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# Uncertainties in runoff projections in southwestern Australian catchments using a global climate model with perturbed physics

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SUMMARY

Future projections of water supply under climate change scenarios are fundamental for efficient water resource planning. However, runoff projections are affected by uncertainties in the modelling process that limit their utility to decision makers. The main source of uncertainty in runoff projections are the Global Climate Models (GCMs) used to produce future climate projections. The impact on projected runoff of this uncertainty has mainly been assessed through comparison of multi-model runs of future climate with little exploration of uncertainties inside the models due to different parameterisations. Here we investigate the uncertainty response of projected runoff due to perturbed physics parameter variations within a GCM using a novel 2500 member ensemble from the HadCM3L model. Our research evaluates the uncertainties in runoff modelling for southwest Western Australia, a Mediterranean climate region which has experienced reductions in precipitation during the last decades. Results for future projections in southwest Western Australian catchments indicate reductions in modelled precipitation between 0% and 40% and increases in temperature that fluctuate between 0.5 °C and 3 °C by 2050–2080 compared to 1970–2000, which lead to reductions in projected runoff of between 10% and 80%. This range of uncertainty for projected runoff is larger than that calculated for previous estimates of within-model uncertainties of runoff. The perturbed physics approach indicates that current water management assessments underestimate uncertainties in runoff projections.



## 1. Introduction/background

Uncertainties in the modelling of the climate system and thus in projections of future changes (Deser et al., 2012, 2014; Hawkins and Sutton, 2009, 2011; Kang et al., 2013; Tebaldi and Knutti, 2007) and their impact on hydrology are an active area of research (Peel and Bloschl, 2011; Peel et al., 2015). The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) (Stocker et al., 2013) includes a review of the main uncertainties in the understanding of the climate system and identified them as crucial in climate change analysis. The IPCC recognized that uncertainties in projections of natural forcing, simulations of clouds in atmosphere–ocean coupled general circulation models (AOGCMs) along with resolution issues in modelling the climate limit the skill of projections on both global and regional scales.

The main source of uncertainties in runoff modelling of future climate arises from the predictions of climate variables (Ardoin-Bardin et al., 2009; Chiew et al., 2009, 2008; Prudhomme and Davies, 2008a; Xu et al., 2011), such as precipitation and temperature. These uncertainties can be partitioned in three groups: the internal variability of the climate system, the model uncertainty, or uncertainties in the Global Climate Models (GCMs) and the scenario uncertainty (Hawkins and Sutton, 2009, 2011). However there are also uncertainties associated with the downscaling and bias correction techniques used to translate the coarse data from the GCM scale to the regional scale of the runoff models, and also in the hydrological model used to simulate runoff.

Quantifying GCM uncertainties is computationally expensive. Currently, two main approaches have been used to assess the uncertainties in GCM analyses: between-GCMs and within-GCMs analysis (Parker, 2013; Peel et al., 2015). The IPCC assessments and the GCMs run in the Coupled Model Intercomparison Project Phase 3 (CMIP3) and Phase 5 (CMIP5; Taylor et al. (2009)) are the main sources of data that researchers have used in multi-model or between-GCMs analyses of uncertainties in climate modelling. An alternative approach employs a "perturbed physics" analysis which explores the impact of parametric uncertainty in climate modelling. This involves using the same model but

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changing in each simulation a selected set of the parameters that characterize the model physics (Parker, 2013), giving an estimate of the range of possible projections from a single model that might be produced by a plausible range of values of the adjustable parameters within the model. This represents what we define here as "within-GCM" uncertainty when combined with uncertainties due to internal variability and initial conditions. This project uses Climateprediction.net data, which is the largest freely available source of climatic data that explores within-GCM uncertainty using perturbed physics. In the Climateprediction.net experiment the model parameters that represent the atmospheric and ocean physics and the sulphur cycle were perturbed between their minimum and maximum plausible values to obtain an ensemble of different parameter values that were then used to create a large ensemble of model runs (Frame et al., 2009).

Within-GCM uncertainties have so far been assessed through statistical methodologies such as bootstrapping techniques (Prudhomme and Davies, 2008a,b), stochastic generation of data (Peel et al., 2015) and hierarchical modelling and Markov chain Monte Carlo simulation techniques (Bastola et al., 2011; Nawaz and Adeloye, 2006). These methodologies involve the generation of multiple replicates of the time series of the climate variables, precipitation and temperature, in which ideally each run has slightly different initial conditions and different trends, all of them physically plausible.

So far, hydrological assessments of climate change have mainly explored the impact of between-GCM uncertainties in runoff modelling. In particular in Australia, CMIP3 model results have been directly used to assess changes in water supply in southwest Western Australia (SWA) (Silberstein et al., 2012) and in southeast Australia (Chiew et al., 2009), and concluded that uncertainties between GCMs are large, with a range of results of around 30% with respect to the median. Teng et al. (2012) compared runoff projections using CMIP3 and CMIP5 data over Australia showing that uncertainties are very large using both sets of GCM runs, and giving differences of about 50% between the 10th and the 90th percentile of projections.

Regarding within-GCM uncertainties, Peel et al. (2015) stochastically replicated precipitation and temperature data from 5 CMIP3 GCM runs 100 times to approximate them for 17 worldwide catchments. The 100 stochastic replicates were passed through a hydrologic model and the standard deviation of the mean annual runoff (MAR) as a percentage of the mean MAR was on average 10.1%, which translates into an uncertainty in MAR of ~20% (2 standard deviations) for each GCM. However, Peel et al. (2015) indicated that their results are likely to underestimate the true within-GCM uncertainty because they only stochastically replicated the noise around the GCM data trend, not the trend itself.

In contrast, perturbed physics experiments allow the generation of simulations of climate variables with different initial conditions and also different trends, all of them physically plausible. To date, there have not been any hydrologic assessments that explore within-GCM uncertainties using the perturbed physics approach. This paper aims to establish the impact on runoff of perturbed physics in a multi-thousand member ensemble of GCM runs with gradually increasing projections of greenhouse gas concentrations (a so-called "transient" experiment). We seek to quantify the true within-GCM uncertainty in runoff projections, used in water availability climate change impact assessments, through the novel approach of using a GCM with perturbed physics. We aim to compare true within-GCM uncertainty from CPDN projections against current approximate statistical approaches or multi-model ensembles. In particular, it is of interest to study these uncertainties in runoff projections in SWA, a region that has already experienced negative trends in precipitation, and where future water resources are endangered (Hennessy et al., 2007).

The IPCC Fifth Assessment Report (AR5) (Stocker et al., 2013) details studies that project significant decreases in precipitation for the period 2081–2100 compared to 1986–2005 in the Mediterranean climate regions of the southern hemisphere; Central Chile, South Africa and SWA (Moss et al., 2008). Current warming trends and future projections of climate variables may impact water resources with important consequences for ecosystems, agricultural and domestic water supply. The present work presents results for southwest Western Australia, due to the current negative trends in precipitation and the projections of drier conditions for this area, however this methodology can be extended to other regions.

### 1.1. Region of analysis: Southwest Western Australia

SWA is the land area located west of 118°E and south of 32°S (Li et al., 2005), where the majority of Western Australia's population resides (Australian Bureau of Statistics, 2014). According to the Köppen-Geiger Classification (Peel et al., 2007), SWA experiences a temperate, Mediterranean climate with a dry and hot summer and wet winter. Almost 80% of precipitation occurs during May to October. Mean annual rainfall in SWA ranges from 500 mm in the north to 1230 mm in the southern coastal area (Silberstein et al., 2012).

Precipitation in this region is driven by mid-latitude frontal systems associated with the position of the subtropical ridge. This centre of high pressure moves northward (north of SWA) in winter months (after May), and then moves southward during spring months (Charles et al., 2010). In winter months, when the centre of high pressure lies to the north of SWA and the SAM (Southern Annular Mode) is in its negative phase, synoptic features and cold fronts can reach SWA, thus increasing precipitation events. A negative trend in SWA winter precipitation since the mid 1960s has been observed by several researchers (Allan and Haylock, 1993; Ansell et al., 2000; Cai and Cowan, 2006a), while some others identify the shift starting in the mid 1970s (Charles et al., 2010; Frederiksen and Frederiksen, 2007; Hennessy et al., 2007; IOCI, 2012; Petrone et al., 2010; Timbal, 2004). The observed reduction in precipitation after the shift is estimated as being between 10% and 15% (Charles et al., 2010). One of the likely causes of the reduction in precipitation is the positive trend in the SAM (Allan and Haylock, 1993; Cai and Cowan, 2006b; Delworth and Zeng, 2014; IOCI, 2002). Using a K-means algorithm to cluster rainfall patterns, Raut et al. (2014) showed that the positive trend in SAM is linked to the reduction of the frequency of strong fronts in June, and the presence of weak fronts in June–July. These two features account for a half and a third of the total reduction of rainfall in winter months (June–July–August) respectively when the El Niño Southern Oscillation Phenomenon (ENSO) is neutral. Regarding climate change projections, according to Silberstein et al. (2012), based on an ensemble of 15 GCMs, a median decline of 8% in rainfall is projected for SWA by 2030 compared to precipitation between 1975 and 2007, which leads to a reduction of 25% in streamflow. Given this background, we have focused our attention on projections of runoff in this region, mainly interested in quantifying how uncertain the projections are when estimated from a GCM with perturbed physics.

As climate is a fundamental driver of water availability, the impacts of climate change on water resources and in particular the uncertainties in the projections of runoff are a fundamental area of study. In this paper we present a methodology to analyse uncertainties in runoff modelling using a perturbed physics ensemble from one GCM, which is a novel data set that represents the within-GCM uncertainties. We present a plausible range of runoff projections over three catchments located in SWA, using a multi-thousand ensemble of the GCM with perturbed physics.