Results for the 10th percentile of the daily flow duration curve are provided in Figure 15, and show an average decrease in flows of 13% for 2016-2045, and 29% for 2071-2100. The reductions in Figure 15 are lower than for mean annual flow (Figure 3); this is in part due to the structure of GR4J, which does not have a cease-to-flow threshold, and also due to the low flow threshold used as part of the weighted least squares likelihood function.

Similar results were found for all four variants of the GR4J model, suggesting that the modification in models $g_{2.2}$ and $g_{3.11}^{*}$ (to include a parameter that controls the proportion of net rainfall that enters the production store) did not significantly influence the climate change projections associated with low flows and hydrograph recessions.

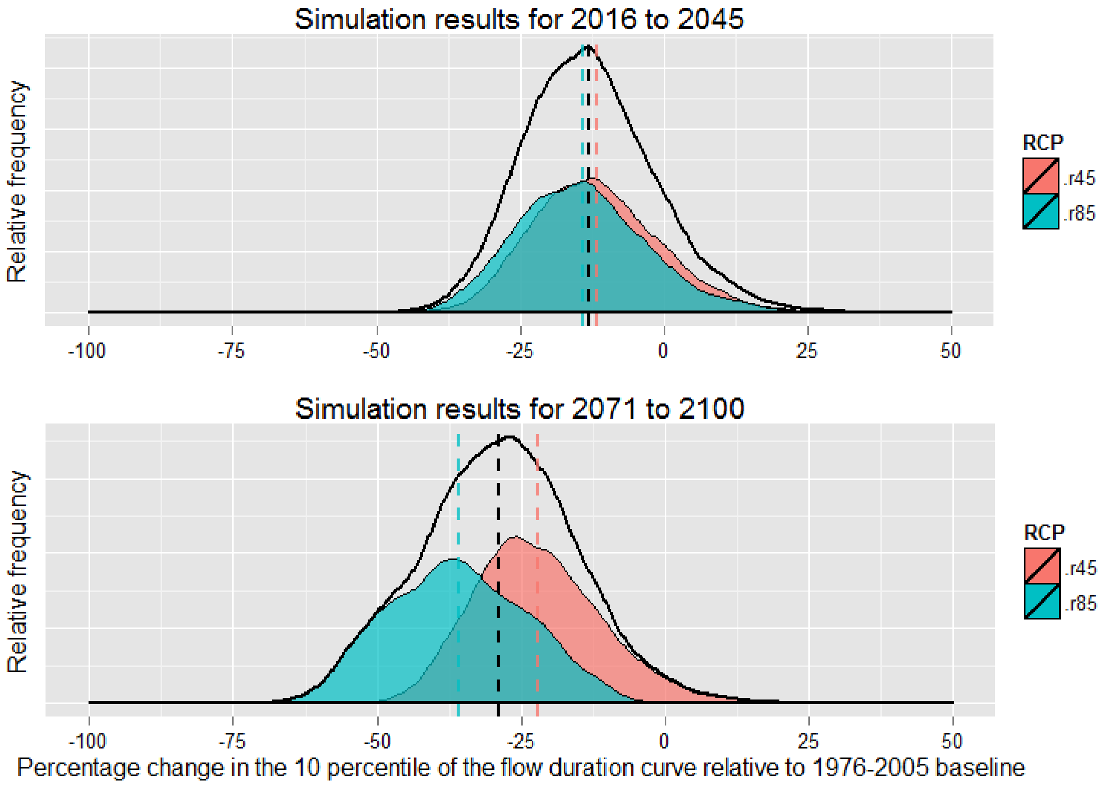



**Figure 15: Percentage change in the 10th percentile of the daily flow duration curve at Houlgrave Weir for all GCMs and hydrological models, for the 2016 to 2045 and 2071 to 2100 time slices relative to the 1976 to 2005 baseline.**

## 6.2 Do the changes vary for spring?

The 10th percentile of the flow duration curve based only on spring flows showed a much stronger decline compared to the annual curve, with a decline of 21% for 2016-2045 and 44% for 2071-2100 (Figure 16). Similar results were found for winter (not shown), with declines of 19% for 2016-2045, and 51% for 2071-2100, whereas the summer and autumn results were consistent with the annual results described in Section 6.1. This is not surprising, as the 10th percentile of the daily flow duration curve taken over a year is likely to be based on flows during low flow seasons of summer and autumn.

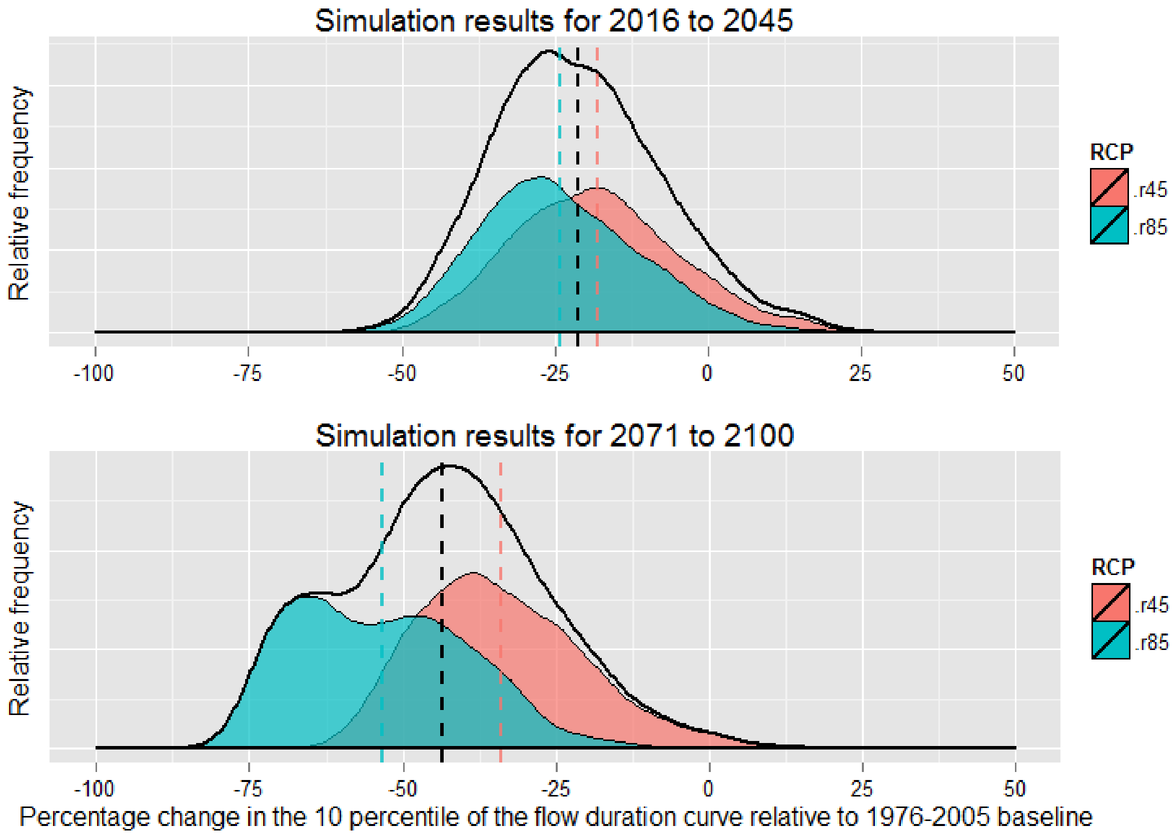



**Figure 16: Percentage change in the 10th percentile of the daily flow duration curve calculated for spring at Houlgrave Weir for all GCMs and hydrological models, for the 2016 to 2045 and 2071 to 2100 time slices**

## 6.3 Do the changes vary for different catchments?

The results for Houlgrave Weir (Figure 15) are now compared with those at Scott Creek and Echunga Creek, for 2016-2045 (Figure 17) and 2071-2100 (Figure 18). The 10th percentile of the daily flow duration curve in Scott Creek declines by 20% and 41% for the 2016-2045 and 2071-2100, respectively, whereas it declines in Echunga Creek by 15% and 30% for the two periods. These results indicate that Houlgrave Weir and Echunga Creek have similar sensitivities, whereas Scott Creek is much more sensitive than both other catchments. Comparison of the GR4J model parameters for the different catchments offered no clear explanation for this difference.

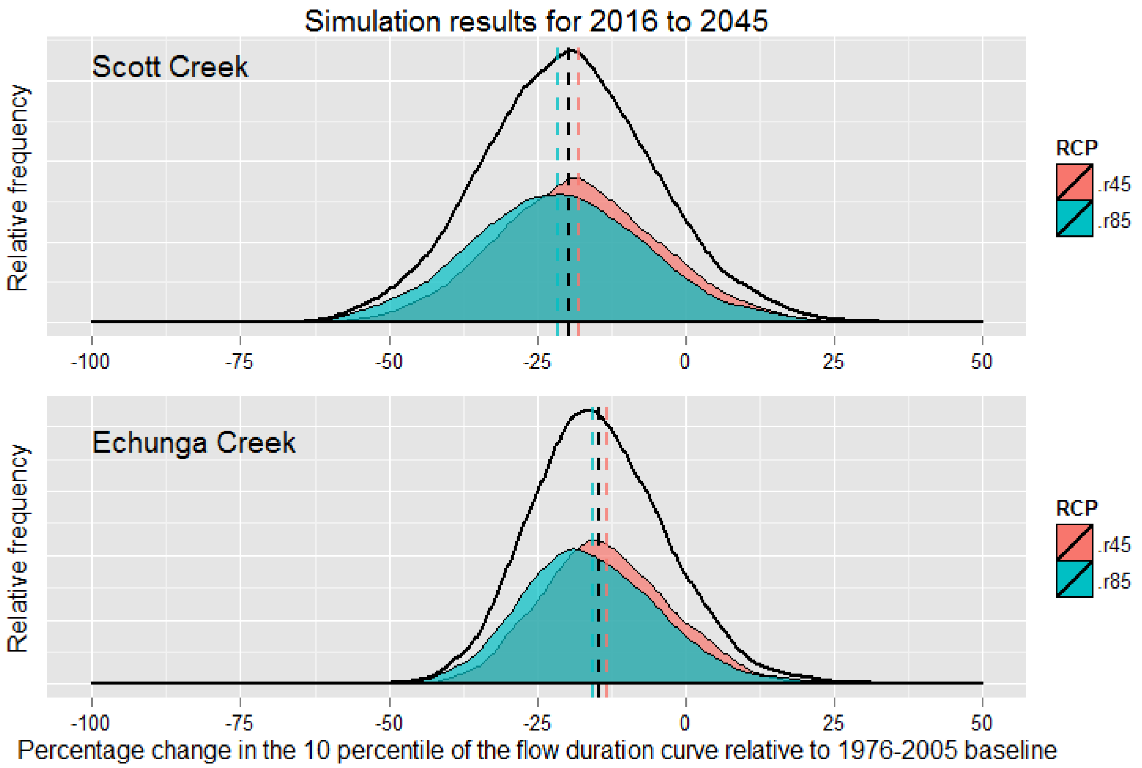



**Figure 17: Percentage change in the 10th percentile of the daily flow duration curve for the 2016 to 2045 time slice at Scott Creek (upper panel) and Echunga Creek (lower panel), for all GCMs and hydrological models.**

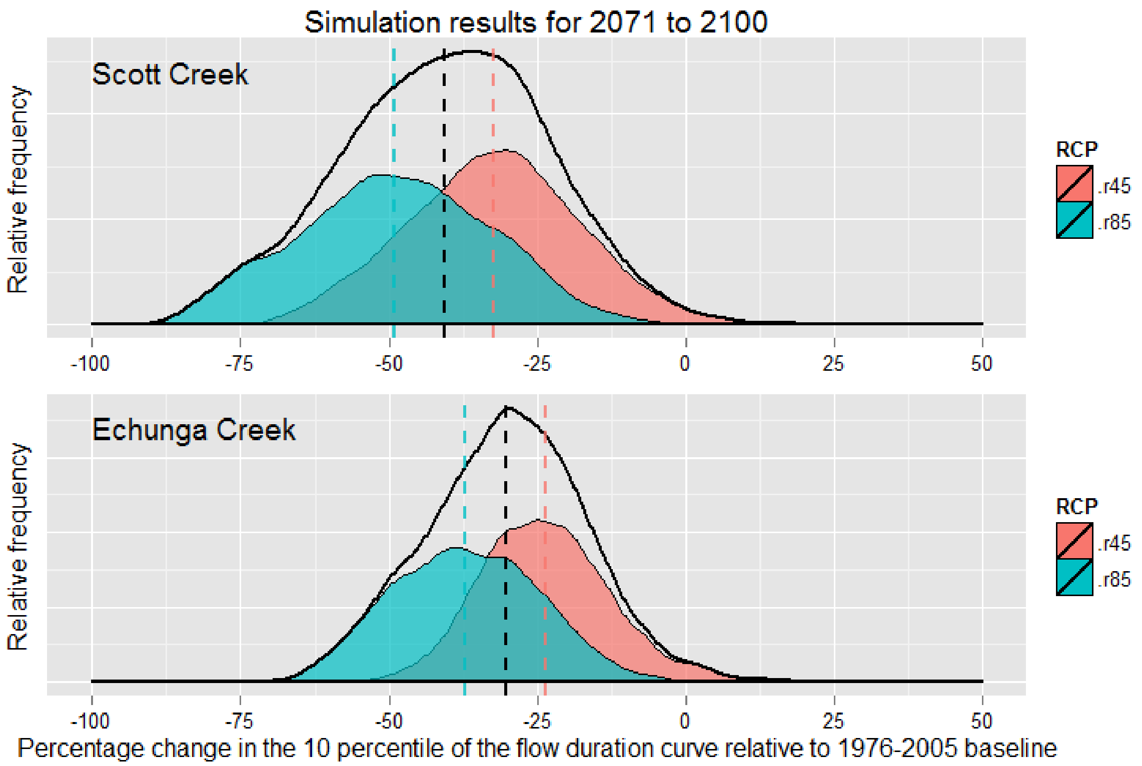



**Figure 18: Percentage change in the 10th percentile of the daily flow duration curve for the 2071 to 2100 time slice at Scott Creek (upper panel) and Echunga Creek (lower panel), for all GCMs and hydrological models.**

# 7 Changes in High Daily Flows

## 7.1 Do the projected changes differ compared to changes in mean annual flows?

Projected changes for the 95th percentile and 99th percentile of the daily flow duration curve are provided for Houlgrave Weir for 2016-2045 (Figure 19) and for 2071-2100 (Figure 20). The 95th percentile flows are on average expected to decrease by 13% for 2016-2045, and by 37 % for 2071-2100. This is almost identical to changes in mean annual flows discussed in Section 4.1. The results for Scott Creek and Echunga Creek (not shown) are also consistent with the changes in mean annual flows for these catchments as described in Section 4.5. In contrast, the projected decreases are somewhat less for the 99th percentile of the flow duration curve, with an average expected decrease of 10% for 2016-2045 and 31% for 2071-2100. This difference can be understood with reference to changes in the flow duration curve discussed in Section 8.

Annual maximum results are presented for a single GCM (Access 1.0) for two time slices: 2016-2045 (Figure 21), and 2071-2100 (Figure 22). The changes for the earlier time slice are relatively small, particularly for RCP 4.5, and are within the uncertainty bounds of the historical simulations. The departures are more significant for the later time slice, with declines particularly notable for RCP 8.5. Generally (and consistent with the results based on the 95 and 99th percentile analyses) the decreases in annual maximum flows are less in percentage terms for the highest flow events. However it should be noted that GR4J is not a flood model and is not designed nor calibrated to simulate rare high flows; therefore these results should be interpreted with caution.

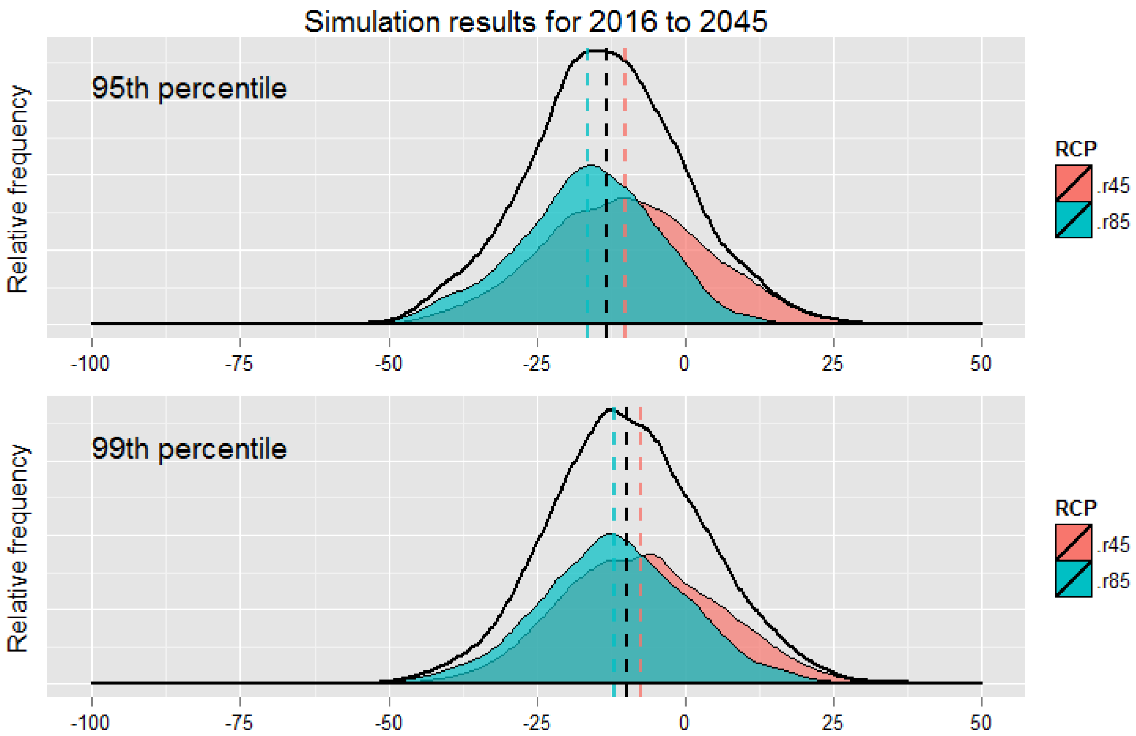



**Figure 19: Percentage change in the 95th and 99th percentile daily flow at Houlgrave Weir for all GCMs and hydrological models for 2016 to 2045 and 2071 to 2100.**

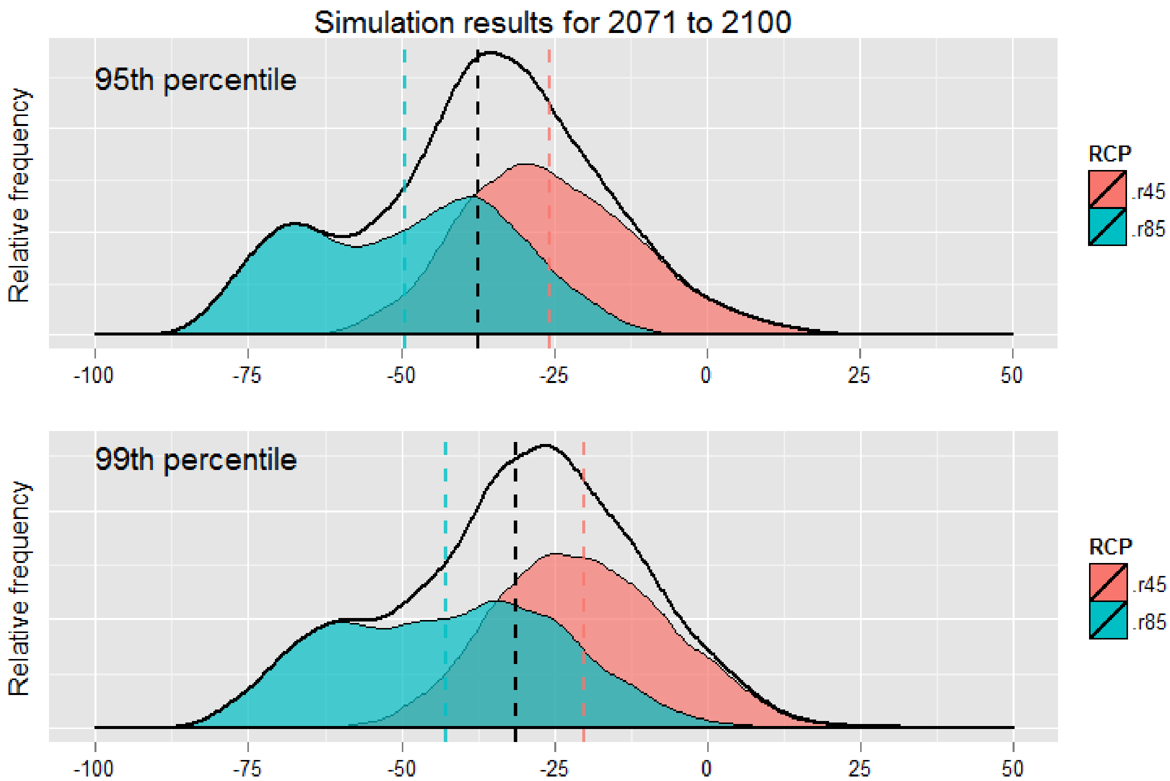



**Figure 20: Percentage change in the 95th and 99th percentile daily flow at Houlgrave Weir for all GCMs and hydrological models for 2016 to 2045 and 2071 to 2100**

---

**Figure 21, over page: Upper panel: exceedance probability plot of annual maxima for Houlgrave Weir (model $g_{1.1}$), based on the 1976 to 2005 time slice (red line) and the 2016 to 2045 time slice based on RCP 4.5 (green line) and RCP 8.5 (blue line). Shading represents the range of projections from the 100 NHMM simulations. Lower panel: Projections for 2016 to 2045 time slice for RCP 4.5 (green line) and RCP 8.5 (blue line) expressed as a percentage change relative to 1976 to 2005 baseline.**

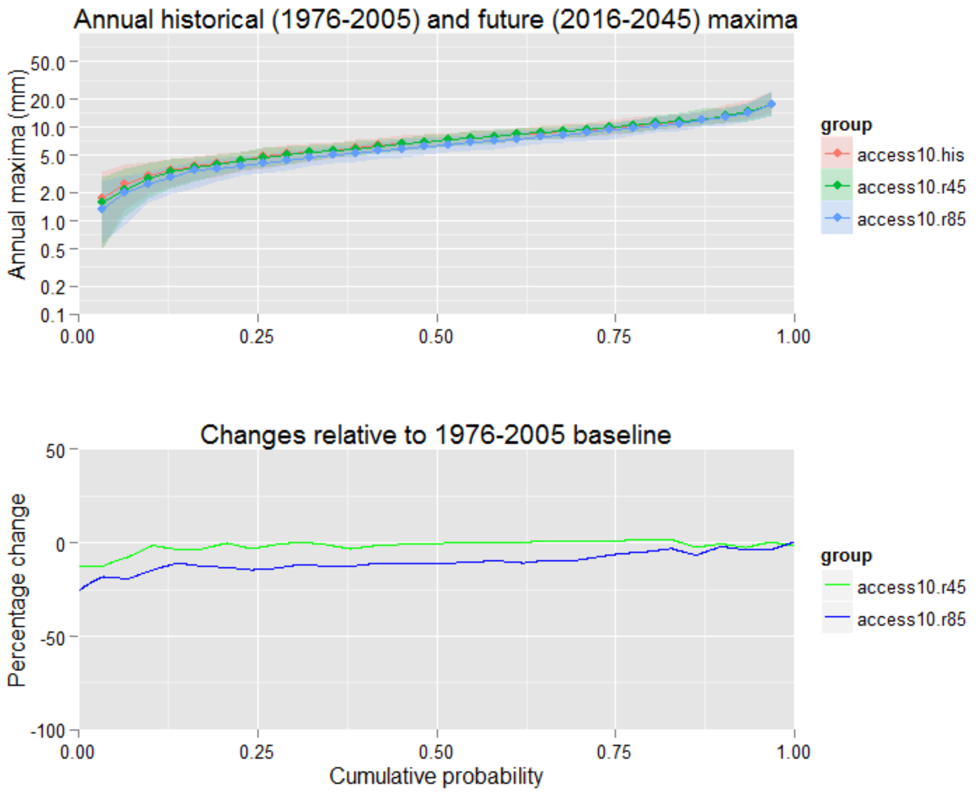



**Figure 21**: **2016-2045 time slice. Figure details given on prior page.**

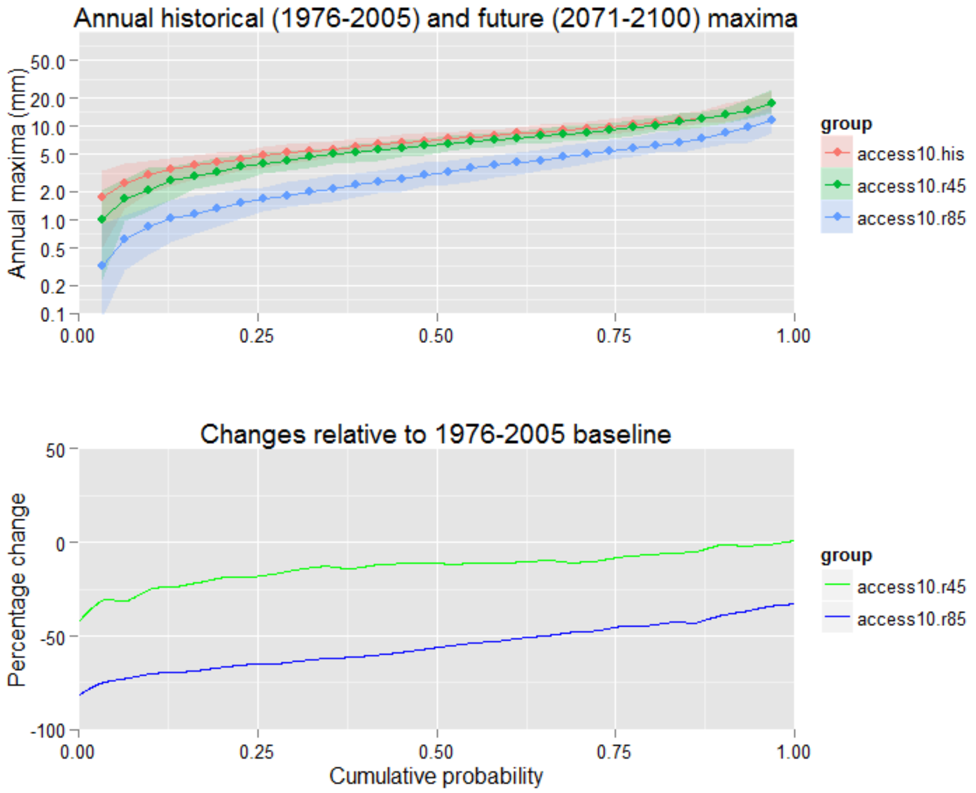



**Figure 22: As per Figure 21 but for the 2071 to 2100 time slice.**

# 8 Changes to the Flow Duration Curve

Comparisons in the flow duration curves between the historical and future climate projections are presented at Houlgrave Weir based on the Access 1.0 model simulations, for 2016-2045 (Figure 23) and 2071-2100 (Figure 24). Examining the relative change in the flow duration curves (lower panel of both figures), it can be seen that the largest change occurs approximately at the 50th percentile (i.e. median) flow, with lower changes for both low and high flows. In particular, for high and extreme flows above the ~95th percentile, the changes become much smaller. These results are consistent with the findings that low (Section 6) and high (Section 7) daily flows are expected to decrease to a lesser extent than average flows (Section 4).

Interestingly, qualitatively similar results to the Access 1.0 model simulations were found for the remaining climate models. Although the absolute magnitude varied amongst models (see upper panel of Figure 4), the changes in the shape of the flow duration curve (i.e. with the largest changes occurring for median flows, and lower changes occurring for higher and lower flows) were apparent across all GCMs. The results were also consistent across sub-catchments.

To better understand the projected changes, equivalent plots are provided for rainfall (Figure 25), again based on the Access 1.0 model. As can be seen from this figure, expected changes include a decrease in the number of wet days, as well as a substantial decrease for low rainfall events but with minimal decreases for the highest rainfall quantiles. Once again, consistent results were found using other GCMs. This is likely to explain why changes in high flow events are generally lower than changes in intermediate flow events. As stated previously, GR4J is not designed for use as a flood model; therefore the results should treated be with caution.

---

**Figure 23, over page: Upper panel: flow duration curve for Houlgrave Weir (model $g_{1.1}$), based on the 1976 to 2005 time slide (red line) and the 2016 to 2045 time slice based on RCP 4.5 (green line) and RCP 8.5 (blue line). Shading represents the range of projections from the 100 NHMM simulations. Lower panel: Projections for 2016 to 2045 time slice for RCP 4.5 (green line) and RCP 8.5 (blue line) expressed as a percentage change relative to 1976 to 2005 baseline.**

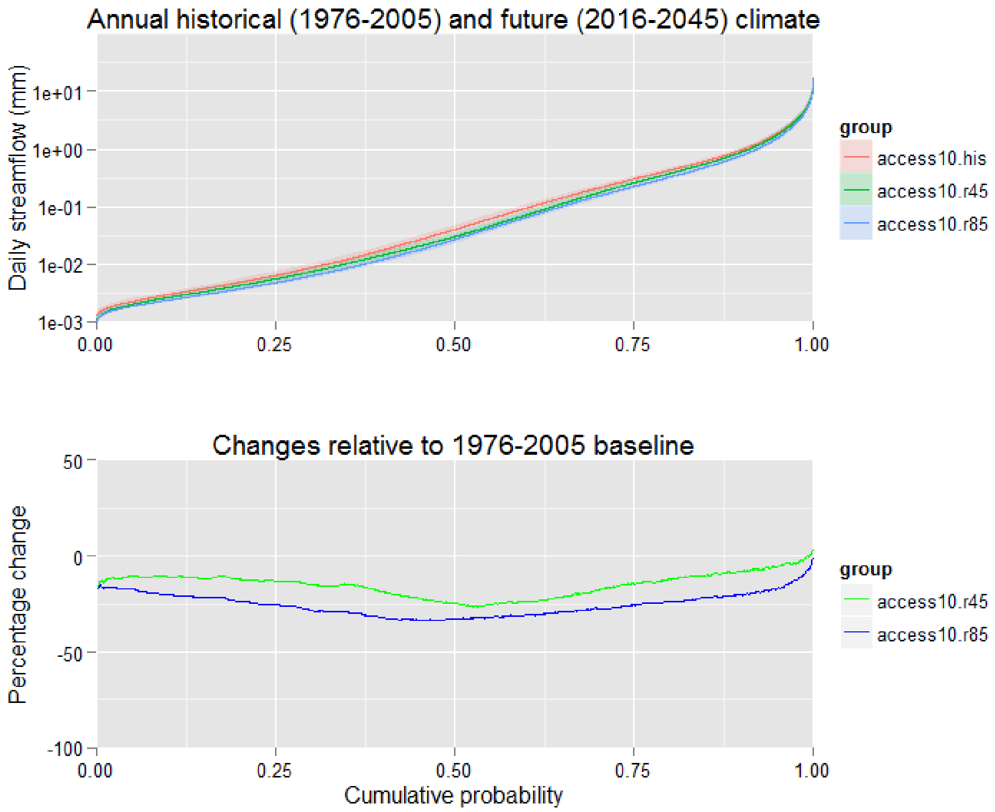



**Figure 23: 2016-2045 time slice. Figure details given on prior page.**

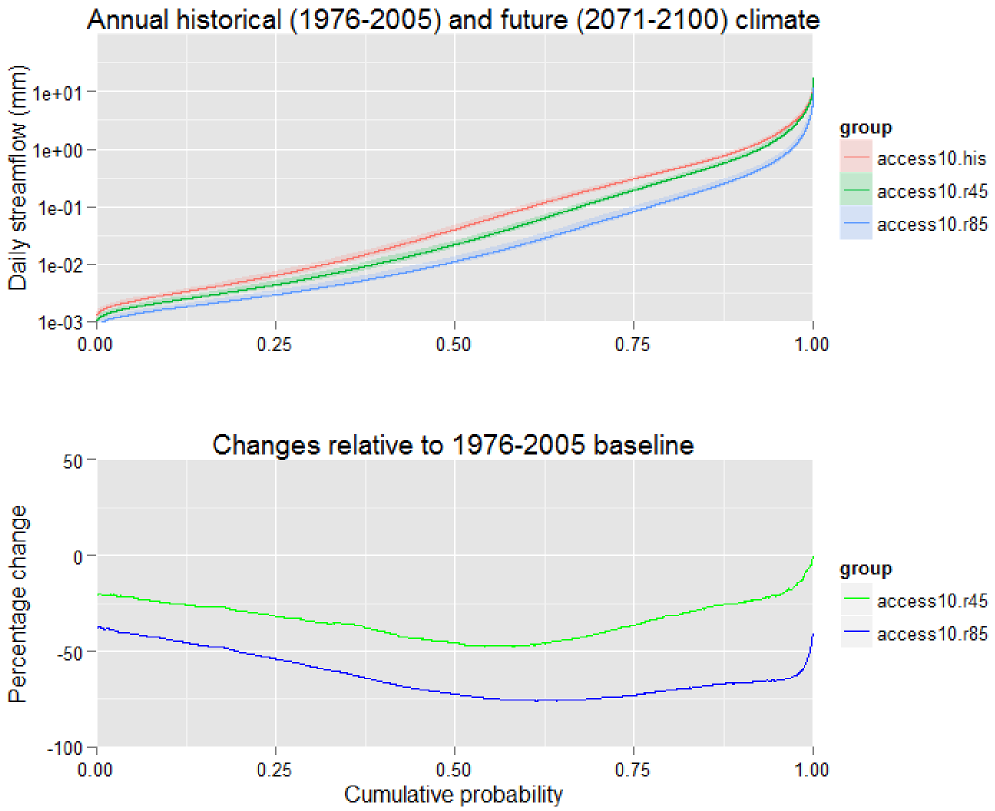



**Figure 24: As per Figure 23 but for the 2071 to 2100 time slice.**

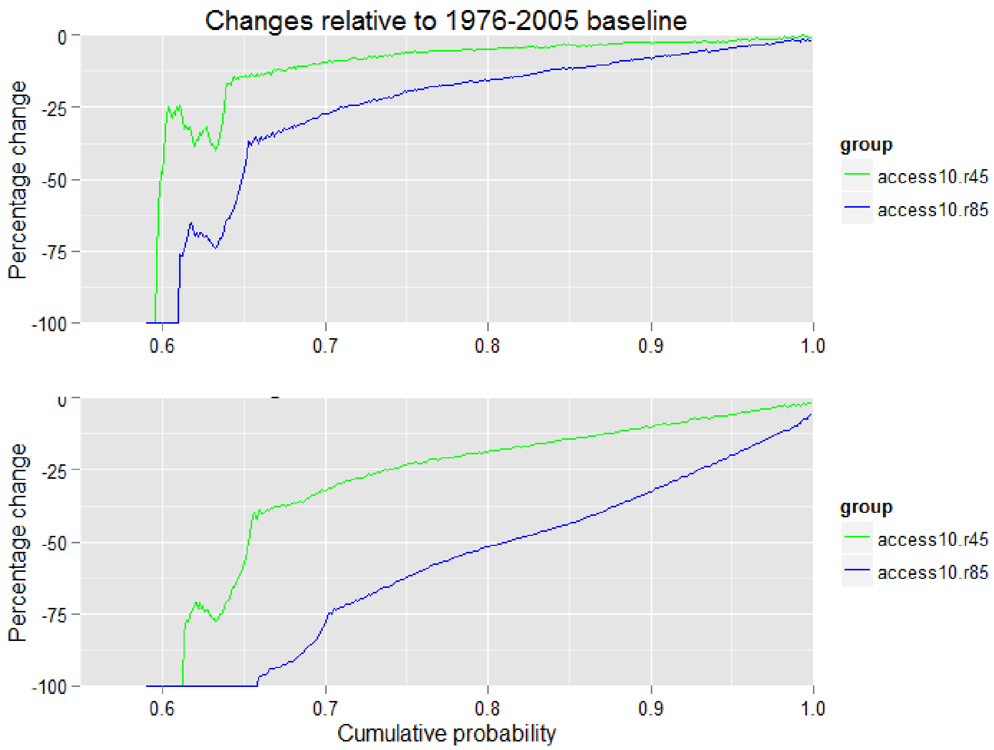



**Figure 25: Changes in rainfall relative to the 1976-2005 baseline based on the Access 1.0 model, for 2016-2045 (upper panel) and 2071-2100 (lower panel)**

# 9 Data Management and Software Package

## 9.1 Data Management

A description of the data collected throughout this project has been registered as a research data collection with DataConnect, the University of Adelaide's data management system. This is connected to Research Data Australia as part of the Goyder Institute for Water Research collection. The link to the collection is http://researchdata.ands.org.au/tobefinalised [note, the research data collection form has been provided with DataConnect – once final link is available it will be updated]

The data included in this collection is listed as follows:

- Observed data
  - Catchment average rainfall, potential evapotranspiration and runoff for each of the three case study catchments;
- Downscaled climate simulations
  - Simulations of daily rainfall and PET time series at each of the 22 rainfall sites [see Westra et al, 2014a, for details] and the catchment average for the three case study case study catchments, for the following scenarios:
    - Periods: historical (1961-2005) and future (2006-2100)
    - 15 GCMS
    - RCP 4.5 and 8.5
- Streamflow simulations
  - Simulations of daily streamflow for four hydrological models, for the three case study catchments, using the downscaled climate data for the scenarios listed above.

This data is stored in an eResearchSA data storage account that is run by the Hydrology and Climate Impacts group of the School of Civil, Environmental and Mining Engineering, University of Adelaide. In the short-term, this data will be made available to other researchers upon enquiry via DataConnect, subject to the constraints of the confidentiality agreement signed by the University of Adelaide researchers with SA Water in regard to the Murray-Bridge Onkaparinga pipeline flows that were used to determine the naturalised flows at Houlgrave Weir. In the long-term, if there is sufficient demand, this data will be made publicly accessible.

A selected subset of the data containing relevant statistics of the flow metrics of the streamflow projections and scripts to interrogate them (see Section 9.2) have also been made available directly to representatives from DEWNR.

## 9.2 Software package

A software package, written in the R statistical computing language, is provided to the Department of Environment, Water and Natural Resources (DEWNR) to facilitate in-depth exploration of the climate modelling results for the Onkaparinga region. This package is able to produce the following plots:

(1) **Box and whisker plots,** itemising results by different flow metrics (annual/seasonal total rainfall; 10th percentile annual/seasonal rainfall; coefficient of variation; 95th percentile and 99th percentile daily rainfall; and annual/seasonal maximum rainfall), with capabilities of plotting separately for different GCMs, hydrological models, RCPs and time slices. Example plots are given in Figure 26 and Figure 27.

(2) **Probability density plots** and **cumulative distribution functions**, for different time slices, seasons and flow metrics (e.g. Figure 3 and Figure 4).

**(3) Elasticity plots**, based on different flow metrics and based on different RCPs and hydrological models (e.g. Figure 12)

These plots collectively allow a thorough exploration of potential changes in flows in the Onkaparinga catchment, including an assessment of the extent and principal contributors to model uncertainty.

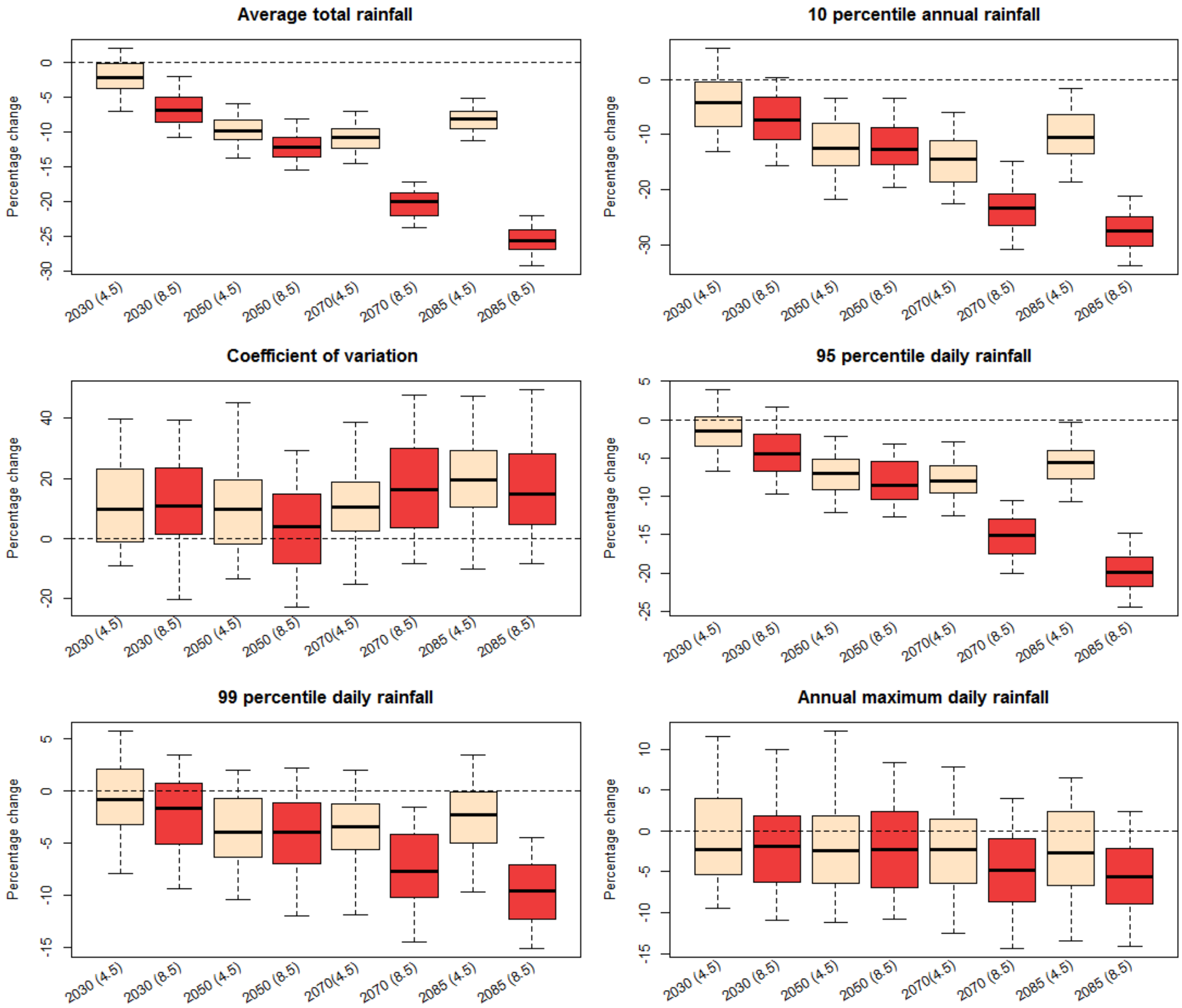



**Figure 26: Box and whisker plot presented by time slice at Houlgrave Weir for the ACCESS 1.0 GCM, hydrological model $g_{1.1}$, at the annual time scale. Similar plots can be generated for each GCM, hydrological model and season.**

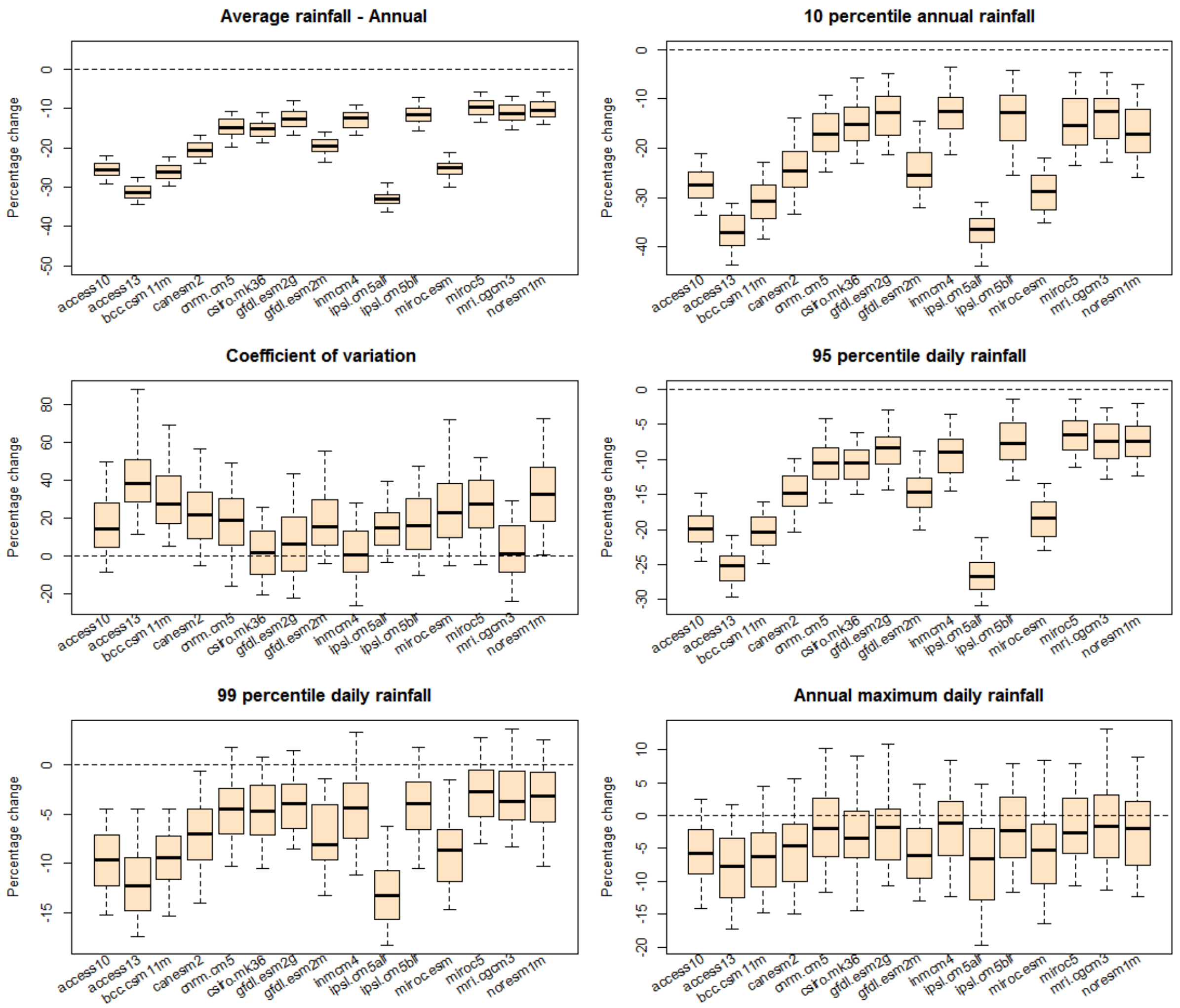



**Figure 27: Box and whisker plot presented by GCM at Houlgrave Weir for the 2071 to 2100 time slice based on RCP 8.5, using hydrological model $g_{1.1}$, at the annual time scale. Similar plots can be generated for each time slice, RCP, hydrological model and season.**

# 10 Conclusions and Recommendations

Flow projections in three sub-catchments of the Onkaparinga catchment (Scott Creek, Echunga Creek and Houlgrave Weir) are provided under a future, greenhouse gas-enhanced climate. The projections are based on 15 GCMs from the World Climate Research Program Coupled Model Intercomparison Project Phase 5, and two RCPs – one representing the upper range of the "baseline scenario" in which society does not take explicit steps to constrain emissions, and the other representing a "mitigation pathway" in which active steps are taken to reduce emissions. These GCM and RCP scenarios are downscaled to catchment-scale estimates of rainfall and potential evapotranspiration using the non-homogeneous hidden Markov model, which was evaluated in the second report of this series. The rainfall and PET projections are converted to streamflow using four hydrological models identified in the first report of this series.

The results indicate that significant decreases in flows are likely during the 21$^{st}$ century, with larger decreases for RCP 8.5 compared to RCP 4.5, and for late 21$^{st}$ century projections compared to early 21$^{st}$ century projections. Averaging across GCMs, RCPs and hydrological models, the median percentage change for the four time slices analysed at Houlgrave Weir are: -14% (2016-2045), -24% (2036-2065), -33% (2056-2085) and -37% (2071-2100). Uncertainty is large, particularly for the late 21$^{st}$ century projections, however confidence about the direction of change is high: by 2071-2100, 98% of simulations show that the mean annual flow will decrease.

The implications of climate change on a range of flow metrics were explored, with each metric corresponding to a specific practical application of the flow predictions. These results are summarised for Houlgrave Weir in Table 4. Spring flows are likely to experience a greater reduction than annual flows; for example, mean spring flows are projected to decrease by median of 44% by 2071-2100. The drought related flow metric (low annual flow) also will likely experience greater reductions than mean annual flow: by 2071-2100 the median reduction in the 10$^{th}$ percentile annual flow is estimated to be 48%. The practical implication is that water resource planners need to prepare for a significantly increased likelihood of low flow years in the future. Finally, peak flows also appear to decrease less than the mean annual flow; however it should be noted that GR4J is not a flood model and is not designed nor calibrated to simulate rare high flows.

**Table 4. Median changes in flow metrics for Houlgrave Weir**

| Flow Metric | Practical Impact | 2016-2045 | 2071-2100 |
|---|---|---|---|
| Mean flow<br>-Annual<br>-Spring | Water Resources | <br>-14%<br>-19% | <br>-37%<br>-44% |
| Low annual flows (10$^{th}$ percentile) | Droughts | -20% | -47% |
| Low daily flows (10$^{th}$ percentile) | Environmental Flows, Water Allocation | -13% | -29% |
| High daily flows<br>- 99$^{th}$ percentile<br>- Annual maximum flow | Floods | <br>-10%<br>-8% | <br>-31%<br>-27% |

For the low daily flows, which are used for assessing environmental flow requirements and water allocation, the relative reduction are likely to be slightly lower than the mean annual flow, albeit still significant. For high daily flows, which are used as an indicator for changes in extreme flow events that cause flooding, the reductions are slightly less than for the mean annual flows.

Similar trends to Table 4 were found for the other two catchments. The main differences was that Echunga Creek experienced greater sensitivity to changes compared to Scott Creek and Houlgrave Weir, except for low flows where Scott Creek is the most sensitive.

To facilitate more in-depth analysis of the results, a software package has been developed in the R statistical computing language that is able to produce a diverse range of diagnostic plots to compare flow metrics between the different RCPs, GCMs, hydrological models, NHMM simulations.

In terms of recommendations for further work, there are three key issues to be resolved:

(1) Development of more robust downscaling techniques to provide greater confidence in the climate change projections. The aim would be to reduce the biases in the stochastic downscaling approach that were identified in volume 2 of this series [*Westra et al.*, 2014b].

(2) Developing more robust approaches to quantify the climate change impacts on high flow events. The results showed that the reductions in high flow events are likely to be far lower than mean annual flow. However, this is the least robust conclusion of this report, because the hydrological model and downscaling approach used in this study does not have the capability to capture the physically processes that generate high flow events. Further research work is needed to better quantify the likely climate change impacts on flooding.

(3) Developing a greater understanding of the contribution of improvements in the hydrological modelling process in developing climate change projections. In this project it was found that despite the improvements in the hydrological modelling undertaken in volume 1 [*Westra et al.*, 2014a], the relative change in flow projection was similar to the baseline hydrological model. It is recommended that further work be conducted to verify this result with a wider range of hydrological modelling schemes, potentially including more physically based approaches.

Irrespective of these issues, this report has clearly shown that due to the likely impacts of climate change, the water resource planners of South Australia need to begin planning for a significantly drier flow regime in the future.

# 11 References

Chiew, F. H. S. (2006), An Overview of Methods for Estimating Climate Change Impact on Runoff, in *30th Hydrology and Water Resources Symposium*, edited, Launceston.

Chiew, F. H. S., J. Teng, J. Vaze, and D. G. C. Kirono (2009), Influence of global climate model selection on runoff impact assessment, *Journal of Hydrology 379*(1-2), 172-180.

IPCC (2014), Working Group III, Summary for Policymakers*Rep.*

Perrin, C., C. Michel, and V. Andreassian (2003), Improvement of a parsimonious model for streamflow simulation, *Journal of Hydrology*, *279*, 275-289.

Westra, S., M. Thyer, M. Leonard, D. Kavetski, and M. Lambert (2014a), Impacts of Climate Change on Surface Water in the Onkaparinga Catchemnt - Volume 1: Hydrological Model Development and Sources of Uncertainty*Rep.*, Adelaide, South Australia.

Westra, S., M. Thyer, M. Leonard, and M. Lambert (2014b), Impacts of Climate Change on Surface Water in the Onkaparinga Catchment - Volume 2: Hydrological Evaluation of the CMIP3 and CMIP5 GCMs and the Non-homogenous Hidden Markov Model (NHMM)*Rep.*, Adelaide, South Australia.

# 12 Appendix 1: Feasibility of using only a subset of NHMM simulations to produce estimates of climate impacts?

This report analysed a large set of GCMs, RCPs, hydrological models, subcatchments and NHMM replicates, which collectively comprises 36,000 daily time series spanning the period from 2006 to 2100, and subsequently split into four 30-year time slices. Given the significant volume of data, it is natural to ask whether it is possible to select a set of 'representative' NHMM simulations that represent, say, the 5, 50 and 95th percentile bounds, rather than modelling the full suite of NHMM runs.

A difficulty with this approach is due to the complex transformation between the climate forcing variables (rainfall and evapotranspiration), and the associated flows, which means that the 5, 50 and 95th percentile series of rainfall (ranked by, say, annual average rainfall) will not necessarily lead to equivalent rankings for flows. In fact, it is likely that applying this technique will on average lead to estimates that underestimate the degree of uncertainty associated with future climate projections. This phenomenon is due to the imperfect correlation (in rank space) between annual average rainfall quantiles and quantiles of interest from an impact assessment (e.g. average flows, low flows or peak flows), and the effect is commonly referred to as *regression towards the mean*.

To illustrate this, consider the results from 100 NHMM simulations from the reanalysis run, in which:

- Various metrics of hydroclimatological forcings are poorly correlated with each other; for example average annual maximum daily precipitation has a correlation with average annual average precipitation of 0.379 (Figure 28), and annual average APET has a correlation of -0.244 with annual average precipitation (Figure 29);

- The association between hydroclimatic forcings and mean annual flow is also not perfect – for example the correlation between mean annual flow and annual average precipitation is 0.868 (Figure 30), whereas the correlation between mean annual flow and average annual maximum daily precipitation is 0.41 (Figure 31).

- This leads to differences between the 5$^{th}$ and 96$^{th}$ ranked points in the flow duration curve, to the 5$^{th}$ and 96$^{th}$ ranked points in terms of annual average rainfall (Figure 32), with the differences particularly clear for the top two percentile of flows (Figure 33). This can be seen even more clearly when plotting the results by month (Figure 34).

The implication is that it is not possible to identify *a priori* which NHMM simulations in terms of rainfall will provide specified uncertainty limits for flows, whether they be expressed in terms of annual or seasonal averages or some quantile of the flow duration curve. Therefore, it is recommended that the full range of simulations be considered, and that uncertainty intervals should only be calculated *a posteriori* based on the full set of NHMM simulations.

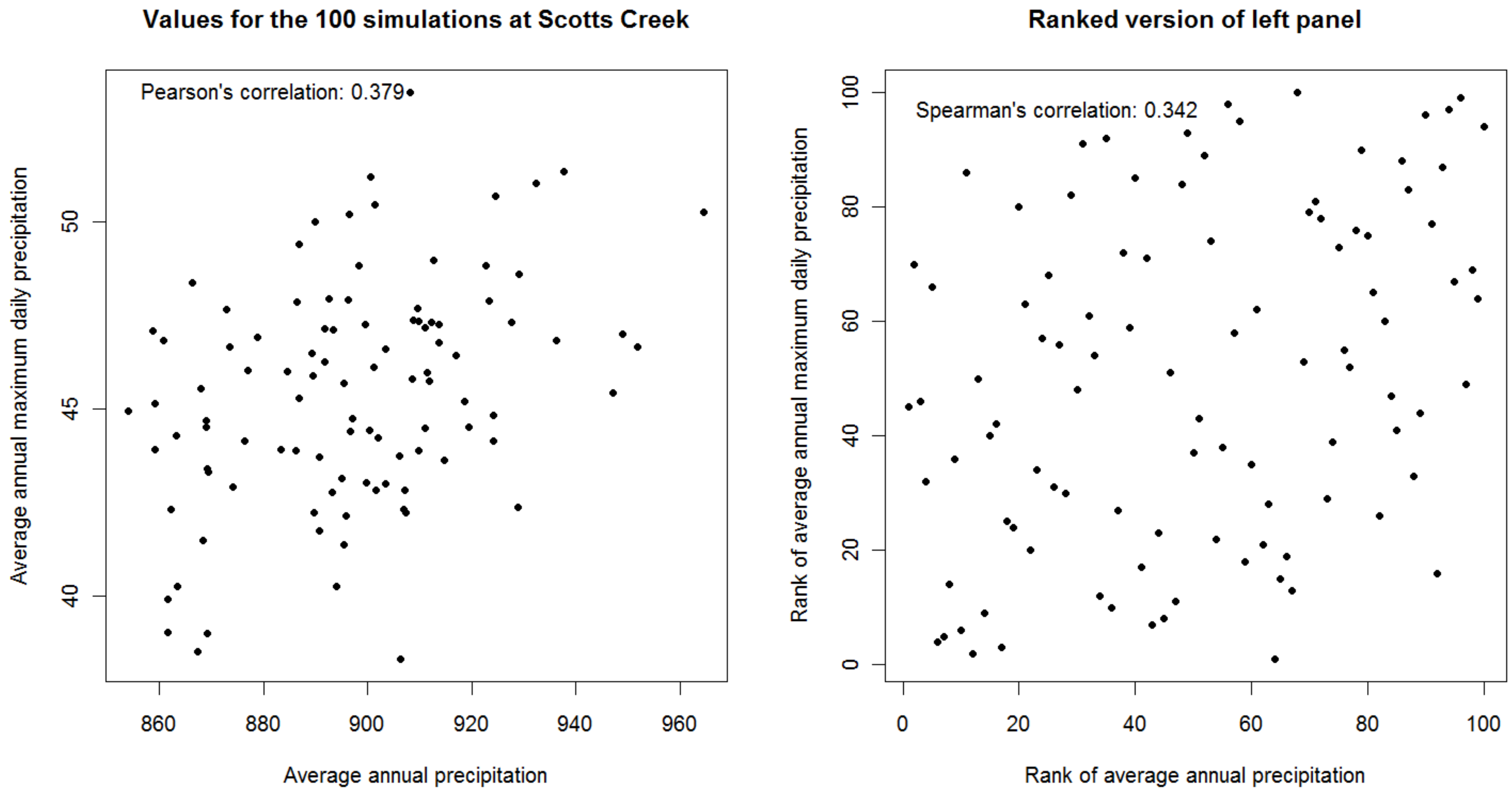



**Figure 28: Association between annual maximum daily precipitation and annual average precipitation, represented in data space (units of mm; left panel) and rank space (right panel).**

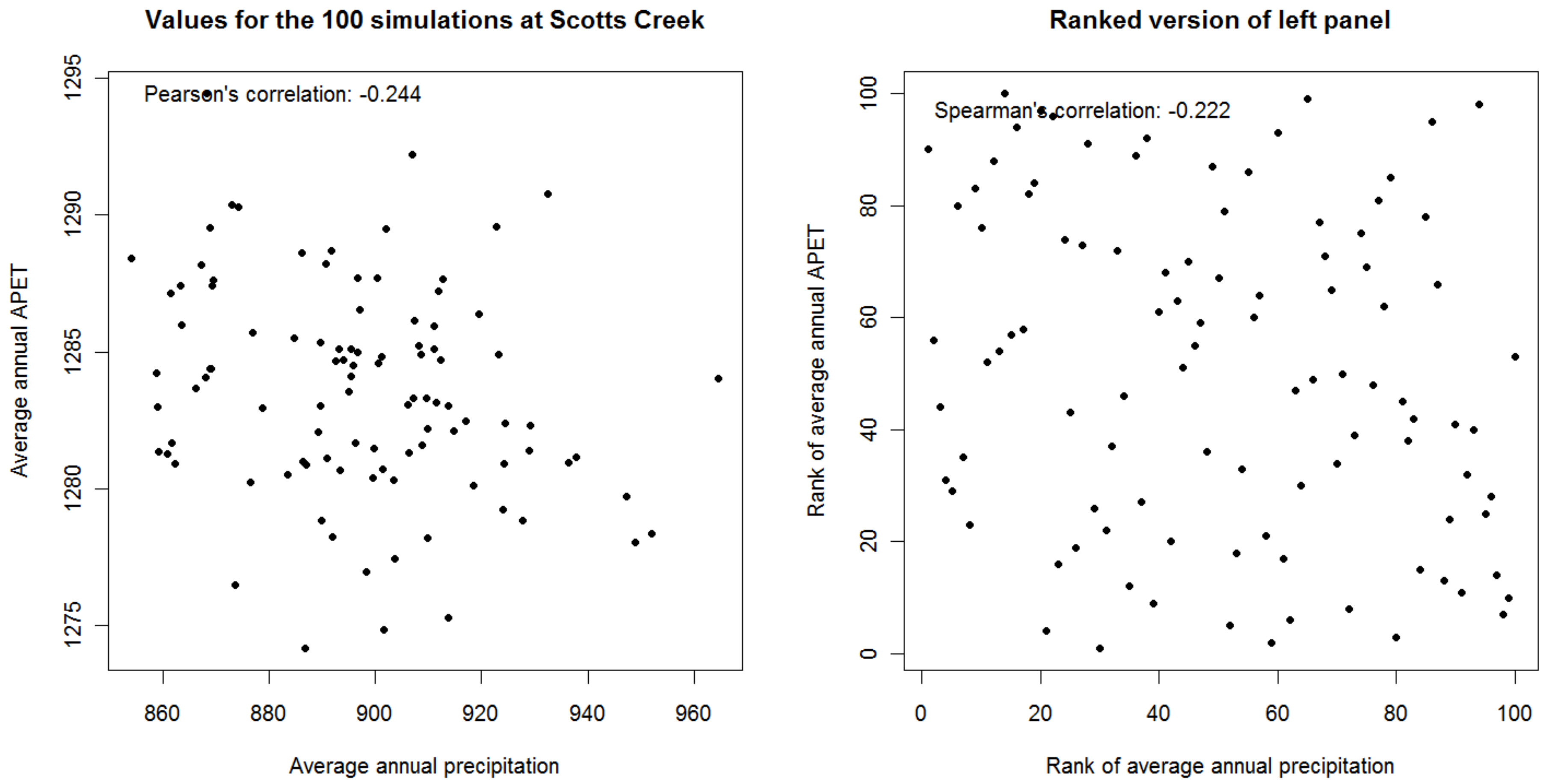



**Figure 29: Association between annual average potential evapotranspiration and annual average precipitation, represented in data space (units of mm; left panel) and rank space (right panel).**

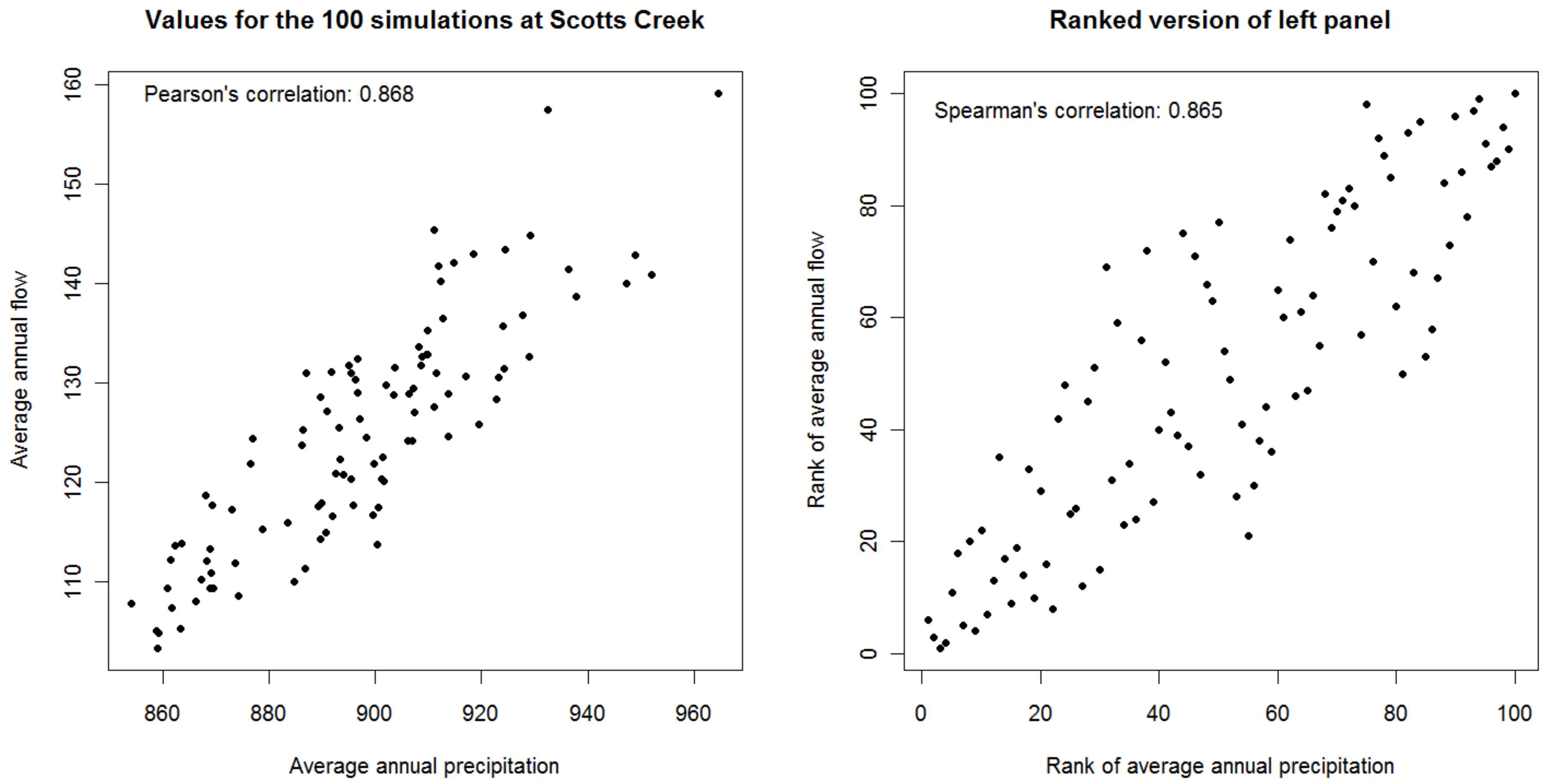



**Figure 30: Association between mean annual flow and annual average precipitation, represented in data space (units of mm; left panel) and rank space (right panel).**

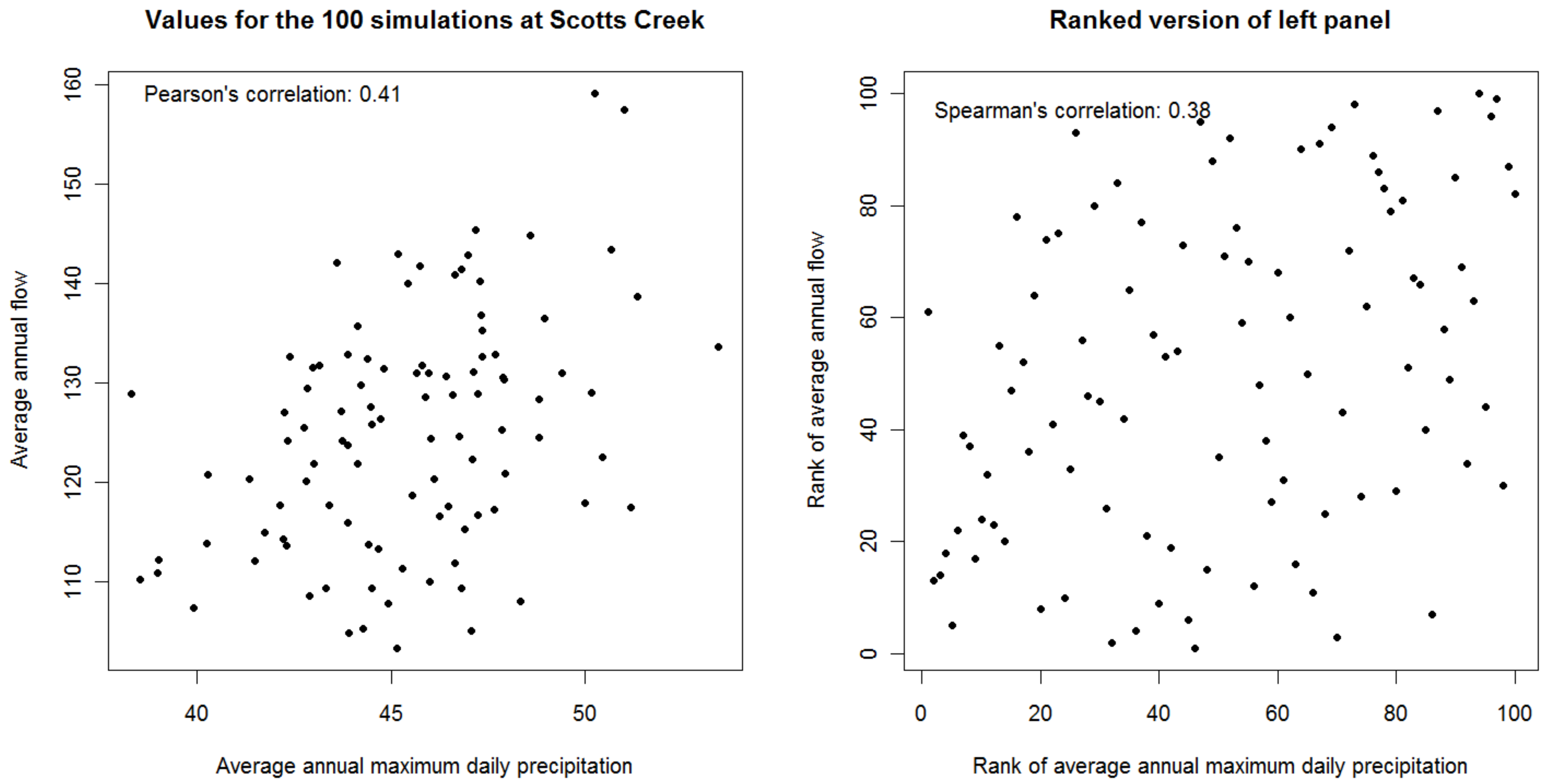



**Figure 31: Association between mean annual flow and average annual maximum daily precipitation, represented in data space (units of mm; left panel) and rank space (right panel).**

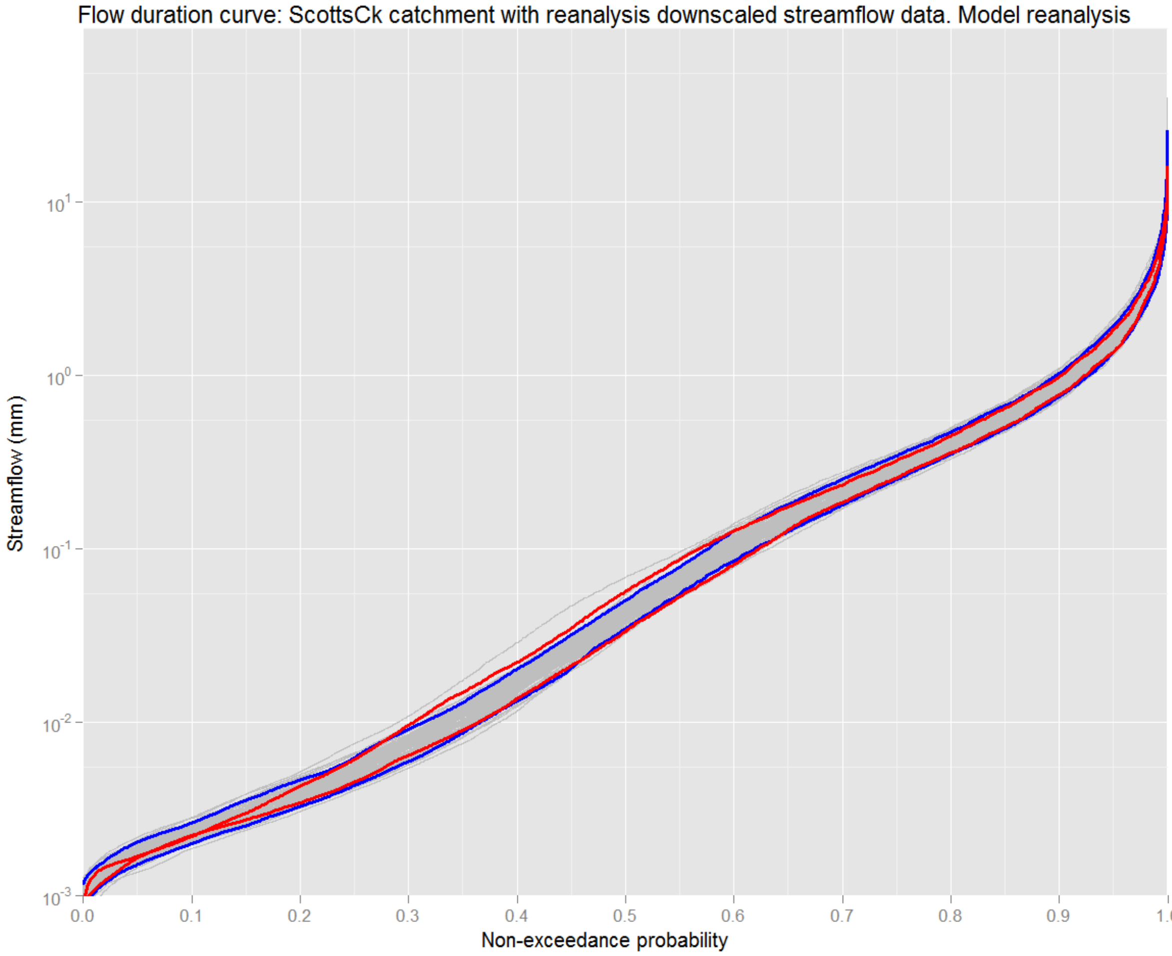



**Figure 32: Grey lines are the 100 simulations. Blue lines are the 5th and 96th value calculated at each exceedance probability (i.e. doesn't represent a single flow duration curve). Red lines are the flow duration curves one would get if using the runs obtained from the 5th and 96th ranked simulations by annual average rainfall.**

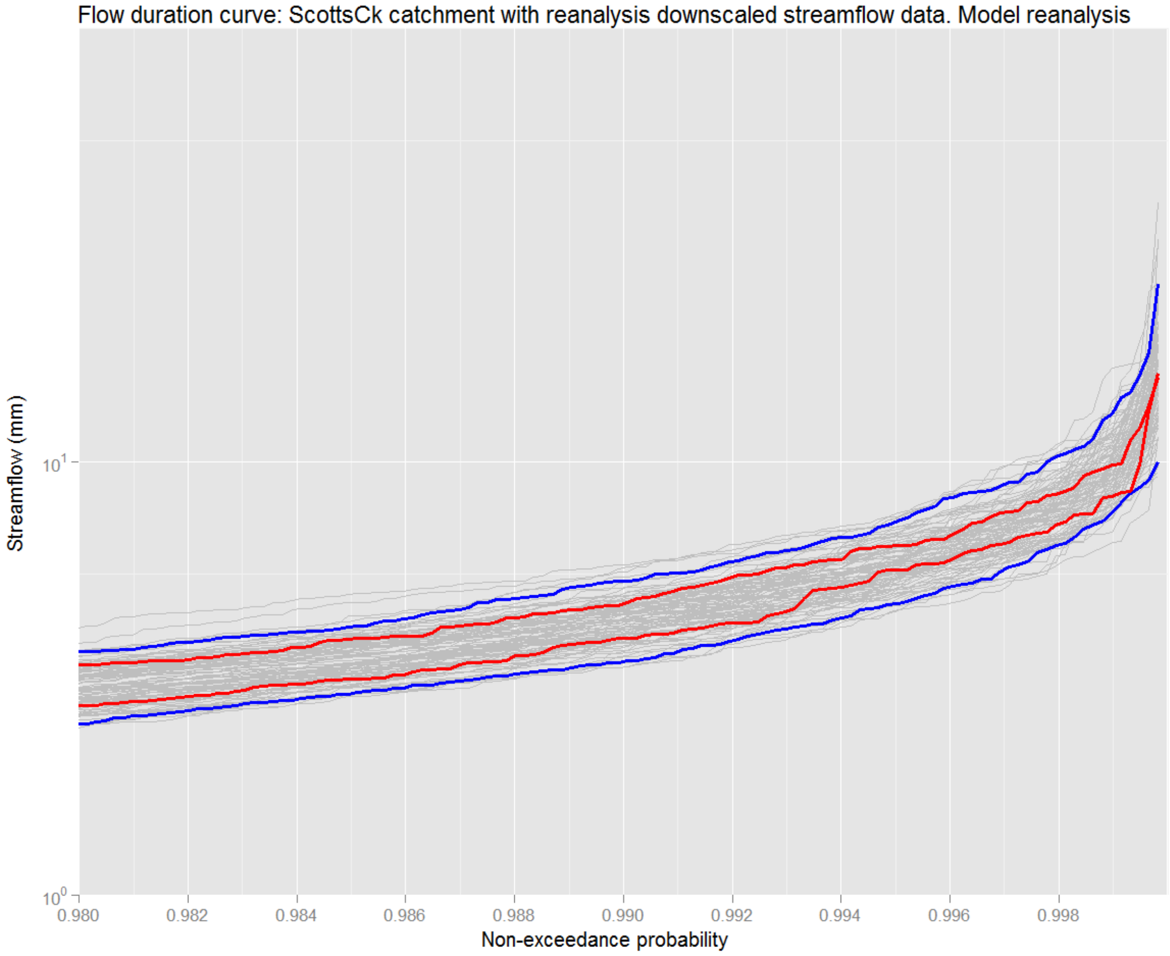



**Figure 33: As per the previous figure but only for the top 2 percentile.**

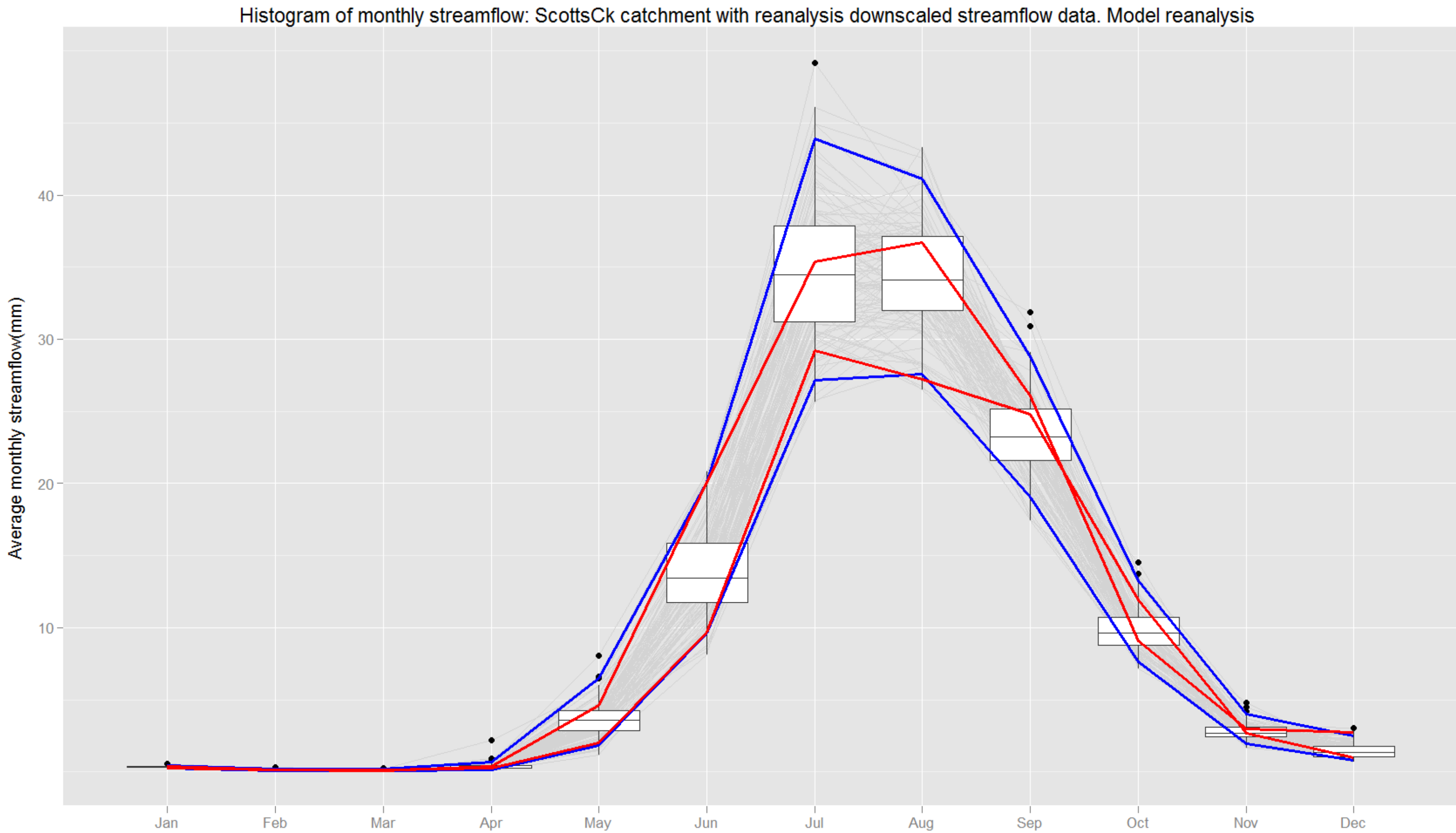
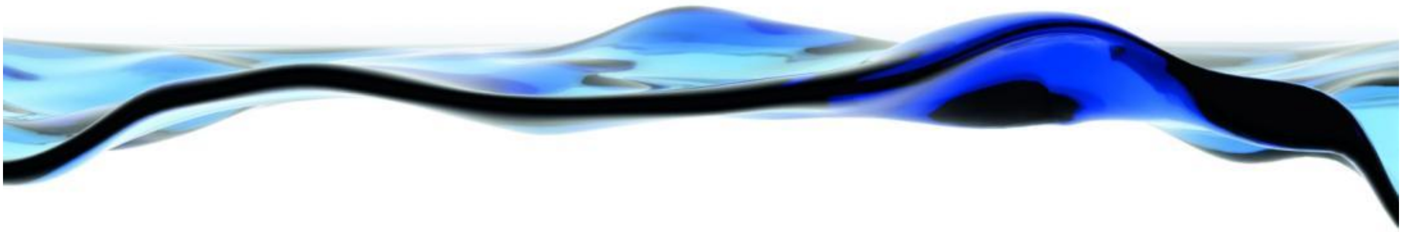



**Figure 34: Monthly average streamflow from the 100 reanalysis simulations. Blue lines are the 5th and 96th ranked values calculated separately for each month. Red lines are the monthly flows from the 5th and 96th ranked simulations calculated based on annual average rainfall.**



The Goyder Institute for Water Research is a partnership between the South Australian Government through the Department of Environment, Water and Natural Resources, CSIRO, Flinders University, the University of Adelaide and the University of South Australia.