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QUANTIFYING GCM SIMULATION UNCERTAINITY AND INCORPORATING INTO WATER RESOURCES ASSESSMENT

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Rainfall and temperature, simulated using Global Climate Models (GCMs), serve as a key inputs for hydrological models in studying catchment response to climate scenarios. GCM simulations of rainfall and temperature, however, are uncertain due to model structure, scenarios and initial conditions, which results in biased outcomes if used for impact assessment without due consideration of the uncertainties. In this study, we quantify uncertainties involved in GCM rainfall and temperature simulations as well as illustrate its application for water resource assessment in two case studies. In the first case, global future drought is estimated using Standard Precipitation Index (SPI) with due consideration of the GCM simulation uncertainties. The results suggest that consideration of the simulation uncertainties in drought assessment is vital, as drought values with and without considering the uncertainties are significantly different. In the second case, an error model is proposed to generate precipitation and temperature realizations, which are used to simulate streamflow and reservoir storage in Warragamba catchment in Australia. It is found that large uncertainty is propagated to the estimated storages from both precipitation and temperature projections with the uncertainty from precipitation being significantly larger than temperature.

INTRODUCTION

Climate change is anticipated to intensify the global hydrologic cycle with occurrence of more-frequent and greater-magnitude extremes, such as floods and droughts [1, 2]. There is a consensus among scientists for a wet-gets-wetter and dry-gets-drier response indicating that floods and droughts may be intensified in already wet and dry areas around the world as a result of climate change [3]. Accurate prediction of such impacts of climate change, however, is difficult to make due to various uncertainties involved in the climate projections as well as conversion of these projections into response using impact assessment models.

The main uncertainties involved in climate projections are model structure uncertainty, emission scenario uncertainty as well as uncertainty as a result of internal variability [4]. Previous studies identified that model uncertainty is the main source of error compared to the other terms based on evaluation of multiple model, scenario and ensemble run simulations [5, 6]. However, these studies are particularly carried out for long term averages than shorter time scales required for water resources assessment.

To appropriately factor in these sources of uncertainties into water resources assessment, it is important to quantify the uncertainties at shorter time scale (such as, monthly). For this reason, we estimate GCM precipitation and temperature uncertainty based on square root error variance (SREV) metric developed by *Woldemeskel et al*.[7] at a monthly time-scale for historical (1960-1999) and future (2001-2099) projections. The method allows one to quantify the three sources of uncertainty as well as their total uncertainty for any GCM output variable. We then implement the estimated uncertainty for water resources assessment in two case studies. In the first case, impacts of climate change on droughts across the world is evaluated with due consideration of the uncertainties involved in the climate projections. In the second case, an assessment of future reservoir storage with evaluation of the propagation of precipitation and temperature uncertainties is carried out.

METHODS

Square root error variance (SREV)

The SREV quantifies uncertainties in GCM simulations based on multiple model, scenario and ensemble runs projections according to the following procedure [7].

i) Conversion of multiple GCM, scenario and ensemble run projections at different spatial scale to a common grid through interpolation.
ii) Correction of biases using the nested bias correction (NBC) approach according to *Johnson et al.* [8].
iii) Conversion of time series, at each grid, into their percentiles.
iv) Estimation of model, scenario and ensemble runs uncertainty at each percentile.
v) Translation of the estimated uncertainty into time series.

Estimation of GCM uncertainty, after converting the data into percentile, helps to estimate uncertainty at each time-step without making an assumption that the time series of multiple GCMs are consistent. The above procedure is used to quantify GCM uncertainty for six GCMs, three scenarios and three ensemble runs across the world, which are then used to investigate uncertainties involved in the assessment of impacts of climate change on droughts and reservoir storages, as follows.

Drought estimation

In this case study, we evaluated droughts across the world using the Standardized Precipitation Index (SPI) with due consideration of the uncertainties associated with the precipitation projections. We analyzed how drought estimates might change if the uncertainties involved in GCM precipitation projections have been taken into account. To carry out this, we applied Simulation Extrapolation (SIMEX) [9], an algorithm that estimates unbiased model parameters when input errors are known. SIMEX is used to specify gamma distribution parameters, which is used for estimating 12 month SPI. Results of drought frequency (i.e., percentage occurrence of a given SPI drought category in a certain time period) is compared before and after consideration of the uncertainties.

Reservoir storage

Whether or not the existing storage capacity of reservoirs is sufficient to meet the future water demands is a question of great interest to water managers and policy makers. Amongst other things, uncertainties in GCM precipitation and temperature projections make accurate estimation of future water availability and reservoir storage requirements extremely complicated. In this study, we propose a method that incorporates the influence of GCM simulation uncertainty on the estimation of reservoir storage. Assuming an additive error model, we generate thousands of precipitation and temperature realizations that are used to estimate streamflow realizations. The streamflow realizations are then used to estimate future reservoir storage requirements with the associated uncertainty. This is implemented for Warragamba catchment in Australia.

RESULTS

Droughts

The square root error variance (SREV) is used to estimate uncertainties associated with GCM projections using six GCMs, three scenarios (A2, A1B and B1) as well as three ensemble runs for precipitation and temperature projections. It was generally found that temperature is simulated more accurately than precipitation. Figure 1 illustrates the percentage contribution of the three sources of uncertainty (model, scenario and natural variability) to the total for both precipitation and temperature. It is shown that model uncertainty contributes about 75 % of the uncertainty while scenario and ensemble runs together contributing the remaining. The large model uncertainty indicates that the models perform poorly that a bias correction step is necessary for using GCM simulations for impact assessment. Hence, we apply bias correction before estimating the droughts using the precipitation projections.

The drought estimates based on SPI for two cases, before and after considering the uncertainties using SIMEX (i.e., pre and post SIMEX respectively) for extreme drought category are shown in figure 2. The results reveal that the drought frequency is more pronounced in the post SIMEX results than the pre SIMEX results particularly in North America, South America, North Africa and Southern Asia. This suggests that it is vital to consider GCM uncertainties in evaluating impacts of climate change on droughts.

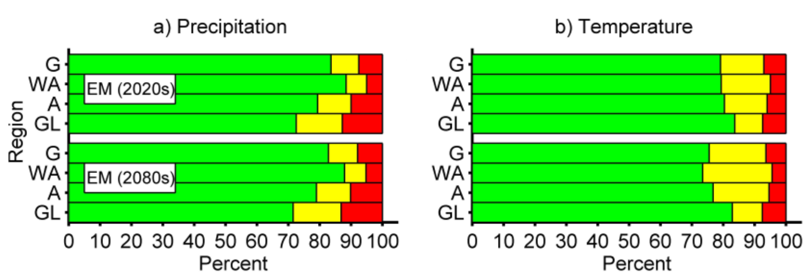

Figure 1: Contribution of model (green), scenario (yellow) and red (ensemble runs) sources of GCM uncertainties to the total uncertainy for EM (ECHAM5) GCM in 2020 (2010-2030) and 2080 (2070-2090) for differetn regions across the world. G – Global, WA – Western Australia, A – Amazon, GL – Green Land (modified from *Woldemeskel et al. 2012*).

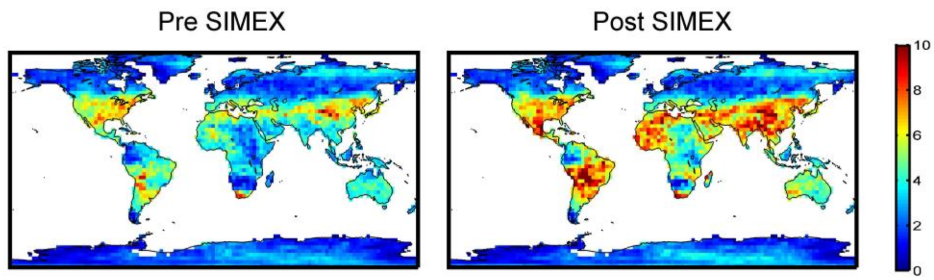

Figure 2: Extreme drought frequency (%) before (Pre SIMEX) and after (Post SIMEX) incorporating GCM uncertainties using SIMEX for ECHAM5 and A2 sceanrio.

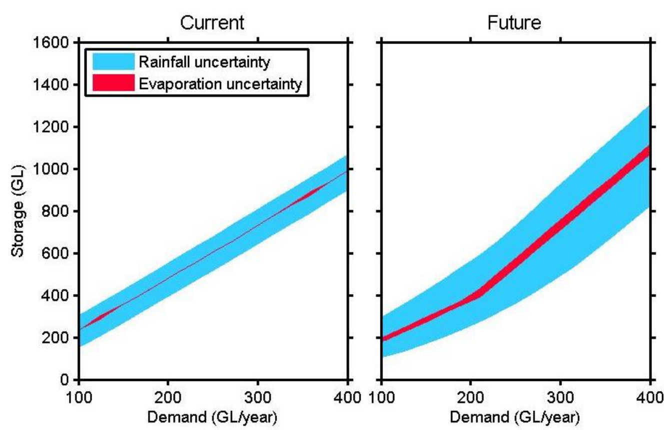

Figure 3: Storage uncertainty (5 % and 95 % uncertainity bands) originating from rainfall and evaporation for current (1960 to 1999) and future (2001 to 2099) periods for different demand levels.

Reservoir storage

The GCM precipitation and temperature projections with their uncertainties are used as an input to a nonlinear autoregressive rainfall-runoff model to generate streamflow realizations. The streamflow realizations are then used to estimate reservoir storage requirements at the Warragamba catchment (Australia) for two time periods – current (1960-1999) and future (2001-2099). As shown in figure 3, the storage requirement increases as the demand level increases. The uncertainty in the storage estimates of the future period are significantly larger than the current period. In addition, unlike the current period, larger storage is required in the future, for a similar demand level, as a consequence of climate change. The 5% and 95% uncertainty bands suggest that there is a large uncertainty in the estimated storages, which is mainly due to uncertainty propagated from rainfall than evaporation. This is not surprising as temperature (the main driver of evaporation) is simulated relatively more accurately than precipitation.

CONCLUSION

In this paper, we described an approach to quantify the main uncertainties in GCM projections. The method is used to ascertain uncertainties of precipitation and temperature. It was found that the main uncertainties in the simulations introduced from the model structural error than emission scenarios and natural variability. The estimated uncertainties are then applied for drought assessment and reservoir storage analysis. In the drought assessment, SIMEX is applied to estimate SPI parameters, which takes into account the precipitation uncertainties in the parameterization. The results reveal that considering GCM uncertainties in drought assessment is vital as the droughts with and without considering the uncertainties significantly differ especially in regions where the drought frequency is large. We also investigated the propagation of GCM precipitation and temperature uncertainty in reservoir storage estimation at the Warragamba catchment (Australia). It was found that large uncertainty propagates into the reservoir storage from both precipitation and temperature with uncertainties propagating from precipitation being significantly large. Overall, the methods to quantify GCM uncertainties and implement for drought and reservoir storage assessment in this study provide an effective platform for quantifying and incorporating climate data uncertainties in water resources assessment.

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