GCM and downscaling uncertainty in modelling of current river flow: why is it important for future impacts?

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Abstract This paper compares the uncertainty in flow simulation due to the modelling of precipitation (using three global circulation Models, GCMs, and two downscaling techniques) with the current natural flow variability in three catchments in Scotland. The reference daily flow series, obtained by running a calibrated continuous rainfall–runoff model with observed catchment rainfall and potential evaporation, is compared with simulations from a range of different precipitation scenarios, representative of the climate modelling uncertainty and current natural variability. Results show that the natural variability can be large and differs from one catchment to another. The reproduction of climate variability from different GCMs is not always within this natural variability and there is some regional variation in the GCMs' and downscaling techniques' ability to reproduce the current climate. The uncertainty due to GCMs is consistently larger than that of downscaling techniques.

Key words climate change impact; downscaling; GCM; RCM; SDSM; uncertainty

INTRODUCTION

Climate change impact studies on water resources focus on quantifying changes between current flow and simulations using scenarios of future climate. Climate scenarios are generally provided by global climate models (GCMs), based upon the fundamental laws of physics and are at present the best and most robust tools for assessing the response of the climate system to changes in radiative forcing. However, the ability of the GCMs to reproduce current climate is rarely assessed despite their known deficiencies (e.g. Hulme *et al*., 1999). A number of limitations affect GCMs, including their limited spatial detail, that prevent GCMs from successfully simulating short time scale variability. Techniques that downscale GCM outputs to scales appropriate for climate change impacts assessments, such as dynamical and statistical techniques (e.g. Wilby *et al*., 1998; Trigo & Palutikof, 2001), have been developed to fill this gap. This paper describes a methodology to assess current climate variability from GCMs and downscaling methods and illustrates how to define the significance of potential bias.

METHODOLOGY

Estimation of natural climate variability

Maritime climates such as observed in the British Isles are extremely variable at all scales, with inter-annual climatic variability particularly significant (Wheeler & Mayes, 1997). A simple methodology of block resampling with replacement is used to define natural climate variability in this paper. The resampling procedure randomly selects 3-month blocks from the original series (respecting the annual sequences) to create a new series of equal length. This use of observed data avoids any systematic bias which could otherwise exist (Arnell, 2003). Here, 99 new series were produced, providing a set of 100 scenarios including the observed series. Natural variability is shown in grey in the figures. The same methodology was used to create GCMs and RCMs (Regional Climate Model) scenarios.

Global climate models

The outputs from the following three GCMs were selected for the availability of their simulations at the daily time scale[1]: HadCM3 from the Hadley Centre for Climate Prediction Research (Met. Office, UK), CGCM from the Canadian Centre for Climate Modelling and Analysis (CCCMA, Canada), and CSIRO-mk2 from the Commonwealth Science & Industrial Research Organisation

[1] Data available from the IPCC Data Distribution Centre gateway http://ipcc-ddc.cru.uea.ac.uk/

(CSIRO, Australia). Here, GCMs ability to simulate current climate variability is only assessed through the analysis of river flows.

Downscaling techniques

Two downscaling methodologies were considered: dynamical downscaling, based on physical/ dynamical links between the climate at the large scale and at smaller scales; and statistical downscaling, that uses empirical relationships between large-scale atmospheric variables and observed daily local weather variables (e.g. rainfall). Sensitivity to downscaling techniques was only considered for rainfall series (Potential Evapotranspiration (PE) series are the resampled observed series).

Statistical downscaling: the model used here, Statistical DownScaling Model (SDSM)[2], is a hybrid between regression-based and stochastic weather generation techniques (Wilby *et al.*, 2002). NCEP/NCAR re-analysis data[3] were used to identify the best variables to predict daily rainfall and to calibrate the models. Twenty separate runs were made for each GCM, thus providing some element of climate variability for the current time horizon (1961–1990). A block resampling produced five resampled series for each run, thus totalling 100 resampled series for each GCM.

Dynamical downscaling of data from the Hadley Centre's Regional Climate Model, HadRM3H was used as an example of dynamical downscaling. HadRM3 is driven directly from the HadCM3 simulations and was developed to provide spatially-detailed scenarios over Europe. The daily output series for the 1961–1990 time horizon were block-resampled to produce 100 series representative of the HadRM3 current climate variability. Dynamically downscaled outputs of the two other GCMs were not available to us and thus could not be analysed.

Construction of scenarios

Reference value and calculation of changes Reference values are derived from daily flow series simulated with observed rainfall and PE, to eliminate bias due to hydrological model errors. For each flow series simulated from a different scenario, the mean monthly flow was calculated and the difference with the reference value expressed as a percentage.

Uncertainty For a given month, the uncertainty is represented by the range comprising 90% of the simulated monthly flow (or 90% Confidence Interval CI) using the 5% and the 95% points of the 100-resampled scenarios from the same technique, either the combination of GCM and down-scaling method (whisker boxes in Figures) or 100-resampled observed series (natural variability).

DATA AND HYDROLOGICAL MODEL

Case study and data

The methodology is applied to three catchments in Scotland so that regional characteristics can be explored (Fig. 1). The Feugh and the Eden are located in the eastern part of the Grampian and Fife regions and have a mixed regime with responsive flows but significant baseflows. The White Laggan Burn is a very small catchment in Galloway exposed to high annual rainfall typical of western Scotland. It has a very responsive regime characterized by a low base flow index (BFI) (Table 1). River flow data were obtained from the UK National River Flow Archive maintained by the Centre for Ecology and Hydrology. Catchment average daily precipitation time series were derived using the UK Meteorological Office daily rainfall library and a simplified version of the Triangular Planes interpolation method described by Jones (1983). PE data were obtained from the Meteorological Office Rainfall and Evaporation Calculation System (MORECS) database (Holmes *et al.*, 2002).

Hydrological model

The hydrological model used is based on the Probability Distributed Model theory (Moore, 1985) that represents the catchment soil storage capacity as a probability distribution and has two

[2] SDSM can be downloaded at https://co-public.lboro.ac.uk/cocwd/SDSM/IDLogin.html
[3] http://www.cdc.noaa.gov/cdc/reanalysis/reanalysis.shtml

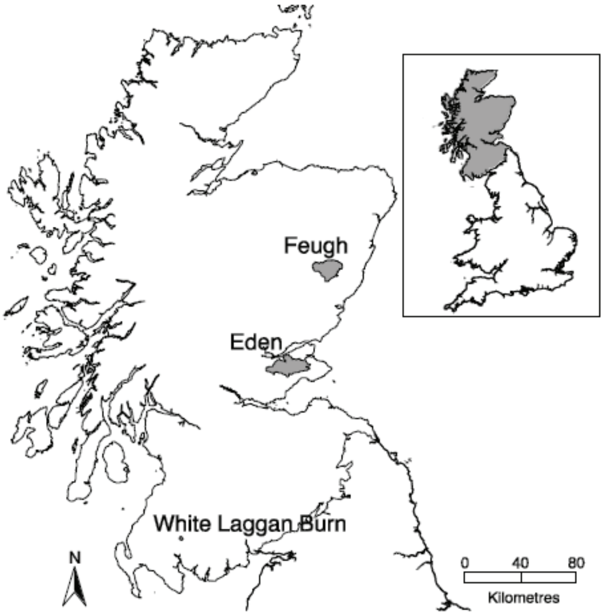

Fig. 1 Location of case study catchments.

Table 1 Case study catchments and their characteristics under current climatic conditions (from Marsh & Lees, 2003).

NWA ID	River	Station	Area (km^2)	Short description	BFI	Mean annual rainfall (mm)
12008	Feugh	Heugh Head	229	Rugged topography, moorland and pasture, granites and metamorphic rocks.	0.45	1151
14001	Eden	Kemback	307	Gently sloping, arable, sandstone, igneous and carboniferous limestone.	0.62	806
80003	White Laggan Burn	Loch Dee	6	Rugged upland with 20% forest. Granite shales and greywackes	0.19	2670

second-order linear routing reservoirs simulating quick and slow flows. The model includes an interception storage term and a soil-moisture related drainage term and has five free parameters for calibration (Young, 2006). Uncertainties due to hydrological modelling are not discussed in this paper.

RESULTS

Reproduction of climate variability by GCMs: GCM uncertainty

Potential bias in reproducing climate variability within a GCM is assessed by comparing the range in river flows simulated from SDSM-derived scenarios with that of natural variability. For the three catchments and three GCMs, the majority of the interannual variability of river flow (as described by the mean monthly flow) is reproduced with a systematic bias (Fig. 2). The box plots, representing the variation captured by the climate variability of the GCM and SDSM combination, are most often on either side of the reference line, showing an overestimation (respectively, underestimation) when boxes are entirely above (resp., below) the reference value (dashed line). However, when considered in context of the natural current climate variability, only a few of these systematic biases are significant, as illustrated by CI within the grey areas.

HadCM3 generates arguably the least biased simulations of the three GCMs with the range of monthly river flow within the expected current natural variability for most of the year. However, this is not true for the Eden in summer (June to August). CSIRO-mk2 and CGCM2 both show deficiencies in reproducing current climate variability. For example, significant biases are observed using CGCM2 in summer months (underestimation) for all three sites and to a lesser extent in winter (overestimation) for the Feugh and Eden. Results using CSIRO-mk2 do not show consistent seasonal bias pattern across the region, winter flows being overestimated in the Feugh and Eden but not in White Laggan Burn, while spring flows are overestimated in the Eden and

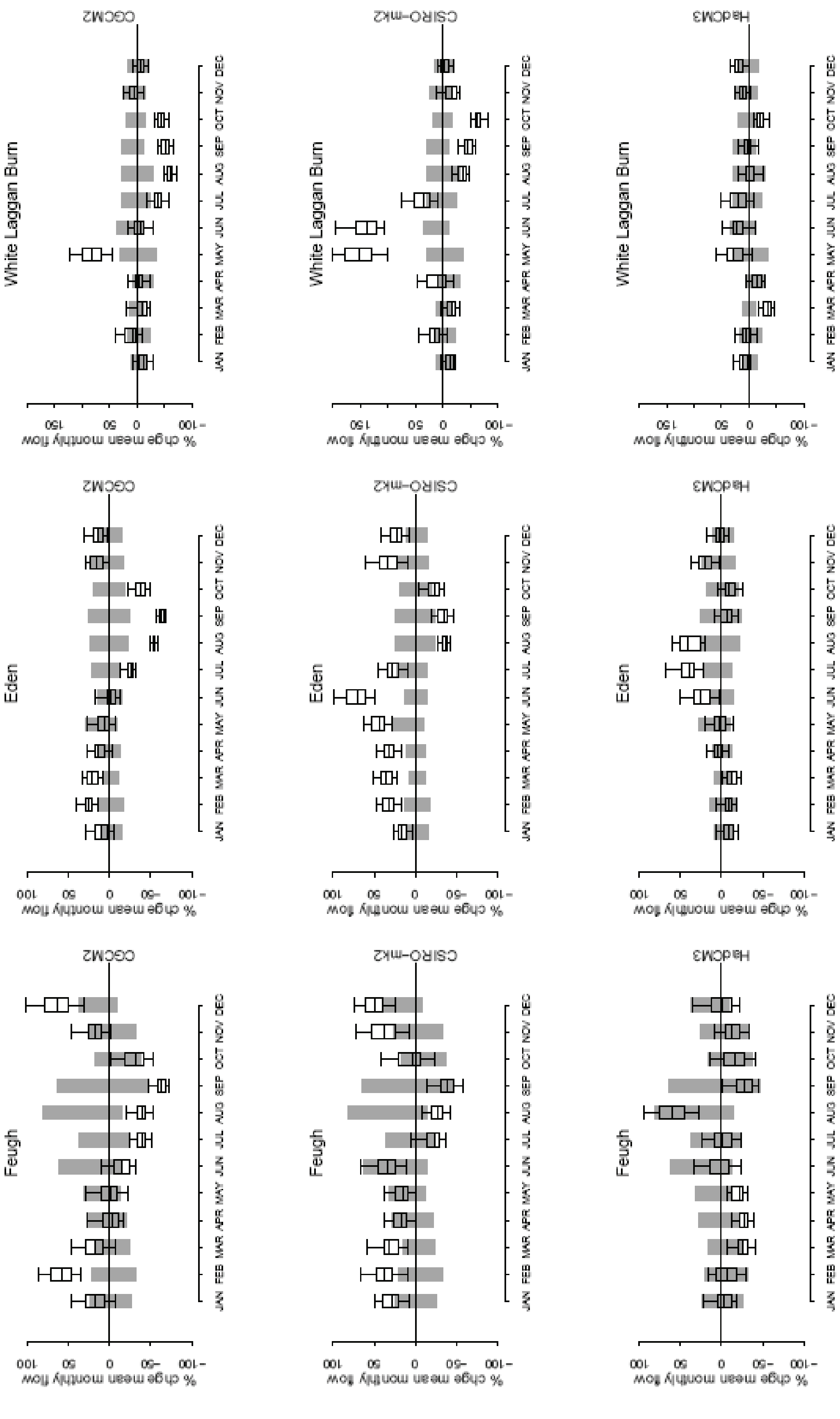

Fig. 2 Reproduction of climate variability by GCMs: monthly river flow confidence intervals from SDSM-downscaled outputs from HadCM3 (top line), CSIRO-mk2 (middle line) and CGCM2 (bottom line) for the Feugh (left), Eden (middle) and White Laggan Burn (right). Grey areas are 90% confidence intervals of current natural variability; Box plots show (from bottom to top) the 5th, 25th, 50th, 75th and 95th percentiles of the 100 simulated series.

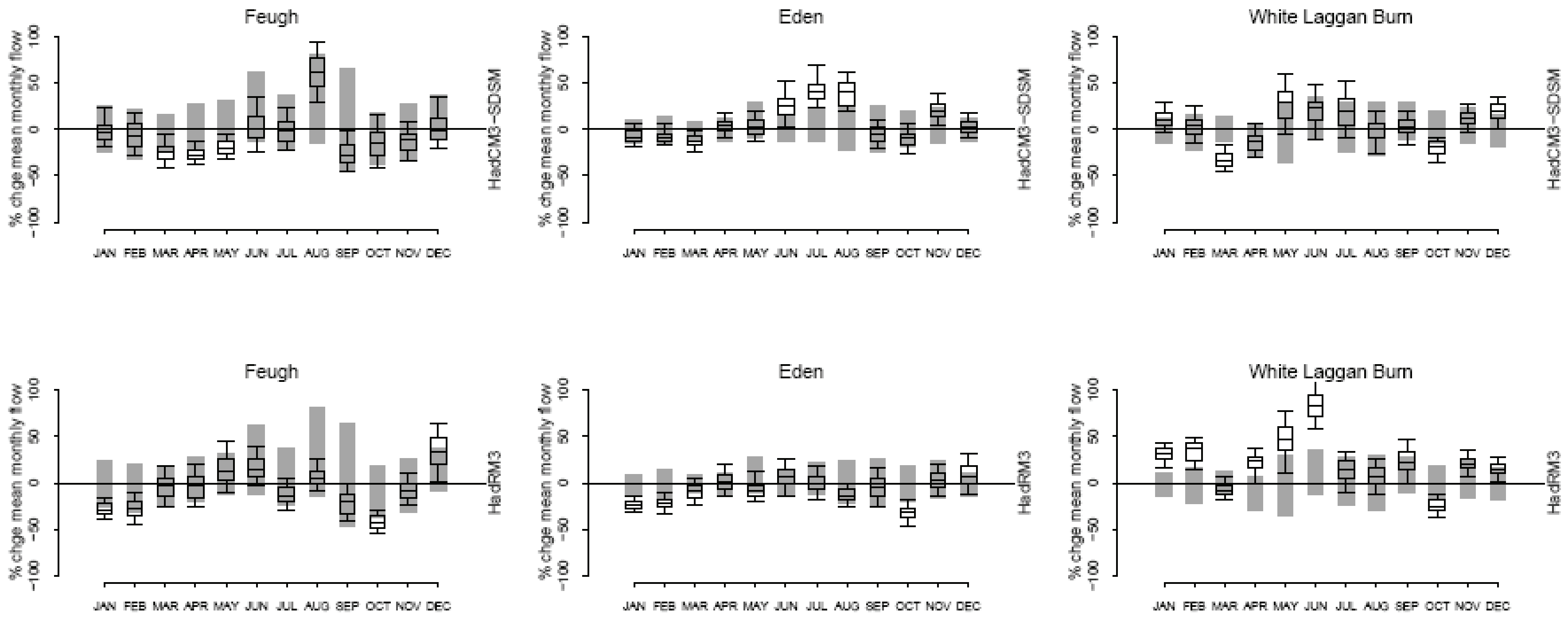

Fig. 3 Sensitivity to downscaling techniques: monthly river flow confidence intervals from HadCM3 outputs downscaled using SDSM (top line) and RCM (bottom line) for the Feugh (left), Eden (middle) and White Laggan Burn (right). Grey areas are 90% confidence intervals of current natural variability; Box plots show (from bottom to top) the 5th, 25th, 50th, 75th and 95th percentiles of the 100 simulated series.

White Laggan Burn, but not the Feugh. Summer flows tend to be underestimated for all sites, but not by the same magnitude in the same months. The ability of GCMs to reproduce correctly current climate variability is not the only factor linked to the results presented in this section. The quality of fit of the SDSM equations and the presence of unusual events in the observed series are elements that could affect the reproduction of the current climate variability and subsequent river flow regime.

Sensitivity to downscaling technique

Sensitivity to downscaling techniques is based on comparing flow series using the 100 resampled scenarios from GCM outputs either downscaled using SDSM, or using the HadRM3 RCM model. The use of two downscaling techniques introduces some uncertainty: the presence or significance of bias is not always similar when the HadCM3 outputs are downscaled with SDSM or through HadRM3 (Fig. 3). For example, SDSM leads to significant overestimation of summer flows (June to August) in the Eden, while river flows remain within the natural variability when using HadRM3. In the White Laggan Burn, winter flows are significantly overestimated when generated using HadRM3 but not when using SDSM-downscaled outputs. Results in the Feugh show similar ranges from both techniques for most of the year (only spring flows are underestimated with SDSM). From the limited sample, no one technique shows better results or any apparent systematic bias for any season. This highlights the difficulty in developing a general methodology that fits all, and uncertainty to downscaling methodology should be considered on a case-by-case basis.

CONCLUSION

The results presented here are from a very limited sample of three catchments in Scotland, three GCMs and two downscaling methodologies, and are not a comprehensive assessment of the skills of GCMs in general or these GCMs in particular. However they illustrate important generic problems arising from the use of GCM outputs in impact assessment. Regional variation in GCM uncertainty is apparent (e.g. Feugh and Eden) and the results are thus only valid for individual catchments and cannot be generalized even at the regional level. Each GCM reproduces the current hydrological regime with variable ability and no GCM was shown to be significantly better nor to have a systematic seasonal bias smaller than the others. Additional uncertainty due to downscaling exists and varies in magnitude from one catchment to another. Despite its flexibility of use, SDSM was found to perform neither better nor worse than HadRM3. Uncertainty due to GCMs, however, is consistently larger than that of downscaling techniques for all three test sites. The existence of a significant bias in reproducing current natural variability and subsequent river flow variations was only assessed from changes in the rainfall series. For a complete sensitivity analysis, biases in modelled PE should be compared with errors introduced by the hydrological modelling.

It is essential that any systematic bias is understood when interpreting the potential impact of climate change as such biases are likely to transfer to the simulations of future flows. Comparing future projections with reference values may result in misleading conclusions if the existing bias in the modelling of the current climate is ignored. While GCMs remain the best tool for providing future water resource scenarios, assessing and allowing for their limitations is a challenge for the hydrology community in particular, and climate change impact researchers in general.

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