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Assessment of climate change impact and comparison of downscaling approaches: a case study in a semi-arid river basin

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Abstract. Rapid population increase, industrialization and pollution are putting a strain on available and diminishing freshwater resources. Recent climate projections suggest a drop of up to 10 % in precipitation in most of Southern Africa by 2050. The main aim of this paper is to assess the impact of climate change on water resources in a semi-arid river basin in South Africa using two downscaling approaches: statistical downscaling (SDE) and dynamic downscaling (CORDEX) approaches. Both SDE and CORDEX data were derived from the GCM simulations of the Coupled Model Inter-comparison Project Phase-5 (CMIP5) and across two greenhouse gas emission scenarios known as Representative Concentration Pathways (RCP) 4.5 and 8.5 with a spatial resolution 25 km × 25 km for SDE and 50 km × 50 km for CORDEX. Four GCM models were used for both approaches. SWAT hydrological model was run using these data for a period of 2020 to 2050. Varied results were obtained depending on the type of climate model used, but generally, the trends were similar in most cases. For SDE approach, the multi-model average showed a possible decrease in precipitation (by 14 %), a decrease in water yield (by 15 %) and an increase in potential evapotranspiration (by 10 %). For CORDEX data, the multi-model average showed a possible decrease in precipitation (up to −3 %), a decrease in water yield (up to −13 %) and an increase in potential evapotranspiration (ET) (up to +22 %). The latter is indicative of possible drought spells between rainy events. The SDE approach showed much more pronounced decrease of precipitation and water yield compared to the CORDEX approach. This difference could be attributed to the difference in spatial resolution of the two downscaling approaches. However, it is expected that the results of this study could assist in policy formulation to mitigate the negative impact of climate change in the region.

Keywords. Climate change; impact; hydrology; modelling; downscaling; South Africa

1 Introduction

Water security is reported to be one of the greatest challenges sub-Saharan African countries are facing. To ensure water security for all, freshwater must be available in acceptable quantity and quality as it is essential for health, livelihoods, ecosystems, and production (AMCOW, 2012). However, rapid population increase, industrialization and pollution are putting a strain on available and diminishing freshwater resources. The problem of water scarcity is likely to deepen according to some projected climate change scenarios. The Southern African region is projected to be generally drier by 2050 (DEA, 2013). Over the past five decades, research has shown that there is a tendency towards a rise in temperature in South Africa (MacKellar et al., 2014) where maximum and minimum temperatures have shown significant increases annually, and in almost all seasons. The frequency of annual high temperature extremes was found to have increased significantly whereas that of low temperatures have decreased significantly across the country (DEA, 2013). Past climate projection suggests that there could be a decrease of up to 10 % in precipitation in most of the Southern Africa by 2050 (Levina, 2006). Globally, it is estimated that almost 50 % the world population will be living in water stressed regions by the year 2025 (World Water Council, 2000). Furthermore, rapid population increase, industrialization and pollution are further straining the available and diminishing freshwater resources. Within this context, it is important to emphasize that development must be sustainable, adaptable and resilient to these global changes, such as climate change. The main aim of this paper is to assess the impact of climate change on water resources in a semi-arid river basin in South Africa using two climate downscaling approaches: statistical downscaling (SDE) and dynamic downscaling (CORDEX) approaches. The results of this study could assist in policy formulation to mitigate the negative impact of climate change in the region.

2 Methodology

This study is focused on a semi-arid river basin in the central region of South Africa (Free State province), known as the Modder River basin (Fig. 1). The Modder River basin has a total area of 17 366 km^2 and is located within the Upper Orange Water Management Area, Central South Africa (latitude 28°50" to 29°40" S and longitude 24°40" W to 27°00" E). The mean annual rainfall of the study area is 551 mm. The rainy season consists of January to April and September to December, leaving the months of May to August as dry winter season (Fig. 2). The highest maximum temperatures vary between 28 and 31 °C while the lowest minimum temperatures vary between −1 and 1 °C.

2.1 Climate modelling

A Global Climate Model (GCM) can provide reliable prediction information over large areas (around 1000 km × 1000 km) with vastly differing landscapes and greatly varying potential for floods, droughts, or other extreme climate events. However, Regional Climate Models (RCM) and Empirical Statistical Downscaling (SDE) can be applied over a limited area and can provide information on much smaller scales providing support for more detailed impact assessment and adaptation planning, which is vital in many vulnerable regions of the world (https://cordex.org/, last access: 15 January 2018).

Downscaled climate data at high resolution are freely available from two sources: the National Aeronautics and Space Administration (NASA) Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) and Coordinated Regional Climate Downscaling Experiment (CORDEX). The NEX-GDDP dataset contains downscaled climate scenarios derived from the GCM simulations of the Coupled Model Inter-comparison Project Phase-5 (CMIP5) and across two greenhouse gas emission scenarios known as Representative Concentration Pathways (RCP) 4.5 and 8.5. The spatial resolution of the dataset is 0.25° × 0.25° (∼ 25 km × 25 km). These datasets provide a set of global, high resolution, bias-corrected climate change projections that can be used to evaluate climate change impacts on processes that are sensitive to finer-scale climate gradients and the effects of local topography on climate conditions on finer-scales. The Bias-Correction Spatial Disaggregation (BCSD) method used in generating the NEX-GDDP dataset is a statistical downscaling algorithm specifically developed to address the current limitations of global GCM outputs (Thrasher et al., 2012). Each of the climate projections includes daily precipitation and daily maximum and minimum temperatures for the periods from 1950 to 2005 (Retrospective Run) and from 2006 to 2099 (Prospective Run). However, only the period from 2006 to 2050 is considered in this study.

Recognizing the availability of limited studies on regional climate downscaling (RCD), the World Climate Research Program established a task force to develop a framework to evaluate and possibly improve RCD techniques for use in downscaling global climate projections. This task force, in consultation with the broader scientific community, initiated a framework called the Coordinated Regional Climate Downscaling Experiment (CORDEX). The downscaled climate data from CORDEX covers the period of 1951–2100, of which 1950–2005 is for Retrospective Run and 2020–2100 is for Prospective Run, and two greenhouse emission scenarios, namely RCP4.5 and RCP8.5. The spatial resolution for Africa is reported to be 50 km grid spacing.

For comparison of these two downscaling approaches, a sub-set of four GCMs (CNRM-CM5, IPSL-CM5A-LR, MIROC5, MPI-ESM-MR) was selected based on the correlation between historical measured rainfall data and simulated historical data (Retrospective Run) for the period of 1975–2005. Daily precipitation, and daily minimum and maximum temperatures for Prospective Run of 30 years (2020–2050) were considered for both datasets. In both cases, two greenhouse gas emission scenarios (RCP4.5 and RCP8.5) were considered, which are said to be the highest priority global model simulations within CIMP5.

2.2 Hydrological modelling

The Soil and Water Assessment Tool (SWAT) is a basin scale hydrological model that operates on a continuous daily time step and is designed to predict the impact of management on water, sediment and agricultural chemical yields in ungauged catchments. The model is physically based and capable of continuous simulation over long-time periods (Gassman et al., 2007). It integrates several parameters, such as weather, surface and groundwater hydrology, soil properties, plant growth, and land management practices to model processes within a watershed (Arnold et al., 1998). In SWAT, watersheds are divided into sub-basins based on outlet points along the stream network. Each sub-basin was then divided into hydrologic response units (HRUs), which are defined as areas with homogeneous soil type, land use, slope, and management practices. Water yields are calculated for each HRUs and summed up to determine the total sub-basin outputs, which in turn contributes to the total watershed yield out-

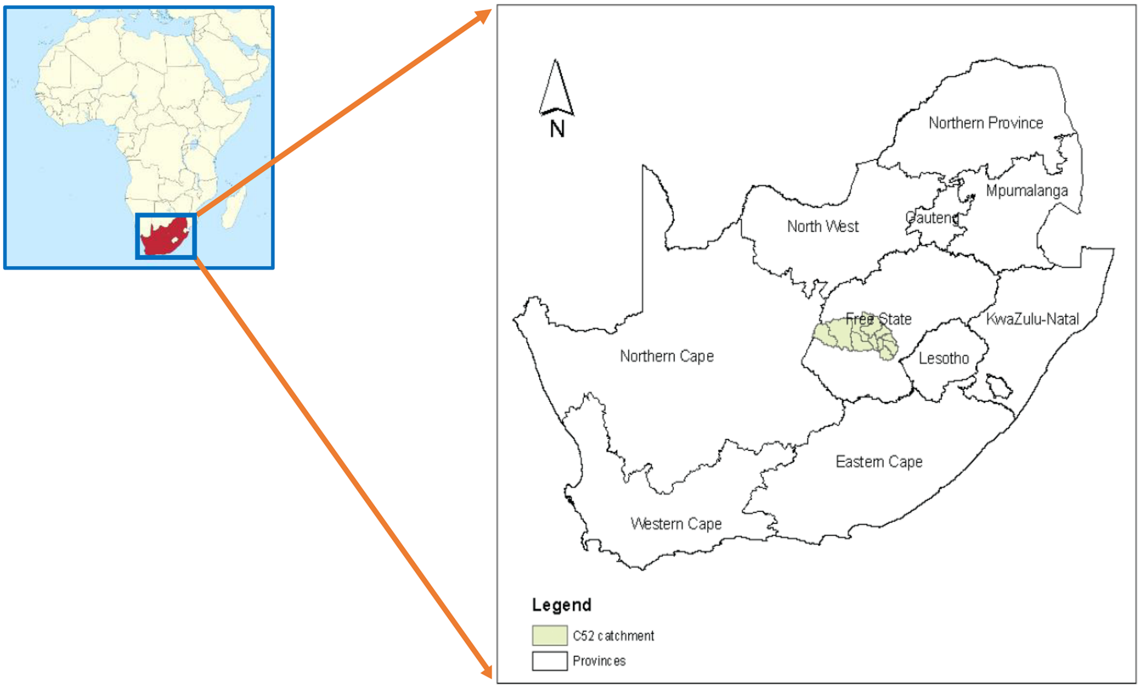


Figure 1. The study site (C52 Catchment) (© Google Maps).

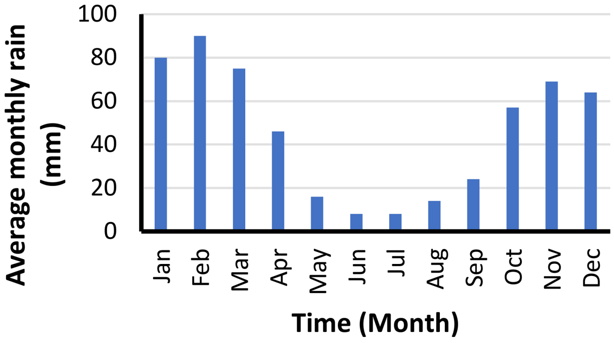


Figure 2. Long-term average monthly rainfall (1975–2005).

put. HRUs are not spatially defined within sub-basins but represented as percentages of total sub-basin area. Therefore, SWAT includes both spatially distributed parameterization at the sub-basin scale and lumped parameterization at the HRU scale (Gassman et al., 2007).

The SWAT model has been successfully applied to assess the impact of climate change and land management practices on water yields (Cousino et al., 2015; Ndlovu and Woyessa, 2020, 2021). For example, Stone et al. (2001, cited in Cousino et al., 2015) used SWAT to predict the impact of increase in atmospheric CO_2 concentration on water yield in a river basin. The authors reported that the overall water yield of the Missouri River basin will decrease by 10 %–20 % during spring and summer months but increase during the fall and winter months in response to doubling atmospheric CO_2 concentrations. Cousino et al. (2015) also used SWAT to model the effects of climate change on water, sediment, and nutrient yields from the Maumee River watershed. They reported that moderate climate change scenarios reduced annual flow (up to −24 %) and sediment (up to −26 %) yields, while a more extreme scenarios showed smaller flow reductions (up to −10 %) and an increase in sediment (up to +11 %).

In this study, the SWAT model was applied to simulate the impact of climate change on water balance components, such as runoff, water yield, evapotranspiration, and potential evapotranspiration. The model inputs are: Digital Elevation Model (DEM), land use and soil maps, daily precipitation and daily maximum and minimum temperatures (of future climate). Sensitivity and calibration analysis for parameters used in the model were carried out using SWAT statistical module during the previous study in the same river basin (Welderufael et al., 2013). Calibration was carried out on the most sensitive input parameters of the model, such as curve number, soil available water capacity, threshold depth of water in the shallow aquifer, etc. There were 13 sensitive parameters in total. In this calibration process, Nash and Sutcliffe efficiency (0.57) together with the coefficient of determination ($R^2 = 0.68$), agreement index (D-Index = 0.86), and residual mean square error (RMSE = 0.87) were used as measure of efficiency, all of which were found to be satisfactory (Welderufael et al., 2013).

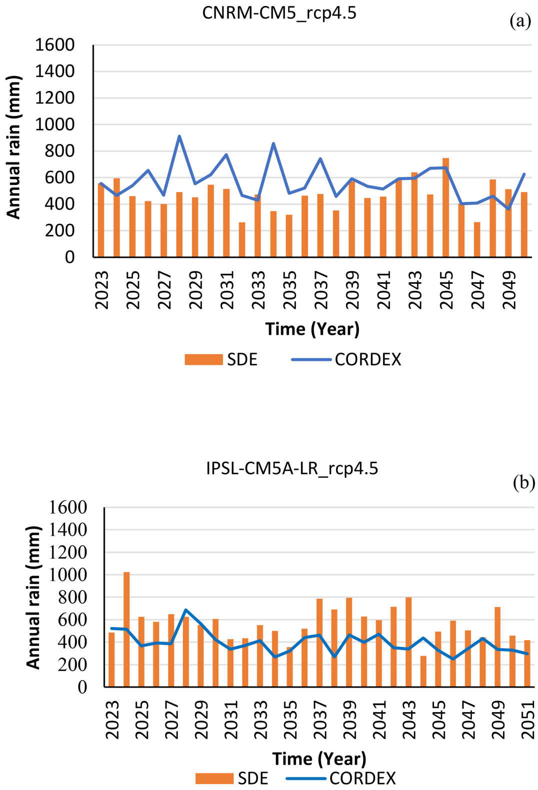


Figure 3. GCM projections of annual rainfall using the two downscaling approaches under RCP4.5 emission scenario.

3 Results and discussion

The SWAT hydrological simulation was run using future climate data based on the four GCM models (under the two downscaling approaches: SDE and CORDEX), and two greenhouse gas emission scenarios (RCP4.5 and RCP8.5). Furthermore, analysis of the GCM projections of future rainfall data was done and compared with historical measured data in order to understand the trend by 2050. Analysis of GCM projections and hydrological simulations were conducted using the four GCMs that were selected and two emission scenarios (RCP4.5 and RCP8.5) for the period of 2020 to 2050. The first two years are considered by SWAT as a warm-up period and were not considered in the simulation. The figures presented hereunder are for two GCMs and two emissions scenarios using the two downscaling approaches with the main purpose of demonstrating the long-term climate using these two approaches and the two emission scenarios. The summary of the analysis of results based on multi-model averages are provided in Fig. 5. Figures 3 and 4 show the annual rainfall trends from 2022 to 2050 using both downscaling approaches and the two greenhouse gas emission scenarios. Closer inspection of these figures shows similar trends for both approaches with a slight overestimation

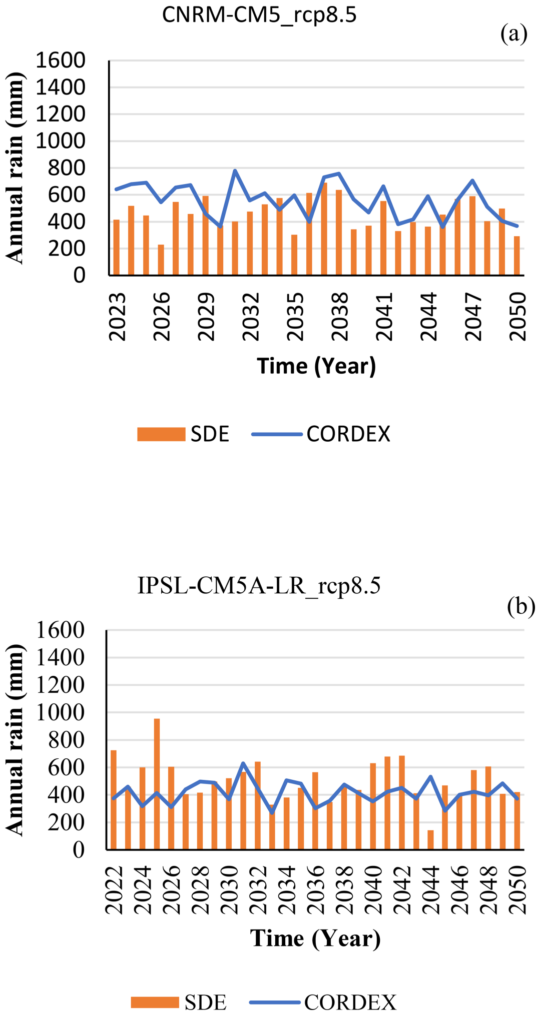
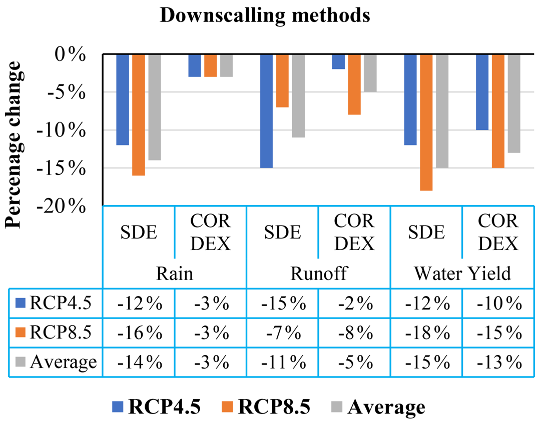


Figure 4. GCM projections of annual rainfall using the two downscaling approaches under RCP8.5 emission scenario.



	SDE	COR DEX	SDE	COR DEX	SDE	COR DEX
	Rain		Runoff		Water Yield	
■ RCP4.5	-12%	-3%	-15%	-2%	-12%	-10%
■ RCP8.5	-16%	-3%	-7%	-8%	-18%	-15%
■ Average	-14%	-3%	-11%	-5%	-15%	-13%

Figure 5. Summary of climate change impact (percentage change) on water balance components according to the two downscaling approaches (SDE and CORDEX).

using CNRM-CM5 under CORDEX approach with emission scenario of RCP4.5 and RCP 8.5 (Figs. 3a and 4a).

Figure 5 shows the summary of potential impact of climate change on future water resources availability. The SWAT model simulation was done using historical data as well as future climate data in order to analyze the expected changes in water balance components, namely rain, potential evapotranspiration (PET), surface runoff, and water yield. The PET has been analyzed using multi-model approach and was found that there will be an increase of 10 %–13 % using the SDE approach and 17 %–22 % using CORDEX.

The multi-model average shows that by 2050 there will be a reduction in rainfall, runoff and water yield by 12 %, 15 %, and 12 %, respectively for SDE under RCP4.5. However, these numbers decrease further to −16 % for rainfall and −18 % for water yield under RCP8.5. This result may not be surprising given the fact that the RCP8.5 is for high emission scenario. For CORDEX approach, slightly lower percentage change is observed but the trend is similar as one goes from RCP4.5 to RCP8.5.

4 Conclusions

Climate change impact assessment was undertaken in a semi-arid river basin in the central region of South Africa using two downscaling approaches, namely Statistical Downscaling (SDE) and Dynamic Downscaling from CORDEX under two greenhouse gas emission scenarios (RCP4.5 and RCP8.4) for a period of 2020 to 2050 using four GCMs. SWAT hydrological model was run using future climate data as input together with other biophysical data. The simulation results based on the two approaches revealed that there will be a reduction of all water balance components in general, and rainfall and water yield in particular. The multi-model average showed that there will be a reduction of rainfall by 14 % and 3 % using SDE and CORDEX, respectively. Similarly, the water yield is expected to decrease by 15 % and 13 % using SDE and CORDEX respectively. These expected decrease in rainfall coupled with increase in PET are going to be the two major drivers in exacerbating the existing problem of water scarcity in the region.

Data availability. The downscaled GCM (Global Circulation Model) data were obtained from from publicly available sources, such as Statistically Downscaled Data (SDE) from NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) (https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp, NCCS, 2017), and Dynamically Downscaled Data from CORDEX (https://cordex.org/, CORDEX, 2017).

The hydrological model used (SWAT) is a freely available model from https://swat.tamu.edu/ (SWAT, 2017).

Competing interests. The author has declared that there are no competing interests.

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