

Use of the Multi-Model Ensemble Mean of Global Climate Models for Hydroelectricity Generation Planning in Zambia

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Abstract – The use of Global Climate Models (GCMs), in particular their Multi-Model Ensemble (MME), in planning for hydroelectricity is essential as GCMs project possible future climate. The MME mean of 35 GCMs was used to evaluate the effects of climate change on hydroelectricity generation in Zambia over the periods 2035-2065 and 2070-2100, based on observed rainfall and temperature data from 1970-2000. The findings revealed a moderate increase in rainfall and a high rise in temperature over these periods, with reference to the baseline. These changes were projected to affect the annual water balance through the reduction in mean annual water discharge, essential for runoff, indicating a substantial reduction in future hydroelectricity generation in Zambia.

Keywords – Climate Change, Global Climate Models, Hydroelectricity, Multi-Model Ensemble, Water Discharge

Introduction

Hydroelectricity can be generated by means of impoundment, using a dam to store runoff from river water in a reservoir; run-of-river, also known as a diversion which depends on actual river flow; or through pumped storage. The amount of river runoff and water held by reservoirs are heavily dependent on the balance of rainfall, temperature, and evaporation, which are all affected by changes in the global and regional energy balance. Blackshear, *et al.* (2011) and Kusangaya, *et al.* (2013) underline the strong positive relationship between runoff and hydroelectricity generation, emphasising that future changes in rainfall and temperature are likely to have grave effects on river systems and eventual discharge. Naturally, changes in rainfall and temperature have a direct effect on the amount of evapotranspiration and the eventual quantity of runoff. Harrison, *et al.* (1998) further point out that, higher temperatures lead to increased evapotranspiration levels, e.g. reservoir evaporation, which may affect hydroelectricity production. These assertions raise the concern on vulnerability of hydroelectric power schemes to the effects of climate change and variability. The Intergovernmental Panel on Climate Change (2001) classified Southern Africa as one region highly susceptible to these impacts, mainly due to the regions over 60% dependency on hydroelectricity, coupled with the its enormous hydropower potential through the Congo and Zambezi River Basins. A justifiable and reliable means of assessing future hydroelectricity generation potential in view of impending climate change is thus necessary. Assessment of hydroelectric power potential has previously solely relied on historic rainfall and river flow data (Harrison, *et al.*, 1998). However, in the face of climate change, relying on historic data alone to plan for hydroelectricity generation is inappropriate. More reliable approaches are

being utilised in this regard. These make use of Global Climate Models (GCMs), which predict future climate based on various projected scenarios.

Jost & Weber (2012) explain that GCMs can reproduce historic, and simulate future, climate at global scales; forecasting variables such as surface air temperature, rainfall, wind, air pressure, and evapotranspiration. The current generation of GCMs, an ensemble of over 60 individual models, developed by the World Climate Research Programme (WCRP) comprise the fifth phase of the Coupled Model Intercomparison Project (CMIP5) (Taylor, *et al.*, 2012). Annan and Hargreaves (2011) indicate that each individual model projects different climate, based on four alternate future emission scenarios known as Representative Concentration Pathways (RCPs)¹ as developed by the IPCC. These are defined by their radiative forcings, described as an accumulation of human emissions of greenhouse gases (GHGs) from all sources, expressed in watts per square metre. Sheffield, *et al.* (2013) and Chen & Frauenfeld (2014) regard RCP8.5 as the closest to the 'business as usual trajectory', which assumes high population growth and high energy demand, without implementation of climate change policies by the year 2100, whereas generally, RCP2.6, RCP4.5, and RCP6.0 are considered less severe as they assume a substantial-to-reasonable reduction in GHG emissions over time.

Few GCM based studies on hydroelectricity in Southern Africa have utilised Multi Model Ensembles (MME) i.e. more than two models, in their climate projections over a selected area. However, Kusangaya, *et al.* (2013) and Harrison & Whittington (2002) observe that individual GCMs within a MME have been observed to predict different changes in climate over the same area, portraying high variability between them. This has necessitated the use of the MME mean, which is the average of the simulations of each model making up the MME. Pan & Zeng (2013) note that the use of the MME mean can reduce this natural variability existing across individual model simulations. Notable studies in Southern Africa, where the MME mean was used include Shongwe, *et al.* (2009), who used the mean of six models to project future rainfall trends in parts of Southern Africa; and the World Bank (2010), which made use of the mid-range of 23 GCMs to project change in runoff from the Zambezi River basin by 2030.

This paper evaluated the vulnerability of future hydroelectricity generation to climate (rainfall and temperature) change in Zambia based on the MME mean of 35 CMIP5 GCMs. The evaluation covered the period 2070-2100 (with an inclusion of 2035-2065 evaluation), under the RCP8.5 future emission scenario, against a 1970-2000 baseline period. Zambia is 99% dependent on hydroelectricity, drawing its hydropower resource from approximately 50% of the Zambezi River Basin.

¹ RCP2.6: Peak in radiative forcing at $\sim 3 \text{ W/m}^2$ ($\sim 490 \text{ ppm CO}_2 \text{ eq}$) before 2100 and decline to 2.6 W/m^2 ; RCP4.5: Stabilization without overshoot pathway to 4.5 W/m^2 ($\sim 650 \text{ ppm CO}_2 \text{ eq}$) at stabilization after 2100; RCP6.0: Stabilization without overshoot pathway to 6 W/m^2 ($\sim 850 \text{ ppm CO}_2 \text{ eq}$) at stabilization after 2100; RCP8.5: Rising radiative forcing pathway leading to 8.5 W/m^2 ($\sim 1370 \text{ ppm CO}_2 \text{ eq}$) by 2100

Methods

Records of total monthly rainfall, in mm, and mean monthly temperature, in °C, for Zambia, covering the 30 year control period (1970-2000), were obtained from the Zambia Meteorological Department (ZMD). Modelled monthly rainfall and monthly temperature data from each of the 35 CMIP5 GCMs was extracted for the control period. Each model simulation was validated against the observed rainfall and temperature to assess a models accuracy in reproducing the climatological variables observed over Zambia for the selected 30 year period. Considering the size of the CMIP5 GCM ensemble, a large variance was expected across individual model simulations. To eliminate this natural variability across the spread of models, the MME mean was obtained from the ensemble of 35 GCMs.

The MME mean for temperature and rainfall was calculated for both the control and future, using the un-weighted procedure, as applied by Tebaldi & Knutti (2014), where each model was allocated equal weighting. The MME mean became a ‘pseudo model’ for each variable, having been aggregated from the model ensemble. The mean annual rainfall (R) and temperature (T) was calculated for both the control and future period. This was done for the control period using both observed data and MME mean data; and for the future scenario using only the MME mean. Results from these computations were used to calculate the following variables to aid in estimation of the future change in mean annual water discharge.

- i. Percentage changes in mean annual rainfall and temperature between the control period and the future period:

$$\% \text{ Change in } R = ((R_P - R_O) / R_O) * 100 \quad (1)$$

$$\% \text{ Change in } T = ((T_P - T_O) / T_O) * 100 \quad (2)$$

Where, R_P and T_P are predicted mean annual rainfall and temperature, and R_O and T_O are observed mean annual rainfall and temperature respectively

- ii. Mean monthly water discharge, using the water balance equation, as applied by Yamba, *et al.* (2011):

$$Q_m = P - E \pm \Delta S \quad (3)$$

Where, Q_m is monthly discharge of water via runoff or subsurface flow, P is rainfall, E is Actual Evapotranspiration (AET), and ΔS represents the change in storage in the soil or bedrock (over time this is assumed to be constant)

AET (E) was obtained from Potential Evapotranspiration (PET), calculated using the Thornthwaite (1957) method, (*Equation 4*), as presented in Watson & Burnett (1995) eq. 19-9, and applied by Kumar, *et al.* (1987), and Ahaneku (2011):

$$PET = 1.6N_m (10T/I)^a \quad (4)^2$$

² $N_m = N/12$, where N is the mean daily duration of maximum possible sunshine hours for different latitudes; T is the monthly mean air temperature (°C); $a = (6.75 * 10^{-7}I^3) - (7.71 * 10^{-5}I^5 + 0.01791I + 0.49239)$; I is the annual heat index, computed from the monthly heat indices. For Zambia,

I is the annual heat index, computed from the monthly heat Indices:

$$I = \sum_{j=1}^{12} i_j \quad (5)$$

where i_j is computed as,

$$i_j = (T_j / 5)^{1.514} \quad (6)$$

and T_j is the mean air temperature in °C for month j ; $j = 1, \dots, 12$.

Monthly water discharge was then calculated for the observations and each of the 35 GCM simulations for both the control period, and the future time-frame. The mean annual water discharge, Q_A , was then obtained by summing up all the Q_m values for each year, and obtaining the respective 30-year average. The MME mean of the ensemble of models for both the control and future was used to project the estimated percentage change in mean annual water discharge over the future time period, using this equation:

$$\% \text{ Change in } Q = ((Q_{Ap} - Q_{Ao}) / Q_{Ao}) * 100 \quad (7)$$

Where, Q_{Ap} is the predicted mean annual water discharge, and Q_{Ao} is the calculated mean annual water discharge for the control period.

the reference latitude used was 15 Degrees South. Table of N values obtained from Watson and Burnett (1995), Table 19-2, pp 436.

Results

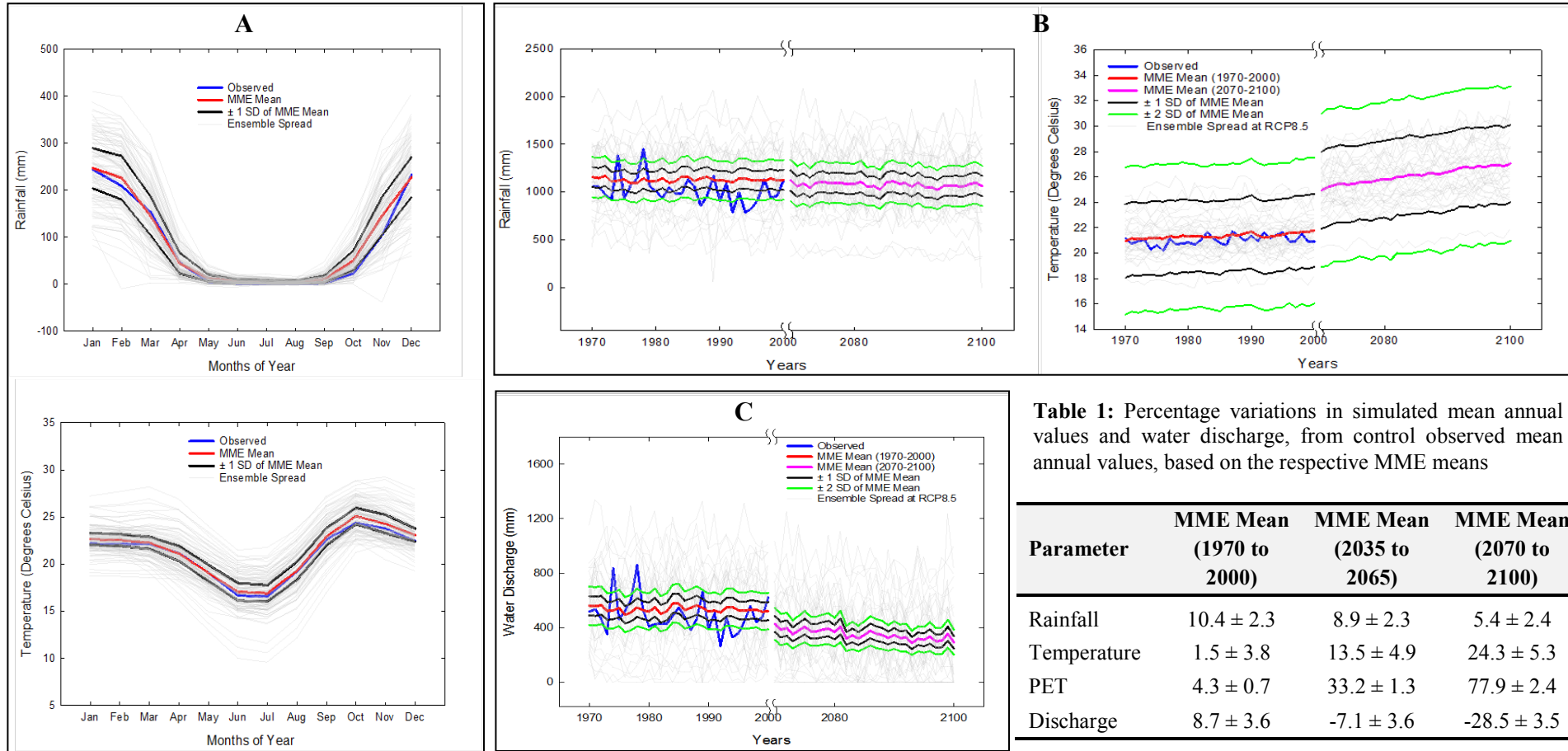


Table 1: Percentage variations in simulated mean annual values and water discharge, from control observed mean annual values, based on the respective MME means

Parameter	MME Mean (1970 to 2000)	MME Mean (2035 to 2065)	MME Mean (2070 to 2100)
Rainfall	10.4 ± 2.3	8.9 ± 2.3	5.4 ± 2.4
Temperature	1.5 ± 3.8	13.5 ± 4.9	24.3 ± 5.3
PET	4.3 ± 0.7	33.2 ± 1.3	77.9 ± 2.4
Discharge	8.7 ± 3.6	-7.1 ± 3.6	-28.5 ± 3.5

Figure A: Comparison of CMIP5 model simulations against observed rainfall and temperature for the control period (1970-2000)

Figure B: Projected changes in mean annual rainfall and temperature for 2070-2100 compared to the control period (1970-2000)

Figure C: Projected change in mean annual discharge at RCP8.5 for the period 2070-2100 (blue line represents the calculated discharge for 1970-2000)

*Note: In all figures, the grey lines represent the ensemble spread, i.e. the simulation of each of the respective 35 CMIP5 GCMs

Discussion

The results of the validation of each model against the observed rainfall and temperature revealed a variability of each projection about the observed parameters. Each model, as presented in Figure A, projected an independent simulation. Though an individual model may have replicated the observed rainfall better than other models, the same model did not replicate the observed temperature better than the others. This variability in simulations was cancelled by the MME mean (red line), which masked and replicated the observed parameters better than each model simulation.

With reference to the control period, and as seen in Figure B (for the period 2070-2100) and Table 1 (for both 2035-2065 and 2070-2100), mean annual rainfall was projected to increase by 8.9% between 2035-2065, and by a smaller margin of 5.4% between 2070-2100; whereas, mean annual temperature was projected to rise by 13.5% over the period 2035-2065 and by 24.3% between 2070-2100. This denotes a gradual reduction in rainfall, with a marked increase in temperature between 2035-2100. This projected exponential increase in temperature, coupled with an estimated decreasing trend in mean annual rainfall, leads to the preliminary conclusion that future periods would experience increased rates of evapotranspiration, which may affect the general water balance.

Mean annual water discharge, as presented in Figure C, was projected to decrease by approximately 28% between 2070-2100, a higher than the 7% reduction (Table 1) in water discharge estimated for the period 2035-2065 from the control period. Given the projected future increase in rainfall, a plausible conclusion would be a corresponding increase in annual water discharge. However, this calculated reduction in water discharge could be attributed to the interaction between other factors such as temperature and evapotranspiration. This assumption is backed by Nyambe & Feilberg (2009), who observe that due to high temperature and high evapotranspiration rates, Zambia has a rainfall deficit of between 100 mm to 1,100 mm, leading to high evaporative losses mainly from large reservoirs. This projected decrease in mean annual water discharge draws the conclusion that future hydroelectricity generation in Zambia under the RCP8.5 scenario will be negatively affected, owing to reduced runoff for both run-of-the-river and reservoir storage, as well as increased evaporation that will affect reservoirs.

Conclusion

The projected decrease in mean annual water discharge in Zambia over the years 2035-2100 denotes a negative effect on hydroelectricity generation. Though the use of the MME mean masked the changes in variability of each model, it was essentially applied to reduce this inherent variability in the large ensemble, and project one simulation. Further, although only rainfall, temperature and PET were utilised, leaving out other important factors, the findings are critical to future hydroelectricity planning.

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