Assessment of localized seasonal precipitation variability in the upper middle catchment of the Olifants River basin

German K. Nkhonjera, Megersa O. Dinka and Yali E. Woyessa

ABSTRACT

This study used the Soil and Water Assessment Tool (SWAT) model together with regional climate downscaled (RCD) data from the CORDEX (Africa project), to assess the local seasonal precipitation variability in the upper middle catchment (UMC) of the Olifants River basin. The study results, based on two scenarios (RCP4.5 and RCP8.5), showed a wider monthly and seasonal variability of precipitation. The study also indicated a strong decreasing trend of east-to-west direction of spatial precipitation, with most precipitation concentrated in the eastern part of the study area. Within the western part of the UMC, we also noted another decreasing trend of precipitation from south-to-north with northern areas of the study area receiving the least amount of precipitation. This study has also revealed a considerable general reduction of future seasonal precipitation especially in the mid-term period (2021–2050). The general reduction in future seasonal precipitation, combined with the increasing temperatures in the area, may exacerbate the drought conditions and reduction in streamflow of the main river (Olifants) and its tributaries, consequently having a negative impact on the economic activities in the basin.

Key words | Africa, climate change, Olifants River basin, precipitation variability

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INTRODUCTION

Climate variability coupled with the understanding of climate change is vitally important as such changes have the potential to exacerbate the existing threats to human security including water, food, health, and economic insecurity, all of which are of particular concern for the continent of Africa. The impact of climate change on different sectors of life on the continent have been studied and documented rather extensively in the last few decades. Most studies (Vermuelen *et al.* 2008; Ziervogel *et al.* 2008; Davies *et al.* 2010; Madzwamuse 2010; Schilling *et al.* 2012; Niang *et al.* 2014; Warnatzsch & Reay 2018) identify Africa as one of the most vulnerable regions to future climate change due to its high exposure and low adaptive capacity. In fact, Moges (2013) argues that, many areas in Africa are already recognized as vulnerably exposed to climate change impacts also because of having climates that are among the most variable in the world both on seasonal and decadal time scales. Although most scientists say single weather events cannot be attributed to climate change, they, however, agree on the fact that climate change is responsible for most of these extreme rainfalls and storms, frequent heatwaves, shrinking harvests, and worsening water shortages in Africa and around the world (Reuters 2019).

The woes of climate change are that while one part of the continent is suffering from extreme floods, like the recent Mozambican floods (*Cyclone Idai*), other parts are languishing at the other extreme of these weather events, such as extreme droughts (UNFCCC 2007). According to the same report, one-third of people in Africa are already

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living in drought-prone areas while 220 million are being exposed to drought each year. In fact, exposure to these extreme weather events as a result of climate change, contributes to compounding the vulnerability and is already having negative effects on the continent's ability to cope with climate change variability and other threats (UNDP 2006). The complexity and uncertainty surrounding the impacts of climate change in Africa, as argued by Thornton *et al.* (2006) and Warnatzsch & Reay (2018), is one of the main challenges hindering effective adaptation planning in the continent. Examples of such challenges, according to Moges (2013), include poverty, illiteracy and lack of skills, weak institutions, limited infrastructure, lack of technology and information, low levels of primary education and health care, poor access to resources, low management capabilities, and armed conflicts. These challenges, according to UNFCCC (2007), contribute to low adaptive capacity and societal resilience to changes and an overexploitation of land and natural resources in Africa. Owing to these factors, the report continues, Africa may face increasing water scarcity and stress with a subsequent potential increase of water conflicts.

Many studies have alluded to the fact that climate change impacts on precipitation alone may have huge negative effects to all of the sectors mentioned above, simply because precipitation is the main input hydrological process in the hydrological cycle and, indeed, the main driver of the hydrological system (e.g., streamflow, groundwater recharge, etc.) over land. Earlier studies on climate change (Gleick & Adams 2000; Xu 2000) and that of Yilmaz & Yazicigil (2011), all indicated that one of the most severe consequences of climate change has been the alteration of the hydrological cycle, with negative impacts on these hydrological systems, resulting in negative effects on both quantity and quality of water resources. In most river basins, precipitation has a direct effect on groundwater recharge and river baseflow. Thus, the natural source of groundwater recharge is precipitation, in particular, rainfall and snowmelt. In many parts of Africa, groundwater is the main source of water supply. On the other hand, baseflow feeds into surface waters through streamflows and eventually dam reservoirs which happen to be the major source of water supply in most African countries, particularly South Africa. Therefore, any negative impact on precipitation in the form of precipitation variability, will eventually affect water supply, be it groundwater or surface water. It is, therefore, important to understand localized precipitation variability as it affects these water resources not only on a global or national level but also at local level where most decisions affecting water resources are carried out.

Climatic factors, such as wind and temperature make precipitation patterns very dynamic and unbalanced in space and time, leading to huge temporal variability in water resources, especially at local level (Karamouz *et al.* 2011). While studies over a broader area like the whole of South Africa or a river basin may yield good results, such results become too general and difficult to be implemented by water resources managers. Hence, the underlining importance of research targeting localized areas as compared to previous studies which, in general, are concentrated on larger basins such as the entire Olifants River basin, is that they tend to miss out localized climate variations such as precipitation which is not only important but very vital, especially where local economy is concerned. This is important since management of water resources, in South Africa as well as in most parts of the world, is based on localized hydrological units, such as the quaternary drainage basins in the case of South Africa. Therefore, it is important to concentrate scientific studies and generate research results on localized drainage areas as compared to just blanketing such studies over larger drainage basins. Also, because of the generality and broadness of such results, they tend to be crude and, in some cases, contradictory to one another, and therefore unfortunately, directly play into the hands of climate change skeptics and cynics and thereby derail climate change policy implementation in many African countries.

Due to the wide spatial climate variability, South Africa is highlighted as one of the most vulnerable countries in the world to the effects of climate change (Ziervogel *et al.* 2014). The large uncertainty around future climate change in the country, coupled with broadly based climate change studies, remains a barrier to mitigation as well as adaptation planning measures. In addition to this high potential vulnerability, relatively very limited research has gone into determining how economically important river basins such as the Olifants may respond to climate change variability both in the near and distant future. Through the use of regional climate data from the Coordinated Regional

Climate Downscaling Experiment (CORDEX) project for the Africa domain, commonly referred to as CORDEX-Africa, this study, therefore, attempts to assess the local seasonal precipitation variability in the upper middle catchment (UMC) of the Olifants River basin by considering four different periods: recent past (1960–2010), current time (2011–2020), mid-term (2021–2050), and long-term (2051–2100).

METHODOLOGY

Study area

The focus area of this study is the UMC of the Olifants River basin in South Africa (Figure 1). This area is located between latitude 24° 38′ 53″ S and 26° 37′ 45″ S, and longitude 28° 02′ 56″ E and 29° 59′22″ E. Along the Olifants River, the area stretches from the river source near Trichardt, north of Secunda, in the province of Mpumalanga just to the east of Johannesburg City, all the way past the Loskop Dam to the confluence with Elands River, just south of the Boshielo Dam (formerly known as Arabie Dam) within the Schuinsdraai Nature Reserve in the Sekhukhune District of Limpopo Province. In the east–westwards direction, it covers an area from Belabela (formally known as Warmbaths) near the N1 toll-road to the R579 road just before the Steelpoort River in the east. Hydrologically, the UMC is part of the Olifants River catchment, itself a principal sub-catchment of the Limpopo River basin. The UMC covers secondary drainage areas, B1, B2, and B3. In total, the study area has three secondary drainage areas, five tertiary drainage areas and a total of 43 quaternary drainage areas. This part of the Olifants River basin receives precipitation in the range of 600–800 mm per year, with DWAF (2004) and McCartney *et al.* (2004) reporting a mean

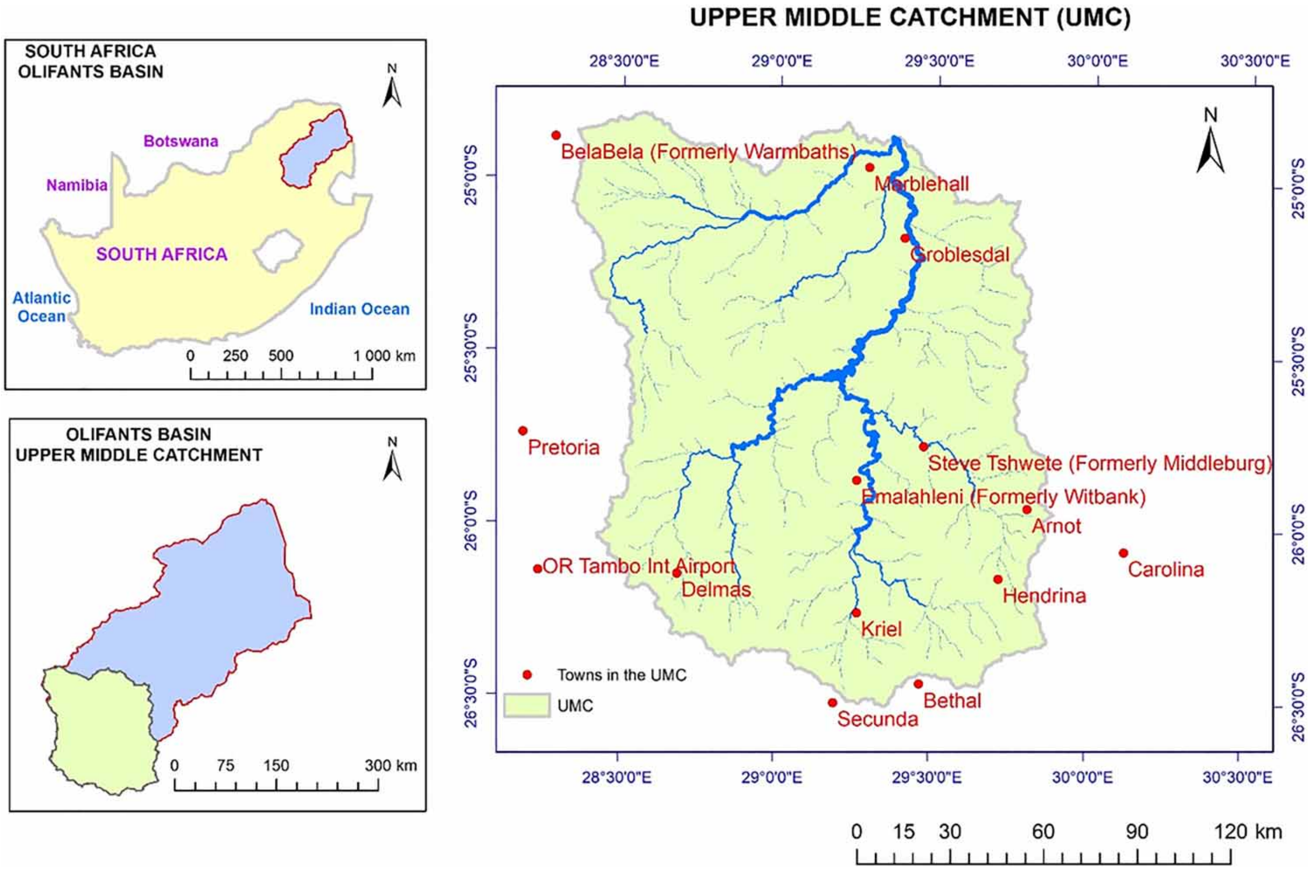

Figure 1 | The study area (upper middle catchment) in relation to the entire Olifants River basin in South Africa.

annual precipitation and evaporation of 659 mm and 2,103 mm, respectively. Most of the rainfall in the area occurs between the summer months of December and February (SAWS 2018).

The Olifants River basin is one of the major river basins in South Africa. The basin is home to both small- and large-scale mining industries in South Africa. In this basin, there are also commercial as well as small holder agricultural farms that are major users of water. The UMC has mines that are regarded as the largest producers of coal in South Africa. This coal is used as a source of energy for 11 ESKOM (the power utility of South Africa) coal-fired power stations in South Africa, eight of which are within the Olifants River basin. These eight power stations produce approximately 70% of South Africa's electricity (McCartney *et al.* 2004). Thus, economic activity in the Olifants catchment is diverse and ranges from mining, power generation, metallurgic industries, agriculture, and ecotourism. According to DWA (2011), approximately 5% of the gross domestic product (GDP) of South Africa is generated within the Olifants catchment, with the largest economic sectors being mining, manufacturing, power generation, and agriculture. The Olifants River basin thus plays a key strategic role in the national economy of South Africa and, therefore, is a very important river basin as far as the economy of South Africa is concerned.

Model selection

In order to assess the local seasonal precipitation variability in the UMC, the Soil and Water Assessment Tool (SWAT) model, interfaced with the ArcGIS program (henceforth referred to as ArcSWAT), was selected. The SWAT model is a watershed model commonly used to estimate the water quantity and quality impacts of land use and land management on surface waters. The SWAT model has been used in many local and international applications to quantify the impact of land management practices on water, sediment, and agricultural chemical yields in large complex watersheds with varying soils, land uses, and management conditions over long periods of time (Di Luzio *et al.* 2002; Gassman *et al.* 2007; Awan & Ismaeel 2014; Gyamfi *et al.* 2016a; Havrylenko *et al.* 2016). The SWAT model has proven to be an effective model for river basin studies under different environmental and climatic conditions (Winchell *et al.* 2013). This model has been used extensively to assess the impact of various land management practices, local hydrological effects of different management strategies, and potential climate change on water quantities and sediment yields in many river basins in the world (Di Luzio *et al.* 2002; Winchell *et al.* 2013; Awan & Ismaeel 2014; Gyamfi *et al.* 2016a; Havrylenko *et al.* 2016).

SWAT input parameters

The model takes data inputs such as land management and land use, soils, elevation (DEM), daily climate (e.g., temperature and precipitation), and routes flow and nutrients in the land and within the river reach. For this study, the SWAT model was configured by providing these input data for the UMC and then using the ArcGIS–SWAT interface (ArcSWAT) to define sub-basins and hydrologic response units (HRUs). The data used in the study are discussed below.

Digital elevation model (DEM)

The DEM used in this study came from the NASA Shuttle Radar Topography Mission (SRTM) Version 3.0 Global, in a coverage of $1^\circ \times 1^\circ$ tiles at 1 arc second (about 30 meters) resolution, and was downloaded in six tiled mosaic rasters from the United States Geological Survey (USGS). Then, it was merged together using the ArcGIS tools. Once the mosaic DEM rasters were merged into one, the new DEM raster was projected. For this study, however, the new raster and all shapefiles used in the study were projected to the WGS 84/UTM zone 35S, a UTM (Universal Transverse Mercator) zone for South Africa. The WGS 84/UTM zone 35S uses the WGS 84 geographic 2D Coordinate Reference Systems (CRS) as its base CRS and the UTM zone 35S (Transverse Mercator) as its projection. The WGS 84/UTM zone 35S is a CRS for large- and medium-scale topographic mapping and engineering surveys (GeoRepository 2017). The processed DEM was then loaded into the ArcSWAT project.

Digital elevation models are digital data files that contain terrain elevations over a specified area, usually at regularly spaced horizontal fixed grid intervals, over the

Earth's surface. The DEM is often a common source of information for developing other models that are dependent on topography. Therefore, the quality of a DEM determines, to a large extent, the quality of the dependent model.

The loaded DEM was then used to delineate the study area, as shown in Figure 1. Watershed delineation is one of the first processes in the preparation of the SWAT model for any hydrological assessment. Watershed delineation based on DEMs is the prerequisite to set up a SWAT model. In this study, the watershed delineation was done automatically using the Watershed Delineation tool in ArcSWAT. The definition of initial stream network for the study area was done based on the drainage area threshold specified for the loaded DEM. Based on this digital elevation model, a stream threshold of 690 km^2 was used which resulted in a number of sub-basins and stream density. In SWAT, the stream threshold function plays an important role in determining the detail of the stream network and the size and number of sub-basins. The threshold area, or critical source area, defines the minimum drainage area required to form the origin of a stream. Thus, the smaller the specified area, the more detailed the stream drainage network delineated by the interface will be.

An outlet point for the basin that marks the study area was added just upstream of the Boshielo Dam but downstream the confluence of Olifants and Elands rivers. This point was selected as the basin outlet and therefore the drainage outlet of the UMC. In SWAT, the outlet of each sub-basin is added automatically after the watershed delineation process is completed. Sub-basin outlets are the points in the drainage network of a sub-basin where streamflow exits the sub-basin area. After the watershed delineation process, SWAT then went on calculating the geomorphic characteristics of the sub-basins and reaches, as well as defining the locations of reservoirs within the UMC. The delineation process resulted in 19 sub-basins delineated for the entire UMC.

Soil and land use/land cover data

The land use/land cover (LULC) maps used in this study were obtained from the Landsat Surface Reflectance data. The Landsat Surface Reflectance data were obtained through a supervised land use classification of Landsat 7 Enhanced Thematic Mapper Plus (ETM+) images. These cloud-free images of a spatial resolution of 30 m were obtained from the United States Geological Survey database using the *EarthExplorer* tool, then clipped to the study area watershed. The LULC maps used in the study were prepared for two time steps, 2009 and 2014. The 2009 LULC map was used for the recent past simulation while the most recent LULC map of 2014 was used in the simulation of the current period, mid-term period, and long-term period. This supervised land use classification was conducted by the Department of Town and Regional Planning – Doornfontein Campus, University of Johannesburg, South Africa.

The digital soil map and information on related soil properties for the study area were obtained from the Food and Agriculture Organization (FAO). The FAO digitized Soil Map of the World, prepared at 1:5,000,000 scale, is in the geographic projection (latitude – longitude) intersected with a template containing water-related features such as coastlines, lakes, glaciers, and double-lined rivers. For this reason, the soil map was then projected to WGS 84/UTM zone 35S as mentioned earlier. FAO developed the database by collecting soil profile information from field projects covering the entire world. A total of 1,700 soil profiles was analyzed and grouped by FAO Soil Unit and Topsoil Texture group (FAO 2005). Working on studies both in Africa and beyond, many researchers (Di Luzio *et al.* 2002; Awan & Ismaeel 2014; Gyamfi *et al.* 2016a; Havrylenko *et al.* 2016) have used these data in a wide range of studies with relative success. For example, most recently, Gyamfi *et al.* (2016a) have used these data to try to evaluate the impact of land-use changes on the hydrological processes of the entire Olifants River basin.

Climate data and processing

The climate data used in this study were obtained from the Climate Systems Analysis Group (CSAG) hosted at University of Cape Town, South Africa. The climate data were in the form of only the three primary climate variables, monthly precipitation totals, maximum and minimum monthly temperatures. CSAG generated these data through the coordinated climate model experiments of the fifth phase of the Coupled Model Inter-comparison Project (CMIP5), and were based on two representative concentration pathways, RCP4.5 and RCP8.5 scenarios. These CMIP5 data were as a result of the Coordinated Regional climate Downscaling Experiment (CORDEX) with a focus on the domain that covers the whole continent of Africa, hence, CORDEX-Africa project. The goal of CORDEX was to provide a framework of CMIP5 climate data accessible to a broad range of the scientific community with maximum use of climate change data.

The SWAT model requires daily climate data as its input data. Therefore, the monthly climate data were converted into daily data using a program called MODAWEC (Eawag 2019). However, for the data to be used in MODAWEC, they were rearranged in a MODAWEC format using Microsoft Excel. After the data were tabulated to the format of MODAWEC, the data were then fed in as input to MODAWEC for the generation of the daily climate data. The MODAWEC program has been used in a wide variety of climate change impact studies with lots of success (Liu *et al.* 2008, 2009; Liu & Yang 2009; Chiang & Chang 2010; Folbertha *et al.* 2012; Xu *et al.* 2013). For example, MODAWEC was used to investigate the impact of climate change on the hydrology of a river reach by Xu *et al.* (2013) in China. It has also been used by Liu *et al.* (2008) to assess hotspots of hunger in sub-Saharan Africa in the context of global climate change. MODAWEC has also been employed in the study of food security (Folbertha *et al.* 2012), water demand (Liu & Yang 2009), and climate change impact studies on landslides (Chiang & Chang 2010).

After the daily climate data were generated, they were then used in the SWAT model together with the soil data, land-use/cover data, and the topographic data (DEM). After all this was done, the SWAT model was run to generate the intended outputs.

Application of the SWAT model in the study

The study itself fundamentally involved the building up of four sets of input data to the SWAT model representing each of the four climate change projections. The first model set up was for the period between 1960 and 2010, and was referred to as recent past (RP). This model represented the historical baseline and therefore was the reference model for assessing the local seasonal precipitation variability in the UMC. The LULC map of 2009 was used for this model. The second SWAT model was set up for the period between 2011 and 2020, representing the current period (CR). Here, the LULC map of 2014 was used. The third model set up represented a projection in the near future, referred to, in this study, as the mid-term period (MT), covering a period between 2021 and 2050. Finally, the fourth model was built for the projection (2051–2100). This period is referred to as long-term (LT) and represented the distant future, covering up to the end of the 21st century. For the CR, MT, and LT periods, all input parameters such as LULC, soil, slope, and DEM, remained unchanged. The varying input parameter in the running of the models was the climate variable, which varied depending on the time slice under consideration.

Model performance evaluation

According to scientists such as Abbaspour *et al.* (2017) and Gyamfi *et al.* (2016b), calibration refers to a procedure where the difference between model simulation and observation are minimized. Through calibration, it is hoped that the hydrological model (in this case, SWAT) correctly simulates true processes in the physical systems of the river basin. Calibration is inherently subjective and, therefore, intimately linked to model output uncertainty (Abbaspour *et al.* 2017). Parameter estimation through calibration is concerned with the problem of making inferences about physical systems from measured output variables of the model (e.g., stream flow). Uncertainty stems from the fact that nearly all measurements are subject to some error. Also, models are simplifications of reality, and the fact that inferences in calibration are usually statistical in nature, all add up to even more uncertainties.

It is normally a required practice that a hydrological model (e.g., SWAT) needs some form of calibration before it can be used in an area other than where it was originally made. Model calibration involves modifying values of sensitive input parameters (Table 1), within an acceptable range, in an attempt to match model output to measured data based on a predefined objective function. In SWAT, the user has the option to calibrate the model manually or automatically. Manual calibration in SWAT is based on trial-and-error analysis, and consists of changing one parameter at a time and re-running the model to obtain output that is

Table 1 | Calibrated parameters for stream flow with sensitivity ranking (t-stat) (Gyamfi *et al.* 2016a)

Parameter	Description	Range	Fitted value	t-Stat
CN2	Runoff curve number	35–98	65^a	37.72
ALPHA_BNK	Base flow alpha factor for bank storage	0–1	0.39	6.97
ESCO	Soil evaporation compensation factor	0–1	0.67	5.57
SOL_AWC	Soil available water capacity	0–1	0.2	4.13
GW_DELAY	Groundwater delay (days)	0–500	345	3.02
GW_REVAP	Groundwater 'revap' coefficient	0.02–0.2	0.15	2.34

^{a}Average basin value.

similar to the measured data. In the automatic calibration, SWAT may use methods such as SUFI2 or PARASOL developed by van Griensven *et al.* (2002). However, the calibration in this study was done manually, using measured daily stream discharge data from the B3H001 streamflow gauge at Loskop Noord on the main course of the Olifants River. Therefore, using the streamflow data from this gauging station, the SWAT model was calibrated with streamflow data from 1991 to 1995 and validated for the period 2002–2006. The first three years prior to 1991 were used as a warm-up period to mitigate unknown initial conditions. For this study, three objective functions, namely, Nash–Sutcliffe efficiency (NSE), root mean square error (RMSE) observations standard deviation ratio (RSR), and percent bias (PBIAS) were compared to the performance statistics ratings (Table 2) for monthly time steps proposed by Moriasi *et al.* (2007) to determine the performance of the SWAT model in the UMC. The manual calibration procedure of the SWAT model has enjoyed wide application by many researchers such as Awan & Ismaeel (2014), Gyamfi *et al.* (2016a) and Havrylenko *et al.* (2016). The sensitive parameters for the UMC were selected from the recent study performed by Gyamfi *et al.* (2016b) in the Olifants River basin (Table 1).

A procedure for manually calibrating SWAT for river discharge and sediment yield was first proposed by Santhi *et al.* (2001). These authors recommended that the results of SWAT calibration are generally acceptable if: (i) the simulated mean flow (monthly or daily) differs from the mean measured flow by a value that is within ±15%; (ii) the coefficient of determination (R^2) is greater than 0.60; and (iii) the Nash–Sutcliffe model efficiency (NSE) is greater than 0.50. However, Gyamfi *et al.* (2016a) further suggested that a hydrological model is generally acceptable if R^2 is greater than 0.5.

Table 2 | General performance ratings for recommended statistics for monthly time step (Moriasi *et al.* 2007)

Performance rating	PBIAS (%)	RSR	NSE
Very good	$PBIAS < \pm 10$	$0.00 \leq RSR \leq 0.50$	$0.75 < NSE \leq 1.00$
Good	$\pm 10 \leq PBIAS < \pm 15$	$0.50 \leq RSR \leq 0.60$	$0.65 < NSE \leq 0.75$
Satisfactory	$\pm 15 \leq PBIAS < \pm 25$	$0.60 \leq RSR \leq 0.70$	$0.50 < NSE \leq 0.65$
Unsatisfactory	$PBIAS \geq \pm 25$	$RSR > 0.70$	$NSE \leq 0.50$

PBIAS: percent bias; RSR: RMSE observation standard deviation ratio; NSE: Nash–Sutcliffe efficiency.

For this study, the calibration and validation performance of the SWAT model was assessed under the two representative concentration pathways, RCP4.5 and RCP8.5 scenarios.

RESULTS AND DISCUSSION

Calibration and validation of the SWAT model

The calibration results generally showed good agreement between simulated and observed runoff (Figure 2) under both scenarios, with $RSR = 0.17$, $NSE > 0.90$, and $PBIAS = -73\%$. The coefficient of determination (R^2) was 0.51, slightly lower than the recommended value of 0.6 proposed by Santhi *et al.* (2001), but greater than the recommended threshold value of 0.5 suggested by Gyamfi *et al.* (2016a). The PBIAS showed a percentage outside the recommended range, thereby implying that the SWAT model actually overestimated the streamflow of the area. This may be due to the observed low streamflows, frequently with zero daily flow during part of the dry season (June, July, and August). Similar to the calibration, the validation results (Figure 3) also

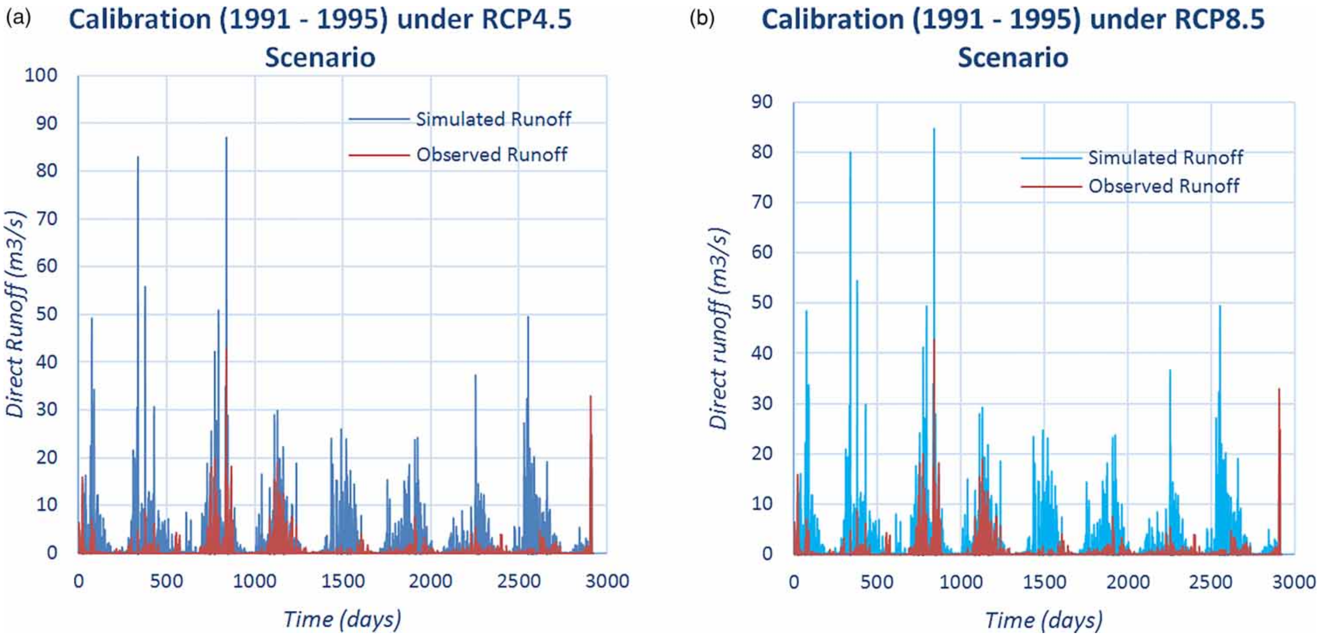

Figure 2 | Observed and simulated daily direct runoff for calibration under (a) RCP4.5 and (b) RCP8.5 scenarios.

showed a good correlation between the simulated and observed runoff. The model goodness-of-fit measure (R^2) was above 0.5. The NSE and RSR were 0.9 and 0.16, respectively. However, the model again showed a PBIAS of −70% which was outside the range suggested by Santhi *et al.* (2001). Nevertheless, the validation shows a good agreement between the simulated and observed daily discharge.

Precipitation variability

Monthly and seasonal variability

Figure 4 shows a general picture of monthly precipitation in the study area predicted by the SWAT model. The UMC's maximum monthly precipitation is 135.84 mm under the

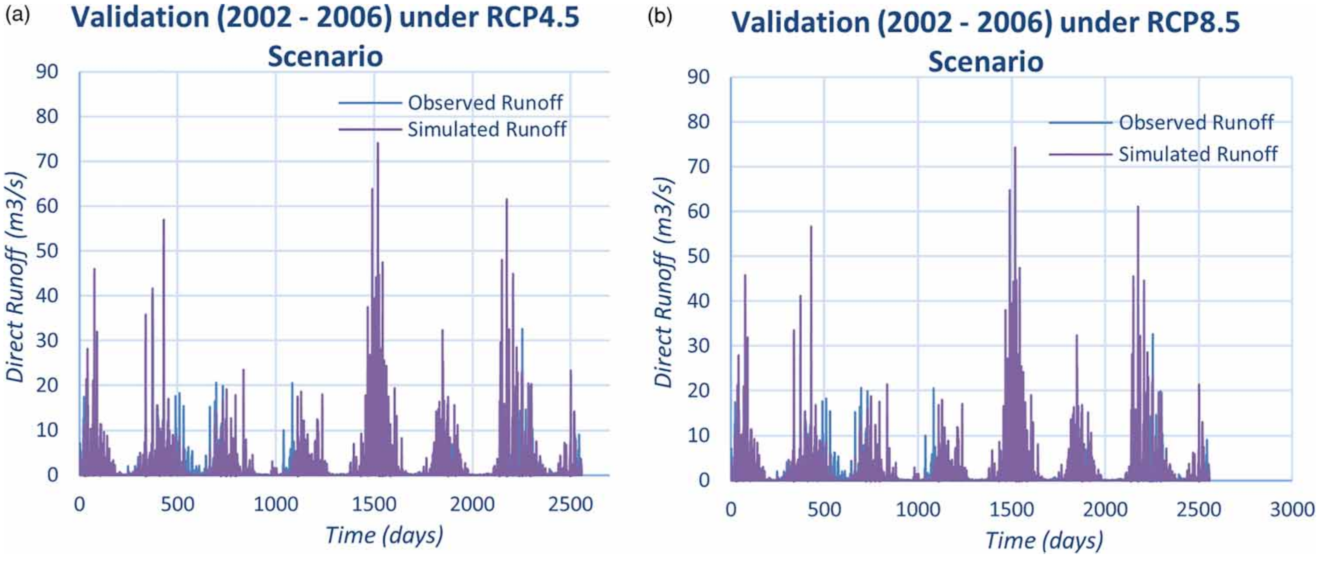

Figure 3 | Observed and simulated daily direct runoff for validation under (a) RCP4.5 and (b) RCP8.5 scenarios.

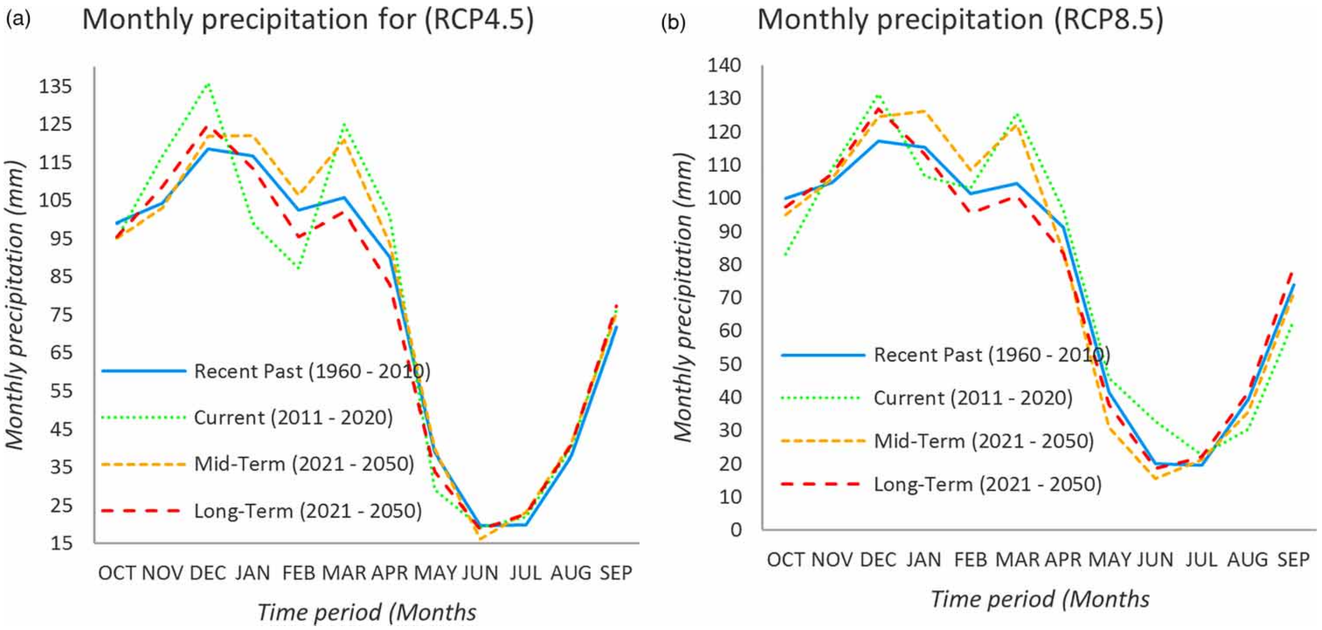

Figure 4 | Precipitation variations on month-by-month basis for the two climate scenarios.

RCP4.5 scenario and happens between the months of December and March. However, under the same scenario, the UMC registers the lowest precipitation (19.15 mm) between the winter months of June and August. Under the RCP8.5 scenario, the respective maximum and minimum precipitation values are 128.93 mm and 22.56 mm for the UMC.

According to the South African Weather Services (SAWS 2018), South Africa has basically four weather seasons, namely, spring (September–November), summer (December–February), autumn (March–May), and winter (June–August). These are the same seasons experienced in the study area. Within these seasons, localized monthly precipitation in the UMC indicates some variations under both the RCP4.5 (Figure 4(a)) and RCP8.5 scenarios (Figure 4(b)) for all the time periods (RP, CR, MT, and LT). The precipitation variations become even more pronounced when considered on a seasonal basis (Figure 5), starting from spring all the way through summer to autumn. Considering the recent past (RP) period as the baseline, Figure 5(a) shows that precipitation has increased under RCP4.5 scenario, by 4.6% in spring while the summer precipitation has dropped by the same amount (−4.6%). The autumn and winter precipitation in the UMC has increased by 8.5% and 5.2%, respectively. For the mid-term period, the precipitation in spring will decrease by −0.6% while precipitation in summer, autumn, and winter show an increase of 3.7%, 8.2%, and 3.9%, respectively, for the same scenario. Seasonal precipitation in the long-term future shows an increase of 2.3% and 6.2% in spring and winter, respectively. However, summer and autumn precipitation in the UMC is expected to decrease by −1.1% and −6.9%, respectively.

Precipitation under the RCP8.5 scenario shows almost a similar trend in the area with an increase in precipitation of 2.1% in summer, 12.9% in autumn, and 8.5% in winter (Figure 5(b)). The spring precipitation, however, seems to break away from this general trend with a decrease of 8.4%. The near future (mid-term period) in the UMC points to a decrease in precipitation, especially in spring (−2.2%), autumn (−0.1%), and winter (−8.2%) seasons, with the exception of the summer season which sees precipitation increase by 7.5% for the same scenario (RCP8.5). Unlike the mid-term period, the long-term period (2051–2100) precipitation shows an increase in spring (1.9%), summer (0.5%), and winter (4.2%), but decreases by −6.5% for the autumn months.

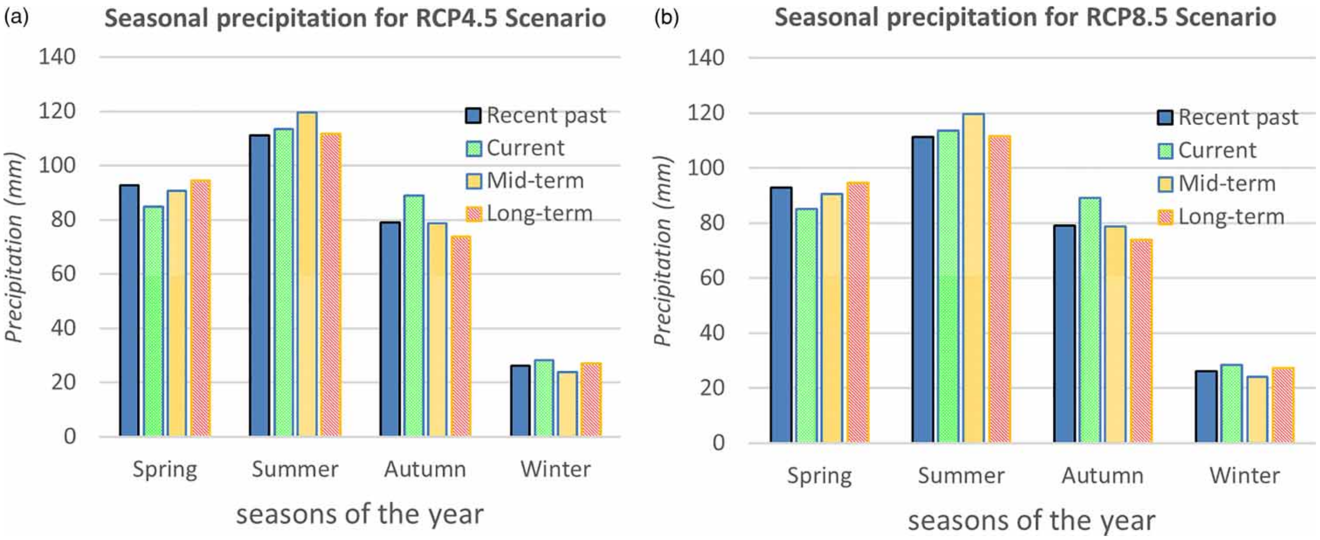

Figure 5 | Precipitation variations on a season-by-season basis for the two climate scenarios.

Spatial annual variability

Figure 6 shows a general trend of spatial variation of annual precipitation in the UMC, with most of the precipitation concentrated in the eastern part. It also shows that there is a strong decreasing trend of precipitation from east to west direction for the RCP4.5 scenario with the western part of the area receiving the lowest annual precipitation. However, within the western part of the UMC, it is also noted that the north-western part receives less annual precipitation (700–800 mm) than the south-western part (800–900 mm), again indicating another decreasing trend of precipitation in the direction of south-western to north-western. This precipitation gradient seems to be the same for all the time periods (RP, CR, MT, and LT) considered in this study.

On the other hand, Figure 7 shows that there is very little difference between the two scenarios insofar as the spatial annual precipitation variation is concerned. The annual precipitation in the north-western part of the UMC under RCP8.5 still remains within the range of 700–800 mm in the current period. However, in the south-western part, especially the middle part, annual precipitation rises up slightly (900–1,000 mm), but in the south-western tip it still remains below 900 mm under the current period. In the mid-term and long-term periods, annual precipitation will still remain below 800 mm, especially in the north-western part of the UMC. Under this scenario, the south-western part will experience annual precipitation in the range of 800–900 mm in the mid-term as well as long-term periods.

Impact of the two greenhouse gas emission scenarios

Figure 8 describes the impact of the two scenarios (RCP4.5 and RCP8.5) on the predicted local precipitation of the UMC. It is noted that under the RCP8.5 scenario, there is 11.4% less precipitation in spring seasons for the present time; however, for the rest of the seasons, Figure 8 shows the RCP8.5 precipitation well above that of the RCP4.5 scenario. Also, opting for the RCP8.5 scenario, will see the seasonal precipitation decreased by −6.8% and −10.3% in autumn and winter, respectively, in the mid-term period. The general reduction in future seasonal precipitation, especially in the mid-term period (as predicted under RCP8.5 scenario), combined with the increasing temperatures as reported by Singh *et al.* (2013), may exacerbate the drying conditions and reduction in streamflow of the main river (Olifants) and its tributaries in the UMC of the Olifants River basin.

These findings agree with the IPCC's 5th Assessment Report published in 2013 and also with findings from previous climate change studies (Christensen *et al.* 2007; Lyon 2009; Mazvimavi 2011; Niang *et al.* 2014), which indicate a considerable decrease in precipitation over the whole of

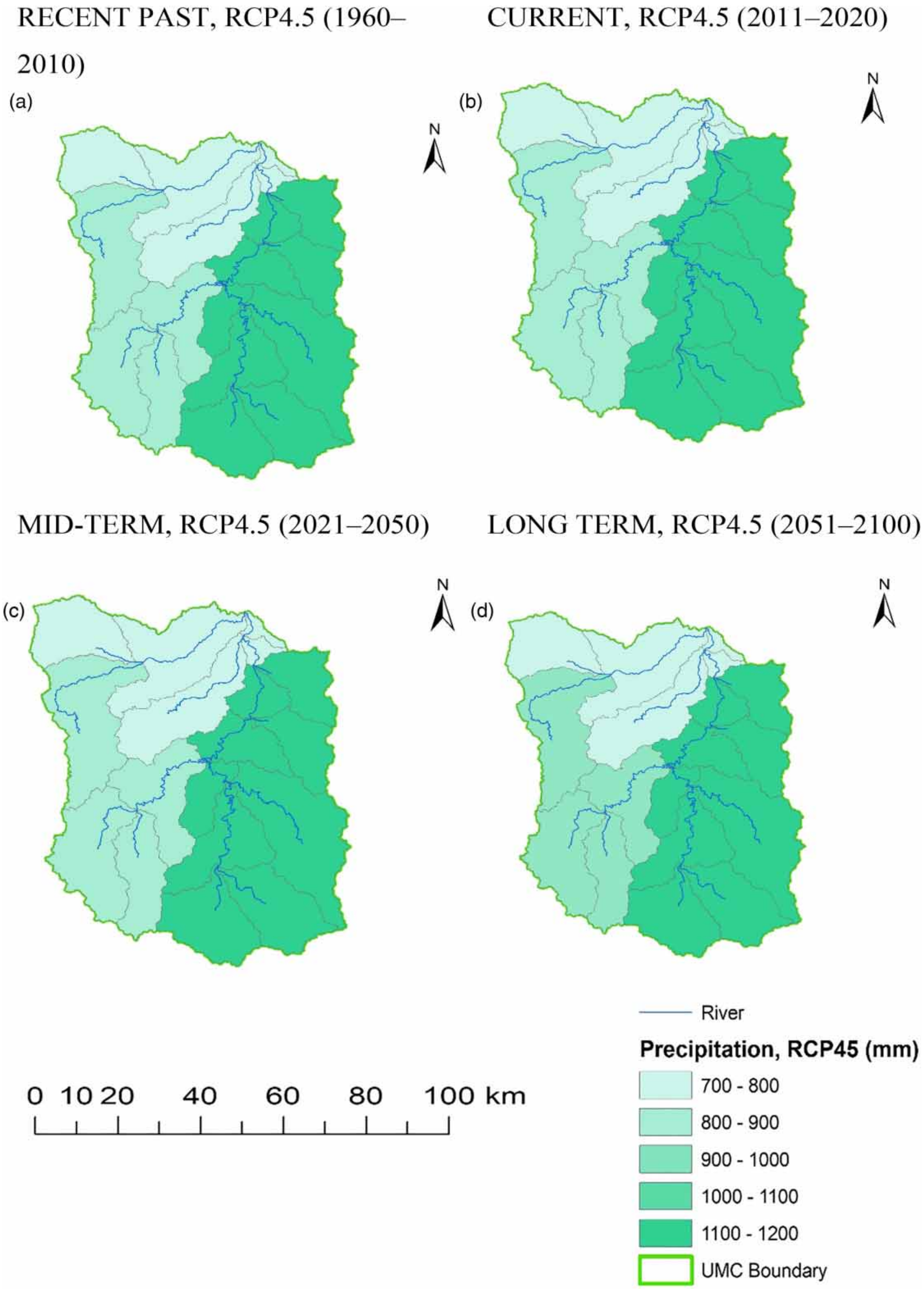

Figure 6 | Temporal-spatial variation of precipitation for the RCP4.5 scenario: (a) recent past (RP), (b) current time (CR), (c) mid-term (MT), and (d) long-term (LT).

southern Africa. However, the findings in the current study slightly do not echo when compared to the findings of Singh *et al.* (2013), who predicted a slight increase in mean annual precipitation (MAP) but generally concluded that climate change in the entire Olifants River basin would result in a general decrease in precipitation. There could be a number of reasons for this slight inconsistency. First, this could be due to the fact that the current study is very specific to the UMC of the Olifants River basin, and thereby very much localized, while that of Singh *et al.* (2013) was broadly

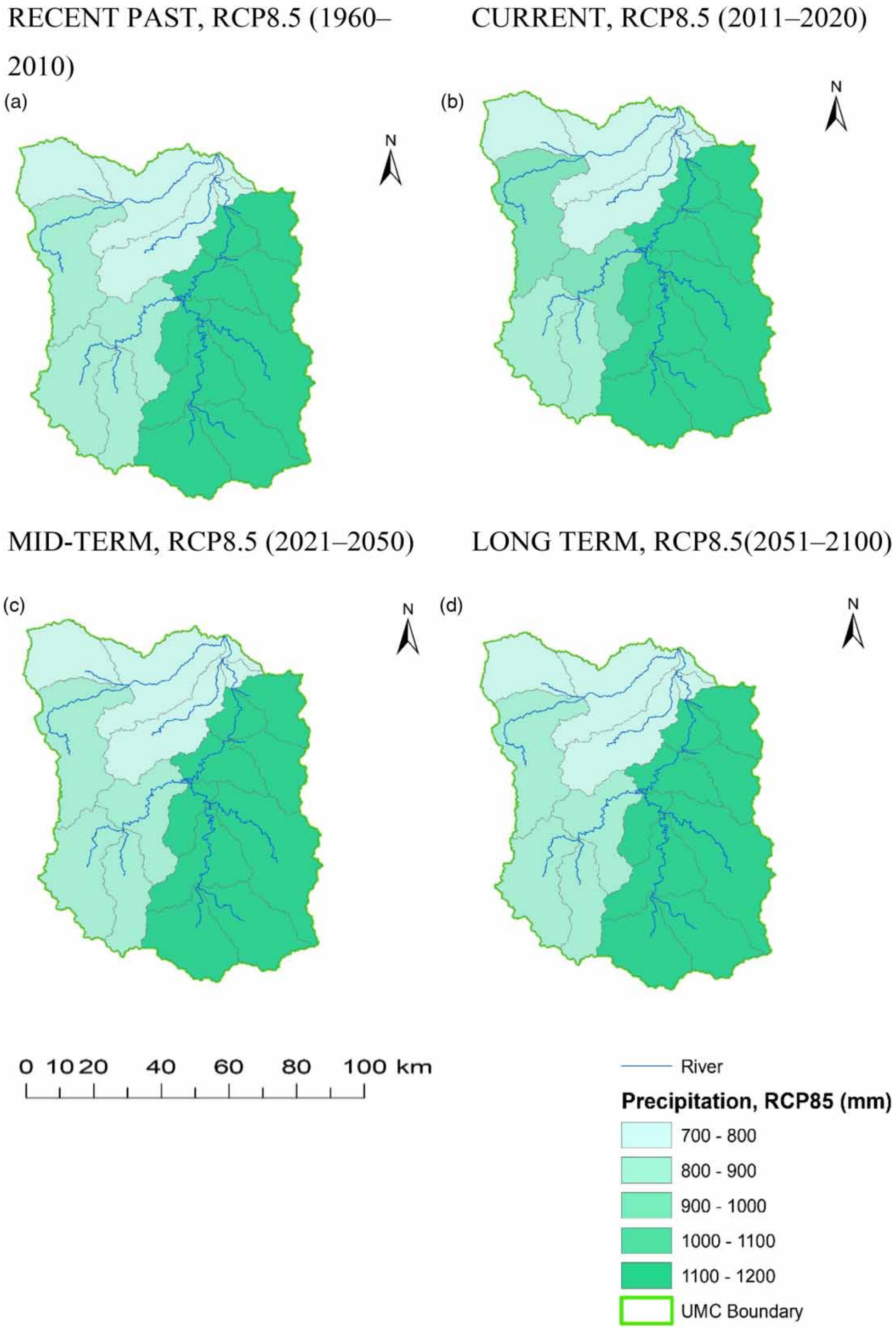

Figure 7 | Temporal-spatial variation of precipitation for the RCP8.5 scenario: (a) recent past (RP), (b) current time (CR), (c) mid-term (MT), and (d) long-term (LT).

based as it covered the entire Olifants River basin, and therefore, resulted in some of the climate variations (e.g., local precipitation) evening out and obscured. Another reason could be that, unlike in the study by Singh *et al.* (2013), the downscaled climate data used in the current study are the CMIP5 climate data originating from the CORDEX-Africa

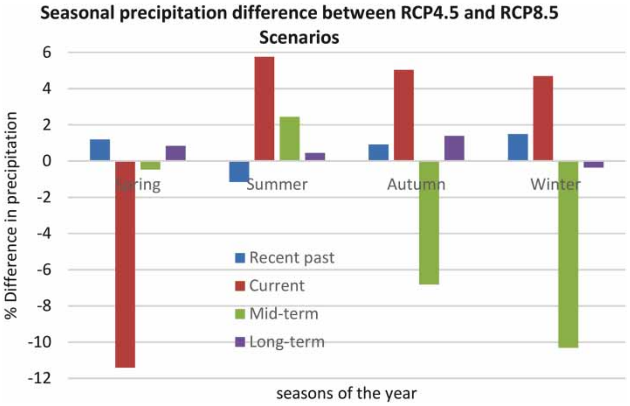

Figure 8 | The impact of the two scenarios (RCP4.5 and RCP8.5) on the predicted precipitation of the study area.

project, perceived to be more accurate and representational for the study area.

CONCLUSIONS

Using the downscaled climate data from CORDEX-Africa, this study has presented the extent of seasonal climate change variability not only at localized level, but also over short- and longer-term futures in the study area. The regional climate downscaled data have been used in this study not only to provide higher-resolution climate information than is available directly from contemporary global climate models, but also, to better understand the seasonal and monthly climate variation, especially at local level such as the UMC. Like other African countries, in South Africa, the economy and livelihood of society is highly correlated with climate (especially precipitation) variability. Compounded with the level of poverty, rapid urbanization, and the low level of adaptive capacity and resilience, there is now no doubt about the importance of understanding local climate variation both on spatial as well as temporal scales. This may only be done when climate studies are localized in order to further improve the results.

Although temporal variation in precipitation shows no major difference, there is a clear spatial variation in annual precipitation in the UMC. A strong decreasing pattern of east-to-west direction of annual precipitation in the entire UMC has been noted in this study with most precipitation concentrated in the eastern part of the study area. Most of the northern areas of the UMC are expected to receive the least amount of annual precipitation. Although the UMC total annual precipitation shows less spatio-temporal variability over the entire period from 1960 to 2100, both the seasonal and monthly precipitation, however, indicate wider variability in spring and summer months compared to autumn and winter seasons. This is more evident for the precipitation under the RCP4.5 scenario than the RCP8.5 scenario.

We have also noted that, while most of these spatio-temporal variations have been lacking in previous studies done on basin level, in this study, such variations have been very evident and visible. This, therefore, indicates the importance of climate studies conducted at localized level.

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