CLIMATE CHANGE AND WATER SECURITY: DEVELOPMENTAL PERSPECTIVES FOR WATER-LINKED SECTORS IN A FUTURE CLIMATE FOR AFRICA

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

The changes in climatic variables such as precipitation and temperature and their associated extremes due to increased global warming from anthropogenic greenhouse gases emission are anticipated to increase in frequency, duration, severity and intensity. Characteristics such as heavy storms, prolonged heat waves as well as the rising sea level will have significant impacts on the natural environment and human-made infrastructure, particularly in most parts of Africa, due to low adaptive capacity, among other factors. The impacts are likely to add pressure on the already stressed water resources for agriculture, industry and households, consequently, resulting in a significant impact on local populations, as well as exacerbating individual- and community-level hardship. With the unprecedented upsurge of climate change and impacts, coupled with frequent occurrences of extreme events, there are calls for the continuous monitoring and appraisal of metrics of climate change across all climate-sensitive sectors. These are essential for adaptation purposes, particularly in the most vulnerable communities. This is to facilitate the provision of supportive tools for policymakers to aid earnest response in support of societal wellbeing and the protection of infrastructure. Furthermore, the focus on climate change and water security are crucial for the development of adaptation strategies, delivery of immediate benefits to the most vulnerable populations, and advancement of the Sustainable Development Goals (SDGs) while strengthening systems and capacity for long-term climate risk management.

To address these challenges, the Water Research Commission (WRC) project no. C2029/2020-00017, entitled "Climate Change and Water Security: Developmental Perspectives for Water-Linked Sectors in a Future Climate for Africa" was jointly contracted to the South African Weather Service (SAWS) and the Kenya Water Institute (KEWI), in collaboration with other South African institution that includes the Central University of Technology (CUT) and Kenyan institutions that include Kenya Meteorological Department, Kenya Water Institute and Maasai Mara University. The project aimed to conduct a comparative analysis of climate change impacts on future development and economic growth for priority water-linked sectors in the Limpopo River Basin (LRB), South Africa, and the Mau Forest Catchment Basin (MFCB), Kenya. In addition, the project aimed to develop a framework that will guide developmental perspectives for water-linked sectors in South Africa and Kenya under a changing climate.

The specific objectives of the project were to analyse future climate and inherent impacts on water security; evaluate the characteristics of extreme weather and climate events; comparatively, analyse the projected impacts of water-linked sectors for urban/rural development over the two study sites; develop a framework for developmental response to climate change taking into account the socio-economic drivers; analyse

adaption and mitigation strategies to climate change; and provide policy recommendations for climate change adaption and mitigation for water-linked sectors.

The project used the Regional Climate Model of the Coordinated Regional Downscaling Experiment (CORDEX) from the 5th phase of the Coupled Model Intercomparison Project (CMIP5), Global Climate Models (GCMs). Additional datasets included observational data from the Department of Water and Sanitation as well as ERA5, a climate reanalysis dataset. Two hydrological models, viz the Agricultural Catchments Research Unit (ACRU) and the mesoscale Hydrologic Model (mHM) were used for streamflow simulations.

According to climate projections, drying conditions, e.g. approximately 12% reduction in rainfall total, are expected in the LRB. Both minimum and maximum temperatures are expected to increase annually and seasonally, e.g. at a rate of between 1°C and 1.5°C (annual), 0.9°C and 1.3°C (during summer), 0.7°C and 1.1°C (autumn), 0.6°C and 0.9°C (winter) and 0.9°C and 1.2°C (spring). On the other hand, the ensemble of eight models generally depicted a wetting trend over the MFCB. An increase in precipitation was found to be more pronounced in the autumn and spring seasons. An increasing trend in temperature averaging between 0.8°C and 2.0°C is projected for the future. In addition, streamflow analysis suggests that the LRB is likely to experience significant hydrological extremes that can lead to either floods or drought, thereby exacerbating the current issues of water shortages and increasing the burden on most water-linked sectors.

The characterisation of extreme climate events over the LRB and MFCB using the WMO-approved extremes indices developed by the Expert Team on Climate Change Detection and Indices (ETCCDI) indicated that both the study sides are likely to experience frequent and prolonged temperature and precipitation extremes throughout the projected period, spanning 2006-2095. The projected changes are likely to result in significant implications for different sectors, including key economic sectors such as water, agriculture, energy and health, among others.

Given the unavoidable and inherent impacts of projected changes in climatic variables and associated extremes, it was imperative to quantify these impacts on the water-linked sectors. This quantification will inform the development of effective responses and adaptation strategies to mitigate the potential impacts on the various sectors. The impact analysis indicated that drought, floods, heatwaves and increased evapotranspiration will pose a significant threat to food and water security and health (well-being) of the vulnerable population in the study sites.

Different frameworks for developmental response options as constrained by socio-economic drivers under a changing climate were reviewed in this project. . The reviewed frameworks provide options for innovative response solutions to adapt and mitigate future impacts on key socio-economic sectors to promote climate resiliency at a local scale. The adaptation options were categorised into physical or structural, social and institutional. This report, therefore, presents strategies for adaptive integrated responses to mitigate the impacts of climate change on the water sector in the Limpopo River Basin, South Africa, and Mau Forest Catchment Basins, Kenya. The report also highlights some of the factors that promote or impede options aimed at multiple objectives and provides possible policy recommendations that can be implemented to enhance response to climate and climate change through adaptation in the two study areas.

The policy recommendations include, among others, the need for climate change response policy to be co-developed and co-implemented with communities and local leaders. This will ensure that they are aligned with community needs and will also contribute towards building the capacity of key stakeholders, for example government actors, women's groups, religious leaders, youth groups, community forest associations and water users associations. There is potential for future work to strengthen existing adaptation actions and improve the management of water resources, access to early warning systems as well as climate literacy at the community level. Other opportunities exist to take advantage of the opportunities presented by the changing climate by diversifying income and livelihood activities through for example growing new crops for the local and international markets.

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ACRONYMS & ABBREVIATIONS

ACRU	Agricultural Catchments Research Unit
ACF	Autocorrelation Function
AMCOW	African Ministers Council on Water
ARIMAX	Autoregressive Integrated Moving Average with Explanatory Variable
CMIP5	Coupled Model Intercomparison Project Phase 5
CDD	Consecutive Dry Days
CDKN	Climate and Development Knowledge Network
CORDEX	Coordinated Regional Downscaling Experiment
COVID-19	Coronavirus Disease 2019
CSDI	Cold Spell Duration Index
CSIR	Council for Scientific and Industrial Research
CWD	Consecutive Wet Days
DD	Drought Duration
DEA	Department of Environment Affairs
DMIs	Drought Monitoring Indicators
DS	Drought Severity
ECMWF	European Centre for Medium-Range Weather Forecasts
EMDAT	International Disaster Database
ET	Expert Team
ETCCDI	Climate Change Detection and Indices
ET_o	Reference Evapotranspiration
FAO	Food and Agriculture Organization
GCMs	Global Climate Models

GDP	Gross Domestic Product
GHG	Greenhouse Gas
HWDI	Heat Wave Duration Index
HWFI	Warm Spell Days Index
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-Tropical Convergence Zone
KEWI	Kenya Water Institute
KNP	Kruger National Park
LIMCOM	Limpopo Watercourse Commission
LRB	Limpopo River Basin
mHM	mesoscale Hydrological Model
MFCB	Mau Forest Catchment Basin
MK	Mann-Kendall
NWP	Numerical Weather Prediction
PACF	Partial Autocorrelation Function
RCA4	Rossby Centre regional model
RCM	Regional Climate Models
RCP	Representative Concentration Pathway
Rx5day	Maximum 5-day precipitation amount
R10mm	Number of heavy precipitation days Pre ≥ 10 mm
R20mm	Number of heavy precipitation days Pre ≥ 20 mm
R95p	Very wet days Pre > 95th percentile
SA	South Africa
SAWS	South African Weather Service
SDG	Sustainable Development Goals

SDII	Simple Daily Intensity Index
SPEI	Standardized Precipitation-Evapotranspiration Index
SS	Sen’s Slope
SSI-6	Standardized Streamflow Index 6
SSI-12	Standardized Streamflow Index 12
UFZ	Helmholtz Centre for Environmental Research
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
USAID	United States Agency for International Development
WASH	Water Sanitation and Hygiene
WHO	World Health Organization
WMO	World Meteorological Organization
WSDI	Warm Spell Duration Index

1. Background

1.1. Introduction

The global climate crisis is inextricably linked to water challenges, and almost all economic sectors (e.g. agriculture, energy, health, tourism, transport and industry) need water for sustainability (Kerres et al., 2020; Cooper and Price, 2021). Climate change has been found to manifest itself through changes in the hydrological cycle, thereby reducing the predictability of water availability and demand, negatively impacting water quality, and exacerbating water scarcity (UN Water, 2019). Higher temperatures, variability in seasonal patterns, and more intense and frequent extreme weather events threaten water security, as are the risks associated with energy and food security (Smith et al., 2019; Mishra et al., 2020; Stringer et al., 2021). Changes in climate significantly impact on people's lives and livelihoods, disproportionately affecting the poor and vulnerable communities in developing countries such as South Africa and Kenya (IPCC 2012). Studies by Wakeford (2017) and Mabhaudhi et al. (2019) highlight some of the evidence and impacts of climate change in these two countries.

Climate change, coupled with environmental and socio-economic drivers such as population growth, urbanization, socio-economic development, land-use change, environmental degradation, and biodiversity loss poses substantial risks to water security. The cumulatively negative impacts successively enhance knock-on repercussions on water-linked sectors such as agriculture, health, energy generation and supply, industry, transport, fisheries, forestry, and recreation, among others (Gallagher et al, 2016). To respond to the ever-increasing and unprecedented pressures of climate change a better understanding of the complex, dynamic and multidimensional interrelationships is essential not only to secure a sustainable and climate-resilient future but to advance efforts towards Sustainable Development Goals (SDGs). In addition, negative outcomes across dimensions of water security can be minimized by constantly monitoring and upraising the metrics of climate change across climate-sensitive sectors and time scales (Dorota, 2017). Consequently, comprehensive and integrated water-related interventions and actions backed by coherent policies are required to build a society that can resiliently adapt to the changing climate and alleviate future impacts (Okpara et al., 2018; Stringer et al., 2021). In this regard, the analysis of future climate change impacts on water-linked sectors plays an important role through two perspectives: 1) water is a problem because it acts as a medium through which the impacts of climate change reach society; 2) water resources offer the society an opportunity to respond to climate change impacts through local adaptation and mitigation options. As a contribution to this global endeavour, the climate change and water security project seeks to comprehend the extent to which climate and extreme events will change, as well as the impacts thereof on water-linked sectors in the Limpopo River Basin (LRB), South Africa and the Mau Forest Catchment Basin (MFCB), Kenya.

The research work will support the development of effective preparedness measures, including policy formulation, and promote climate change resilience within the selected study sites.

1.2. Project Aims

The project aimed to conduct a comparative analysis of climate change impacts on future development and economic growth for priority water-linked sectors in the Limpopo River Basin (LRB), South Africa and the Mau Forest Catchment Basin (MFCB), Kenya. The following were the specific objectives of the project:

i) Characterisation and assessment of the impacts of the projected future climate on water security
ii) Evaluation of expected changes in extreme climate and weather events
iii) Comparative analysis to characterise and assess the risks and impacts of the projected future climate on water security and other linked sectors across the two regions.
iv) Recommendation of short, medium- and long-term adaptation strategies including opportunities for developmental response,
v) Recommendation of policy actions including communal land management policies that can reduce the impacts of climate change and variability.

1.3. Scope and Limitations

The climate change and water security project was jointly contracted to the South African Weather Service (SAWS) and the Kenya Water Institute (KEWI), in collaboration with other South African and Kenyan institutions. The scope of the project was to conduct a comparative analysis of climate change impacts on future development and economic growth for priority water-linked sectors in the Limpopo River Basin (LRB), South Africa and the Mau Forest Catchment Basin (MFCB), Kenya. The project was executed during the unforeseen circumstances caused by the Covid-19 pandemic. This created unprecedented delays in the overall execution of the project. Specific challenges experienced during the execution of the climate change and water security project include:

- Delays in concluding the partnership approval processes between the institutions involved in the project
- Interruptions in physical stakeholder engagements due to both local and international travel restrictions resulting from COVID-19
- Challenges with obtaining data for the Kenya study site hence some of the deliverables were not fully achieved due to unavailability of specific datasets such as streamflow observations and social-related information.

In this report, each deliverable is reported as a chapter. Thus, the report is structured as follows:

- Chapter 2 (Deliverable 3) – Projected future climate and anticipated impacts on water security.
- Chapter 3 (Deliverable 4) – Characterization of extreme climate and weather events in limpopo river and mau forest catchment basins
- Chapter 4 (Deliverable 5) – Assessment of projected future climate change impacts on water-linked sectors: A case study of the Limpopo River Basin
- Chapter 5 (Deliverable 6) – A framework for developmental response options constrained by socio-economic drivers under a changing climate
- Chapter 6 (Deliverable 7) – Strategies for adaptive response to mitigate the impacts of climate change on the water sector
- Chapter 7 (Deliverable 8) – Draft Policy Recommendations
- Chapter 9 – Conclusions and recommendations

2. Projected Future Climate And Anticipated Impacts on Water Security

2.1. Introduction

The world has, over the years, witnessed a significant change in its climate, as confirmed by the Intergovernmental Panel on Climate Change (IPCC) 4th and 5th Assessment Reports, imposing earnest environmental, social and economic coercion (IPCC, 2007; 2013). According to IPCC, observations have provided evidence of increases in global average air and ocean temperatures, widespread melting of snow and ice, as well as rising global average sea level (IPCC, 2007; 2013). Africa, in particular, is one of the most vulnerable continents to climate change and variability, due to various factors, that include the continent's high dependence on agriculture and natural resources, the aridity attributes, warmer baseline climates, low annual precipitation and low climate change adaptative capacity (Kurukulasuriya and Mendelsohn 2007; 2008; Hassan and Nhemachena 2008; Thornton et al., 2008).

For over a century, observed near-surface temperature in most African countries has increased by approximately 0.5 ^{0}C, as reported in, for example, Kruger and Shongwe (2004), Mohamed (2011), Collins (2011), Stern et al. (2011), Nicholson et al. (2013), and references therein. In addition, climate projections have reported a potential increase in climatic variables such as mean temperature (Almazroui et al., 2017; Bucchignani et al., 2018), average air temperature (Niang et al., 2015), heat stress and frequent and prolonged heat waves (Diedhiou et al., 2018; Sylla et al., 2018), as well as highly variable precipitation (Niang et al., 2015) in most parts of Africa. Consequently, the continuous rise of temperature and unpredictable precipitation are likely to exacerbate future impacts on socio-economic development.

The impacts of climate change and variability have been widely addressed in the literature, as evidenced in Figure 1, which depicts frequent occurrences of keywords within the subject matter. As noted, climate change dominates in the green cluster and has links across various sectors, including water resources, agriculture (food security), biodiversity, health, and energy among others. Most of these sectors are sensitive to climate variables such as rainfall, temperature, runoff, streamflow, etc., and hence inter-linked as shown by the keywords occurrences network. The unprecedented increase of climate-related impacts is a manifestation of societies' realization of the inherent vulnerability and dangers of climate change. There is, therefore, a need to continually monitor and upraise the metrics of climate change across climate-sensitive sectors. In this regard, analysis of future climate change impacts on water-linked sectors plays an important role in two perspectives: 1) water is a problem – it acts as a medium through which the impacts of climate change reach society; 2) water resources offer society an opportunity to respond to climate change impacts through adaptation and mitigation and therefore improve resilience. It is against this background that the understanding of the projected future climate and anticipated impacts on water security across the LRB and

MFCB Mau Forest Catchment BasinMFCBwill contribute towards taking stock of the parallels of climate change impacts on climate-sensitive sectors across the two study sites. This study will contribute toward enhancing climate change adaptation and mitigation policy decisions and implementation thereof, for sustainable livelihoods in support of vulnerable communities.

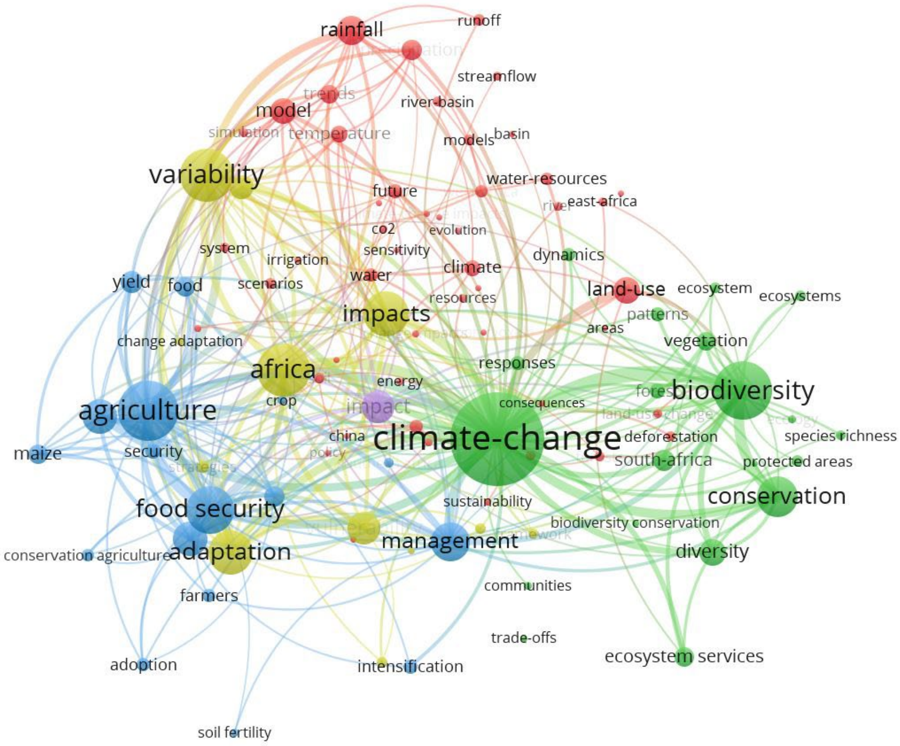

Figure 1. Frequent keywords occurrences within the topic of climate change and variability

2.2. Study Area

2.2.1. Limpopo River Basin

The LRB spreads across four countries: South Africa, Botswana, Zimbabwe, and Mozambique with each country accounting for about 45%, 19%, 15% and 21% of the total area, respectively (see Figure 2). The basin is home to about 14 million people distributed across the urban and rural landscape, covering an area of about 142 938 km^2. The LRB is also known as a major agricultural and game production zone in southern Africa as well as rich in ecosystem and biodiversity. Irrigation is the largest water user in the LRB accounting for about 30% of usage, the remainder used for mining, power generation and household use (Petrie et al., 2014). Mining, agriculture and poor waste management in the upstream countries have increased the pollutants, with impacts on water quality downstream with the Olifants River being noted to be one of the most polluted rivers in the LRB (LIMCOM, 2020). Acid mine drainage from the defunct coal mines on the Mpumalanga highlands has, for example, contributed to poor water quality in tributaries within the basin

(Petrie et al., 2014). The LRB also faces challenges with the over-abstraction of water (Petrie et al., 2014). Furthermore, most of the LRB catchment area is semi-arid with a highly variable climate that is prone to extreme weather and climate events such as floods, droughts and tropical cyclones The river basin is also influenced by various climate factors such as dry continental tropical, equatorial convergence zone, moist marine subtropical eastern and marine western Mediterranean air masses (FAO, 2004).

The Limpopo catchment area is characterized by a highly seasonal distribution of rainfall (Mosase and Ahiablame, 2018) and this has a significant impact on the hydrology of the LRB. The area receives most of its rain (95%) between October and April, with mean monthly totals in February. The distribution of rainfall varies from as low as 200 mm/year in the western semi-arid areas of the catchment to over 1 500 mm/year in the south-middle part of the catchment, and 600 mm/year in the eastern part, near the Indian Ocean. The mean annual precipitation of the basin is approximately 530 mm, although much of the rainfall events are intense (resulting in flash floods) and highly sporadic, associated with convective thunderstorms and occasionally, tropical cyclones (WMO, 2012). Mean annual minimum and maximum temperatures range between 8^0C in the south to 20^0C in the east of the basin, and 23^0C in the south to 32^0C in the east of the basin, respectively. Due to the elevated temperature and high humidity values, the communities within the catchment area, many of which are poor, are vulnerable to heat stress and related sicknesses. Other health risks that are noted in the area are vector and waterborne diseases, including malaria and cholera, the latter of which is aggravated by lack of access to safe drinking water, inadequate sanitation facilities and poor personal hygiene. In the present study, there are instances (which are depicted on the specific relevant maps) where the analysis is limited to the South African section of the LRB.

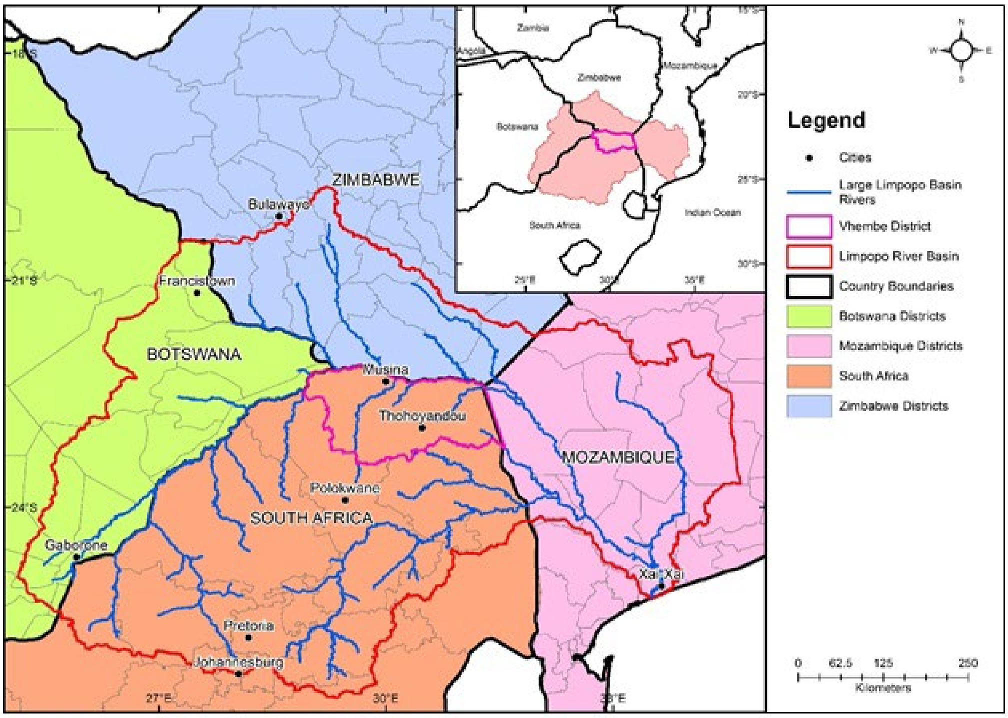

Figure 2. Limpopo River Basin, in southern Africa

2.2.2. Mau Forest Catchment Basin (Ewaso Ng'iro)

The MFCB is one of the five largest water towers in Kenya known to support agriculture, tourism and hydro energy production (Odawa and Sewo, 2019). Generally, the MFCB encompasses four counties namely Narok, Bomet, Kericho and Nakuru The basin is dominated by high poverty levels regardless of the existence of abundant natural resources (e.g. Bomet 48.8%, Nakutu, 29.1% and Narok, 22.6%) (USAID, 2019). Figure 3 shows the extent of the study area which is part of the Mara River sub-basin in the west/south and the Ewaso Ng'iro South sub-basin in the north, central and east of the delineated study area.

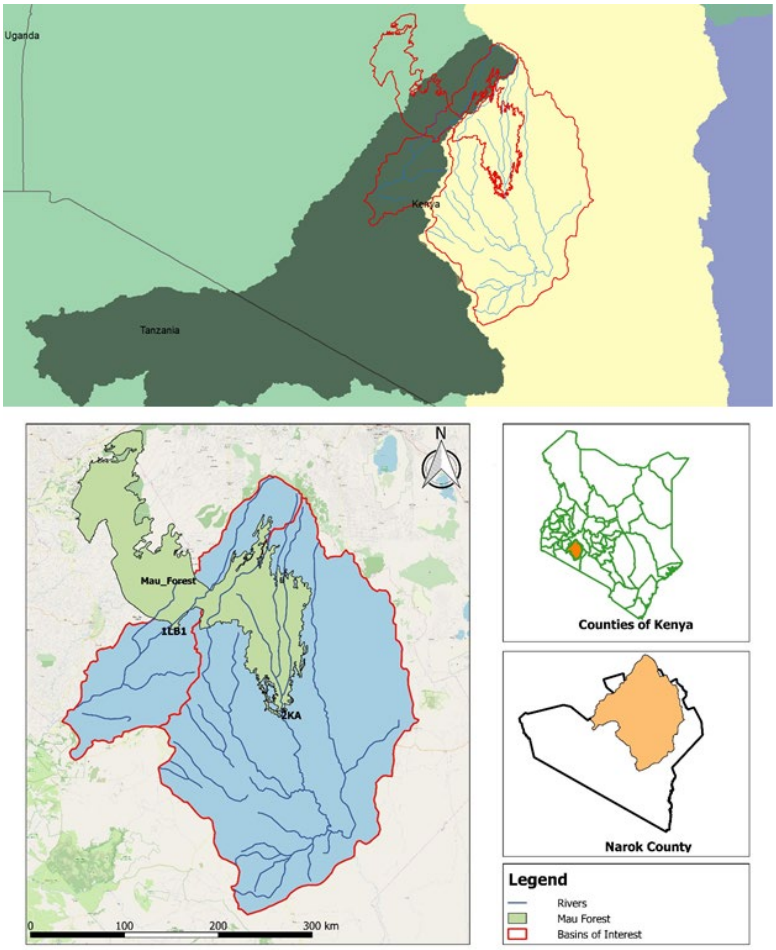

Figure 3. The Ewaso Ng'iro including the Mau Forest and the Mau Forest Catchment Basin (MFCB) in the Narok County in Kenya

Annual rainfall ranges from 650 mm in the southeast part of the catchment to 1300 mm in the northwestern regions. The seasonality of rainfall is influenced by Inter-Tropical Convergence Zone (ITCZ). The communities within the MFCB are equally impacted by similar health outcomes as those noted in the LRB that is aggravated by poverty, food insecurity, poor sanitation and increased prevalence of vector-borne diseases. In addition, land-use changes in the area have affected water availability and quality. More than 70% of the households are using water from unprotected wells, springs and rivers that are susceptible to pollution from land use activities such as agriculture and human settlements. The main sources of energy in Kenya are solar, biogas/biofuels, wind, hydro, geothermal, oil and gas. Electricity supply is mostly generated by renewable sources with the majority coming from geothermal power (i.e. the largest producer of geothermal energy in Africa) and hydroelectricity.

2.3. Data and Methods

2.3.1. Observations

Monthly rainfall, minimum and maximum temperature data were obtained from the Hadley Center Climate Research Unit (CRU) TS2.0 monthly 50 km resolution observed dataset (Hulme et al. 1999). Daily streamflow observational data was obtained from the Department of Water and Sanitation (http://www.dwa.gov.za/Hydrology/). Two downstream streamflow gauge stations were selected for the study. The selected stations have been operational for over three decades; hence they provide reliable and continuous datasets. In this study, the averaged streamflow data from the two stations, spanning from 1979-2019 was utilized to bias correct simulated streamflow across four periods, namely historical (past), current climatology, near- and distant future.

2.3.2. CORDEX Models

The spatial resolution of Global Climate Models (GCMs) grid squares is relatively coarse, especially when applied to produce South African provincial scale climate change projections. Hence, to address the spatial scale limitations posed by the GCM fields, the Coordinated Regional Downscaling Experiment (CORDEX) dynamically downscaled simulations over the African domain of spatial resolution (0.44°x 0.44°) was used. The Rossby Centre regional model (RCA4), forced across its lateral boundaries by the GCMs models (table 1) of the 5th phase of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012) was used. The RCA4 is a coupled ocean-atmosphere Regional Climate Model (RCM) based on the Numerical Weather Prediction (NWP) model HARLAM (Undén et al., 2002). Consequently, for the climate change projection component of this report, outputs from historical and projected (historically: 1976 to 2005; projected: 2006 to 2035; 2036 to 2065 and 2070 to 2095 simulations by nine downscaled GCMs were analysed for which the ensemble means and trends were computed. Climate change projections for annual and seasonal rainfall, minimum and maximum temperatures were generated using the medium-to-low Representative Concentration Pathway (RCP) 4.5 and high RCP8.5.

For hydrological modelling, single CORDEX RCM forced by a selection of six CMIP5 GCMs (see summary of the models in Table 1) was used to drive two hydrological models, namely the Agricultural Catchment Research Unit (CRU) and the mesoscale Hydrological Model (mHM) to generate historical and projected streamflow simulations under RCP 4.5 and 8.5 scenarios. The ACRU model was used to generate projected streamflow across the current, near- and far-future timescales under both RCP4.5 and RCP8.5 scenarios.

Table 1. The CMIP5 GCMs used in the current study

Model name	Country	Resolution	Literature
CanESM2m	Canada	2.8° x 2.8°	Arora et al. (2011)
CNRM-CM5	France	1.4° x 1.4°	Voldoire et al. (2013)
IPSL-CM5A-MR	France	1.9° x 3.8°	Hourdin et al. (2013)
MICRO5	Japan	1.4° x 1.4°	Watanabe et al. (2011)
NorESMI-M	Norway	1.9° x 2.5°	Tjiputra et al. (2013)
GFDL-ESM2M	USA	2.0° x 2.5°	Dunne et al. (2012)

2.3.3. ACRU Agro-hydrological Model

The ACRU agro-hydrological modelling system, is a physical-conceptual, multi-purpose, multi-soil-layered and daily time-step model, (Schulze, 1995; Schulze and Perks, 2000) was used to simulate streamflow for both historical and near-future periods. The model requirements include inputs of known and measurable Spatio-temporal variable factors that characterize the watershed. The minimum catchment information required to operate ACRU is the daily precipitation as well as maximum and minimum temperature datasets. Output information derived from ACRU includes daily streamflow, peak discharge, irrigation water supply and demand, crop yields, and sediment yield. For a detailed description and theoretical background of the ACRU model, the reader is referred to Schulze (1995).

2.3.4. mHM hydrological model

The mHM is a spatial overt distributed open-source model developed by the Helmholtz Centre for Environmental Research – UFZ in Germany. This grid-based conceptual model has been tested in more than 30 basins in Germany, see, for example, Samaniego et al. (2010). The mHM model was set-up using the bare minimum data required to run a basic catchment. Various input datasets had to be processed for the catchments. In addition, the data had to be re-projected and resampled to fit on a uniform grid and meet the requirements for the model and modelling area. The physical data like soil and land cover had to be reclassified to fit the classes used by the model. Datasets such as slope, aspect, sink filled elevations, flow direction and flow accumulation were created from digital elevation model data. Historical meteorological data (1976-2005) were used in conjunction with the historical observed streamflow to calibrate, optimize and parameterize each catchment to each model member. The resulting parameterized model set up for each model member and catchment combination was then used to produce the future simulations for the historical, current and near-future periods (i.e. 1976-2005; 2006-2035 and 2036-2065) using both the RCP4.5 and RCP8.5 scenarios.

Figure 4 illustrates the method of analysis considered in this study. As depicted in the figure, historical and three projected periods of CORDEX models (present-, near- and far-future) under the RCP4.5 and RCP8.5, were forced into ACRU and mHM hydrological models to simulate historical and projected streamflow. Bias-correction using observed streamflow was applied to simulated streamflow across the models and projected periods. Streamflow metrics were then calculated and analysed to assess the features of historical and projected streamflow in the LRB. In addition, other factors like projected baseflow, drought and drought monitoring indicators were analysed. The results were then used to assess potential the impact of the projected streamflow on key water-linked sectors.

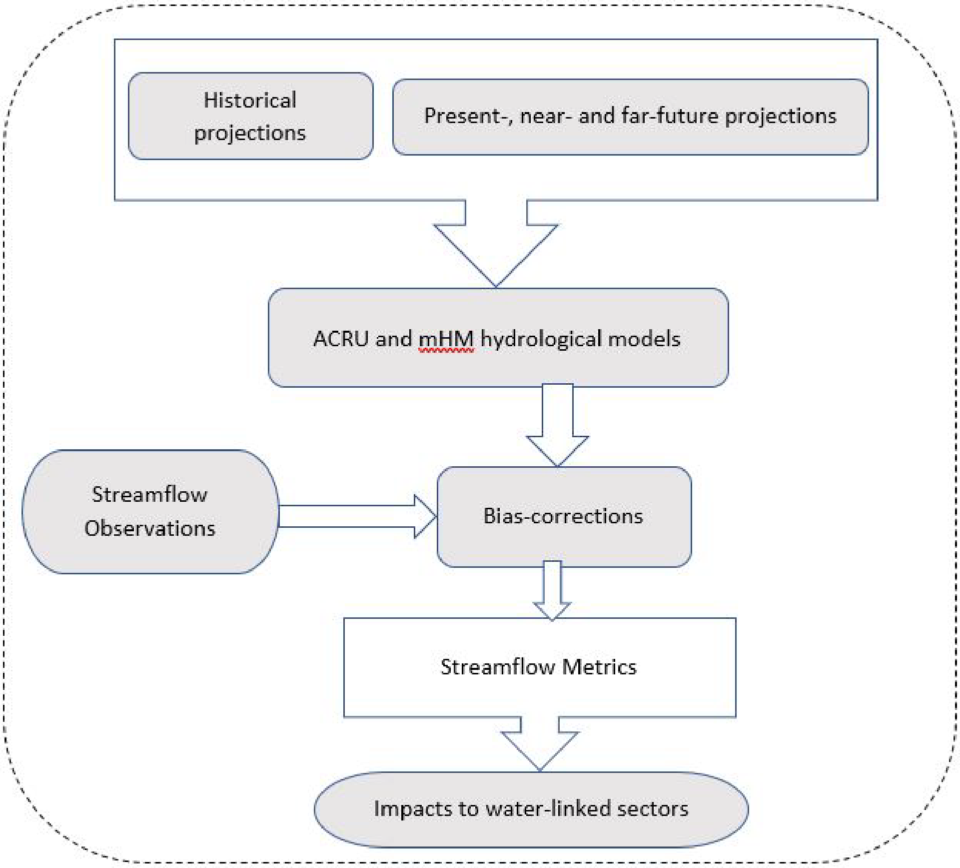

Figure 4. Schematic representation of streamflow analysis

2.4. Results

2.4.1. Historical Climate Characteristics of the Limpopo River Basin

2.4.1.1 Rainfall Features

The annually totals of the observed rainfall across the LRB for the period 1976-2005 are shown in Figure 5. The results indicate that the south-eastern part of the basin received more rainfall ranging between 600-

1700 mm per year. The years 1997, 1998 and 2000 were significantly wet and are depicted in both the observations and model. According to the International Disaster Database (EMDAT) , there was widespread flooding within the Limpopo River, covering the Mozambique portion in 1977, 1978 and 1996 of which about 300 people died and 400,000 were affected. There were major floods recorded in the LRB in 2000 due to the landfalls of cyclone Eline and Gloria in February and March of the same year. The south-eastern of Mozambique, and South African portion of the basin extending to Komati River were significantly affected. Below-normal rainfall observations related to drought were also observed in 1982-1984. In 1992 the widespread African drought and in 1994 and 2002-2003 the Southern African widespread drought can be deduced with annual rainfall less than 500 mm. This led to major crop failure and outbreaks of water-borne diseases such as cholera in several parts of Africa and the southern Africa. In this analysis, the historical baseline period ended with below normal rainfall in 2005.

The LRB has also experienced a high spatial variation in the amount of rainfall received annually (Figure 6) and seasonally (Figure 2A - 1), with JJA being the driest months and DJF the wettest months. The reference period depicts a mean range of about 250 to 960 mm, and a coefficient of variation (CoV) ranging from 18 to 36%, see Figure 2A - 2.

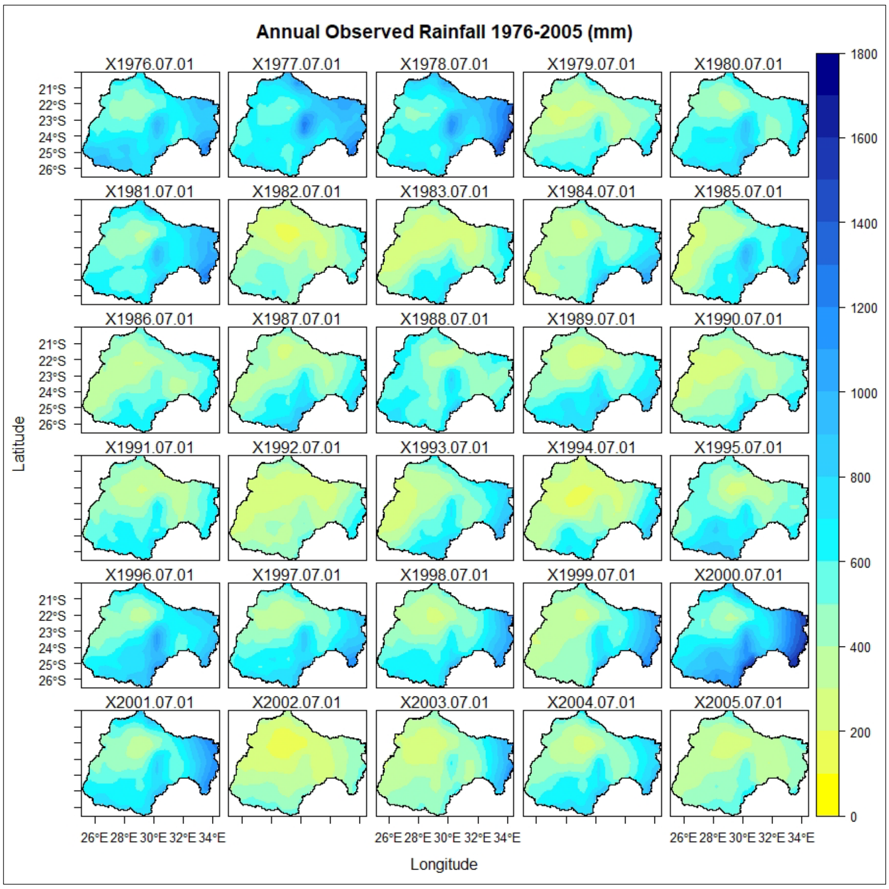

Figure 5. Historical annually observed rainfall in Limpopo River Basin

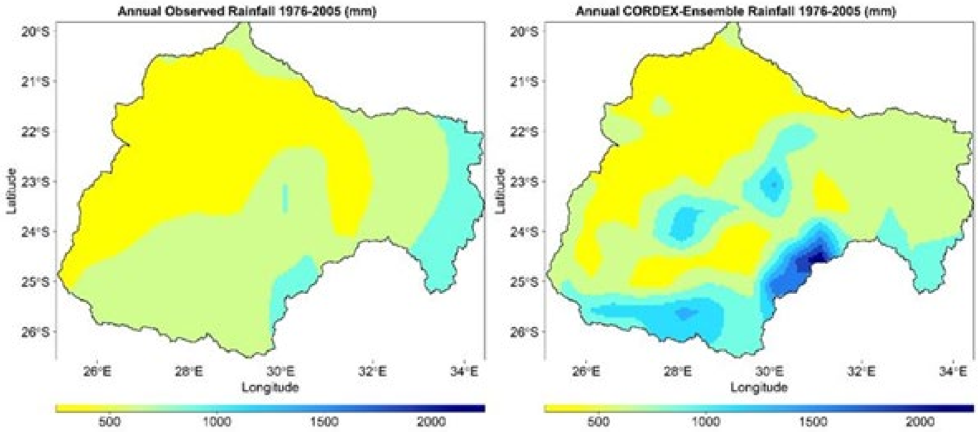

Figure 6. Annual distribution of an average total of observed and CORDEX-ensemble rainfall for the baseline period in Limpopo River Basin

2.4.1.2 Temperatures Features

There is about 81% correlation between the historical and CORDEX-ensemble temperatures. The minimum and maximum temperatures across the LRB for the period 1976-2005 are depicted in Figure 7, and Figure 8 and in Figure 9, and Figure 10, respectively. Minimum temperatures are lower in the southern region of the basin, ranging between 6°C and 13°C, and increase towards the central-eastern parts, with minimum annual temperatures ranging from 17°C to 22°C. Seasonally, the low-altitude eastern portion of the LRB in Mozambique has higher summer temperatures about 30°C than the northeastern region towards Botswana with around 25°C (see Figure 2A - 3 and Figure 2A - 5). Significant increasing trends in both minimum and maximum temperatures are noticed (Figure 2A - 4 and Figure 2A - 6). The mean ranges between 7°C and 20°C for minimum temperature and between 21°C to 32°C for maximum temperature. Both temperatures exhibit less spatial variability with CoV ranging between 2% and 5% for minimum temperature and 1% to 3% for maximum temperature.

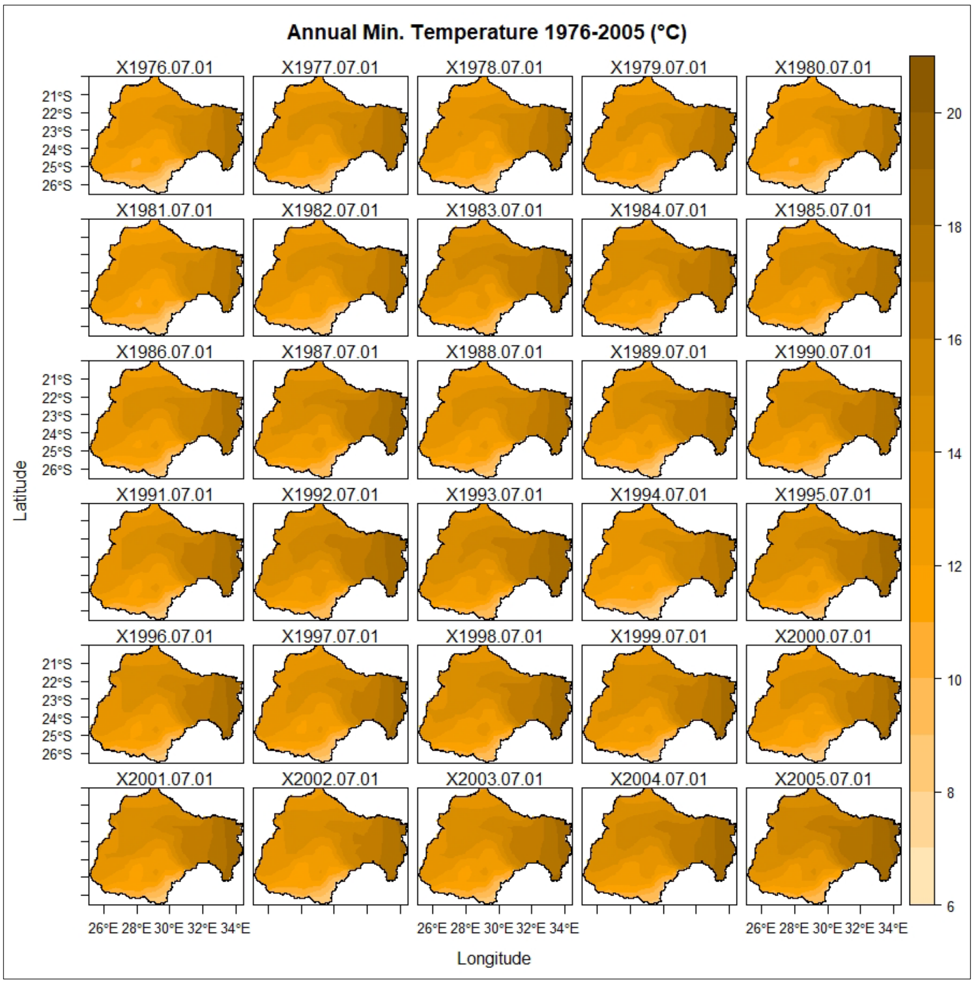

Figure 7. The historical annually observed minimum temperature in Limpopo River Basin

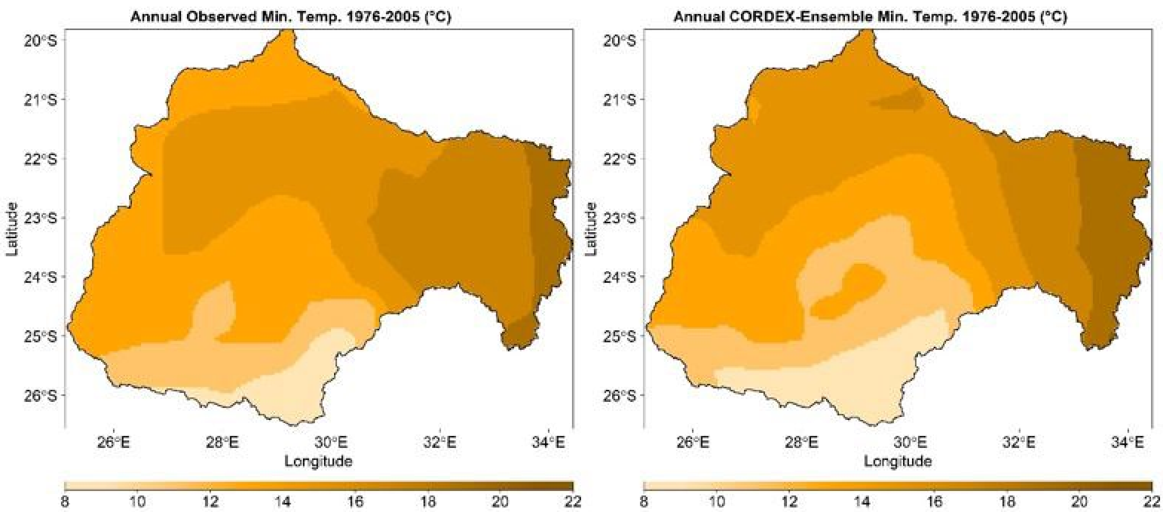

Figure 8. Same as Figure 7 but for annual observations and CORDEX-ensemble model

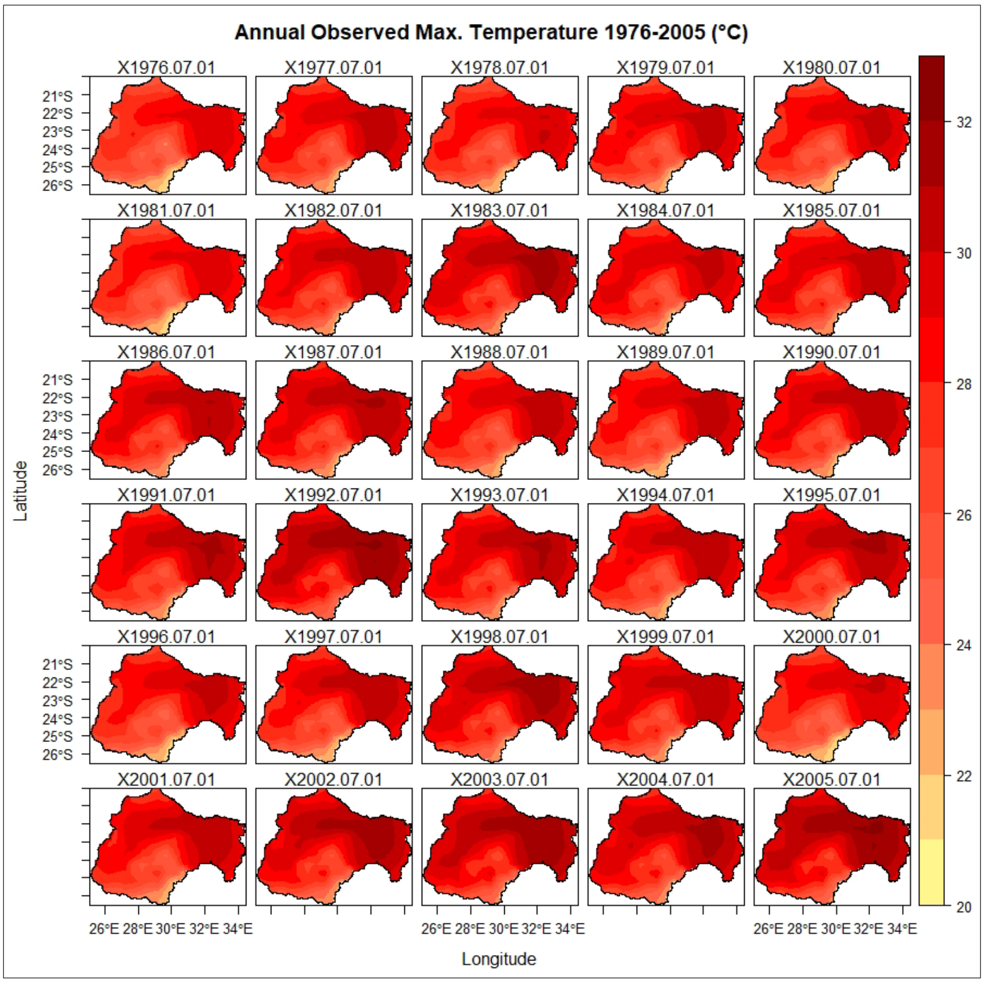

Figure 9. Historical annually observed maximum temperature in Limpopo River Basin

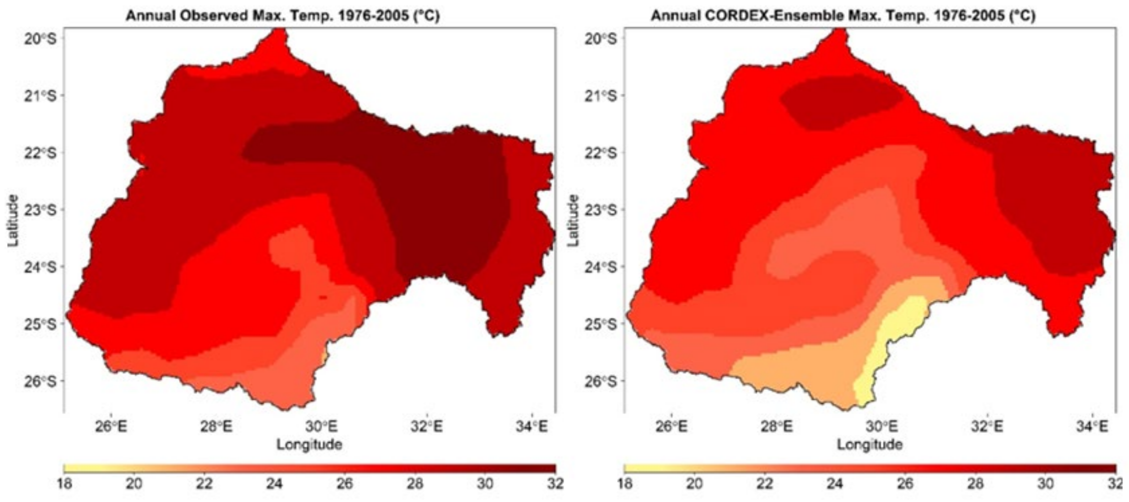

Figure 10. Same as Figure 9 but for annual averages across the observations and the CORDEX-ensemble model

2.4.2. Projected Climate Characteristics of Limpopo River Basin

2.4.2.1 Projected Rainfall

Projections of mean annual and seasonal rainfall are depicted in Figure 11 and Figure 2A - 7), respectively. The results indicate that mean annual rainfall over the basin may be limited, but spatially coherent decreases in rainfall in the near future (2036-2065) and decrease by up to 12% in the far future (2070-2099) *(Not included in this report)*. In addition, frequent high-intensity rainfall events are generally projected, with a consequent increase in local and large-scale flooding. The decrease in seasonal rainfall is most significant during the summer and autumn months, as these are the rainy season in the basin. In some areas, especially the northeastern side of the basin, the reduction in rainfall maybe by as much as 20% in summer (Figure 2A - 7).

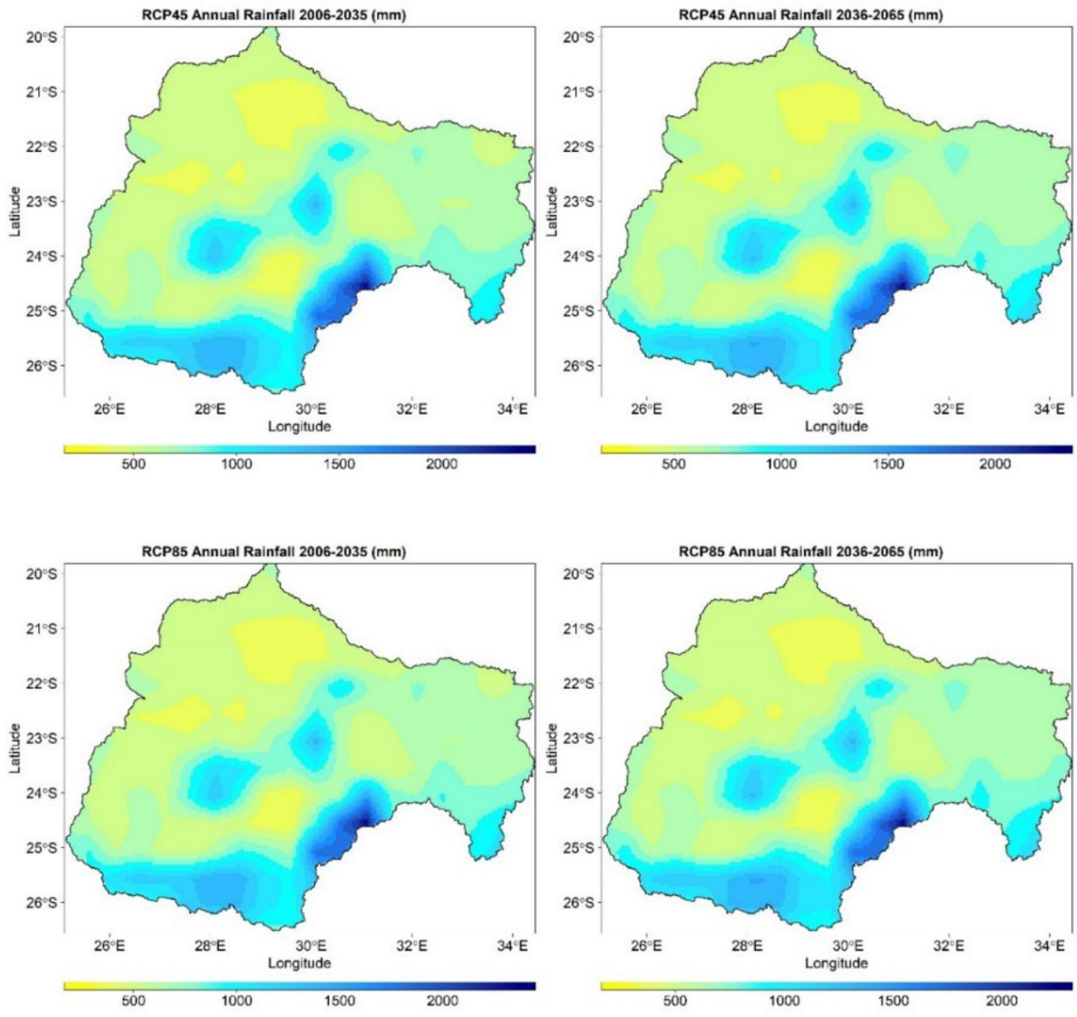

Figure 11. Annual total rainfall for 2006-2035 (top left), 2036-2065 (top right) under conditions of the RCP4.5 pathway and 2006-2035 (bottom left), 2036-2065 (bottom right) under conditions of the RCP8.5 pathway

2.4.2.2 Projected Temperatures

Projections indicate that in the short term (2006-2035) and medium-term 2036-2065, both minimum and maximum temperatures are increasing at an average rate of between 1^{o}C and 1.5^{o}C, 0.9^{o}C and 1.3^{o}C, 0.7^{o}C and 1.1^{o}C, 0.6^{o}C and 0.9^{o}C and 0.9^{o}C and 1.2^{o}C annual, summer (DJF), Autumn (MAM), Winter (JJA) and spring (SON) months respectively in the LRB (see Figure 12, Figure 2A - 8, Figure 13 and Figure 2A - 9). The maximum temperature is projected to increase by between 1.5^{o}C and 2^{o}C from 2036-2065 warmer than the baseline of 1976-2005. The southern and western parts of the basin will experience the highest warming temperatures in the summer months.

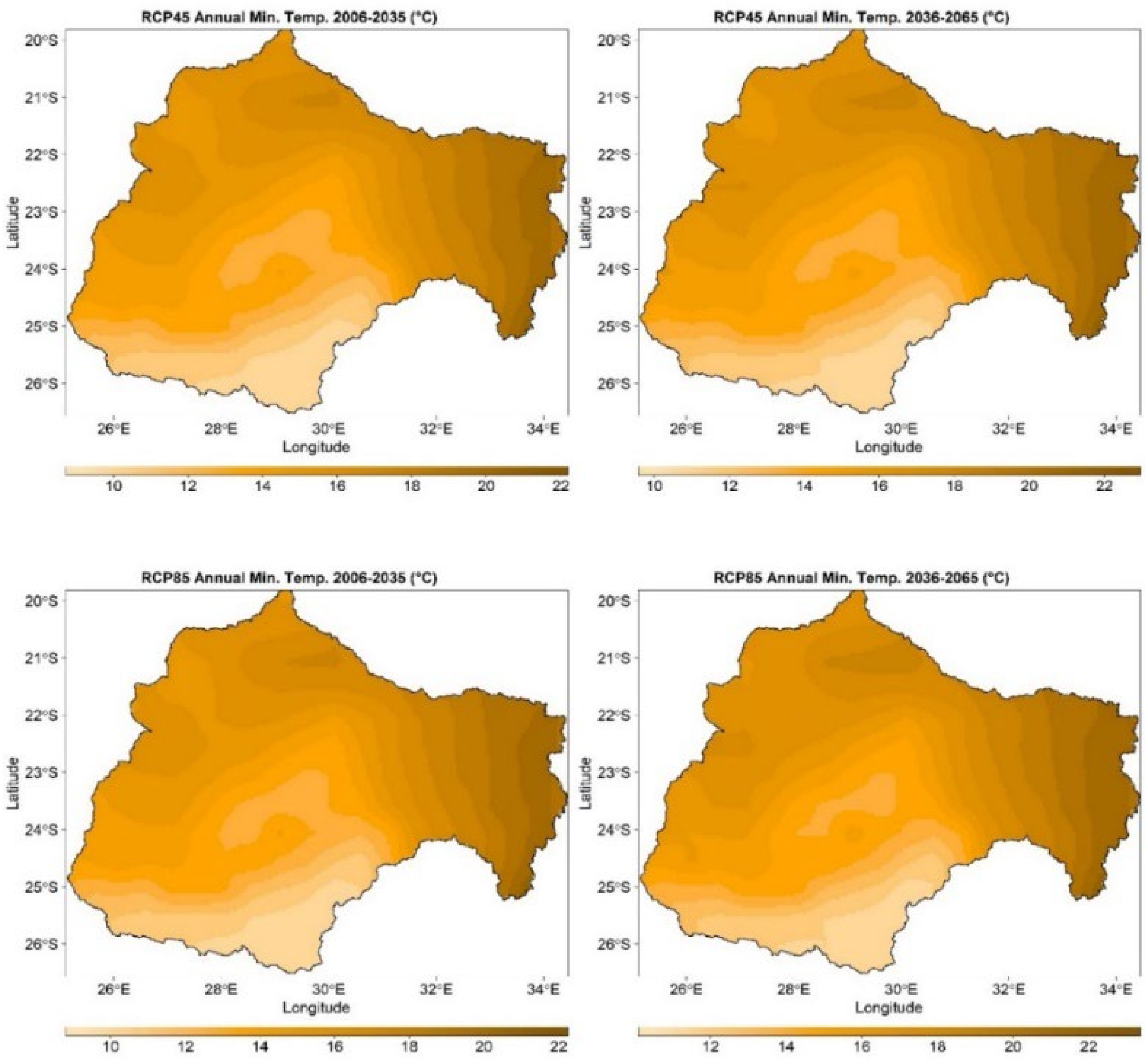

Figure 12. Same as Figure 11, but for annual minimum temperature

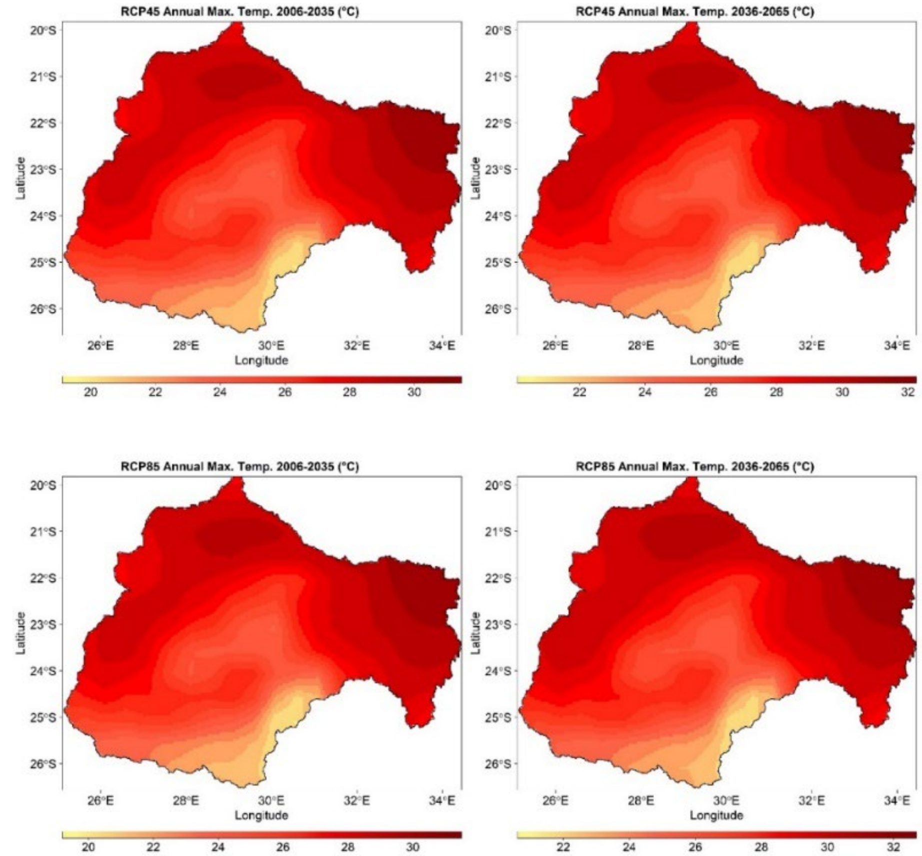

Figure 13. Same as Figure 11, but for annual maximum temperature

Climate Change Summary for Limpopo River Basin

Climate change is projected to have significant impacts on the LRB with consequences for the economies across the basin. A larger portion of the basin is semi-arid and is likely to worsen considering the impacts of climate change. This is coupled with the fact that the basin is already water-stressed as depicted in the hydrological modelling. According to IPCC reports and Abiodun et al., 2019, annual temperatures have increased by about 1.5^{o}C in the central interior regions of southern Africa over the last century. In this current study, the results suggest that both minimum and maximum temperatures are increasing at a rate of between 1^{o}C and 1.5^{o}C, 0.9^{o}C and 1.3^{o}C, 0.7^{o}C and 1.1^{o}C, 0.6^{o}C and 0.9^{o}C and 0.9^{o}C and 1.2^{o}C annual, summer (DJF), Autumn (MAM), Winter (JJA) and spring (SON) months respectively in the LRB. Major increases are seen in the western and southern parts of the basin. The climate change projected mean annual rainfall over the basin suggests that there may be limited, but spatially coherent decreases in rainfall in the near future (2036-2065). Annual rainfall is projected to decrease by up to 12% in the far future (2070-2099). In addition, rainfall events with high intensity are projected to occur more frequently, consequently leading to an increase in local and large-scale flooding particularly in the northern and eastern parts of the basin. The projected climate change is foreseen to negatively impact on the ecosystem of the basin. The human population faces a major threat socio-economically. Food and water security in the basin hang in the balance with major impacts for the small-scale farmers who have lower adaptive capacity. The inter-linkage between water and food production might force large-scale/commercial farmers to reduce production as a result of less water available for irrigation.

2.4.3. Historical Climate Characteristics of Mau Forest Catchment Basin

2.4.3.1 Rainfall Features

The historical observed compares to the model simulation for about 70%. As shown in Figure 14, Figure 2A - 10 and Figure 2A - 11, rainfall exhibit a high spatial variability over the basin with more rainfall received in the north-central ranging from 950-1850 mm annually, while the south-eastern part receives the lowest amount of rainfall of 300-800 mm annually. Historically, the wettest years, which also coincide with years with flood occurrence (EMDAT) are 1977, 1978, 1988,1989, 1998 and 2002. Significant dry years are noticed in the years 1976, 1984 (significant drought), 2000, and 2003-2005, particularly in the wetland areas. Basic statistical information is given in Figure 2A - 12.

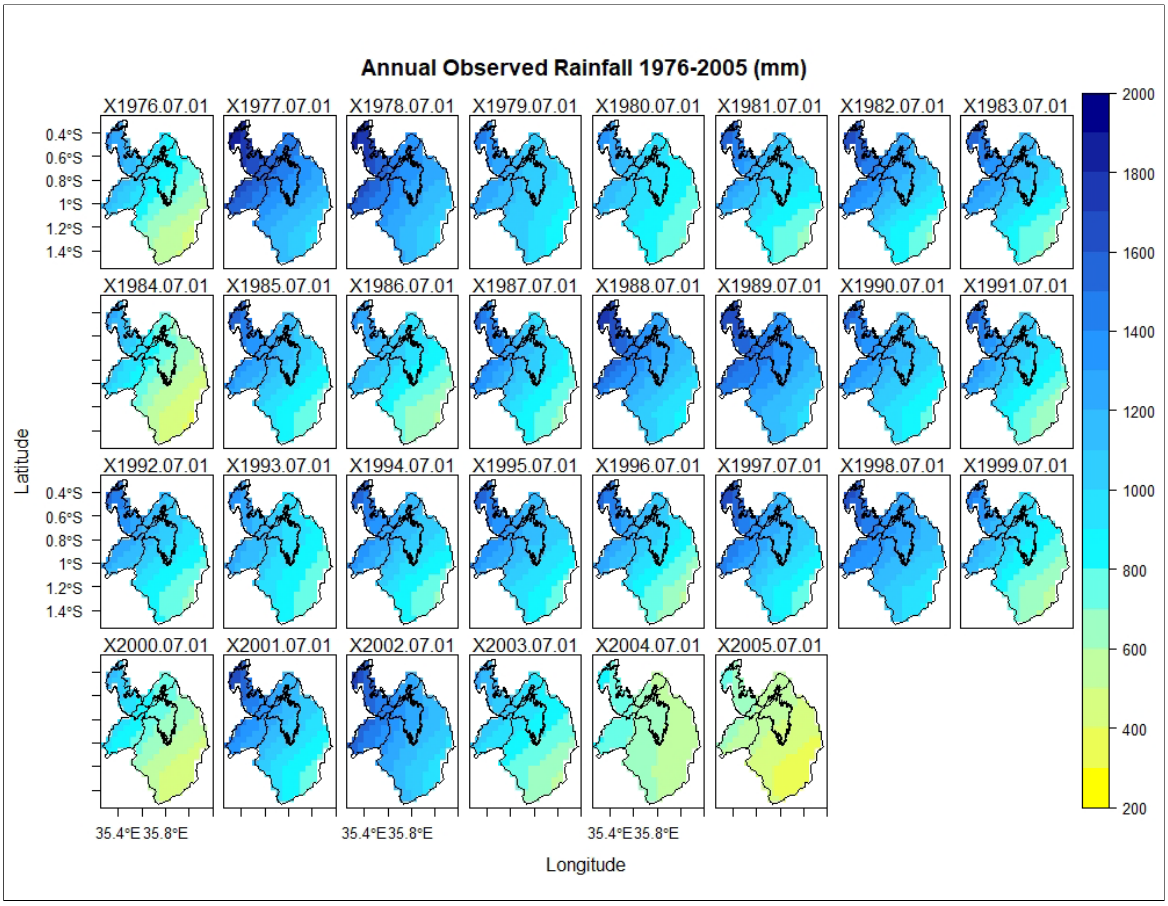

Figure 14. Historical annually observed rainfall in Mau Forest Catchment Basin

2.4.3.2 Minimum and Maximum Temperature Features

Results for the annual, seasonal and basic statistics for minimum temperature across the MFCB study site are shown in Figure 15 and Figure 2A - 13 to Figure 2A - 15, respectively. Similarly, Figure 16 and Figure 2A - 16 to Figure 2A - 18 depicts the annual, seasonal and basic statistics results for maximum temperature, respectively Generally, temperatures exhibit spatial variability, and are generally lower in the north part of the basin, ranging between 18°C and 20°C, and increase toward the south, ranging between 22°C to 24°C.

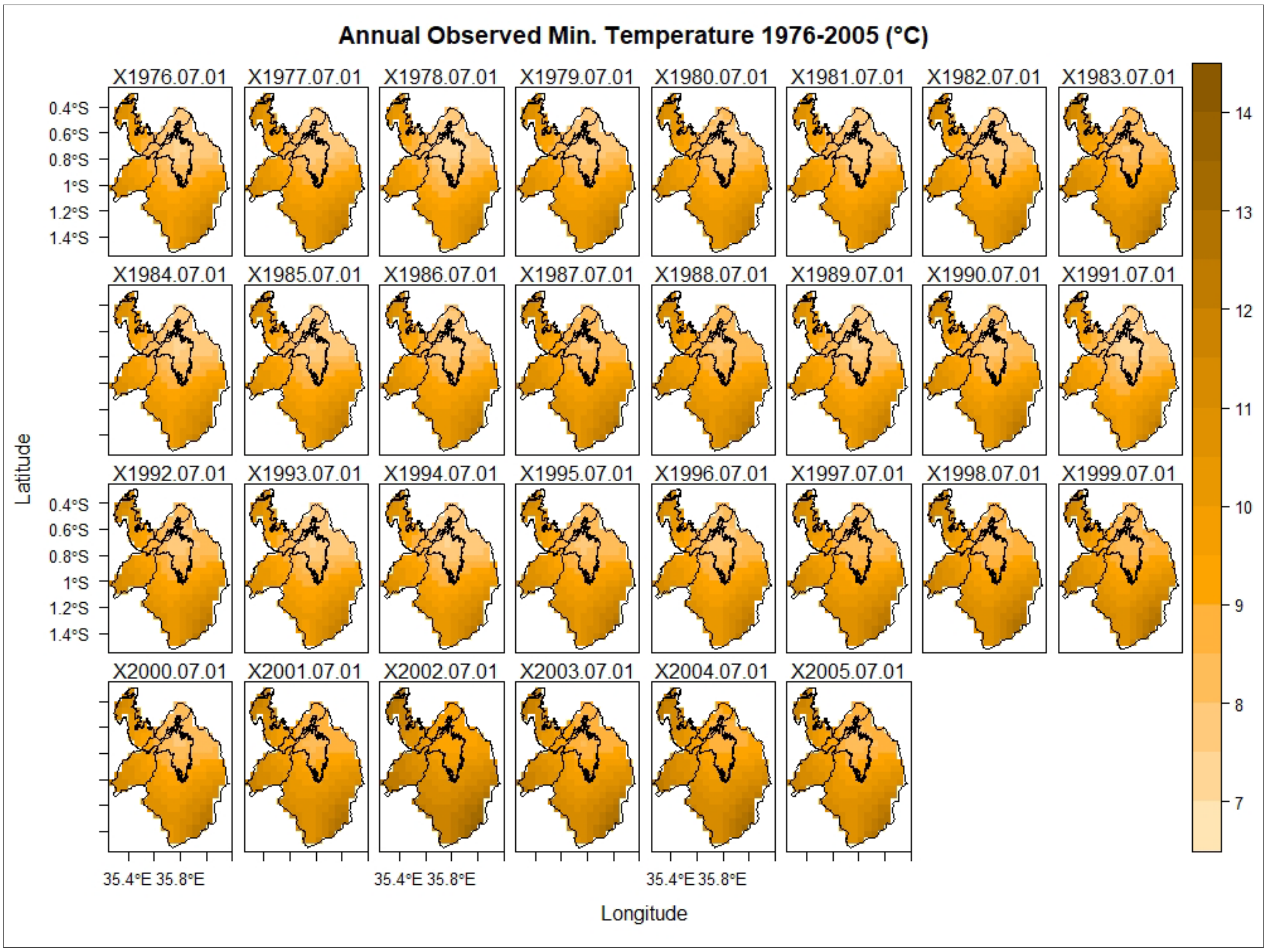

Figure 15. Historical annually observed minimum temperature in Mau Forest Catchment

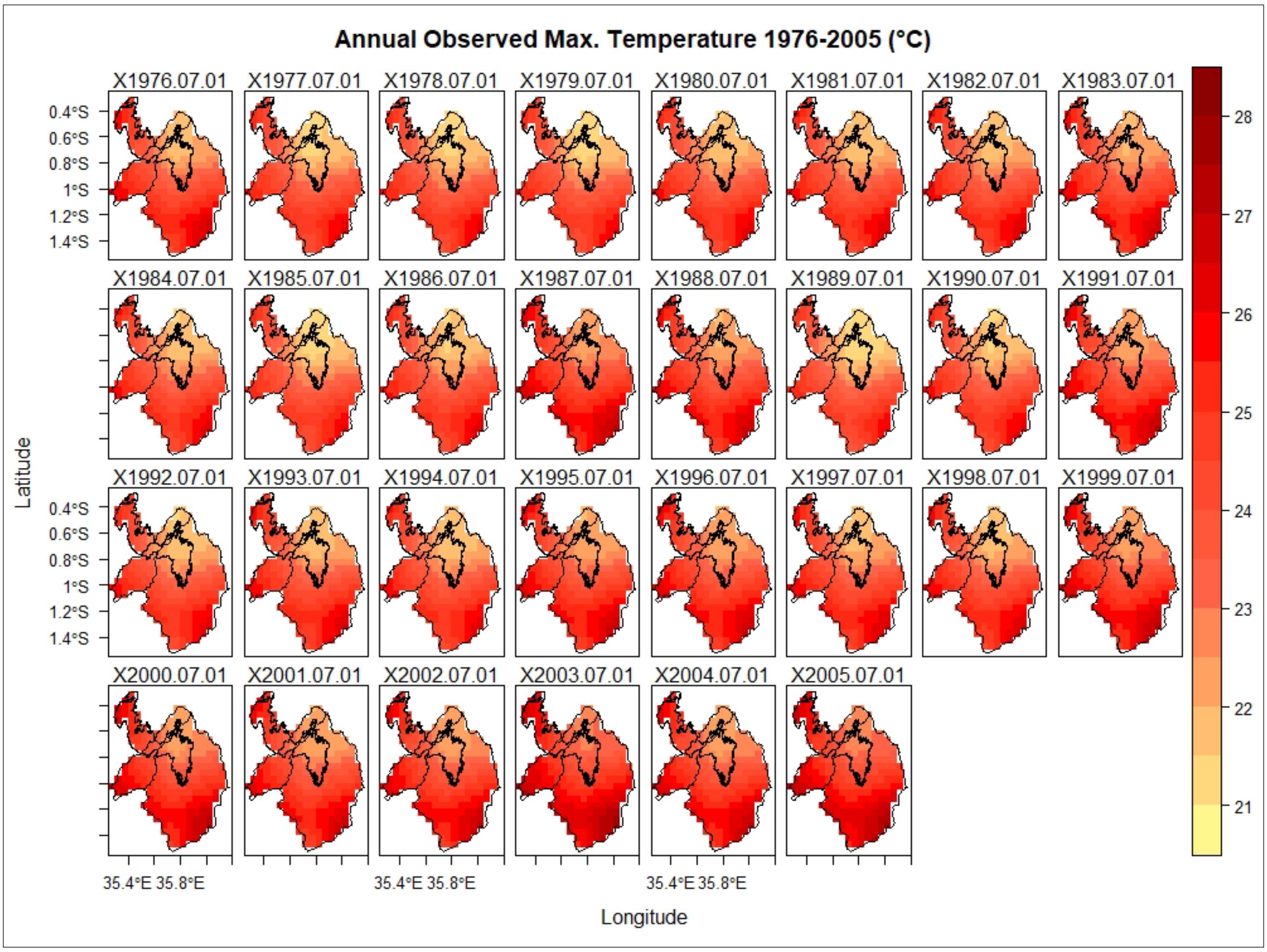

Figure 16. Historical annually observed maximum temperature in Mau Forest Catchment

2.4.4. Projected Future Climate for Mau Forest Catchment Basin

2.4.4.1 Rainfall Projections

Precipitation projections are considerably less certain for rainfall. The ensemble model generally suggests a wetting trend over the the MFCB region, see results in Figure 17 and Figure 2A - 19. Increase in precipitation is more pronounced in March to May (MAM) and September to November (SON) seasons.

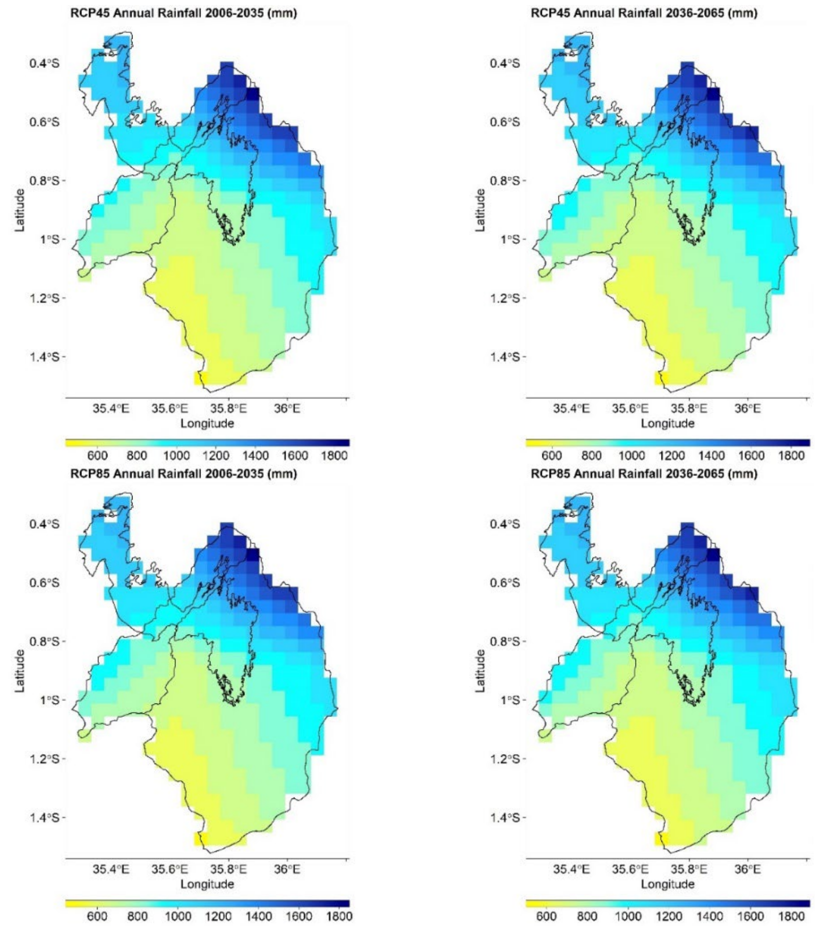

Figure 17. Annual total rainfall for 2006-2035 (top left), 2036-2065 (top right) under conditions of the RCP 4.5 pathway and 2006-2035 (bottom left), 2036-2065 (bottom right) under conditions of the RCP 8.5 pathway for Mau Forest Catchment Basin

2.4.4.2 Temperature Projections

The climate of the MFCB is projected to get warmer as depicted in Figure 18, and Figure 2A - 20 for annual and seasonal minimum temperatures as well as in Figure 19 and Figure 2A - 21 for annual and seasonal maximum temperatures, respectively. The ensemble model suggests an increasing trend in temperature averaging between 0.8°C and 1.9°C by 2036 and 1°C to 2°C by 2065, with the highest range in temperature increases during the months of MAM (see Figure 2A - 21).

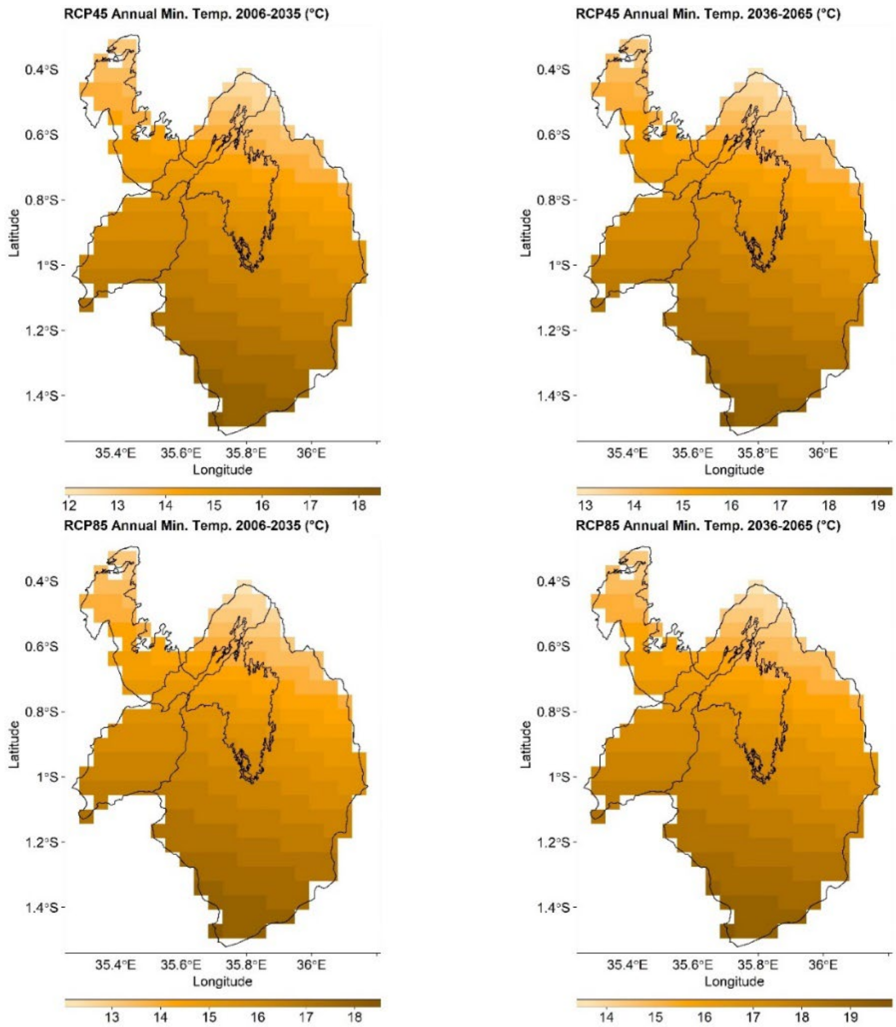

Figure 18. Annual minimum temperature for 2006-2035 (top left), 2036-2065 (top right) under conditions of the RCP 4.5 pathway and 2006-2035 (bottom left), 2036-2065 (bottom right) under conditions of the RCP 8.5 pathway in Mau Forest Catchment.

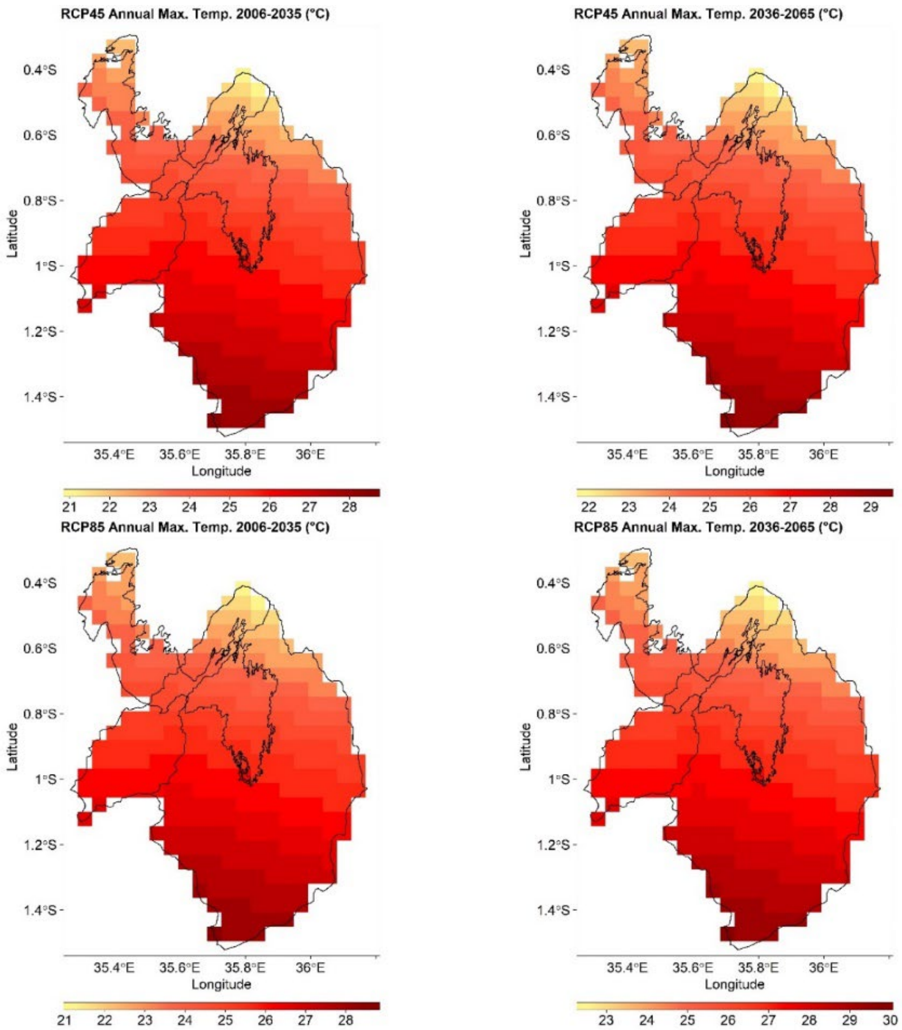

Figure 19. Annual maximum temperature for 2006-2035 (top left), 2036-2065 (top right) under conditions of the RCP 4.5 pathway and 2006-2035 (bottom left), 2036-2065 (bottom right) under conditions of the RCP 8.5 pathway in Mau Forest Catchment

Climate Change Summary for Mau Forest Catchment Basin

Projections are considerably less certain for rainfall. The ensemble model generally suggests a wetting trend over the Mau Forest Catchment. Increase in precipitation is more pronounced in March to May (MAM) and September to November (SON) seasons. In addition, the climate of the Mau catchment is projected to get warmer. The ensemble model suggests an increasing trend in temperature averaging between 0.8°C and 1.9°C by 2036 and 1°C to 2°C by 2065, with the highest range in temperature increases during the months of MAM. The projected climate change is foreseen to negatively impact the ecosystem in the basin. The human population faces a major threat socio-economically. Food and water security in the basin hang in the balance with major impacts for the small-scale farmers who have lower adaptive capacity. The interlinkage between water and food production might force large-scale/commercial farmers to reduce production as a result of less water available for irrigation.

2.4.5. Streamflow Analysis for the Limpopo River Basin

2.4.5.1 Historical Streamflow Trends

The impacts of climate change on the quality and quantity of available water resources are undeniable, as confirmed in the literature (Schulze 2000, 2005, 2010 and Mazvimavi, 2008). In this regard, the impact of climate change on water resources was investigated using streamflow analysis. Historical streamflow simulated from ACRU and mHM hydrological models based on six (the 7th being the ensemble model) CORDEX models spanning from 1976-2005 were compared with ground-based streamflow observations for the same period. Based on ACRU simulations (see Table 2), CORDEX models significantly underestimated the annual mean streamflow, e.g. SF_{model} (0.5 mm) < SF_{obs} (~4 mm), whereas MIROC5 and NorESM1 overestimated the annual mean streamflow under mHM simulations. Based on the annual mean streamflow comparison across the observations and the hydrological models, we note that the mHM model performs better than ACRU given the closeness of the actual annual mean streamflow with the observed annual mean streamflow. Bias-correction based on the quantile mapping approach was applied to both ACRU and mHM simulations, leading to much improved annual mean streamflow across the hydrological models.

The Mann-Kendall (MK) and Sen's Slope (SS) trends in annual mean, minimum, median and maximum streamflow are also presented in Table 2. The MK and SS trends seem to follow a similar pattern, although the SS trend values are always much less compared to those computed from the MK trend test. The CORDEX models depict negative trends in almost all the four variables, (except the annual minimum and maximum under ACRU and mHM simulations, respectively) across the hydrological model simulations. Such a decreasing trend suggest that there has been a reduction in streamflow in the LRB during the study period. In each case, statistically significant trends are shown in bold, and it can be noted from the table that only a few of the trends are statistically significant at 95% significant level.

Table 2. Mean and trends (Mann-Kendall [MK] and Sen's Slope [SS]) in annual actual and bias-corrected [BC] historical streamflow; bold means statistically significant trends at 95% confidence level

CORDEX Model	**ACRU model simulations**				
	Mean-SF Actual [B-C]	MK_{Mea} [SS_{Mea}]	MK_{Min} [SS_{Min}]	MK_{Med} [SS_{Med}]	MK_{Max} [SS_{Max}]
Observations	4.201	0.07 [0.02]	-0.04 [-1.7e-04]	0.16 [0.03]	0.03 [0.10]
CanESM2	0.472 [3.778]	-0.20 [-0.04]	-0.02 [0.00]]	-0.11 [-0.001]	-0.19 [-0.46]
CNRM	0.550 [3.951]	-0.12 [-0.03]	0.24 [-0.003]	**-0.26 [-0.02]**	0.12 [-0.60]
GFDL-ESM2M	0.572 [4.133]	**0.02 [0.01]**	0.24 [0.01]	0.17 [0.03]	-0.14 [-1.00]
IPSL-CM5A	0.696 [4.019]	-0.56 [-0.19]	**-0.25 [-0.005]**	**-0.39 [-0.07]**	**-0.63 [-3.14]**
MIROC5	0.448 [3.884]	-0.05 [-0.02]	0.03 [0.00]]	-0.03 [-0.002]	-0.18 [--1.16]
NorESM1	0.602 [3.793]	-0.01 [-0.003]	0.02 [0.00]	-0.04 [-0.003]	-0.02 [-0.15]
Ensemble	0.557 [4.191]	**-0.45 [-0.13**	0.24 [0.00]	-0.14 [-0.01]	**-0.43 [-2.57]**

	mHM model simulations				
Observations	4.201	0.07 [0.02]	-0.04 [-1.7e-04]	0.16 [0.03]	0.03 [0.10]
CanESM2	3.837 [4.252]	**-0.41 [-0.10]**	**-0.48 [-0.06]**	**-0.47 [-0.9]**	0.05 [0.50]
CNRM	3.576 [4.038	**-0.47[-0.13]**	**-0.50 [-0.04]**	**-0.52 [-0.11]**	-0.14 [-1.44]
GFDL-ESM2M	4.131 [4.139]	-0.13[-0.04]	-0.12 -0.02]	-0.12 [-0.04]	0.002 [0.03]
IPSL-CM5A	3.445 [4.000]	-0.19 [-0.06]	**-0.37 [-0.09]**	**-0.37 [-0.10]**	0.05 [0.50]
MIROC5	7.784 [4.097]	-0.09 [-0.03]	**-0.27 [-0.04]**	-0.22 [-0.05]	0.03[0.39]
NorESM1	4.922 [3.948]	**-0.44 [-0.09]**	**-0.54 [-0.08]**	**-0.49 [-0.09]**	-0.17 [1.48]
Ensemble	4.626 [4.221]	**-0.33 [-0.07]**	**-0.42 [-0.03]**	**-0.40 [-0.06]**	-0.05 [-0.64]

Seasonal trends, across the hydrological and CORDEX models, were detected based on SS trend estimator, and the results are presented in Figure 20, where a) and b) correspond to mHM and ACRU simulations, respectively. Trends in streamflow during DJF (December-January-February), MAM (March-April-May), JJA (June-July-August) and SON (September-October-November) seasons are highly noticeable across CORDEX models under mHM hydrological model simulations. On the other hand, negative trends in streamflow are noticeable during the summer and autumn seasons, under ACRU simulations, fluctuate between negative and positive (although they are negligibly small), and negligible positive during the spring season. Most of the trends, particularly from the mHM simulations, are statistically significant at 95% significant level. Slight differences in ACRU and mHM simulations can be attributed to the model parameterizations.

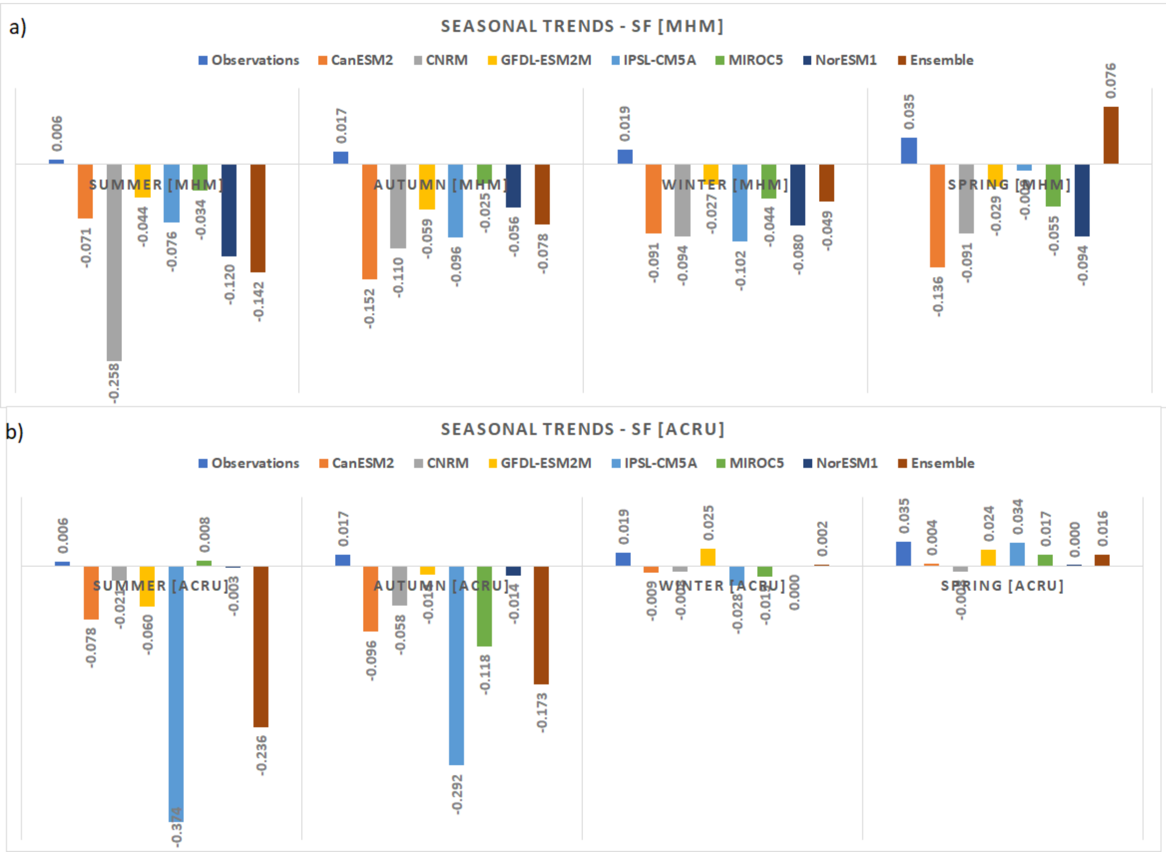

Figure 20. Seasonal trends in historical streamflow; a) mHM simulations and b) ACRU simulations

2.4.6. Characteristics of the Present Climate in the LRB: 2006-2035

2.4.6.1 Dissimilarity Analysis

Dissimilarities/similarities of CORDEX models across the hydrological models were investigated for the present climate based on CORDEX models. The analysis was carried out using R package TSclust (Time Series Clustering), described in Montero and Vilar (2015). The analysis was based on the comparison of simulated streamflow between pairs of CORDEX models under both the RCP4.5 and RCP8.5 scenarios, across the hydrological models. The periodogram was used as a measure of dissimilarity/similarity between the paired models. The results are summarized in Table 3 and Table 4 for ACRU and mHM streamflow simulations, respectively. In both tables, the upper triangle (in yellow colour) corresponds to streamflow simulations under the RCP4.5 scenario whereas the bottom triangle (in blue) represents simulations under the RCP8.5 scenario. Higher periodogram coefficients represent high dissimilarities between the paired models, while lower values represent similarities between them. The results suggest that the CORDEX models are more similar to each other across the hydrological models and the RCPs scenarios (with the exception of IPSL-CM5A – NorESM1 pair that gives the highest coefficient of 4, under the RCP4.5). In general, the CORDEX models are expected to exhibit similar characteristics, given that they are from the same domain, however, inherent differences may arise due to differences in the model parameterizations. Such differences may then propagate into hydrological process flows that generate the streamflow simulations.

Table 3. Matrix of similarity/dissimilarity based on ACRU streamflow simulations for present climate [2006-2035] (yellow/upper and blue/lower triangles corresponds to RCP4.5 RCP8.5, respectively)

	CanEMS2	CNRM	GFDL-ESM2M	IPSL-CM5A	MIROC5	NorESM1	Ensemble
CanESM2	0	2	2	2	3	3	2
CNRM	2	0	2	2	3	3	2
GFDL-ESM2M	2	2	0	2	3	3	2
IPSL-CM5A	2	2	2	0	3	4	2
MIROC5	3	3	3	3	0	2	3
NorESM1	3	2	2	2	3	0	4
Ensemble	3	2	2	2	3	2	0

Table 4. Matrix of similarity/dissimilarity based on mHM streamflow simulations for present climate [2006-2035] (yellow/upper and blue/lower triangles corresponds to RCP4.5 RCP8.5, respectively)

	CanEMS2	CNRM	GFDL-ESM2M	IPSL-CM5A	MIROC5	NorESM1	Ensemble
CanESM2	0	2	2	2	2	2	2
CNRM	2	0	2	2	2	2	2
GFDL-ESM2M	2	2	0	2	2	2	2
IPSL-CM5A	3	2	2	0	2	2	3
MIROC5	2	2	2	2	0	2	2
NorESM1	2	2	2	2	2	0	2
Ensemble	2	2	2	3	2	2	0

2.4.6.2 Statistical Characteristics of Streamflow from 2006-2035

Figure 21 depicts the annual mean streamflow, calculated using the calendar year, across the hydrological and CORDEX models under both the RCP4.5 and RCP8.5 scenarios. Simulations based on mHM model result in slightly higher annual mean streamflow, in both RCP scenarios. Mean streamflow ranges between 1.7 mm and 5.5 mm for ACRU simulations and 3.0 mm to 6.0 mm for mHM, under the RCP4.5 scenario. Similarly, the annual mean streamflow ranges between 2.0 mm and 5.0 mm for both the hydrological models under the RCP8.5 pathway. Table 5 presents the MK and SS trends in streamflow, by the calendar year, across the hydrological and CORDEX models, under RCP4.5 and RCP8.5 pathways. Negligible negative trends are detected in over 70% of the CORDEX models under RCP8.5 based on ACRU simulations and in both RCP4.5 and RCP8.5 scenarios under mHM model simulations, although most of such trends are not statistically significant. It is worth noting that the ACRU simulations under the RCP4.5 depict negligible positive trends in most of the CORDEX models.

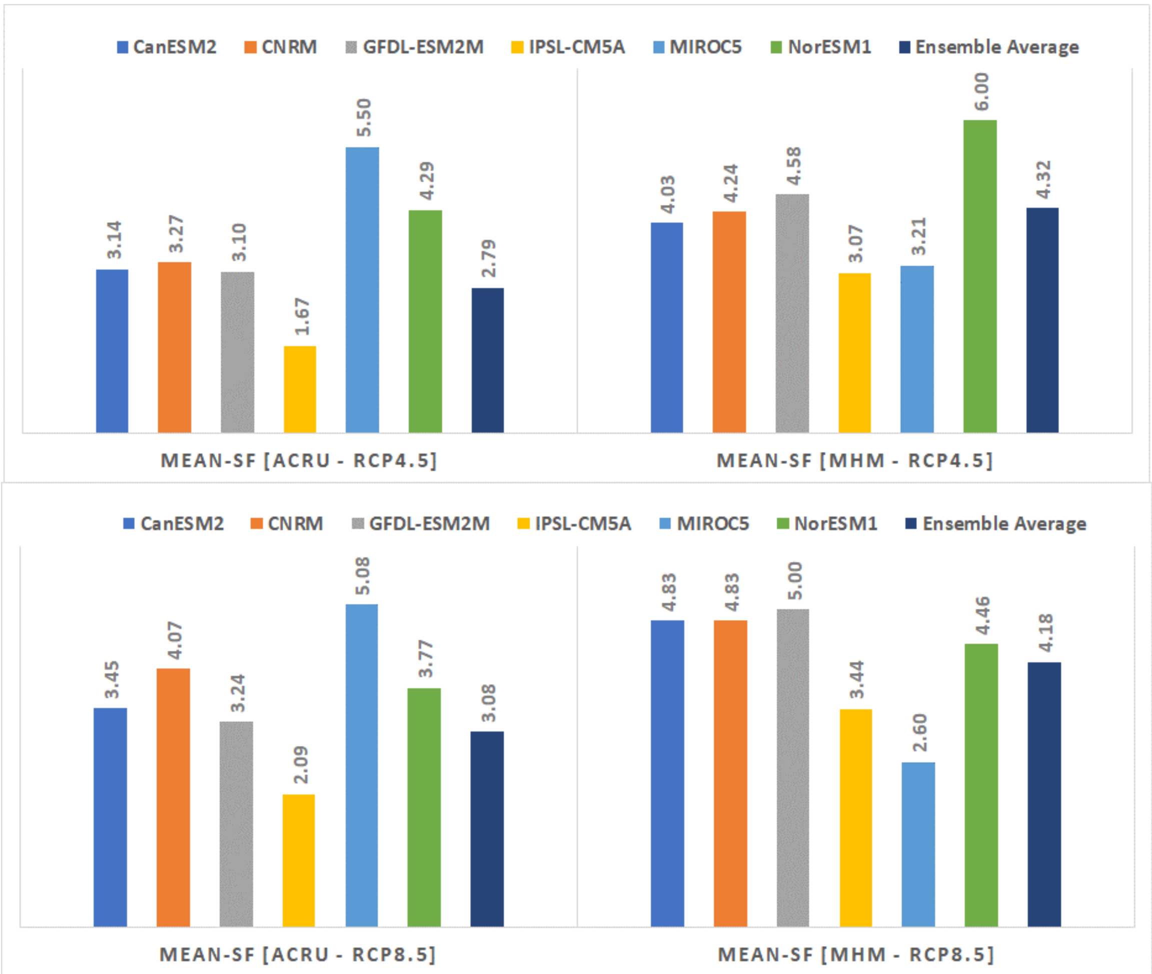

Figure 21. Annual mean streamflow (a) RCP4.5 and (b) RCP8.5 across ACRU and mHM hydrological models

Table 5.Trends [MK – Mann-Kendall, SS – Sen's Slope] in streamflow for the 2006-2035 period. Calculations were based on a calendar year; bold means statistically significant trends at 95% confidence level

CORDEX Model	**ACRU simulations [2006-2035]**		**mHM simulations [2006-2035]**	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5
	MK trend [SS]	MK trend [SS]	MK trend [SS]	MK trend [SS]
CanESM2	-0.01 [-0.002]	-0.09 [-0.03]	**-0.31 [-0.08]**	0.04 [0.01]
CNRM	0.15 [0.04]	-0.002 [-0.001]	-0.05 [-0.03]	**-0.44 [-0.14]**
GFDL-ESM2M	0.05 [0.01]	0.03 [-0.01]	-0.04 [-0.01]	-0.24 [-0.06]
IPSL-CM5A	0.22 [0.04]	-0.06 [-0.01]	-0.05 [-0.02]	**-0.36 [-0.14]**
MIROC5	0.20 [0.07]	-0.01 [-0.004]	0.05 [0.02]	-0.19 [-0.02]
NorESM1	0.03[0.02]	0.09 [0.03]	-0.02 [-0.003]	-0.24[-0.07]
Ensemble	**0.27[0.03]**	-0.10 [-0.03]	0.08 [-0.02]	-0.23 [-0.05]

The results for seasonal trends, computed from the SS trend estimator, are presented in Figure 22, where a) and b) correspond to ACRU and mHM simulations under RCP4.5, whereas c) and d) are for ACRU and mHM simulations under RCP8.5, respectively. While all CORDEX models depict a positive trend in streamflow during the DJF season for ACRU simulations under the RCP4.5, only three models depict similar trend pattern in mHM model simulations. Positive trends in streamflow during DJF are expected given the LRB receives most of its rainfall during the summer season, although due to time delays and high temperature, most of the moisture is likely to be lost through evapotranspiration, hence the immediate negative trends observed during MAM season. Overall, noticeable negative trends across the seasons, particularly from mHM simulations, are observed across the models, although most of these trends are not statistically significant at 95% significant level.

Table 6 presents the MK and SS trends in annual mean discharge (streamflow) based on the hydrological (discharge) year and annual mean baseflow across the hydrological models and RCPs scenarios. The baseflow is considered in this study since it is an important variable that supports streamflow; hence it can be used to inform the current and future use of water resources. Negative trends in annual mean discharge and baseflow dominate under mHM simulations under both the RCP4.5 and RCP8.5 scenarios and in ACRU simulations under the RCP8.5 pathway. Statistically significant trends across the hydrological and CORDEX models under both RCP scenarios are depicted in bold and are mostly observed in mHM simulations under RCP8.5. Overall, the statistical characteristics of streamflow between 2006-2035 point to reduced streamflow, and this is confirmed by the ongoing drought conditions in the LRB, leading to water supply restrictions and limitations.

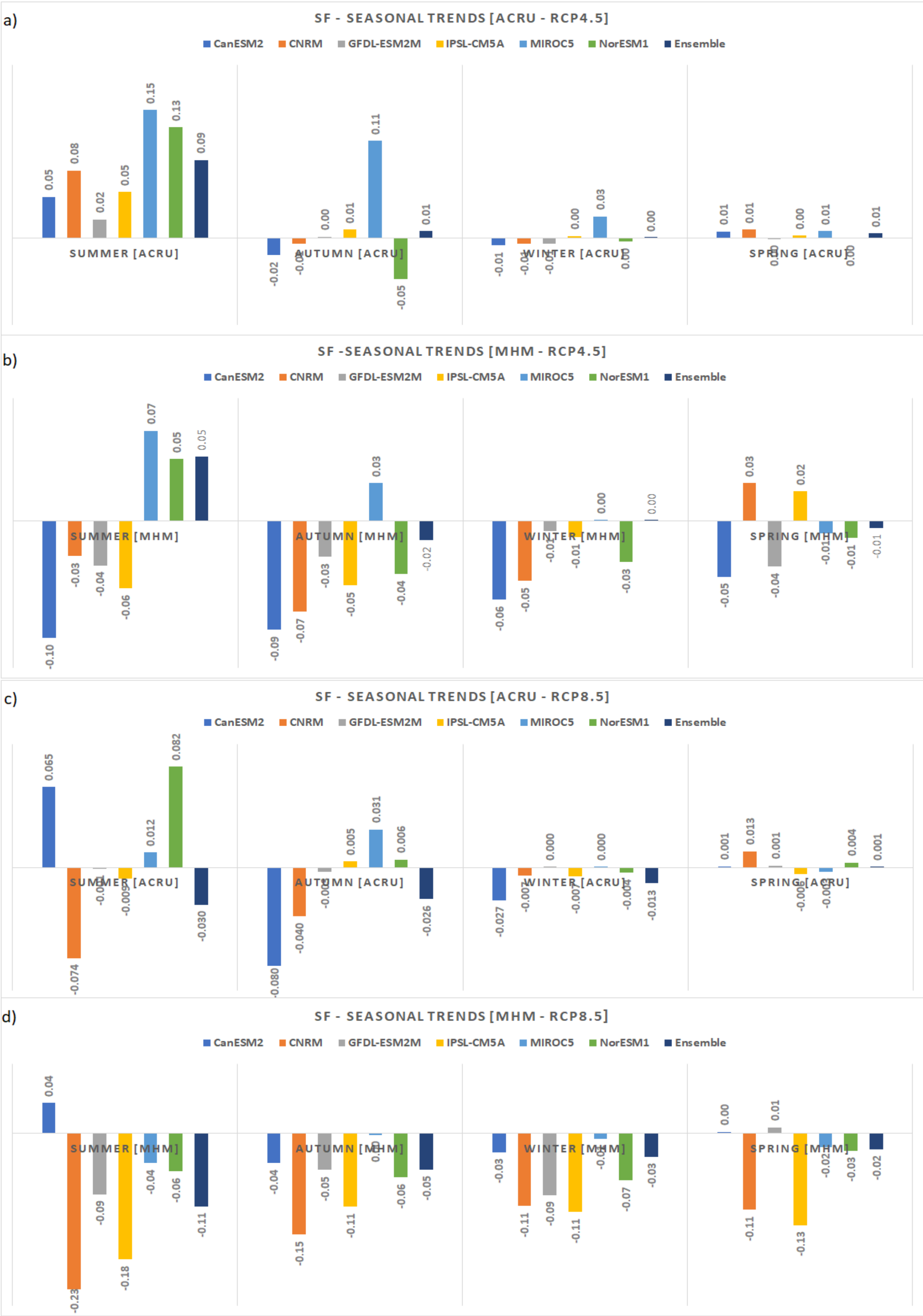

Figure 22. Streamflow seasonal trends (Sen's Slope) across hydrological models and CORDEX models

Table 6. Trends in annual discharge [Q] based on a hydrological year and baseflow [BF]; bold indicate statistically significant trends at 5% significance level

CORDEX	**ACRU [2006-2035] simulations**				**mHM [2006-2035] simulations**			
	RCP4.5		**RCP8.5**		**RCP4.5**		**RCP8.5**	
	MK [SS] (Q)	**MK [SS] (BF)**	**MK [SS] (Q)**	**MK [SS] (BF)**	**MK [SS] (Q)**	**MK [SS] (BF)**	**MK [SS] (Q)**	**MK [SS] (BF)**
CanESM2	-0.05 [-0.01]	-0.06 [-0.01]	-0.11 [-0.03]	-0.12 [-0.03]	**-0.35 [-0.08]**	**-0.40 [-0.06]**	-0.01 [-0.01]	-0.11 [-0.02]
CNRM	0.05 [0.01]	0.05 [0.01]	-0.09 [-0.02]	-0.13 [-0.02]	-0.06 [-0.02]	-0.15 [-0.40]	**-0.43 [-0.13]**	**-0.48 [-0.10]**
GFDL-ESM2M	0.09 [0.02]	0.08 [0.01]	-0.08 [-0.02]	-0.08 [-0.02]	-0.05 [-0.02]	-0.12 [-0.03]	-0.2 [-0.06]	**-0.36 [-0.05]**
IPSL-CM5A	0.16 [0.03]	0.11 [0.02]	-0.11 [-0.02]	-0.11 [-0.02]	-0.06 [-0.01]	-0.17 [-0.02]	**-0.30 [-0.13]**	**-0.35 [-0.10]**
MIROC5	0.15 [0.06]	0.15 [0.04]	-0.08 [-0.03]	-0.08 [-0.02]	0.09 [0.02]	0.06 [0.01]	-0.21 [-0.03	**-0.25 [-0.01]**
NorESM1	0.02 [0.01]	0.02 [0.004]	0.07 [0.02]	0.07 [0.01]	0.05 [0.02]	-0.03 [-0.01]	-0.14 [-0.05]	**-0.28 [-0.06]**
Ensemble	0.14 [0.02]	0.12 [0.01]	-0.19 [-0.04]	-0.18 [-0.03]	0.06 [0.02]	0.10 [0.01]	-0.21 [-0.04]	**-0.28 [-0.03]**

2.4.6.3 Hydroclimatic Extremes in Streamflow from 2006-2035

- **Hydrological Drought**

The Standardized Streamflow Drought Index (SSI) was used to evaluate the current hydrological drought conditions in the LRB. The SSI was computed based on streamflow simulated from ACRU model based on CORDEX models under both the RCPs. For this report, only 6- and 12-months accumulation periods were considered, since these periods related to hydrological droughts and impacts. The results for selected CORDEX models under RCP4.5 and RCP8.5 scenarios are presented in Figure 23 andFigure 2A - 22, respectively. In each figure, the positive SSI values correspond to wetter conditions, whereas negative values represent drier conditions, and the overall interpretation is similar to the Standardized Precipitation Index (WMO, 2012). In both figures, hydrological extreme events that can lead to potential drought and floods are evident within the LRB. In particular, the LRB seem to be experiencing drought and the region is likely to continue experiencing drought conditions amounting to at least four main drought episodes, categorized as ranging from moderate to severe, by the end of 2035. Moderate to very wet conditions with varying durations are also expected. Furthermore, more frequent drought events persisting for longer periods are expected under SSI-12 accumulation period, towards the end of the study period.

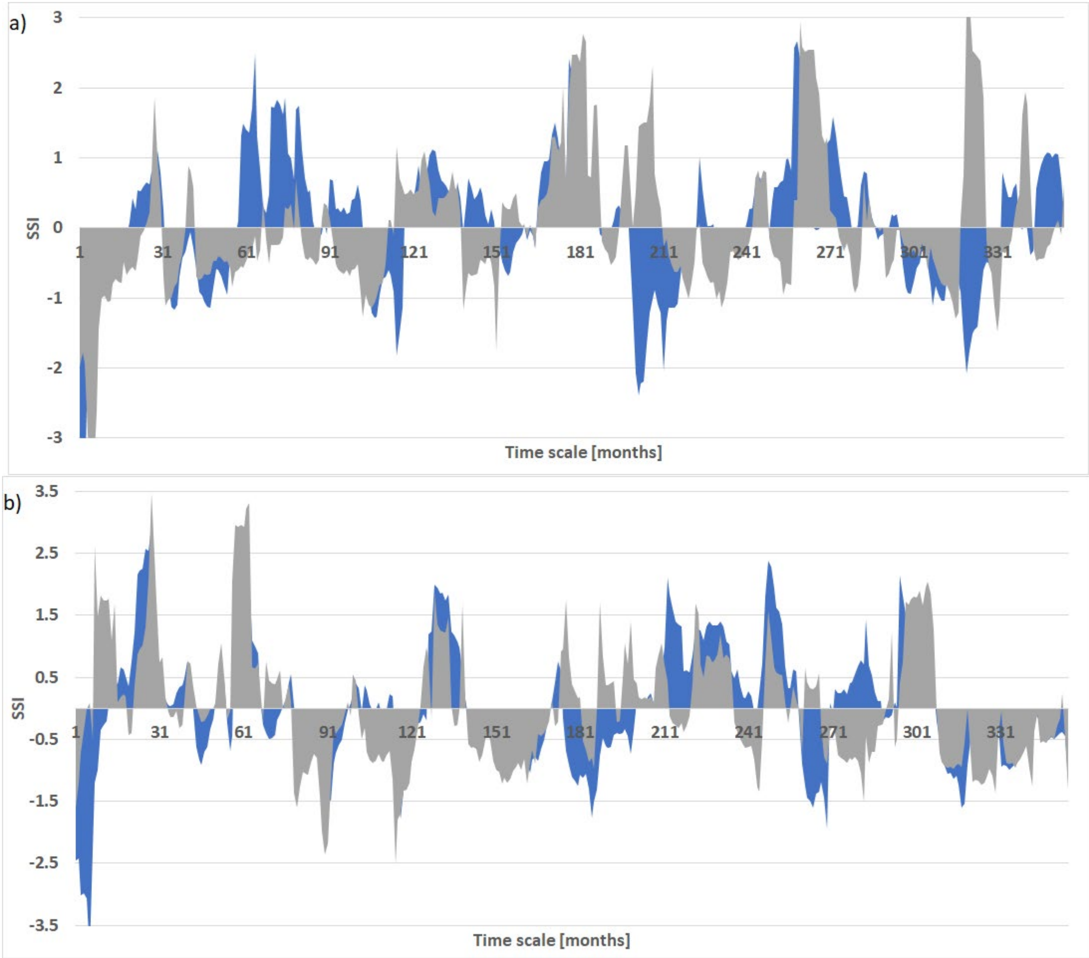

Figure 23. Standardize Streamflow Index (SSI-6) time series for selected CORDEX models; a) for RCP4.5 and (b) RCP8.5

- **Trends in Drought Monitoring Indicators**

Drought Monitoring Indicators (DMIs), e.g. drought duration and drought severity, were computed using the SSI-6 and -12 time series across the hydrological and CORDEX models. The DMIs' trends are presented in Table 7 for both ACRU (top panel) and mHM (bottom) models and across the RCP scenarios. Based on both hydrological simulations, approximately 70% and 85% of CORDEX models depict zero, and negligible positive trends in drought duration and severity for the 6- and 12-month accumulation periods, with exceptions to drought severity under RCP8.5. Only a few of the observed trends, positive (negative) are statistically significant, see the trends in bold-faced. In general, the ongoing drought conditions experienced from 2006 in the LRB are likely to persist towards the entire period, up to 2035, as confirmed by the drought episodes in Figure 23 and Figure 2A - 22, although such conditions are likely to be less severe.

Table 7. Trends in Drought Monitoring Indicators based on SSI-6 and SSI-12; bold represents statistically significant trends at a 95% confidence level. DD – drought duration; DS – drought severity

Model	ACRU [2006-2035] simulations							
	Standardized Streamflow Index 6				Standardized Streamflow Index 12			
	RCP4.5		RCP8.5		RCP4.5		RCP8.5	
	DD	DS	DD	DS	DD	DS	DD	DS
	MK [SS]	MK [SS]	MK [SS]	MK [SS]	MK [SS]	MK [SS]	MK [SS]	MK [SS]
CanESM2	0.07 [0.00]	0.11 [0.02]	**0.42 [0.05]**	0.07 [0.01]	0.01 [0.00]	**-0.35 [-0.07]**	**0.47 [0.08]**	**-0.45 [-0.04]**
CNRM	0.04 [0.00]	**0.43 [0.05]**	0.10 [0.00]	**0.63 [0.09]**	0.07 [0.00]	0.02 [0.002]	**0.37 [0.13]**	0.24 [0.04]
GFDL-ESM2M	-0.07 [0.00]	0.18 [0.03]	-0.09 [0.00]	0.21 [0.03]	0.25 [0.00]	**-0.39 [-0.09]**	**0.76 [0.13]**	**-0.31 [-0.03]**
IPSL-CM5A	**-0.33 [-0.05]**	-0.08 [-0.01]	-0.25 [0.00]	-0.06 [-0.02]	**-0.35 [-0.06]**	0.05 [0.01]	-0.12 [0.00]	**-0.38 [-0.09]**
MIROC5	0.24 [0.08]	0.11 [0.05]	**0.47 [0.14]**	0.33 **[0.14]**	0.13 [0.00]	-0.18 [-0.04]	-0.08 [0.00]	-0.04 [-0.01]
NorESM1	0.07 [0.00]	-0.15 [-0.04]	0.31 [0.06]	**0.26 [0.05]**	0.15 [0.00]	**0.35 [0.100]**	**0.40 [0.09]**	**0.27 [0.07]**
Ensemble	0.02 [0.00]	-0.10 [-0.04]	**0.45 [0.10]**	**0.26 [0.06]**	-0.05 [0.00]	**-0.27 [-0.06]**	**0.48 [0.07]**	-0.10 [-0.02]
	mHM [2006-2035] simulations							
CanESM2	0.21 [0.00]	0.12 [0.03]	0.11 [0.00]	-0.17 [-0.03]	**0.44 [0.08]**	**0.42 [0.10]**	0.02 [0.00]	**-0.31 [-0.04]**
CNRM	-0.04 [0.00]	-0.22 [-0.05]	**0.40 [0.06]**	**0.57 [0.18]**	0.12 [0.00]	-0.23 [-0.04]	**0.39 [0.06]**	**0.54 [0.18]**
GFDL-ESM2M	**0.40 [0.06]**	**0.49 [0.07]**	**-0.29 [0.00]**	-0.23 [-0.05]	0.09 [0.00]	**0.46 [0.08]**	**-0.29 [0.00]**	-0.24 [-0.02
IPSL-CM5A	0.18 [0.00]	**0.46 [0.10]**	0.04 [0.00]	**-0.40 [-0.09]**	0.05 [0.00]	**0.56 [0.14]**	-0.23 [0.00]	**-0.55 [-0.08]**
MIROC5	**0.31 [0.07]**	-0.10 [-0.02]	-0.06 [0.00]	0.09 [0.02]	**0.08** [0.00]	**0.24 [0.03]**	0.22 [0.00]	0.02 [0.01]
NorESM1	0.05 [0.00]	-0.15 [-0.02]	**0.42 [0.00]**	**0.25 [0.08]**	-0.04 [0.00]	**-0.29 [-0.03]**	**0.63 [0.08]**	**0.47 [0.12]**
Ensemble	0.19 [0.00]	0.05 [0.01]	0.22 [0.00]	**0.31 [0.07]**	0.09 [0.00]	-0.01 [-0.003]	0.13 [0.00]	0.12 [0.02]

2.4.7. Characteristics of Near-future Streamflow Projections: 2036-2065

2.4.7.1 Dissimilarity Analysis

Results for similarity/dissimilarity matrix between CORDEX models across the hydrological models are shown in Table 2A - 1 and Table 2A - 2, corresponding to ACRU and mHM streamflow analysis, respectively. The results are more similar to Table 3 and Table 4 for the present climate projections, with exceptions to CanESM2 – MIROC5, GFDL-ESM2M – MIROC5 under ACRU simulations and RCP4.5 and MIROC5 – GFDL-ESM2M paired models under the RCP8.5 scenario, which depict the most dissimilarity features to others. The rest of the paired CORDEX models have the least distance of 2 or 3, hence displaying similarities between pairs.

2.4.7.2 Statistical Characteristics of near-future Projected Streamflow

Results for near-future projected mean annual streamflow from ACRU and mHM simulations, based on a calendar year, across CORDEX models and RCP projected scenarios, are presented in Figure 24. The annual mean is highly variable across the models. For ACRU simulations, the annual mean streamflow ranges from the lowest of 1.8 mm (IPSL-CM5A, RCP4.5) to the highest of 4.9 mm (MIROC5, both RCPs). On the contrary, mHM simulations depict the lowest annual mean of 2.2 mm (MIROC5, both RCPs) and the highest mean value of 6.4 mm (5.2 mm) for CNRM under RCP4.5 (RCP8.5). Overall, the annual mean streamflow for the 2036-2065 period is within the same range as the observed annual mean for 2006-2035.

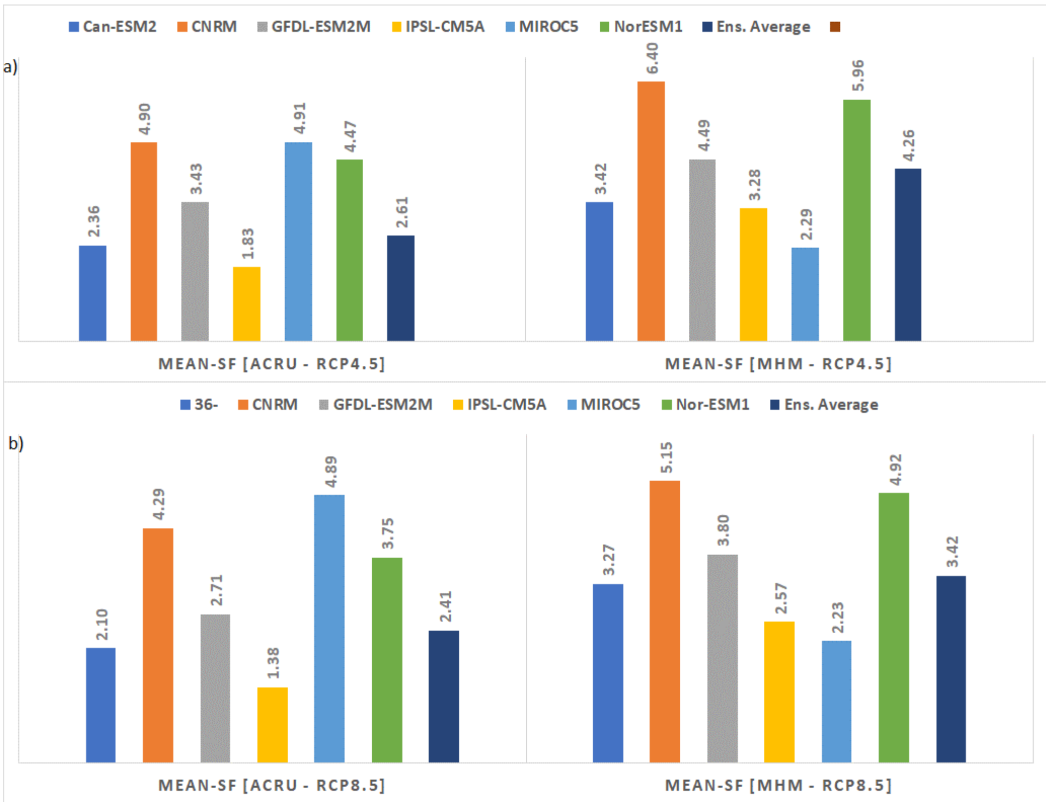

Figure 24. Projected annual mean (a) RCP4.5 and (b) RCP8.5 across ACRU and mHM hydrological models

The MK and SS trends in near-future projected streamflow are depicted in Table 8. Both the MK and SS trend tests depict negative (or negligible negative in terms of SS) trends across the CORDEX models and RCPs under the mHM hydrological model simulations. Similar trend pattern is observed in approximately 60% of CORDEX models under ACRU simulations. Consequently, the results suggest a decrease in near-future projected streamflow. In particular, the overall trend results in simulated streamflow for the present climate and near-future projected streamflow suggest that there will be a general decrease in projected streamflow, in the LRB, as we move further into the future.

Table 9 depicts trends in annual discharge based on a hydrological year and annual baseflow across ACRU and mHM hydrological models and CORDEX models under the considered RCP scenarios. All the CORDEX models under mHM simulations depict negative trends in annual discharge and baseflow. Most of the detected trends are statistically significant. Over 70% of the CORDEX models under ACRU simulations depict negative trends in annual mean discharge and baseflow, although most of them are not statistically significant. The MK and SS trends computed from both ACRU and the mHM hydrological models are very comparative and collaborate with the initial findings that the LRB is likely to experience reduced streamflow as we move more into the near-future.

Table 8. Trends in projected near-future annual streamflow across the hydrological models and CORDEX models, by calendar year; bold indicate statistically significant in trends at 95% confidence level

CORDEX Model	**ACRU simulations [2036-2065]**		**mHM simulations [2036-2065]**	
	RCP4.5	**RCP8.5**	**RCP4.5**	**RCP8.5**
	MK trend [SS]	**MK trend [SS]**	**MK trend [SS]**	**MK trend [SS]**
CanESM2	-0.01 [-4.5E-04]	-0.12 [-0.02]	-0.19 [-0.05]	**-0.30 [-0.08]**
CNRM	0.15 [0.06]	0.04 [0.03]	**-0.07 [-0.01]**	-0.18 [-0.07]
GFDL-ESM2M	**-0.26 [-0.08]**	0.07 [0.02]	**-0.42 [-0.12]**	**-0.13 [-0.02]**
IPSL-CM5A	-0.17 [-0.02]	-0.06 [0.01]	-0.26 [-0.07]	-0.41 [-0.10]
MIROC5	0.14 [0.05]	0.14 [0.04]	-0.21 [-0.03]	-0.23 [-0.03]
NorESM1	-0.05 [-0.02]	-0.08 [-0.01]	**-0.45 [-0.14]**	-0.19 [-0.04]
Ensemble	0.05 [0.01]	-0.03 [-0.004]	**-0.41 [-0.07]**	-0.23 [-0.04]

Table 9. Trends in annual discharge [Q] by the hydrological year, and annual baseflow [BF]; bold indicate statistically significant trends

CORDEX	**ACRU [2036-2065] simulations**				**mHM [2036-2065] simulations**			
	RCP4.5		**RCP8.5**		**RCP4.5**		**RCP8.5**	
	MK [SS] (Q)	**MK [SS] (BF)**	**MK [SS] (Q)**	**MK [SS] (BF)**	**MK [SS] (Q)**	**MK [SS] (BF)**	**MK [SS] (Q)**	**MK [SS] (BF)**
CanESM2	-0.06 [-0.01]	-0.05 [-0.01]	-0.11 [-0.02]	-0.15 [-0.02]	-0.23 [-0.06]	**-0.27 [-0.05]**	**-0.26 [-0.07]**	**-0.35 [-0.06]**
CNRM	0.18 [0.08]	0.15 [0.05]	-0.07 [0.03]	0.06 [0.01]	-0.02 [-0.01]	**-0.11** [-0.2]	-0.19 [-0.09]	**-0.29 -0.08]**
GFDL-ESM2M	**-0.31 [-0.09]**	**-0.31 [-0.07]**	-0.02 [-0.01]	-0.002 [-0.002]	**-0.44 [-0.13]**	-0.52 **[-0.09]**	-0.15 [-0.04]	-0.18 [-0.02]
IPSL-CM5A	-0.24 [-0.03]	**-0.25 [-0.02]**	-0.09 [-0.01]	-0.11 [-0.01]	**-0.27 [-0.08]**	**-0.33 [-0.05]**	**-0.44 [-0.10]**	**-0.55 [-0.06]**
MIROC5	0.07 [0.04]	0.08 [0.03]	0.06 [0.03]	0.05 [0.02]	-0.18 [-0.03]	**-0.26 [-0.02]**	-0.17 [-0.02]	**-0.27 [-0.02]**
NorESM1	-0.11 [-0.04]	-0.11 [-0.03]	-0.15 [-0.02	-0.17 [-0.03]	**-0.41 [-0.12]**	**-0.46 [-0.09]**	-0.16 [-0.04]	**-0.24 [-0.04]**
Ensemble	-0.04 [-0.01]	-0.04 [-0.004]	-0.10 [-0.01	-0.12 [-0.01]	**-0.36 [-0.06]**	**-0.59 [-0.04]**	-0.15 [-0.03]	**-0.26 [0.02]**

2.4.7.3 *High and Low Streamflow Analysis*

Flow quantiles and baseflow percentiles are essential in hydrological studies as they relate to conditions of water resources, and more generally, both measures provide information on the potential status of hydrological extremes such as drought and floods. In the current study, trends in the 0.1 and 0.9 flow quantiles and the 10th and 90th baseflow percentiles were calculated across the models, results are given in Table 10. Here, the 0.1 and 0.9 quantiles relate to dry and wet conditions that can lead to drought and floods (flash floods) in a region. Similarly, the 10th and 90th percentiles give the lowest and highest baseflow peaks within a given period, persistent lowest and highest peaks have the potential to cause drought and flood. Negative trends (mostly statistically significant) in low and high flows dominate, particularly under mHM simulations and ACRU simulations under RCP8.5. In addition, while trends in high baseflow peaks are mostly negative, those in low peaks are either trendless or positive trends. The results suggest that while the LRB is likely to experience frequent dry conditions that can translate to drought, the region is also likely to experience wet conditions that can result in (flash) floods.

Table 10. Trends in flow quantiles and baseflow percentiles; bold indicate statistically significant trends

	ACRU [2036-2065] simulations							
CORDEX	RCP4.5				RCP8.5			
	$Q_{0.1}$	$Q_{0.9}$	BF_{10}	BF_{90}	$Q_{0.1}$	$Q_{0.9}$	BF_{10}	BF_{90}
CanESM2	0.02 [0.00]	-0.05 [-0.01]	0.12 [0.33]	-0.18 [-0.55]	**-0.26 [-0.001]**	-0.15 [-0.05]	-0.11 [-0.12]	**-0.32 [-1.61]**
CNRM	-0.06 [0.00]	0.11 [0.09]	0.15 0.31]	-0.19 [-0.73]	0.12 [0.00]	0.09 [0.06]	-0.13 [0.00]	0.07 [0.33]
GFDL-ESM2M	-0.13 [-0.003]	-0.23 [-0.11]	0.19 [0.22]	-0.07 [-0.38]	0.19 [0.002]	0.12 [0.03]	0.14 [0.08]	0.07 [0.31]
IPSL-CM5A	-0.20 [0.00]	-0.21 [-0.04]	0.07 [0.00]	-0.23 [-1.23]	-0.01 [0.00]	-0.06 [-0.01]	-0.02 [0.00]	-0.12 [-0.68]
MIROC5	0.06 [0.01]	0.18 [0.17]	0.04 [0.00]	-0.33 **[-1.13]**	0.10 [0.01]	0.14 [0.13]	0.04 0.00]	-0.08 [-0.42]
NorESM1	-0.09 [-0.001]	-0.08 [-0.06]	-0.02 [0.00]	0.17 [0.48]	-0.03 [0.00]	-0.14 [-0.06]	-0.03 [0.00]	-0.02 [-0.08]
Ensemble	-0.14 [0.00]	0.03 [0.01]	-0.11 [-0.09]	-0.24 [- 0.57]	-0.06 [0.00]	-0.08 [- 0.01]	-0.10 [0.00]	0.01 [0.00]
	mHM [2036-2065] simulations							
CanESM2	-0.23 [-0.03]	-0.11 [-0.02]	0.13 [0.00]	-0.20 [-1.00]	**-0.40 [-0.05]**	-0.21 [-0.03]	0.24 [0.00]	**-0.34 [-2.50]**
CNRM	-0.19 [-0.04]	-0.16 [-0.05]	0.17 [0.00]	-0.13 [-0.24]	**-0.31 [-0.05]**	-0.09 [-0.03]	-0.15 [0.00]	-0.20 [-0.65]
GFDL-ESM2M	-0.51 **[0.08]**	-0.24 [-0.04]	[0.00]	-0.34 **[-1.10]**	-0.17 [-0.01]	-0.11 [-0.01]	[0.00]	0.04 [0.20]
IPSL-CM5A	**-0.47 [-0.02]**	-0.24 [-0.06]	0.19 [0.00]	-0.25 **[-3.80]**	**-0.72 [-0.02]**	**-0.29 [-0.05]**	[0.00]	**-0.61 [-5.79]**
MIROC5	**-0.50 [0.00]**	-0.20 [-0.07]	[0.00]	-0.26 **[-1.80]**	**-0.50 [0.00]**	0.02 [0.002]	[0.00]	-0.10 [-0.67]
NorESM1	**-0.42 [-0.08]**	**-0.31 [-0.11]**	[0.00]	-0.30 **[-0.63]**	**-0.30 [-0.05]**	-0.14 [-0.05]	[0.00]	-0.13 [-0.33]
Ensemble	**-0.70 [-0.03]**	**-0.60 [-0.08]**	[0.00]	-0.59 **[3.76]**	**-0.39 [0.00]**	**-0.26 [-0.02]**	[0.00]	[-0.17 [-1.00]

2.4.7.4 Seasonal Trends in Near-future Projected Streamflow

Seasonal trends in near-future projected streamflow are given in Figure 25, where a) and b) correspond to ACRU and mHM simulations under RCP4.5. whereas, c) and d) are for ACRU and mHM simulations under RCP8.5, respectively. Based on ACRU simulations, trends in DJF (December-January-February) and MAM (March-April-May) fluctuate between negative and positive trends. Overall, negative trends across the seasons, particularly from mHM simulations, are highly noticeable, and most of these trends are found to be statistically significant at 95% significant level. Slight differences in ACRU and mHM simulations can be attributed to the model parameterizations.

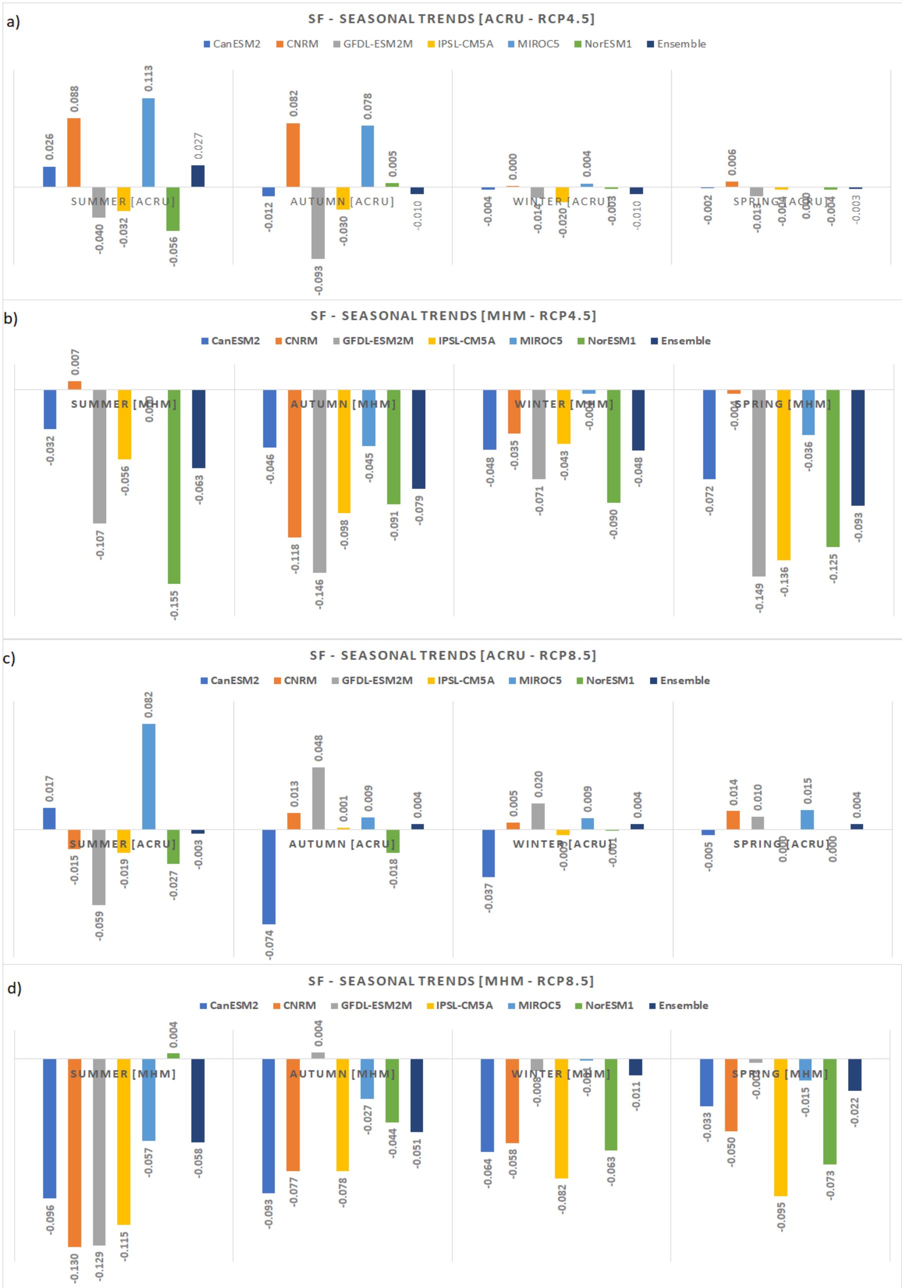

Figure 25. Seasonal trends (Sen's Slope) across hydrological models and CORDEX models

2.4.7.5 Evaluation of Near-future Hydrological Drought

Figure 26 and Figure 2A - 23 represent the SSI 6- and 12-time series derived from selected CORDEX models under both the RCP4.5 and RCP8.5 scenarios. The figures depict the frequency of occurrence of projected dry and wet conditions in months within the LRB. The SSI-6 under both RCP4.5 and RCP8.5 demonstrate a significant variation in seasonal to annual streamflow, which fluctuates between wet and dry months. Drought events are likely to be more frequent but in most cases at shorter time scales. In addition, the LRB is projected to experience intra-annual moderate to very wet conditions, however, lasting for shorter periods.

On the other hand, the SSI analysis at a 12-month accumulation period depicts a strong variation in annual streamflow, that fluctuates between wet and dry years. Drought events are projected to be more frequent and persistent for longer periods. A total of five main drought episodes with extended periods are projected to occur between 2036-2066. Most of the projected drought episodes could be categorized as moderate, with different durations. Furthermore, the region is likely to experience significant wet conditions (up to five different episodes), categorized as ranging from moderate to very wet. Such wet conditions are susceptible to cause flash flooding within the area.

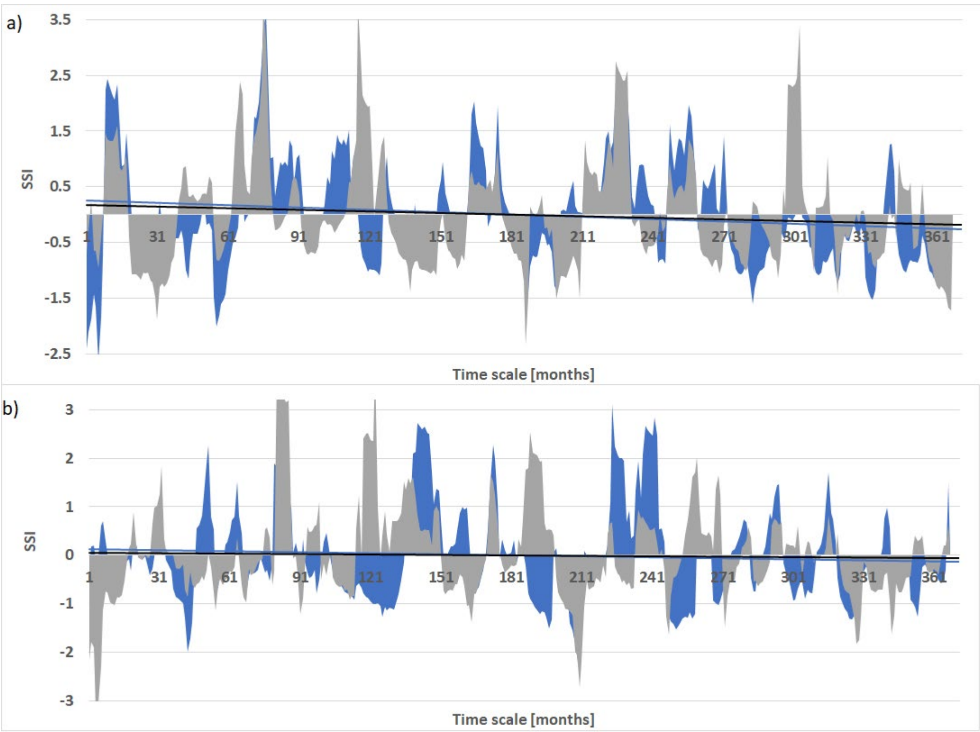

Figure 26. Near-future SSI-6 time series for selected CORDEX models; a) RCP4.5 and b) RCP8.5 scenarios

2.4.7.6 Trends in Drought Monitoring Indicators

The SS trends in DMIs computed for the near-future are given in Table 11 (the MK trends showed an almost similar pattern with the SS, hence results were only limited to SS trend-tests). The trends were computed for both ACRU and mHM simulations, across the CORDEX models, based on SSI-6 and SSI-12 time series. Most of the CORDEX models across the RCP scenarios and hydrological models depict trendless features in both drought duration and severity under the analysed 6- and 12-months accumulation periods. It is worth to acknowledge that there are few CORDEX models, particularly from ACRU simulations under both RCP4.5 and RCP8.5 scenarios that exhibit negligible negative trends in both drought duration and severity, with the majority of the trends being statistically significant at 95% significance level. The results suggest that, while drought is expected to occur more frequently, but in shorter time scales, its harshness is likely to less severe, across the LRB.

Table 11. Trends in Drought Monitoring Indicators [DD – drought duration; DS – drought severity] across the hydrological models and CORDEX

Model	**ACRU [2036-2065] simulations**							
	Standardized Streamflow Index 6				Standardized Streamflow Index 12			
	RCP4.5		RCP8.5		RCP4.5		RCP8.5	
	SS [DD]	SS [DS]	SS [DD]	SS [DS]	SS [DD]	SS [DS]	SS [DD]	SS [DS]
CanESM2	**-0.09**	**-0.11**	0.00	**-0.11**	**-0.09**	**-0.08**	**-0.04**	-0.05
CNRM	-0.04	-0.05	0.00	**-0.08**	0.00	**0.09**	**0.04**	**-0.07**
GFDL-ESM2M	**0.08**	0.07	**0.08**	**0.14**	**0.00**	0.04	**0.09**	**0.00**
IPSL-CM5A	**-0.04**	0.01	0.00	0.02	**0.00**	0.00	**-0.08**	-0.02
MIROC5	0.00	0.03	0.00	-0.02	**0.00**	0.00	**0.11**	**0.11**
NorESM1	0.00	**-0.05**	-0.04	-0.03	0.00	0.00	**0.08**	0.05
Ensemble	0.00	-0.02	0.00	**-0.09**	**-0.11**	**0.13**	**0.16**	**0.06**
	mHM [2036-2065] simulations							
CanESM2	0.00	**0.06**	-0.06	-0.06	0.00	**0.02**	0.00	-0.04
CNRM	0.00	0.07	0.00	0.04	**0.07**	0.07	**0.00**	0.04
GFDL-ESM2M	0.00	0.01	0.00	0.00	0.00	0.01	0.00	**0.07**
IPSL-CM5A	0.04	**0.06**	0.04	**0.06**	**-0.07**	0.02	**0.10**	**0.15**
MIROC5	**0.09**	0.03	**0.05**	0.05	0.00	0.03	0.00	**0.06**
NorESM1	0.00	0.07	0.00	0.03	**0.02**	0.00	**0.00**	0.00
Ensemble	**0.06**	**0.09**	0.00	0.00	0.00	**0.08**	0.00	**0.02**

2.4.8. Characteristics of Far-future Streamflow Projections: 2070-2099

2.4.8.1 Annual Trends

The annual mean streamflow, as well as the MK and SS trends in annual mean, minimum, median and maximum streamflow, are presented in Table 12. While most CORDEX models under RCP8.5 exhibit negative trends (particularly those computed from the MK trend test) across the four variables, only approximately 40% of the models depict negative trends under RCP4.5. The rest of the models under RCP4.5 are either trendless or exhibit negligible positive trends. Most of the trends, as shown in the table, are not statistically significant.

Table 12. Mean and trends (Mann-Kendall [MK] and Sen's Slope [SS]) in far-future projected streamflow; bold means statistically significant trends at a 95% confidence level

CORDEX Model	RCP4.5				
	Mean-SF	MK_{Mea} [SS_{Mea}]	MK_{Min} [SS_{Min}]	MK_{Med} [SS_{Med}]	MK_{Max} [SS_{Max}]
CanESM2	2.568	**0.49 [0.10]**	**0.42 [0.001]**	**0.45 [0.06]**	0.36 [0.88]
CNRM	3.957	0.20 [0.06]	0.21 [0.00]	**0.27 [0.03]**	0.11 [0.30]
GFDL-ESM2M	2.415	-0.02 [-0.01]	0.21 [0.00]	0.06 [0.01]	-0.06 [-0.05]
IPSL-CM5A	1.590	0.15 [0.02]	-0.04 [0.00]	0.08 [0.01]	0.16 [0.19]
MIROC5	4.860	-0.08 [-0.04]	-0.05 [-0.001]	-0.15 [-0.02]	-0.03 [-0.05]
NorESM1	2.863	0.02 [0.01]	-0.04 [0.00]	-0.05 [-0.01]	0.07 [0.14]
Ensemble	2.414	**0.28 [0.03]**	1.00 [0.00]	0.19 [0.01]	**0.05 [0.10]**
	RCP8.5				
CanESM2	1.884	-0.15 [-0.03]	**-0.28 [0.00]**	-0.22 [-0.02]	-0.04 [-0.02]
CNRM	4.407	-0.08 [-0.03]	-0.05 [0.00]	-0.18 [-0.01]	-0.02 [-0.04]
GFDL-ESM2M	2.189	-0.04 [-0.01]	-0.09 [0.00]	-0.06 [-0.01]	0.09 [0.15]
IPSL-CM5A	1.318	-0.08 [-0.02]	-0.01 [0.00]	-0.10 [-0.001]	-0.06 [-0.15]
MIROC5	4.608	-0.07 [-0.02]	-0.12 [-0.004]	-0.13 [-0.01]	-0.03 [-0.09]
NorESM1	2.936	**-0.27 -0.09]**	**-0.29 [0.00]**	-0.24 [-0.04]	-0.15 [-0.35]
Ensemble	2.201	-0.20 [-0.03]	1.00 [0.00]	**-0.30 [-0.3]**	-0.08 [-0.10]

2.4.8.2 Seasonal Trends in Far-future Projected Streamflow

Seasonal trends in far-future projected streamflow are given in Figure 27. The computed trends are based on ACRU simulations, for the 2070-2099 projected period. Positive trends are observed in DJF and MAM seasons, whereas, zero and negligible positive trends are observed during JJA and SON seasons under RCP4.5 scenario. On the contrary, CORDEX models under RCP8.5 depict a noticeable but negligible negative trend across the seasons, suggesting a reduction in projected streamflow in the far future. The trends are mostly statistically at 95% significant level.

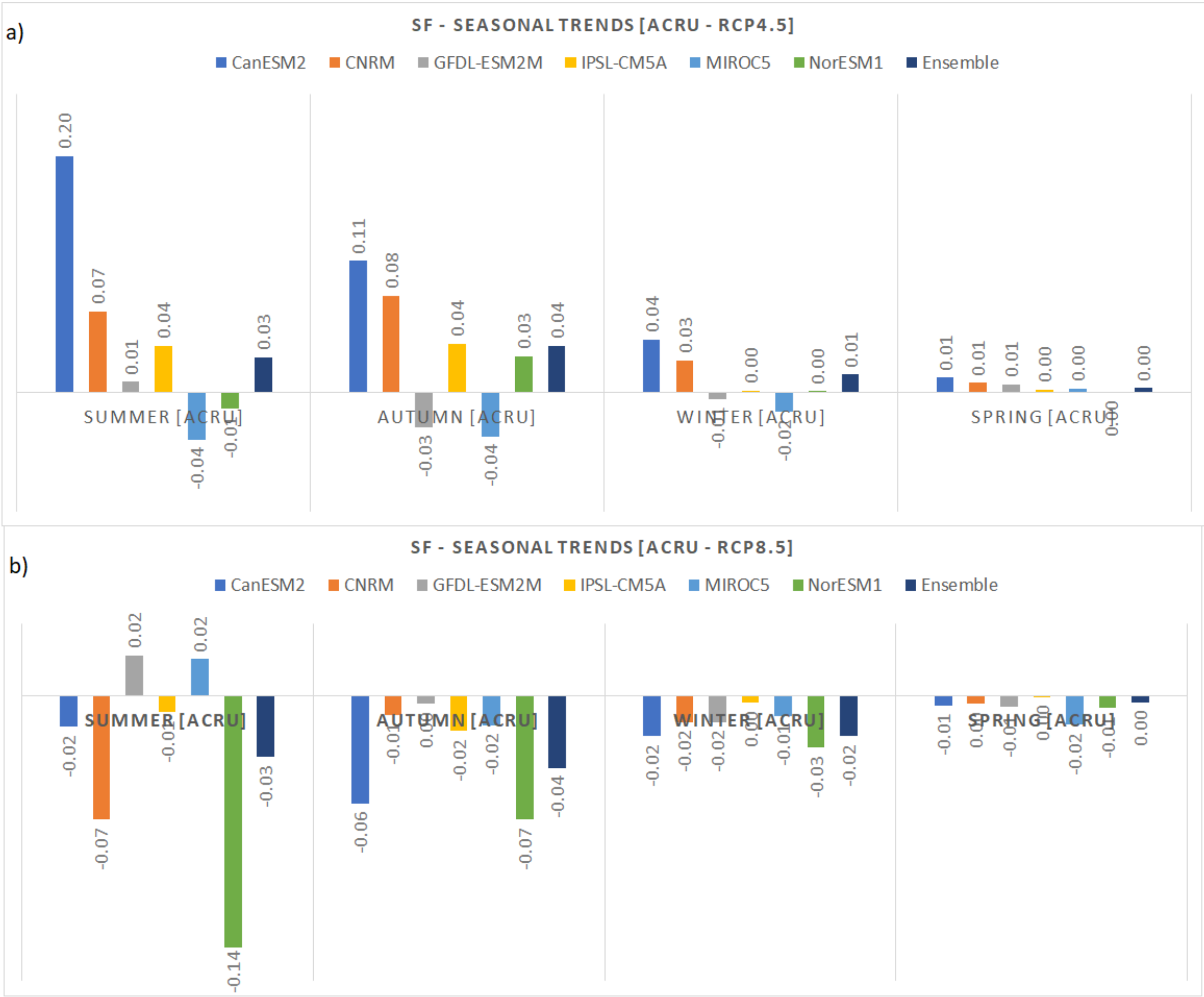

Figure 27. Seasonal trends (Sen's Slope) in far-future projected streamflow across CORDEX models, based ACRU hydrological model simulations

2.5 Concluding Remarks

According to climate projections analysis, minimum and maximum temperatures are likely to increase, whereas rainfall will be highly variable in the near- and far future across the LRB of South Africa and in the MFC in Kenya. Streamflow simulated from ACRU and mHM hydrological models for historical, e.g. 1976-2005 and the present climate, running from 2006-2035, was analysed and considered as baseline in our quench to understand future projected streamflow in the LRB (presented in this report) and the MFC (to be added at a later stage) and assess the anticipated impacts to water-linked sectors. The results depict a consistent decrease in streamflow for both the historical and the present climate, with most of the observed trends being statistically significant at a 95% significance level. Streamflow reduction is notably observed as we move towards the near-future, 2036-2065, and continue to reduce into the far-future, 2070-2099, although such conclusions for the far-future are based on the observed zero and very negligible negative trends, that are mostly not statistically significant. Results for far-future projections are expected given that the accuracy of climate projections is always questionable as we move further into the future, due to various factors, including uncertainties in the CORDEX and hydrological models. Trends in hydrological variables such as baseflow as well as low and high flows also point to reduced streamflow in the LRB over the near- and far-future periods. Consequently, hydrological extremes such as droughts are projected as observed from the derived SSI time series. Significant wet conditions that can lead to flooding episodes are also observed in the SSI time series for both 6- and 12-month accumulation periods. While the impacts are expected to vary across different water-linked sectors as highlighted in the discussion, the citizens, particularly the most vulnerable within these areas are expected to face the full spectrum of direct and indirect costs accrued from increasing environmental damages and the general disruptions of quality of life.

3. Characterization of Extreme Climate And Weather Events in Limpopo River and Mau Forest Catchment Basins

3.1. Introduction

The recent Intergovernmental Panel on Climate Change reports affirmed that our climate and its extremes are changing (Allen et al., 2018; IPCC 2018). The impacts of changing climate and extreme weather events disproportionately affect the socio-ecological systems as these vary in the spatial extent, duration, intensity, and frequency. As noted in Ebi and Bowen (2016), the type and pattern of extreme events have shifted over the years, with alternating floods and droughts regimes noted in regions such as Africa. In some instances, these shifts have occurred over periods as short as a few years to decades even over centuries. Climate projections indicate high confidence in the likelihood of increased incidences of extreme weather patterns. Exposure to weather and climate events for vulnerable communities can result in economic losses, damage to property and infrastructure, injury, and even loss of life. According to data from the international disasters database http://www.emdat.be maintained by the Centre for Research on the Epidemiology of Disasters in Brussels, 195 per cent more Africans were affected by extreme weather events in 2019, with the continent witnessing an increase in such events when compared to 2018.

As widely understood, the severity of impacts from climate extremes depends not only on extremes but also on exposure and vulnerability (IPCC, 2012), the latter defined as “the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes” (IPCC, 2001). Sub-Saharan Africa (SSA) encompassing 46 countries, including South Africa and Kenya has been identified by the Intergovernmental Panel on Climate Change (IPCC) as being the most vulnerable region, the majority of concern being the increase in extreme events such as storms, floods, droughts, heatwaves, wildfires, and landslides in SSA (CDKN, 2014). Key factors increasing vulnerability in Sub-Saharan Africa include high levels of poverty, inequality, food insecurity, poor governance, limited ICT infrastructure to facilitate efficient communication of early warning information to communities at risk.

This study focused on South Africa and Kenya with selected study sites in the Limpopo River Basin and Mara Forest Catchment Basin, respectively. In South Africa, the mean annual temperatures have increased by at least 1.5 times the observed global average of 0.65∘C over the past five decades and extreme rainfall events have increased in frequency (WIREs,2014). Meanwhile, the scientific, municipal, and media reports have highlighted the prevalence of extreme weather events such as floods, droughts, and heatwaves in Limpopo (SAWS, 2018; Mabhaudi et al., 2019; Mpandeli et al., 2019). For example, Mpandeli et al., (2019) reported that between 2000 and 2018, Capricorn District Municipality in Limpopo was one of the municipalities in Limpopo that had experienced heatwaves and changes in rainfall with impacts on water security and agriculture productivity. In Kenya, observed mean annual temperatures have increased by 1.0°C since 1960, or an average rate of 0.21°C per decade with changes in rainfall patterns observed over the same period (McSweeney et al., 2009). The Mau Forest Catchment Basin also experiences flooding and drought incidents that impact crop and livestock production, food security, wildlife, and biodiversity. Kilavi et al., (2018) pointed out that, 2018 was one of the wettest seasons on record, resulting in extensive flooding with over 140 deaths in Kenya given the current experiences of extreme weather events, it is imperative for research to support improved understanding of the projected increase in frequency and intensity of these extremes and support planning and decision making at the local level.

Understanding, modelling, and predicting weather and climate extremes is identified as a major area necessitating further progress in climate research (Sillmann et al., (2017). This includes evaluating the drivers and specific processes at local to regional scales, the temporal variability, and the evolution of extreme events. Reliable predictions of extremes are needed on short and long-time scales to inform local and national climate change adaptation plans as well as other policies to reduce potential risks and damages that result from weather and climate extremes (IPCC, 2012). Such information is a prerequisite to acting on the risks and opportunities that climate change presents for the achievement of national, sectoral, and community development priorities, including the Sustainable Development Goals (WMO, 2019). In addition, this information is useful in developing integrated solutions to enhance disaster preparedness for extreme weather events, at local scales. Hence this study aims to characterize weather and climate extremes in Limpopo River and Mau Forest Catchment Basins.

3.2. Data and Methods

3.2.1. Observations and model data

Datasets used in this study are the ERA5 climate reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). The ERA5 climate reanalysis datasets are available from 1979 to current. The datasets provide hourly estimates of numerous quantities of, for instance, atmospheric, land-surface and sea-state, as well as uncertainty estimates of such variables at reduced resolution. The ERA5 climate reanalysis datasets are available in the Climate Data Store on regular latitude-longitude grids at 0.25° x 0.25° resolution. For the current study, ERA5 datasets spanning from 1979-2005 (27 years) were analysed and considered as a benchmark, i.e. historical reference period. On the other hand, models simulation of the Coordinated Regional Downscaling Experiment (CORDEX) dynamically downscaled simulations over the African domain of spatial resolution (0.44°x 0.44°) was utilized. Specifically, the Rossby Centre regional model (RCA4), forced across its lateral boundaries by the GCMs models (shown in Table 1) of the 5th phase of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012) was used. In terms of climate projections, three projected time intervals were considered. These are the current climatology, spanning from 2006-2035; the near-future, defined as the period starting from 2036-2065 and the distant future, spanning from 2066-2095. The CORDEX-Africa model simulations under the Representative Concentration Pathway (RCP) 4.5 and high RCP8.5 scenarios across the selected time intervals were inter-compared with the ERA5 analysed data.

3.2.2. Methods

3.2.2.1 Simple multi-model averaging

Multi-model ensembles, i.e. models produced by combining multiple model ensemble members, are often described as "ensembles of opportunity" (Tebaldi and Knutti, 2007). This is attributed to the way they are created, which involves the combination of information from all participating models (Pincus et al., 2008), a process that is believed to increase the skill, reliability, and consistency of ensemble models (Cantelaube and Terres, 2005). Consequently, multi-model ensembles are often found to out-perform single-models (Duan and Phillips, 2010; Miao et al., 2012). In the current study, multi-model ensembles refer to a set of model simulations from different CORDEX-Africa models. These model ensembles were created by use of the Simple Multi-model Averaging (SMA) technique (Georgakakos et al., 2004).

The SMA approach can be described as per Equation 1,

$$(Q_{SMA})_t = \overline{Q_{obs}} + \sum_{i=1}^{N} \frac{(Q_{sim})_{i,t} - (\overline{Q_{obs}})_i}{N} \qquad \text{Eq. 1}$$

where $(Q_{SMA})_t$ is the multi-model variable (e.g. precipitation, minimum or maximum temperature) simulations from CORDEX-Africa models derived using SMA at time t, $(Q_{SMA})_{i,t}$ corresponds to the i^{th} model variable simulation for time t, $(\overline{Q_{sim}})_{i,t}$ is the time average of the i^{th} model variable simulation, $\overline{Q_{obs}}$ corresponds to the observed average variable and N represents the number of models under consideration. For comparison purposes between the observed data and model simulations, the eight CORDEX RCMs outputs were re-gridded using Climate Data Operator (CDO) bilinear interpolation to the same resolution as that of the observed data (0.25° × 0.25° grid).

3.2.2.2 Climate Extreme Indices

The present research study analysed twelve climate extreme indices selected from the original 27 core climate indices developed by the Expert Team (ET) on Climate Change Detection and Indices (ETCCDI) (Peterson, 2005). The selection of these climate indices was based on their relevance to the climatology of both the LRB and MFCB and these are given in Table 13. For this purpose, four and seven temperature and precipitation extreme-related indices were analysed, respectively, to assess the impacts of climate change and variability changes within both basins. Consequently, to understand the dynamics of extreme precipitation and temperature in the past 30 years and to make projections for the next century, were analysed the observed dataset ERA5 (1979-2005) and future dataset (2006-2095) to evaluate the climate extremes. Climate indices are calculated based on RClimDex package. For detailed information on the calculation of climate extreme indices, the reader is referred to the following websites, http://cccma.seos.uvic.ca/ETCCDI and http://etccdi.pacificclimate.org/list_27_indices.shtml. In this study, the selected climate change indices relating to temperature and precipitation were used in the trend analysis, based on both the observed datasets and the projections across the three-time intervals. The results were then inter-compared with the reference period to assess the projected change in climate extremes over time, in relation to the historical period.

Table 13. Selected temperature and precipitation indices analysed in the current study (adopted from (Zhang et al., 2011): Pre – precipitation; T_{mx} – maximum temperature; T_{mn} – minimum temperature

Temperature Extreme Indices		
Index	**Indicator name**	**Definition**
WSDI	Warm Spell Duration Index	The annual count of days with at least 6 consecutive days when T_{mx} > 90th percentile
CSDI	Cold Spell Duration Index	The annual count of days with at least 6 consecutive days when T_{mn} < 10th percentile
HWDI	Heat Wave Duration Index	Longest days in at least 5 consecutive days with daily T_{mx} 5°C greater than the base period mean
HWFI	Warm spell days index	Warm spell days index with respect to the 90th percentile of the reference period
Precipitation Extreme Indices		
Rx5day	Maximum 5-day precipitation amount	Maximum consecutive 5-day precipitation
SDII	Simple Daily Intensity Index	Total precipitation divided by the number of wet days in the year
CDD	Consecutive Dry Days	Maximum number of consecutive days with *Pre* < 1 mm
CWD	Consecutive Wet Days	Maximum number of consecutive days with *Pre* ≥ 1 mm
R10mm	Number of heavy precipitation days	The annual count of days when *Pre* ≥ 10 mm
R20mm	Number of heavy precipitation days	The annual count of days when *Pre* ≥ 20 mm
R95p	Very wet days	Annual total precipitation when *Pre* > 95th percentile

3.3. Results

3.3.1. Model Comparison

Figure 28 and Figure 29 Fshow the comparison between the historical observed and model simulation for rainfall over the LRB and MFCB respectively. Most of the models give reasonably accurate predictions of the mean temperature and precipitation. The ensemble of the 8 models, gives about 85% correlation with observation for temperature and about 70% correlation with precipitation. Generally, the models tend to underestimate the precipitation.

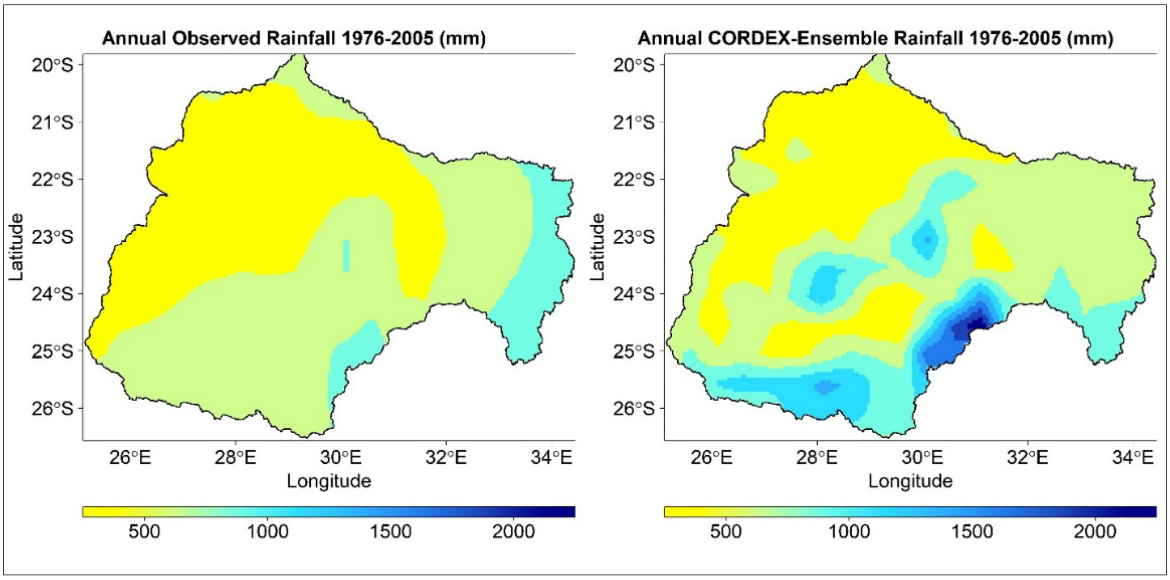

Figure 28. Observed and modelled simulation of historical precipitation over the Limpopo River Basin

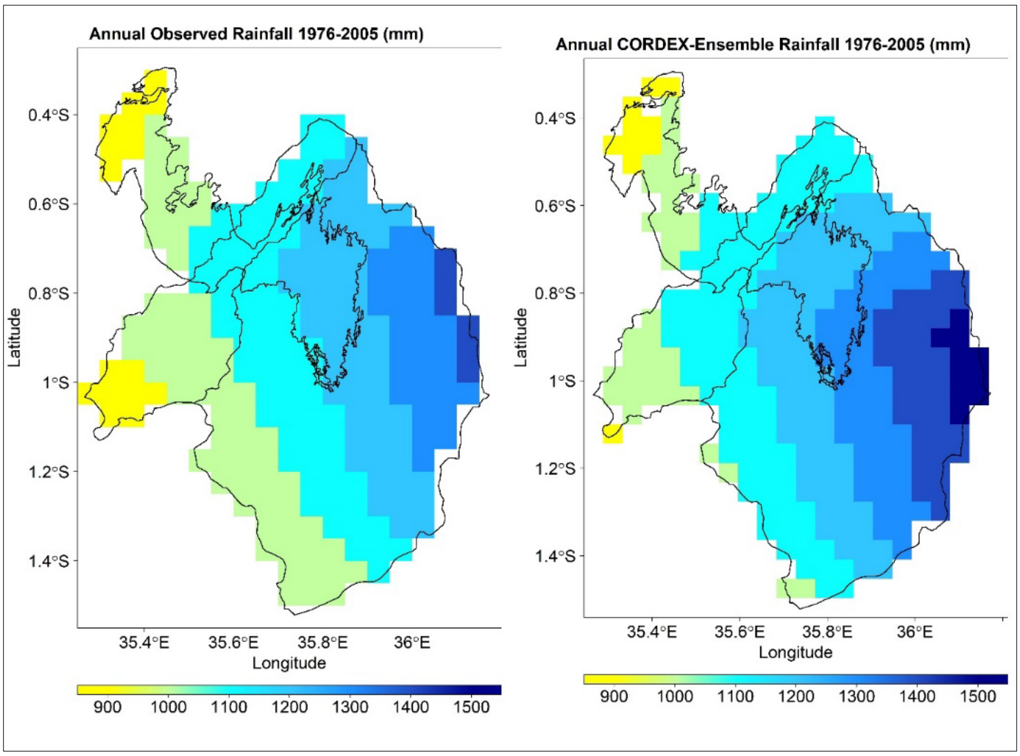

Figure 29. Observed and modelled simulation of historical precipitation over the Mau Forest Catchment Basin

3.3.2. Precipitation extreme indices

3.3.2.1 Maximum 5-day Precipitation per time period

The projected change in Rx5day “highest five-day precipitation amount per time period (mm)” and “number of 5-day heavy precipitation periods per time period” for three time periods regarding the base period under RCP4.5 and RCP8.5 are depicted in Figure 30 and Figure 31 for the LRB and MFCB, respectively. In each figure, (a) and (b) correspond to the projected change in RX5Day under the RCP4.5 whereas, (c) and (d) are based on RCP8.5 model simulation. As shown in Figure 30 (a) and (c) the northeastern part of the LRB is projected to receive the highest 5-day rainfall under both RCP4.5 and 8.5 scenarios for all periods including the western part in 2006-2035. The projections indicate a significant decrease in both the highest 5-day precipitation amount per time period and the number of 5-day heavy precipitation periods per time period in the central part of LRB. While it is projected that the entire MFCB will experience a significant decline in the highest 5-day rainfall amount under the RCP4.5 for the period 2006-2035 with a marginal increase in other projected periods under both RCP4.5 and RCP8.5 scenarios, see Figure 31 (a) and (c). The number of 5-day heavy precipitation periods per time period varies spatially over the LRB, however, the western and eastern parts are projected to record more 5-day heavy precipitation under both projection scenarios. On the other hand, the entire MFCB is projected to experience a significant decrease in the number of 5-day heavy precipitation periods per time period for all the projected time periods under both scenarios except for the 2066-2095 time period under the RCP8.5.

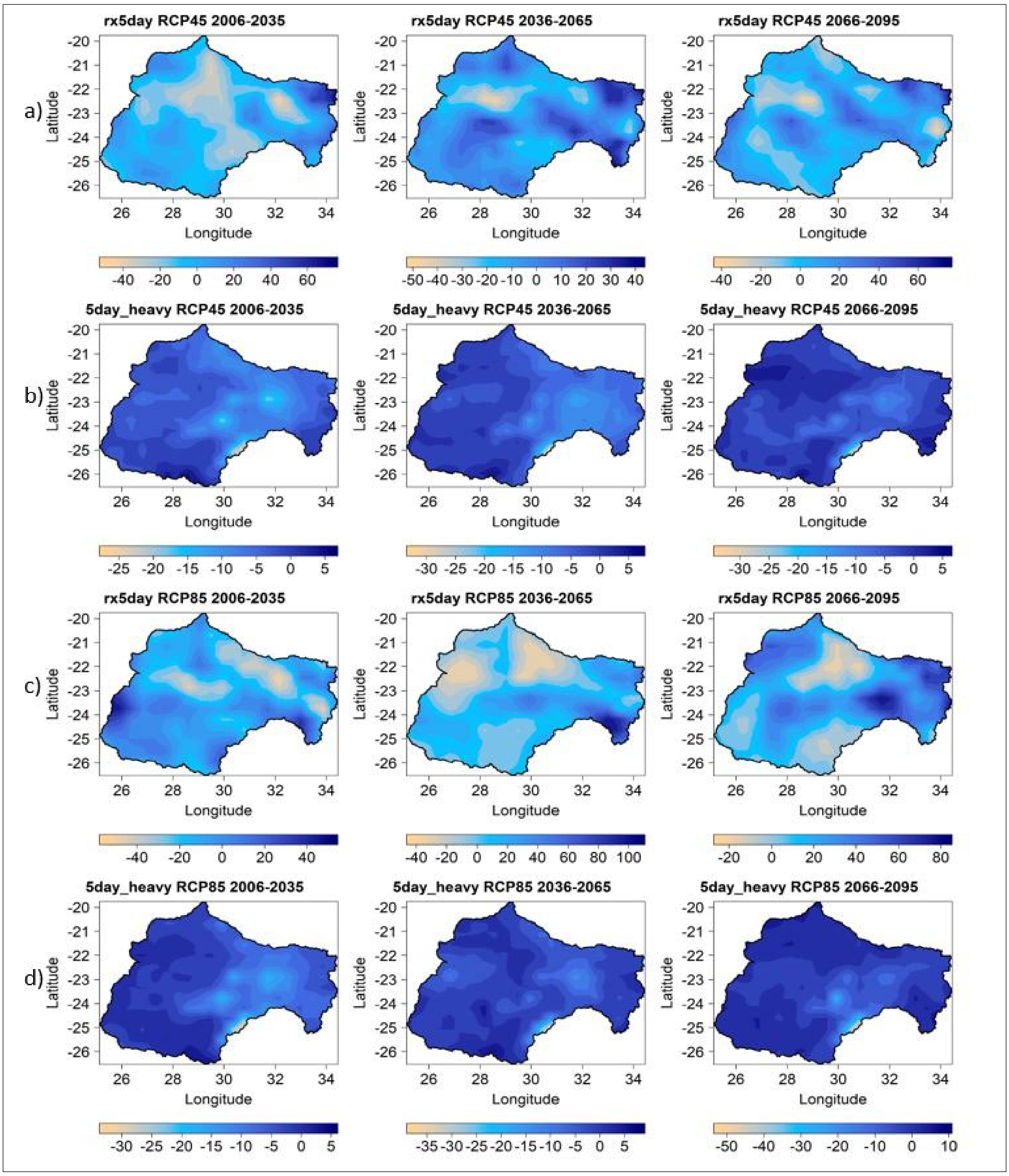

Figure 30. Projected change in highest five-day precipitation amount per time period (a & c) and number of 5-day heavy precipitation periods per time period (b & d) for LRB with reference to 1976-2005 for three projection time intervals, based on RCP4.5 (a & b) and RCP8.5 (c & d) scenarios

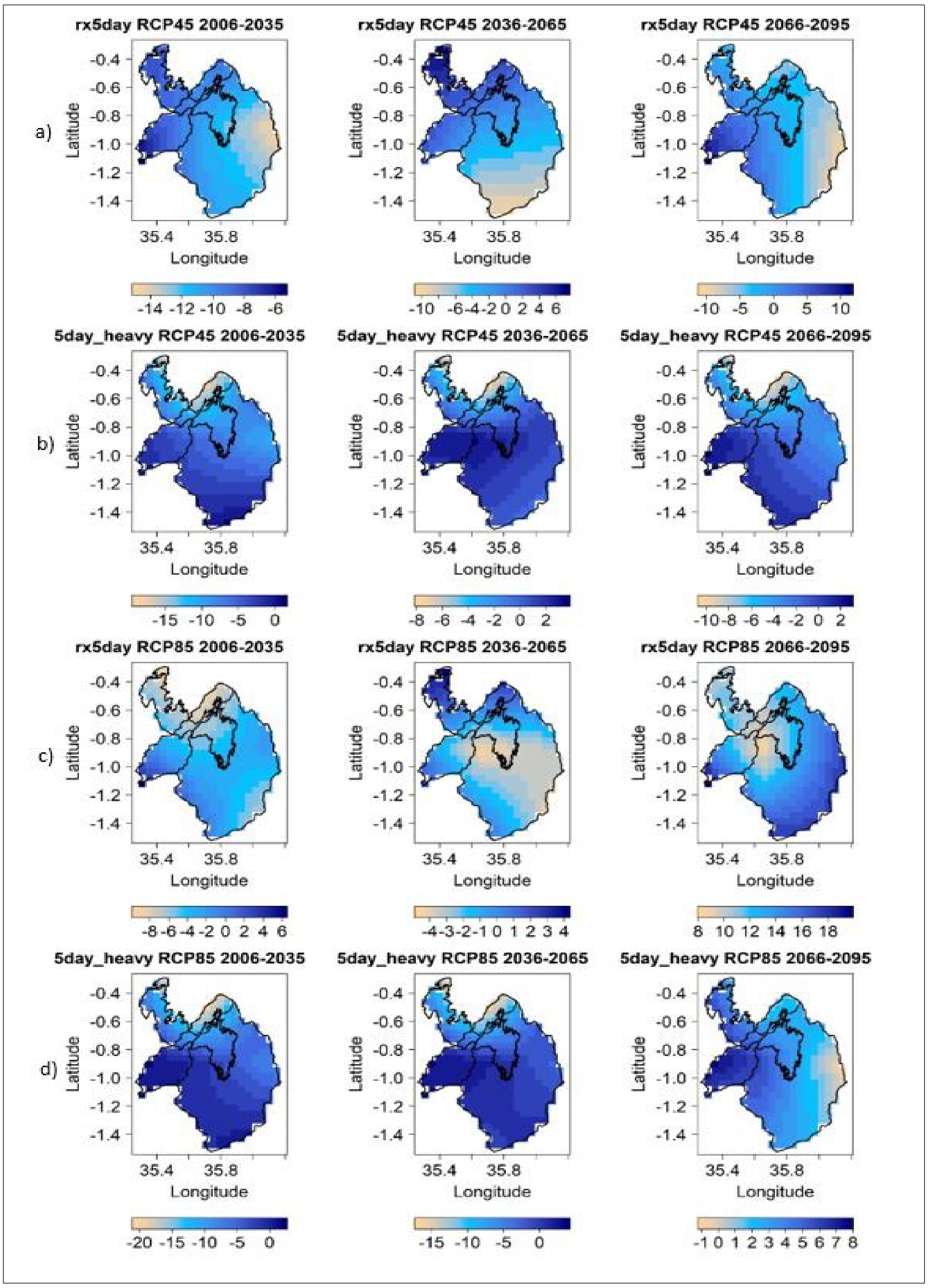

Figure 31. Same as Figure 30 but for the MFCB

3.3.2.2 Consecutive Dry Days

Results of the projected consecutive dry days index per time period (CDD), as well as the CDD periods with more than 5 days per time period, are shown in Figure 32 and Figure 33 for the LRB and MFCB, respectively. Based on the results, CDD with rainfall less than 1 mm, is projected to increase in the northern, central, and eastern parts and to decrease in the western part of the LRB for all periods under RCPs 4.5 and 8.5 (see Figure 32 (a) and (c). The projected CDD over the northeastern part of the LRB is likely to increase by an average of 5 to 40 days when compared to the referenced period under the RCP4.5 and RCP8.5. As shown in Figure 33

(a) and (c), it is also projected that the MFCB will experience an increase of about 1 to 5 days CDD dominantly in the central and southern part of the basin under both scenarios and all time periods. As shown in Figure 32 (b) and (d), the number of projected CDD periods with more than 5 days per time period is shown to increase in the central-southern part and to decrease in the north-eastern part of LRB for both scenarios across all the time periods. While an increase of 1 to 10 days is projected for CDD periods with more than 5 days per time period in the northern parts of MFCB under both scenarios (see Figure 33 (b) and (d). The northeastern part of the LRB and the southern part of MFCB will experience an increase in CDD.

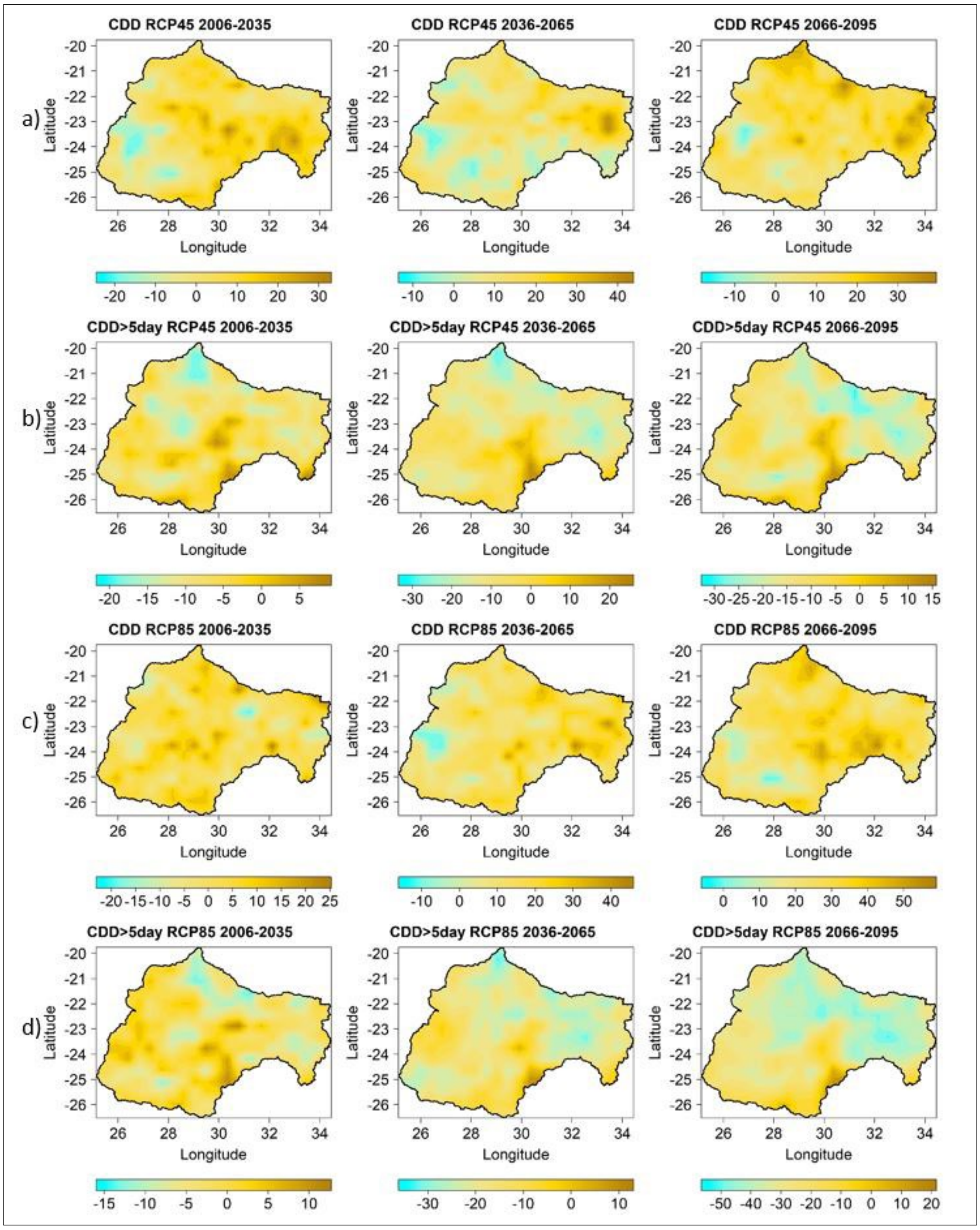

Figure 32. Projected change in consecutive dry days (CDD) index per time period (a & c) and number of CDD periods with more than 5 days per time period (b & d) for LRB with reference to 1976-2005 for three projection time intervals, based on RCP4.5 (a & b) and RCP8.5 (c & d) scenarios

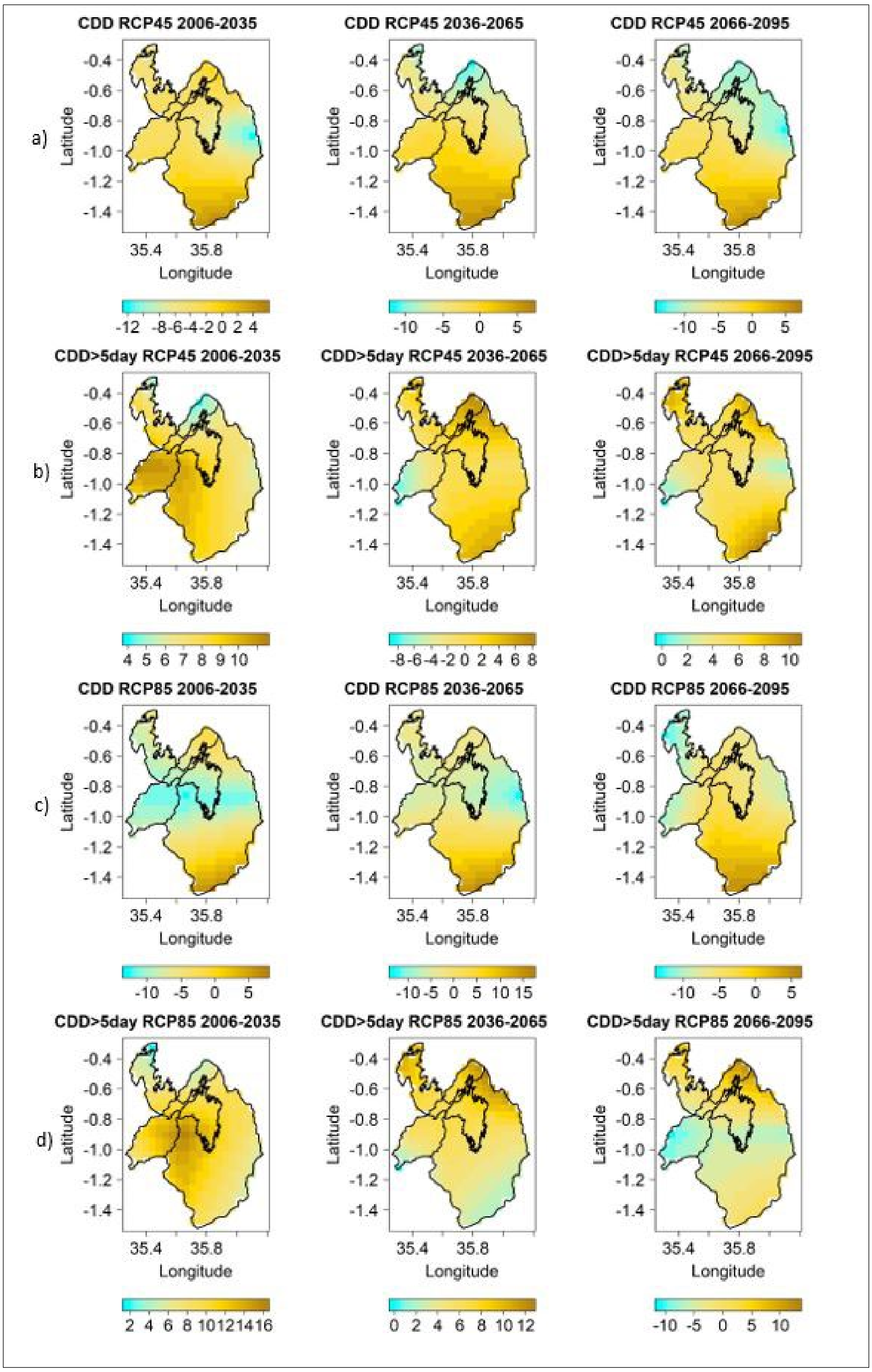

Figure 33. Same as Figure 32, but for the MFCB

3.3.2.3 Consecutive Wet Days

Figure 34 and Figure 35 show results of projected consecutive wet days index (CWD) per time period and the number of CWD periods with more than 5 days per time period with reference to the base period for the LRB and MFCB based on the RCP4.5 and RCP8.5 scenarios, respectively. The CWD is defined as the largest number of consecutive wet days of a time series of daily precipitation amounts greater than 1 mm. The west, south and eastern part of LRB is projected to have more numbers of CWD per time period under both RCP4.5 and 8.5, see Figure 34 (a) and (c), respectively. The number of CWD periods with more than 5 days per time period is projected to increase by about 1 to 5 days in the south-western and eastern part of LRB for all time periods under the RCP4.5 scenarios but remained unchanged under the RCP8.5 for 2036-2095 with an increase of about 5 to 10 days in the south-western part in 2006-2035 period (see Figure 34 (b) and (d). In MFCB, the consecutive wet days index (CWD) per time period is projected to significantly decrease over the entire basin for all time periods under both scenarios except for 2006-2035 under RCP8.5 where an increase of 1 to 3 days is projected for the northern part of the basin (see Figure 35 (a) and (c). Additionally, as shown in Figures 35 (b) and (d) the number of CWD periods with more than 5 days per time period is projected to increase by 1 to 15 days in the far future period under both RCP 4.5 and 8.5.

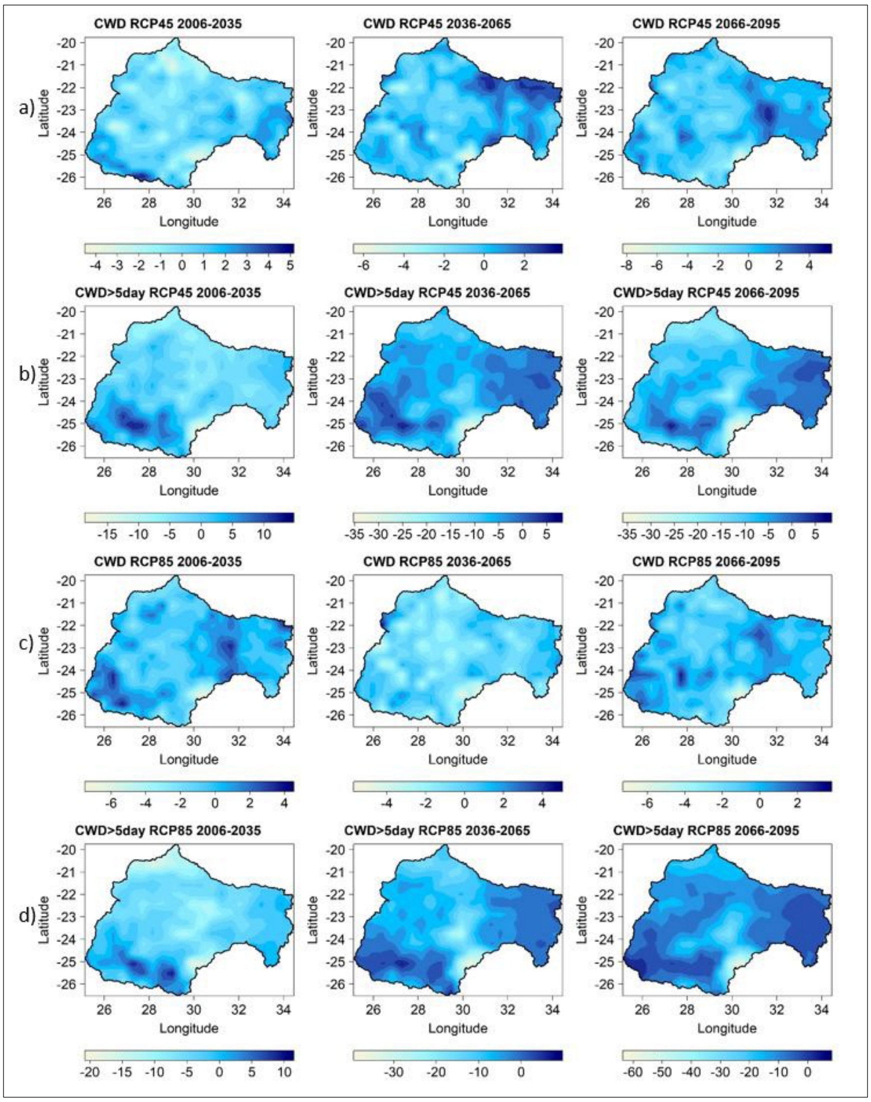

Figure 34. Projected change in consecutive wet days (CWD) index per time period (a & c) and number of CWD periods with more than 5 days per time period (b & d) for LRB with reference to 1976-2005 for three projection time intervals, based on RCP4.5 (a & b) and RCP8.5 (c & d) scenarios

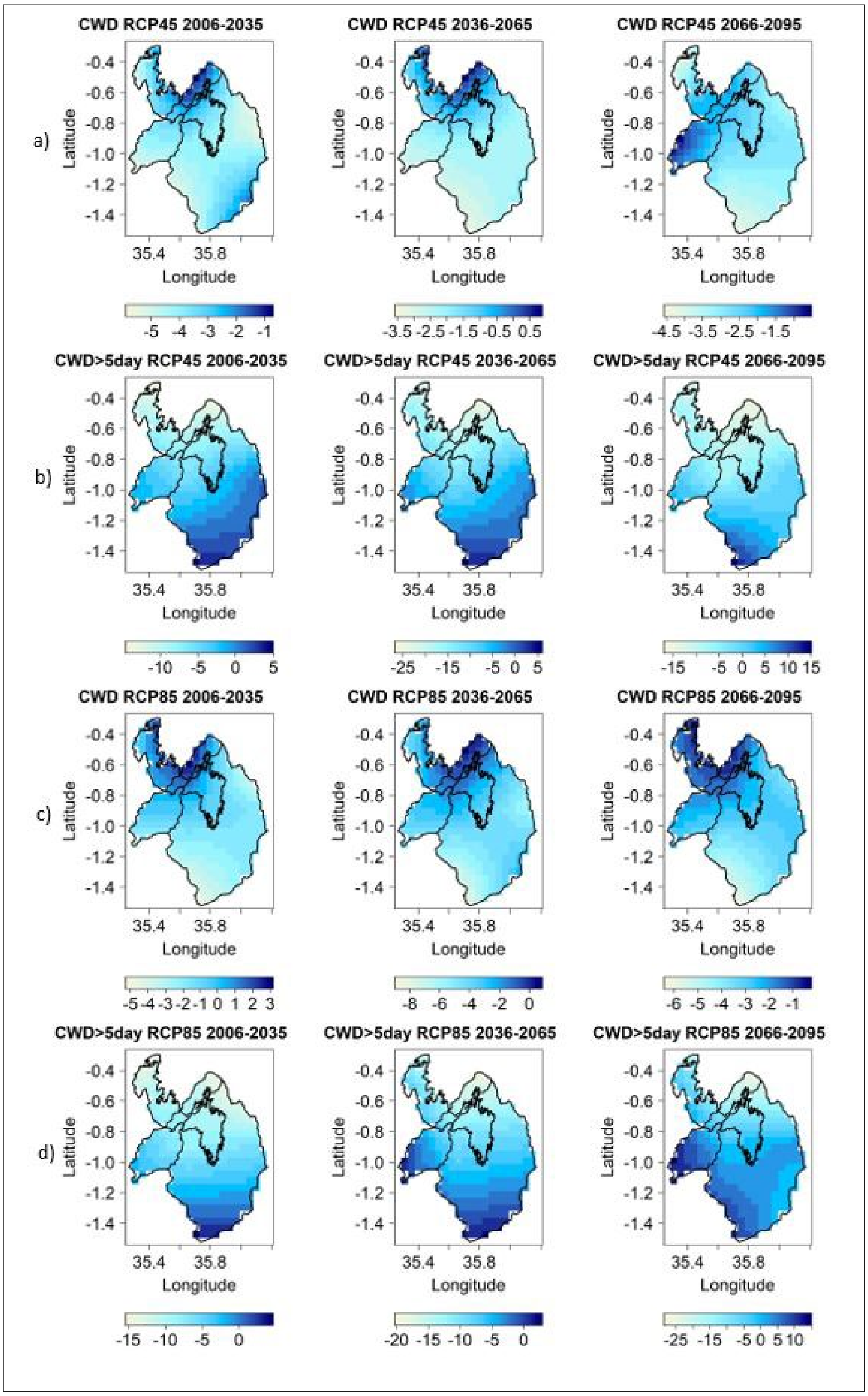

Figure 35. Same as Figure 34 but for the MFCB

3.3.2.4 Simple Daily Intensity Index

Results for the projected simple daily intensity index (SDII) for the LRB and MFCB are depicted in Figure 36, (where a and b represent the LRB and c and d correspond to the *MFCB*) under the RCP4.5 and RCP8. The SDII is defined as the ratio of time series total precipitation to the number of rainy days (precipitation ≥ 1 mm/day). As shown in Figure 59 (a) and (b) the north, west, south and eastern part of LRB is projected to have an increase in SDII for all periods under RCP4.5 and 8.5 with a further increase in SDII to about 1.5 r in the far future under RCP8.5. Similarly, SDII is projected to increase by 0.1 to 0.7 in the west-southern part of MFCB under both RCP4.5 and 8.5 for all periods except for 2066-2095, where SDII is projected to increase to a maximum of about 1.2 (see Figure 59 (c) and (d).

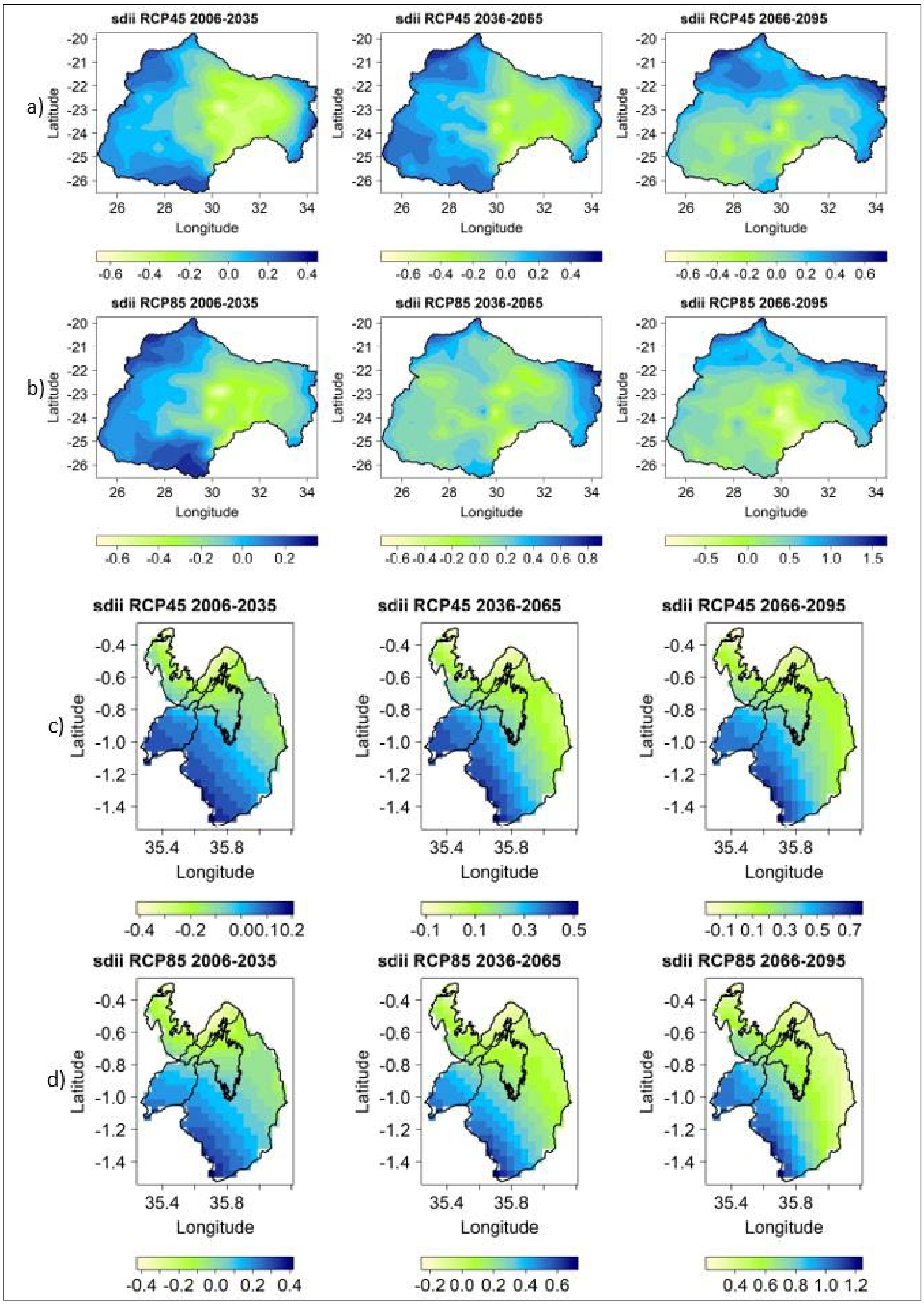

Figure 36. Projected change in Simple Daily Intensity Index (SDII) for LRB (a: RCP4.5; b: RCP8.5) and MFCB (c: RCP4.5; d: RCP8.5) scenarios with reference to 1976-2005 for three projection time intervals

3.3.2.5 Number of Heavy Precipitation Days

The projected heavy precipitation days index per time period (R10mm) for RCP4.5 and 8.5 for both LRB and MFCB are shown in Figure 37. The R10mm is defined as the number of days with a daily precipitation sum exceeding 10 mm. As illustrated in Figures 37 (a) and (b), more days with greater than 10 mm are projected to increase in the west, south and eastern part of LRB for all time periods under RCP4.5 and 8.5. However, no increase in the number of days greater than 10 mm is projected in the far future under the RCP8.5. On the other hand, a significant increase is projected in the number of days greater than 10 mm in the southwestern part of the MFCB for all time periods for both climate change scenarios (see Figure 37 (c) and (d).

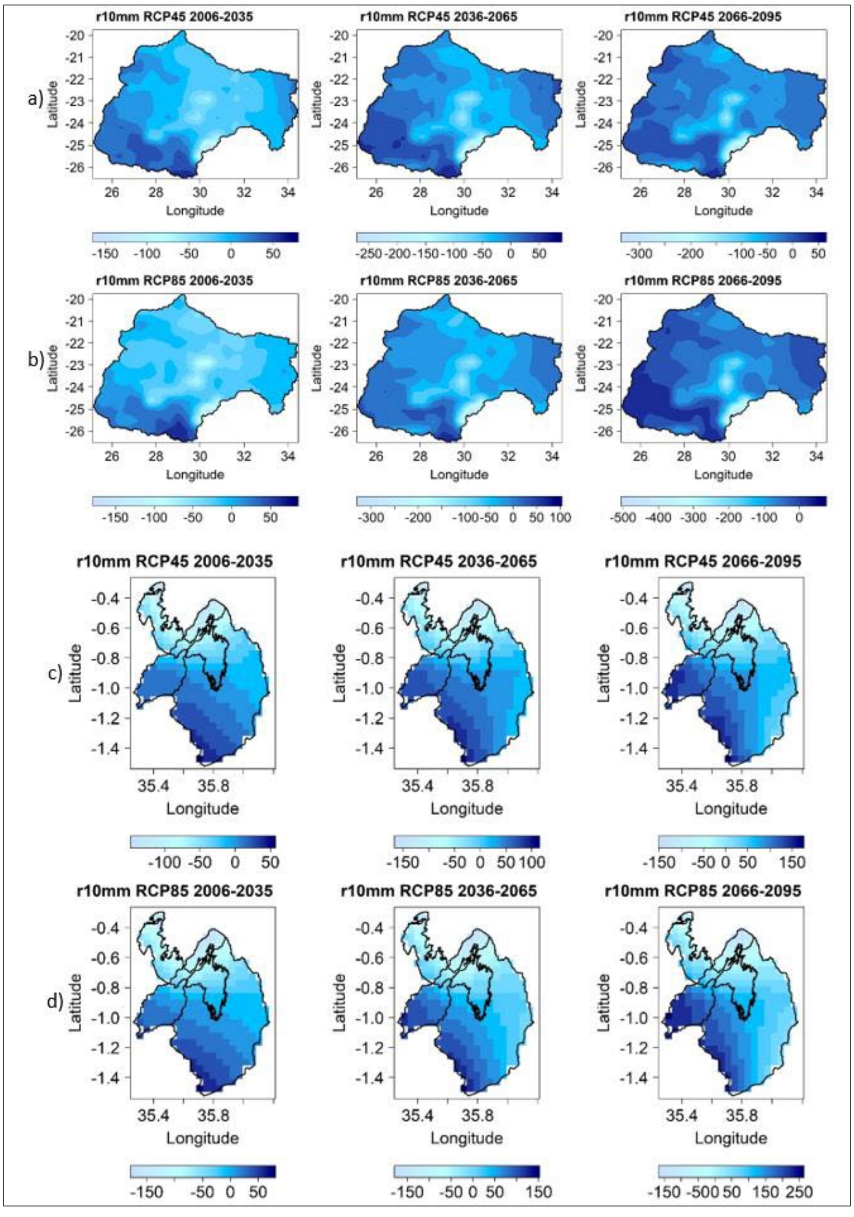

Figure 37. Projected change in the number of heavy precipitation days (10 mm) for LRB (a: RCP4.5; b: RCP8.5) and MFCB (c: RCP4.5; d: RCP8.5) scenarios with reference to 1976-2005 for three projection time intervals

3.3.2.6 Number of Very Heavy Precipitation Days

The projections for very heavy precipitation days index per time period (R20mm) for RCP4.5 and RCP8.5 for both LRB and MFCB are shown in Figure 38. The R20mm is defined as the number of days with a daily precipitation sum exceeding 20 mm (very heavy precipitation). As shown in Figure 38 (a and b), more days with very heavy rainfall are predominantly found in the western north and south of the LRB projected to increase by 1 to 40 days under RCP 4.5 for the period 2006-2065. No increase is projected in the far future under RCP4.5 and in 2036-2065 under RCP8.5. On the other hand, the southwestern part of the MFCB is projected to experience significantly more days with very heavy rainfall for all time periods for both RCP4.5 and 8.5.

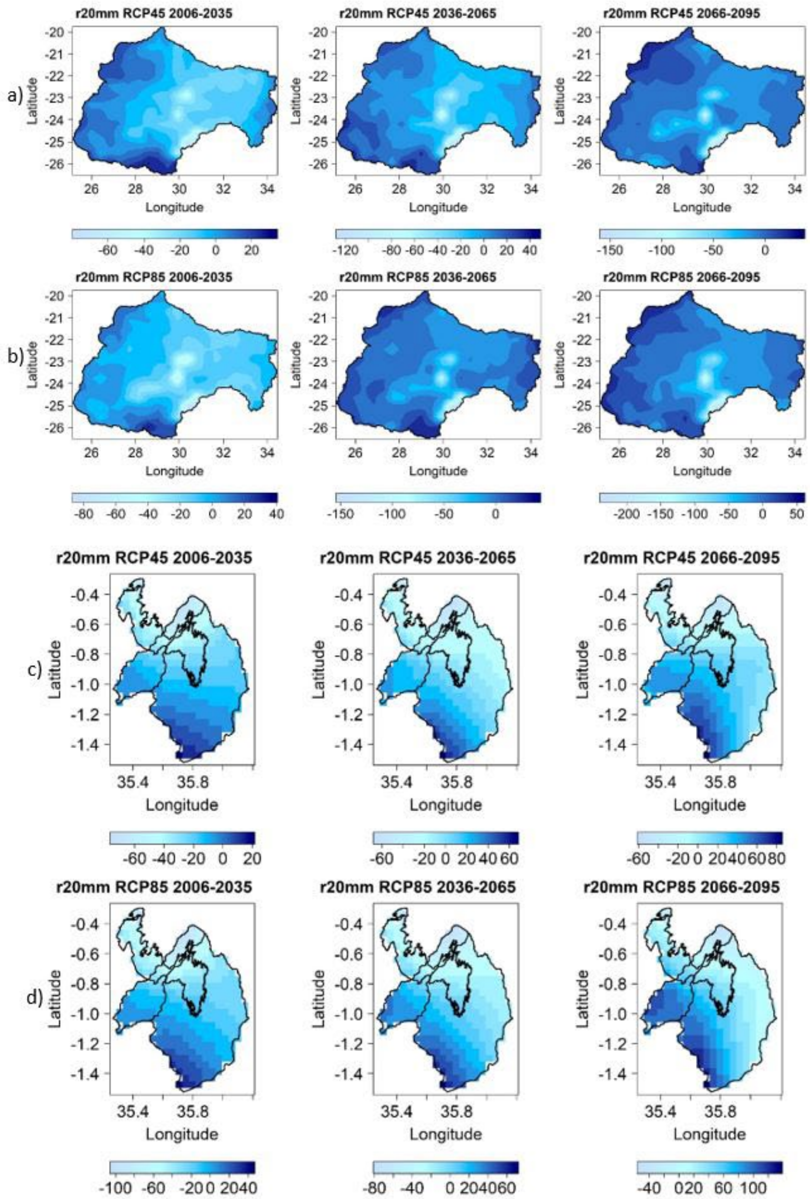

Figure 38. Projected change in the number of very heavy precipitation days (R20mm) for LRB (a: RCP4.5; b: RCP8.5) and MFCB (c: RCP4.5; d: RCP8.5) scenarios with reference to 1976-2005 for three projection time intervals

3.3.2.7 Very Wet Days

The R95p is defined as the percentage of wet days where the daily precipitation amount is greater than the 95th percentile of the daily precipitation amount on wet days for any given reference period. The projections for "very wet days for 95th percentile of the reference period of 1979-2005" (R95p) under RCP4.5 and RCP8.5 for both LRB and MFCB are shown in Figure 39. The percentage of wet days where the daily precipitation amount is greater than the 95th percentile of the daily precipitation amount at wet days for the reference period (R95p) varied between 7 to 15 under RCP 4.5 for LRB as shown in Figure 39a. Similarly, the range of R95p values for LRB under RCP8.5 were between 6 and 15 for all projection periods (Figure 39b). The percentage of very wet days, r95p for MFCB ranged between 9 and 13% under RCP4.5 for the three projection periods (Figure 39c). Likewise, r95p under RCP8.5 varied between 9 and 15 for MFCB for all projection periods (Figure 39d). The percentage increase in very wet days for the reference period is higher for the northeastern part of LRB and the southern part of MFCB (Figure 39).

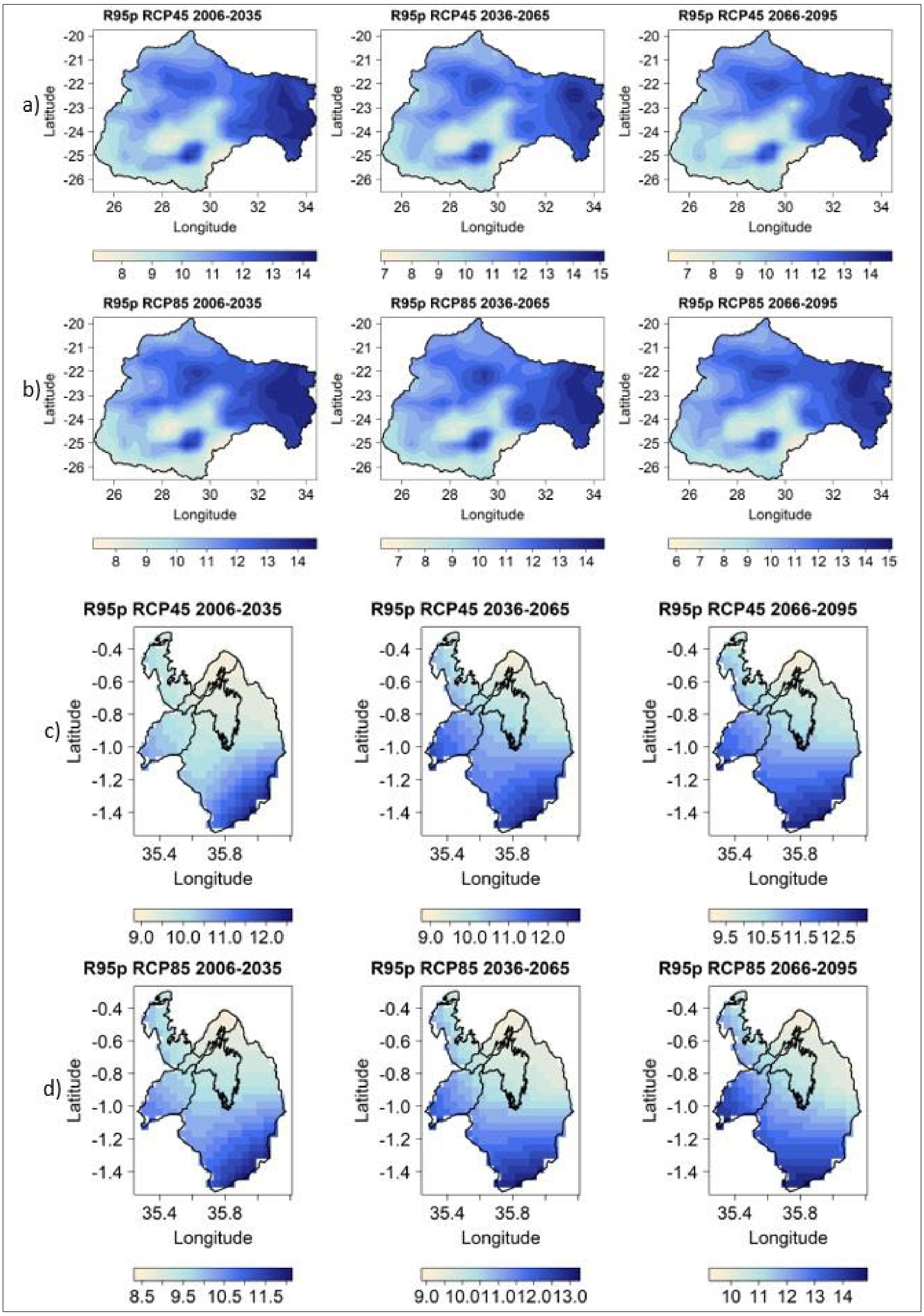

Figure 39. Projected change in Very wet days (R95p) for LRB (a: RCP4.5; b: RCP8.5) and MFCB (c: RCP4.5; d: RCP8.5) scenarios with reference to 1979-2005 for three projection time intervals

3.3.3. Temperature extreme indices

3.3.3.1 Heat Wave Duration Index

The heat wave duration index (HWDI) is defined as the maximum period in a time series with 6 consecutive days where the maximum temperature is at least 5^{o} C warmer than the mean daily maximum temperatures of the reference period. The projection of heat wave duration index (HWDI) for means of reference period of 1979-2005 and heat waves per time period (hw) for RCP45 and RCP 8.5 are shown in Figures 40 and 41 for LRB and MFCB, respectively. For the LRB, the maximum projected HWDI values for the mean of the reference period are 446 (2006-2035), 893 (2036-2065), and 1398 (2066-2095) under RCP4.5 as presented in Figure 40a. The maximum number of heat waves longer than 5 days per time period varied from 55 to 155 under RCP4.5 (Figure 40b). The maximum HWDI values increased to 496 for 2006-2035, 1275 (2036-2065), and 1398 (2066-2095) under RCP8.5 for LRB (Figure 40c). The maximum number of heat waves longer than 5 days per time period also varied from 61 to 300 under RCP8.5 (Figure 40d).

The maximum projected HWDI values for the MFCB, for the mean of the reference period, are 19 (2006-2035), 73 (2036-2065), and 190 (2066-2095) under RCP4.5 as presented in Figure 41a. The maximum number of heat waves longer than 5 days per time period varied from 1 to 23 under RCP4.5 (Figure 41b). The maximum HWDI values under RCP8.5 increased to 19, 268, and 2192 for the 2006-2035, 2036-2065, and 2066-2095 periods, respectively (Figure 41c). Similarly, the maximum number of heat waves (hw) longer than 5 days increased to 3, 29, 181 under RCP8.5 for the 2006-2035, 2036-2065, and 2066-2095 periods, respectively (Figure 41d). The northern and western parts of LRB and south and eastern parts of MFCB will experience higher heat wave duration for all projection periods.

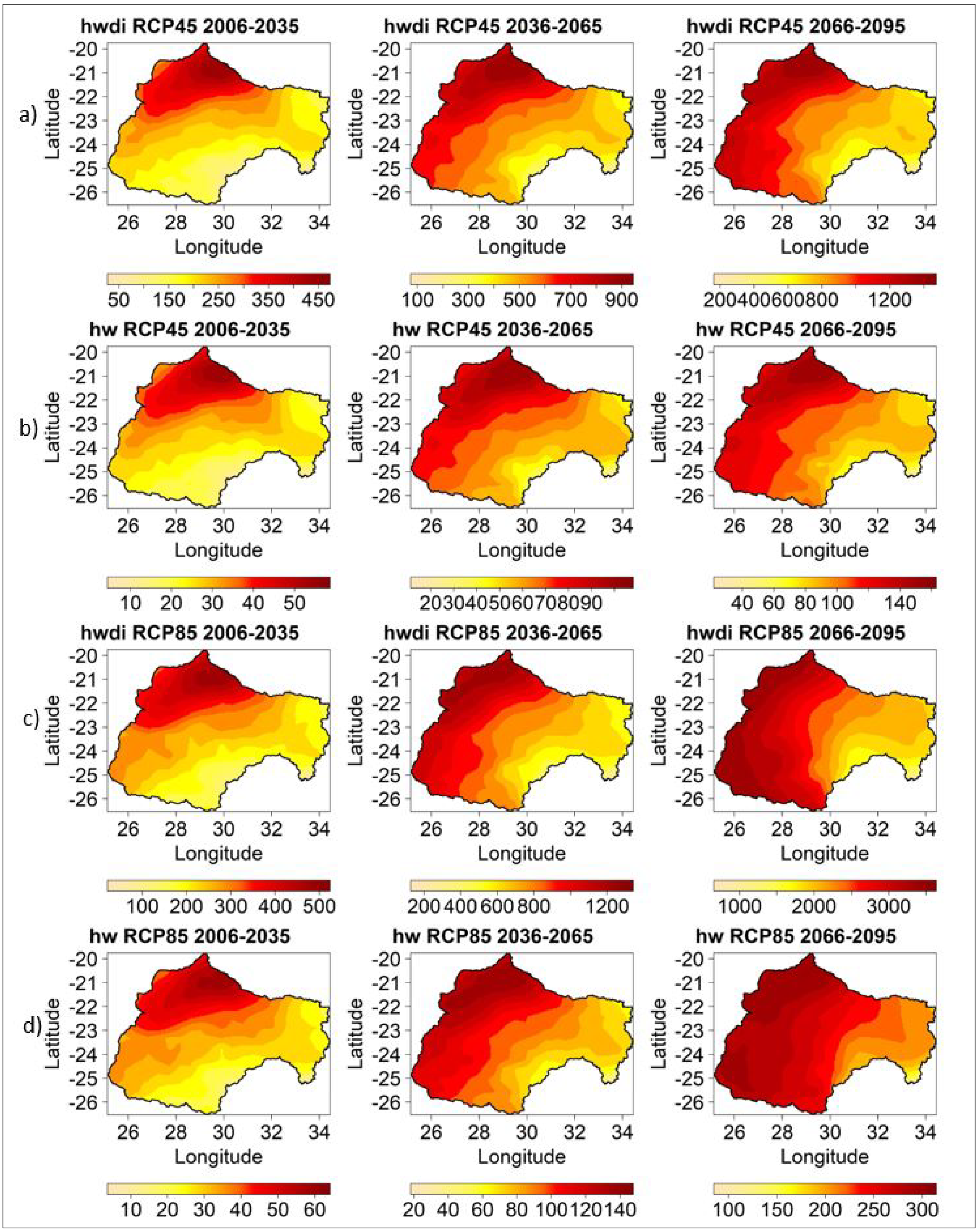

Figure 40. Projected change in heatwave duration index (HWDI) for mean of the reference period of 1979-2005 and (a & c) and heat waves per time period (hw) (b & d) for LRB for three projection time intervals, based on RCP4.5 (a & b) and RCP8.5 (c & d) scenarios

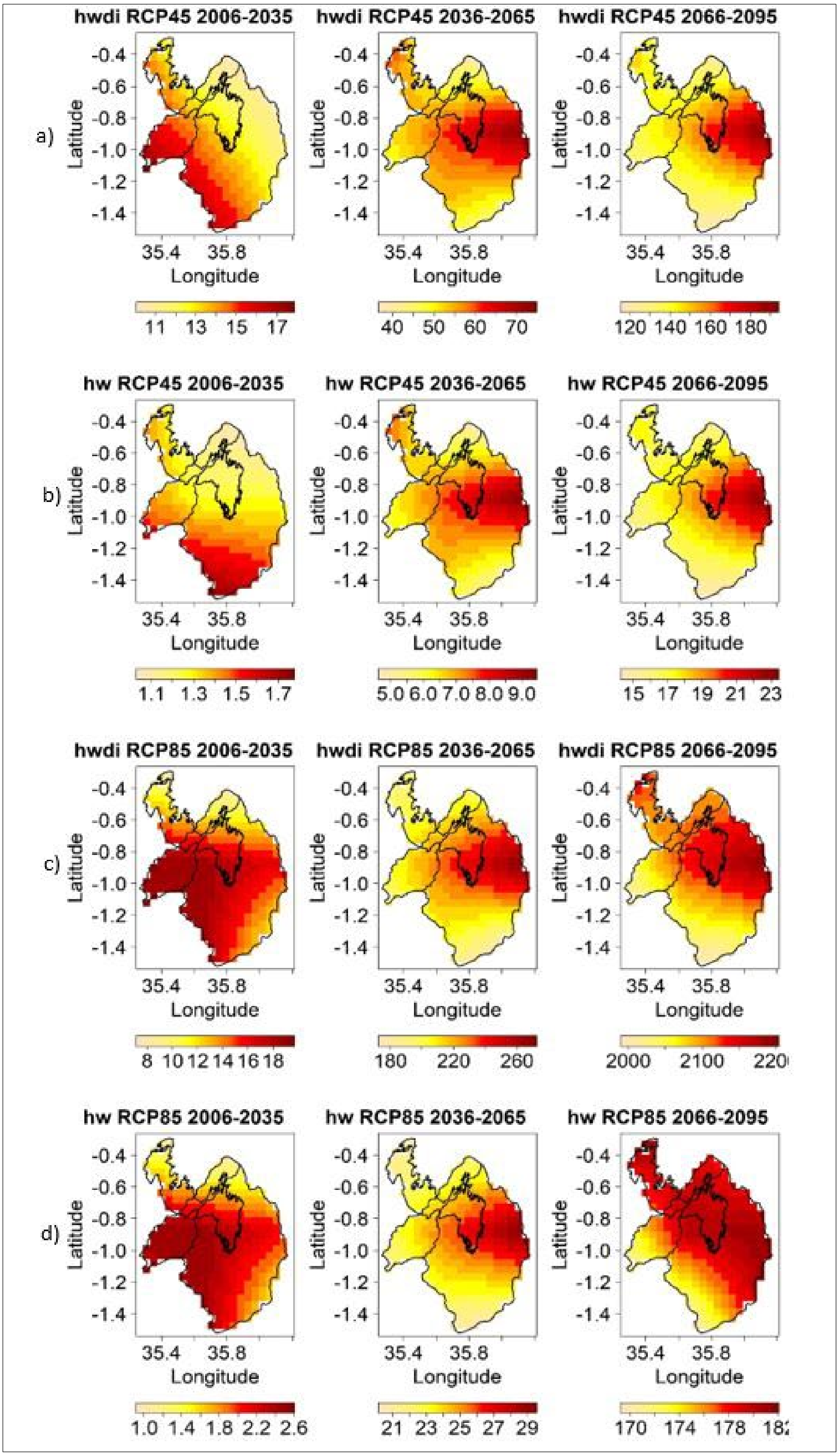

Figure 41. Same as Figure 40 but for the MFCB

3.3.3.2 Warm Spell Days Index

Warm spell duration index (HWFI) is defined as a time series count of days with at least 6 consecutive days when the daily maximum temperature exceeds the 90th percentile of the daily maximum temperatures of a five-day window centred on each calendar day of a given climate reference period. The warm spell periods per time is defined as number of warm-spell periods longer than or equal to 6 days. The projection of warm spell days index for the 90th percentile of reference period 1979-2005 (HWFI) and warm spell periods per time period (WSP) for RCP45 and RCP85 are shown in Figures 42 and 43 for LRB and MFCB, respectively.

An increasing trend of warm spell duration index is observed for LRB under RCPs 4.5 and 8.5 as shown in Figure 42. A significant increase in HWFI is noticed under RCP8.5 for the 2066-2095 period with values greater than 4500 for the southern parts of LRB. Likewise, an increasing trend in HWFI is observed for MFCB under RCPs 4.5 and 8.5 as shown in Figure 43. A significant increase in the warm spell duration index is also observed for MFCB for the distant future (2066-2095) under RCP8.5 with maximum values close to 8000.

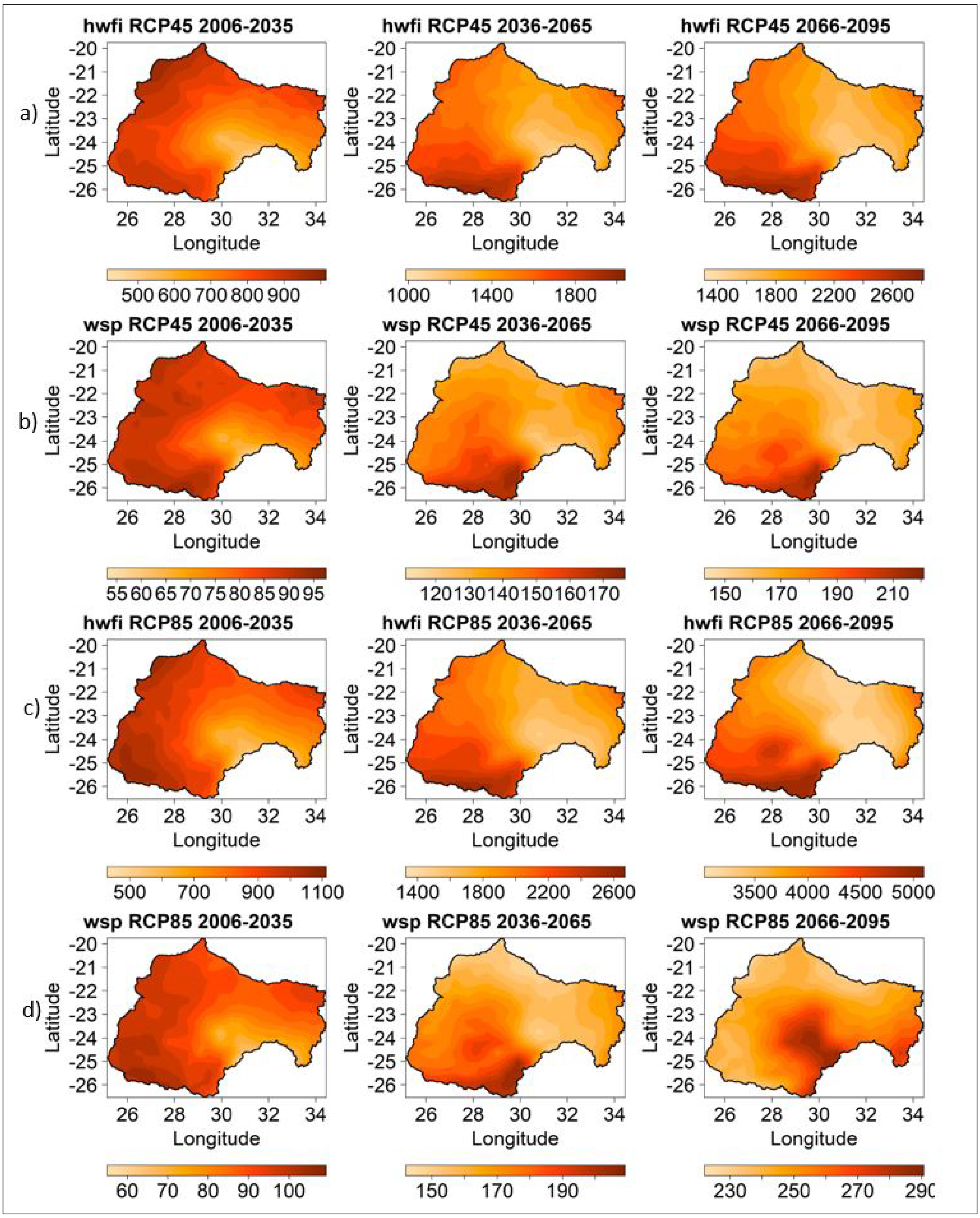

Figure 42. Projected change in warm spell days index (HWFI) for 90th percentile of reference period 1979-2005 (a & c) and warm spell periods per time period (WSP) (b & d) for LRB for three projection time intervals, based on RCP4.5 (a & b) and RCP8.5 (c & d) scenarios

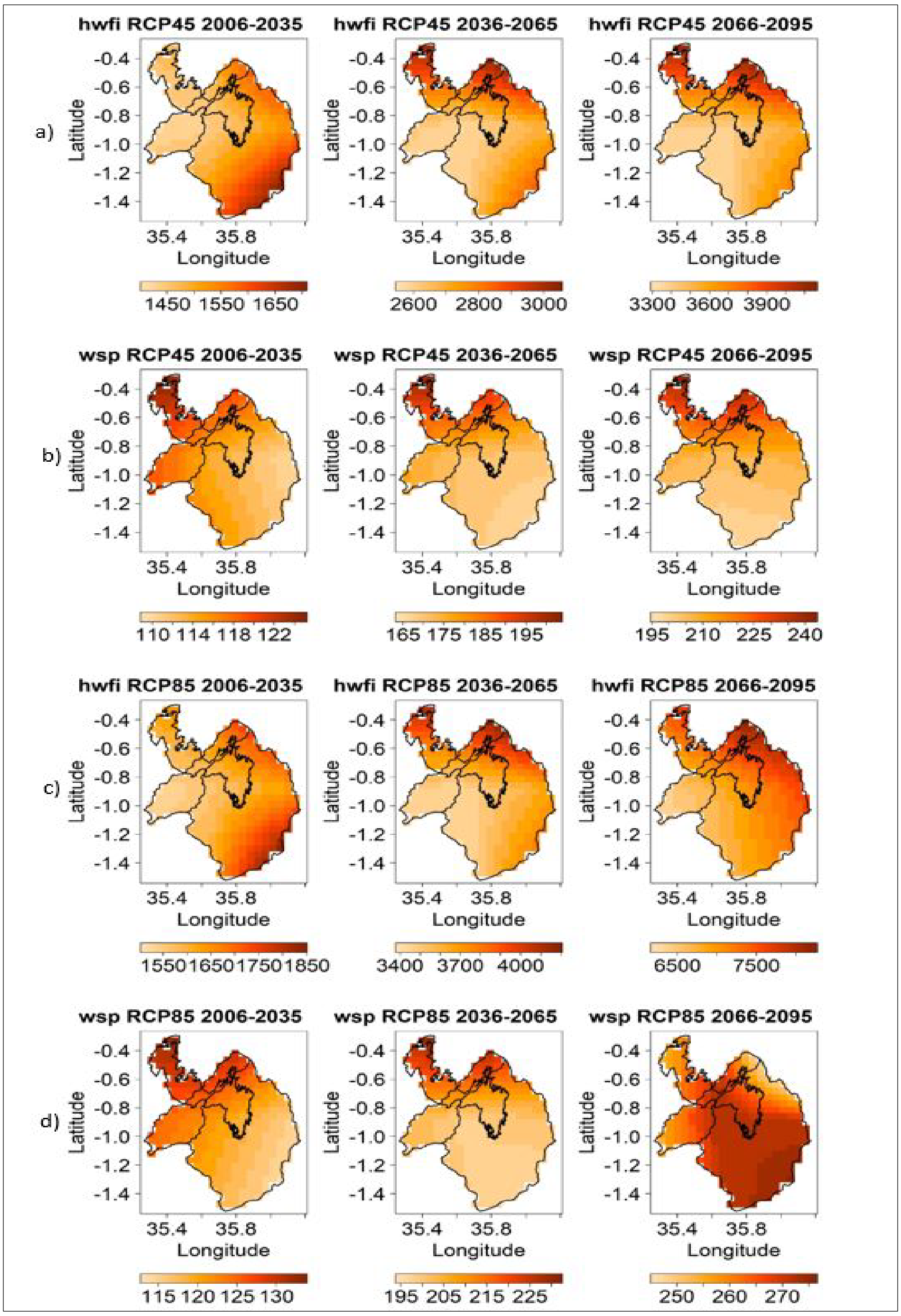

Figure 43. Same as Figure 42 but for the MFCB

3.3.3.2 Cold Spell Days Index

Cold Spell Duration Index (CWFI) is defined as the time series count of days with at least 6 consecutive days when the daily minimum temperature is less than the 10th percentile of daily minimum temperatures of a five-day window centred on each calendar day of a given climate reference period. The spell periods per time is defined as the number of cold-spell periods longer than or equal to 6 days. The projections of the Cold Spell Days Index (CWFI) for 10th percentile of reference period 1979-2005" and cold spell periods per time (CSP) for RCP4.5 and RCP8.5 are shown in Figures 44 and 45 for LRB and MFCB, respectively. Cold Spell Duration Index (CWFI) varied between 20 and 350 for LRB under RCPs 4.5 and 8.5, with maximum values on the western part of LRB for the 2006-2035 period (Figure 44).There is a noticeable decrease in CWFI for the 2036-2065 and 2066-2095 projection periods as shown in Figure 44, with more pronounced decreases in the eastern part of LRB.

For MFCB, CWFI values ranged between 10 and 110 under both RCP4.5 and 8.5, with the highest values observed in the eastern part for the 2006-2035 period (Figure 45). Similarly, there is a significant decrease in CWFI values for the 2036-2065 and 2066-2095 projection periods (Figure 45) under RCP4.5 and with even more significant decreases under RCP8.5.

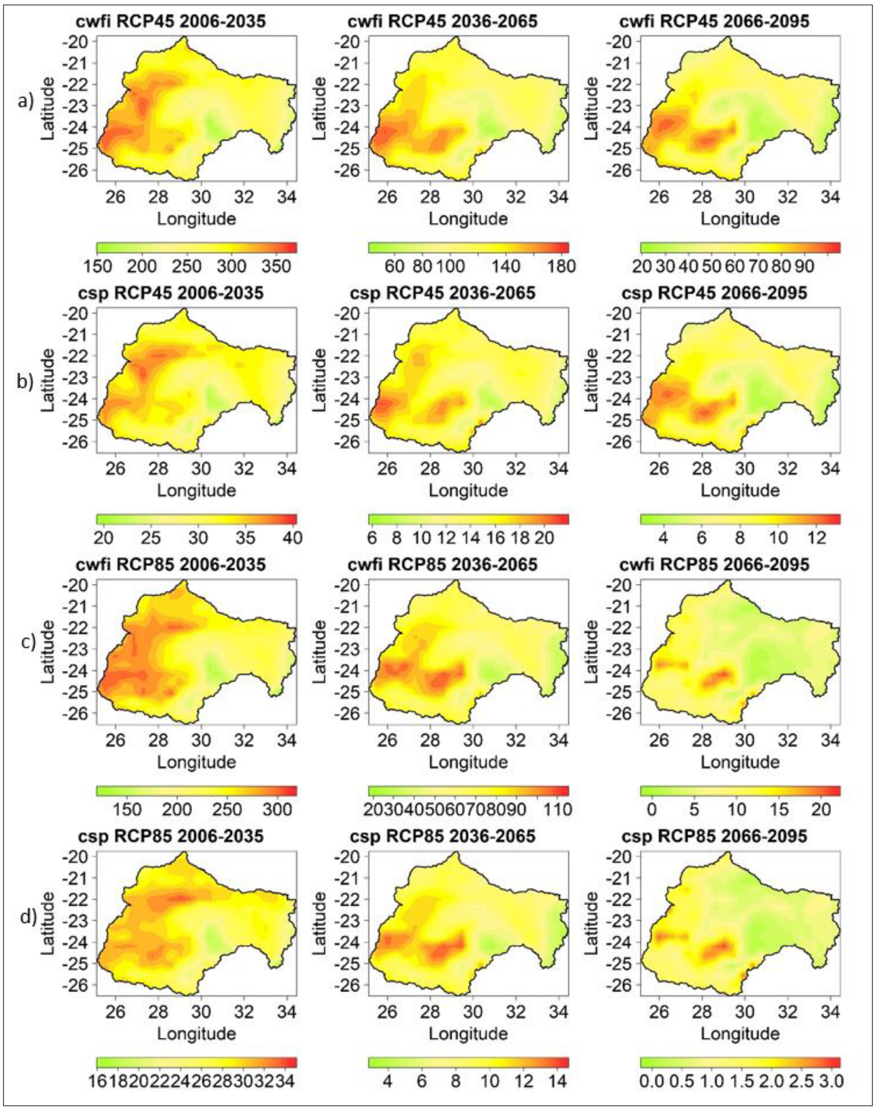

Figure 44. Projected change in Cold Spell Days Index (CWFI) for 10th percentile of reference period 1979-2005 (a & c) and cold spell periods per time period (CSP) (b & d) for LRB for three projection time intervals, based on RCP4.5 (a& b) and RCP8.5 (c & d) scenarios

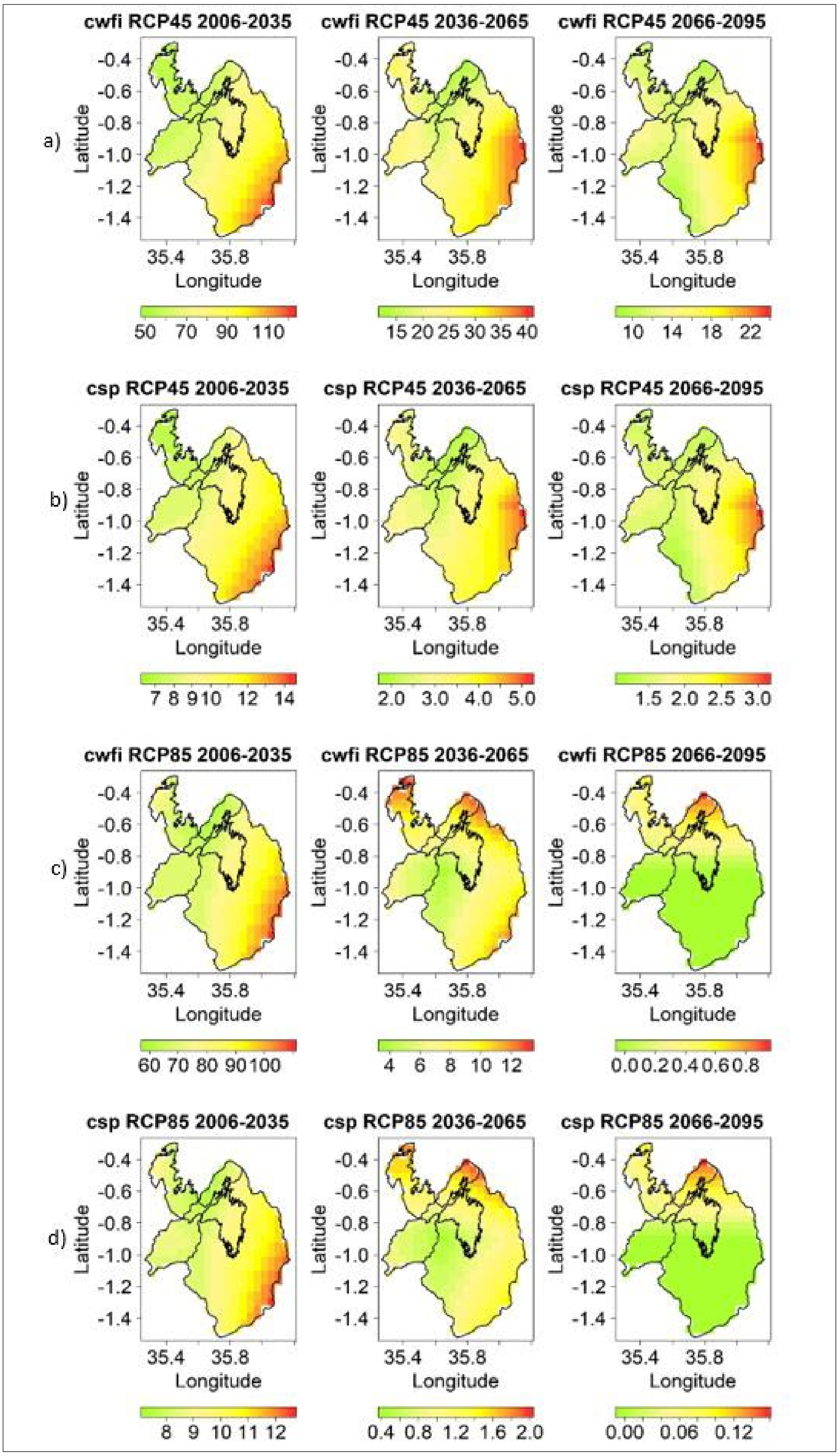

Figure 45. Same as Figure 44 but for the MFCB

3.4. Summary of Implications of Climate Indices on Water-Linked Sectors

As the results presented in this chapter indicate, climate change and variability, will have significant implications to various sectors, including key economic sectors such as water, agriculture, energy and health, among others in both LRB and MFCB. Future projections also highlight a negative trend in both the severity and duration of drought with climate change expected to contribute to this increasing negative trend, posing more significant risks to the society, the environment and those sectors dependent on rainfall and water resources (IPCC, 2014).. The impacts which manifest in a variety of complex ways are dependent on the regional environmental risk exposures and socio-economic vulnerabilities. In Limpopo climate change is expected to bring changing temperature and rainfall patterns in most parts of the LRB, with increased variability of floods and droughts (Shewmake, 2008; IPCC, 2018). Agricultural water use is expected to face serious water scarcity from the combined effects of climate change and intensified competition for water from other sectors. Water resources of the Limpopo River Basin are already stressed, and projected rainfall and stream flow show a decreasing trend.

In the MFCB, climate change projections show that the MFCB is expected to experience an increase in temperatures of 0.7-1.97°C by 2030 and 1.5-2.71°C by 2050 (Zermoglio et al., 2019). The basin is also expected to experience an increase in both the incidence and magnitude of flood and drought events (Coldrey and Turpie, 2019). Projections indicate that temperatures will continue to increase and seasonal rainfall patterns will shift (Zermoglio et al., 2019). These changes will have negative impacts on agriculture and ecosystems such as: loss of crops or decreased yields caused by decreased soil moisture and infiltration rates; changes in the suitability of certain crops; shift in the growing season of crops; increased poverty and food insecurity caused by loss of crops or decreased yields, loss of livestock, or loss of other sources of food and income; and declining wildlife populations due to heat stress and reduced water availability from increased evaporation, leading to both a loss of biodiversity and decreased revenue from tourism.

Other climate sensitive sectors are likely to be impacted by the changes in climate indices for example drought conditions will expose communities in the LRB and MFCB to a range of diseases related to water and lack of sanitation. According to Petrie et al., (2014), water is scarce in the LRB, and many people living in the area are impoverished and face limited access to essential services such as sanitation which prevent hygiene practices in the process resulting in greater exposure to diseases. Waterborne and vector-borne diseases such as Malaria, Cholera and Bilharzia (Schistosomiasis), are a notable concern in both study sites with participanstin Narok ndicating that they have to treat most river and borehole water before drinking it. Furthermore, droughts and floods affect agricultural productivity and had impacts on food security and can lead to malnutrition as a result of inadequate caloric. A summary of the possible challenges in climate sensitive and water-linked sectors is presented in Table 14 below and can be used adapted to suit local communities as they plan for both short term and long term adaptation actions for both the MFCB and LRB.

Table 14. Summary of climate indices and implications for water linked sectors

Climate Index	Sectoral Vulnerabilities and potential impacts			
	Water	**Agriculture**	**Health**	**Energy/society**
WSDI	Increased water demand	Decline in yields Increased food insecurity	Reduced human mortality	Reduced power production efficiency; increased energy demand (e.g. pumping for irrigation systems and drinking water)
CSDI	Increased water demand	Food insecurity problems due to decreased yields	Increased risk-related mortality	Reduced energy demand for heating; increased demand for cooling; decline air quality
HWDI	Increased evapotranspiration rate; Reduced water availability; Increase in water demand	Decrease in water for irrigation; food insecurity (crop displacement; loss of seed production); risk of livestock deaths	Increased risk of water and food-borne diseases; risk of heat-related mortality	Increased demand for power generation to support irrigation systems and drinking water; Reduced power production efficiency
HWFI	Increased water demand; water quality problems	Food insecurity; reduced crop yields and heat stress for livestock	Increased risk of water and food-borne diseases; risk of heat-related mortality	Increased demand for power generation; Reduced power production efficiency
Rx5day	Decline in water quality; risk of flooding/drought	Food insecurity: loss of soil fertility due to soil erosion	Increased risk of water and food-borne diseases	Increased societal vulnerability
SDII	Decline in water quality; risk of flooding/drought	Food insecurity: loss of soil fertility due to soil erosion	Increased risk of water and food-borne diseases	Increased societal vulnerability; increased power production from hydroelectric plants; flooding affects mining operations
CDD	A decrease in water availability; increased water demand; drought; water stress	Reduced crop yields; risk of livestock deaths	Increased risk of water and food-borne diseases	Reduced hydropower potential; migration; increased energy demand
CWD	Water reservoirs recovery; decline in water quality; flooding	Potential damage to crops, soil erosion leading to loss of soil fertility	Increase in/ emergence of infectious diseases, e.g. malaria & cholera	Disruption of settlements; increased costs for settlement relocations; Increased power production (e.g. from hydroelectric plants); disruptions to mining and transport operations
R10mm	Decline in fresh water quality; risk of flooding	Potential damage to crops, soil erosion	Infectious diseases, e.g. malaria, cholera, etc.	Increased societal vulnerability
R20mm	Fresh water quality problems; risk of flooding	Potential damage to crops, soil erosion	Injuries, infectious diseases, e.g. malaria, cholera, etc.	Increased societal vulnerability, disruption of settlements; increased costs for disaster response
R95p	Fresh water quality problems; risk of flooding	Increased damage to crops, soil erosion	Injuries, risk of drowning in floods; infectious diseases, e.g. malaria, cholera, etc.	Increased societal vulnerability, disruption of settlements; increased costs for relocation; risk of disruptions of mining operations

3.5. Concluding Remarks

Climate change extremes cause a series of social, environmental and ecological problems, particularly in the most vulnerable communities. Consequently, estimation of the frequency of climate extremes and their relative magnitude are essential for decision-making to ease the inherent impacts on vulnerable sectors. The current study focused on characterising projected precipitation and temperature-related extreme indices in the LRB and MFCB study sites. The results reported in this study depict significant variations in the selected climate indices. As expected, the variations of the climate indices are localised. In general, the results reported in this study, which are attributed to climate change and variability, will have significant implications to various sectors, including key economic sectors such as water, agriculture, energy and health, among others. The results presented in this study for LRB and MFCB will significantly contribute to identifying the challenges in climate-sensitive and water-linked sectors and will assist in policy and decision-making in support of effective management and planning of sector-specific resources.

4. Assessment of Projected Future Climate Change Impacts on Water-Linked Sectors: A Case Study of the Limpopo River Basin

4.1. Introduction

The impacts of climate change (e.g. rising temperatures, changes in precipitation, among others) coupled with natural climate variability, exacerbate the frequent occurrences of extreme weather and climate events such as heat waves, drought, floods, storms, and extreme temperatures, among others. Depending on their intensity, duration, and severity, these events pose significant challenges to key socio-economic sectors such as agriculture, water, health, energy, tourism, transport, etc. In particular, the impacts of weather climate extreme events attributed are often felt from a mere personal level, particularly in the most vulnerable communities, including small-scale farmers to the regional scale, leading to disruption of economic developments, environmental degradation and exacerbating natural hazards in the form of wildfires (Mukherjee et al., 2018). There is a growing body of information suggesting that climate change impacts are likely to increase in future, as a result of increases in global average air and ocean temperatures, widespread melting of snow and ice, as well as rising global average sea level (IPCC, 2007; 2013; Council for Scientific and Industrial Research (CSIR). Green Book). Climate projections, have highlighted an increase in climatic variables such as mean temperature (Almazroui et al., 2017; Bucchignani et al., 2018), average air temperature (Niang et al., 2015), heat stress and frequent and prolonged heat waves (Diedhiou et al., 2018), as well as highly variable precipitation (Niang et al., 2015), also support the predicament situation of exacerbated future climate impacts.

Assessment of the impacts of climate change is essential for effective policy and decision-making to mitigate the inherent impacts, including providing supportive measures for proper management and sustainability of key economic resources as well as promot resilience within communities to manage these hazardous conditions. Various framework methods used for climate change impact assessments have been reported in the literature, depending on the identified climate impact, e.g. drought, flood, agriculture, heat stress/wave, etc. According to the IPCC (2001; 2007), Engstrom et al., 2020), and references therein, climate impact assessments can be structured based on the framework summarized in Figure 46. In general, this process involves three steps: (1) identify potential climate impact attributed to climate change, (2) select the determinants' indicators (e.g. sensitivity/hazard and exposure) and the corresponding metrics to measure the impacts and (3) estimate the combined climate impact, using the selected determinants' indicators.

In this chapter, projected future climate impacts were assessed in the LRB with the main aim being to understand the projected future climate impacts. The identified climate impacts included agricultural impacts, drought, heatwave and tourism. This is essential, given that the regional changes in climate extremes, both observed and projected, in the literature show that the changes vary with regions hence the analysis at catchment levels allows for a more comprehensive understanding and comparisons of the dynamics in different geographical locations.

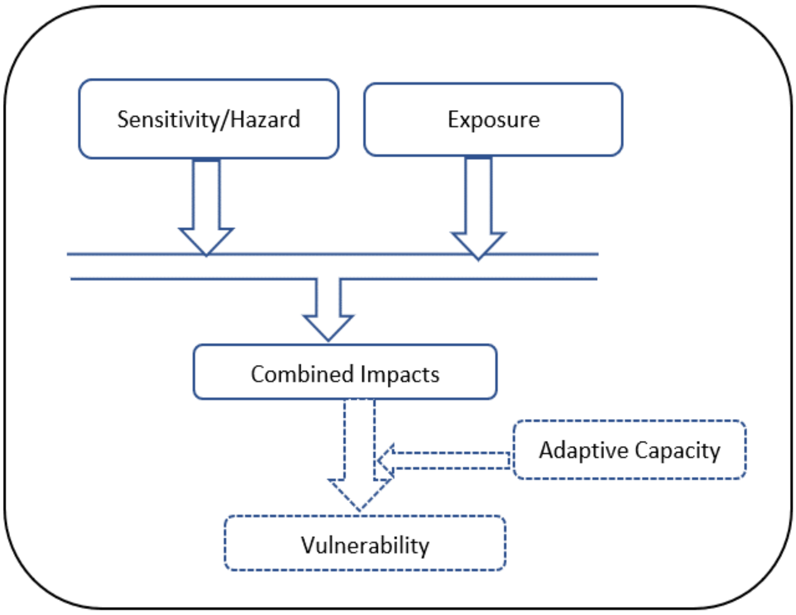

Figure 46. Framework for climate impact assessment

4.2. Study Site Characteristics

Detailed information on the LRB study site has been provided in Chapters 2. Some of the features, e.g. topography, climate, population, etc. are summarized in Table 15.

Table 15. Site characteristics

Site features	South Africa
Basin area	21, 407 km^2
Topography	Two main physiographic regions - western plateau topography in upper and western areas; mountainous in the southern regions, - the lower, eastern floodplain, or coastal plain - undulating rolling hills with flat plains to the east - characterised by Soutpansberg ("Salt Pan Mountain")- mountain range to the north - Altitude ranges between 250 and 1748 m above mean sea level - estimate terrain elevation of 1206 m above sea level
Population	1.4 million
Climate factors	dry continental tropical, equatorial convergence zone, moist marine subtropical eastern and marine western Mediterranean air masses
Major hazards	Floods, droughts
Key economic sectors	Agriculture, mining, tourism,

4.3. Model Data and Methods

4.3.1. Model Data

The comparative study used a multi-model ensemble from model simulations of the Coordinated Regional Downscaling Experiment (CORDEX) dynamically downscaled simulations over the African domain of spatial resolution (0.44°x 0.44°), through the Coordinated Regional Climate Downscaling Experiment (CORDEX) (Jones et al., 2011). The Regional Circulation Models (RCM) of the Rossby Centre regional (RCA4) was used. The RCA4 is a coupled ocean-atmosphere Regional Circulation Model (RCM) based on the Numerical Weather Prediction (NWP) model HARLAM (Undén et al., 2002).

4.3.2. Conceptual Framework and Methods

The conceptual framework for the impact assessment on the climate-sensitive sectors such as water, health, agriculture and tourism is presented below. This information will support the development of the adaptation responses that will be developed with the stakeholders in the two study sites.

4.3.2.1 Agricultural Impacts Assessment

Climate change is projected to increase temperatures and extreme weather events and alter precipitation patterns over the LRB. Climate change is predicted to negatively impact the agricultural sector through the potential reduction in crop yield and livestock production (Petrie et al., 2014; Zermoglio et al., 2019). In the current studies, climate change impacts on agriculture are assessed based on the method used by Lewis et al. (2018). This method can be summarized as follows:

(i) Identifying major farming systems,
(ii) Develop a conceptual framework,
(iii) Generate maps using data.

The conceptual framework for assessing the impact of climate change

The absence of local data is one of the major limitations to conducting climate change impact studies in most developing countries (Mendelsohn, 2009). Furthermore, climate change impacts studies on agriculture are constrained by the complexity of the input data required, e.g. the yield for different crops, livestock, input costs, farm size, agronomic practices, and farming choices. Tubiello and Rosenzweig (2008) highlighted that there is extensive literature on climate change impacts on agriculture, however, they stressed the need to develop an analytic framework (a system of metrics) for comprehensive comparisons of climate change projections across different scales and regions. In addition to observed data, models are used to project the impacts of future climate change and socio-economic development on agricultural systems. Two distinct model classes are used to estimate metrics in agriculture: dynamic crop/agroecosystem models (with or without coupling to economic trade models) and Ricardian economic approaches (Tubiello and Rosenzweig, 2008). The Ricardian method has been used to measure climate impacts using cross-sectional evidence (Mendelsohn, 2009). With the Ricardian method, land values or net revenues are regressed on climate, soils, and geographic and economic variables that are independent of the farmer (Mendelsohn, 2009). Tubiello and Rosenzweig (2008) have specified a list of metrics: biophysical factors (indexes for soil and climate resources, crop calendars, water status, biomass and yield dynamics); agricultural system characteristics (percentage of arable land, inputs management, percentage of area that is irrigated; and statistical production data); and socio-economic data (rural welfare, poverty and nutrition, crop insurance, protection and trade).

Several studies have underlined the concept of potential impacts on the agricultural system as a function of exposure of the system to climate hazards and sensitivity to the exposure. The framework developed by Morton (2007) and used by Lewis et al. (2018) which accounts for the impacts at the physical and socio-economic levels will be adopted in this study. The conceptual framework established by Morton (2007) stated that a conceptual framework for understanding these should: recognise the complexity and high location-specificity of these production systems; incorporate non-climate stressors on rural livelihoods and their contribution to vulnerability; study three different categories of climate change impacts upon smallholder farmers livelihoods (biological processes affecting crops and animals, environmental and physical processes and impacts of climate change on human health and non-agricultural livelihoods.

Recognising complexity and high location specificity using maps

The impacts of climate change indicators (changes in temperature and precipitation) and other pertinent changes at the farming system level and draw interpretations of the impact that this will have on the livelihoods of the small-scale farmers dependent on these systems to recognise the complexity and high location-specificity of these production systems.

Categories of climate and non-climate stressors

Potentially impacted farming systems are then analysed using different criteria to determine the impact of climate change throughout the farming system outlined in Morton (2007):

- biological processes (changes in temperature and precipitation),
- environmental and physical processes (changes in temperature and precipitation),
- and non-agricultural livelihoods.

Morton (2007) identifies the following non-climate stressors affecting smallholder and subsistence agriculture, including population increase driving fragmentation of landholding; environmental degradation caused by population, poverty and ill-defined and insecure property rights; regionalised and globalised markets, and regulatory regimes, increasingly concerned with issues of food quality and food safety; market failures in product marketing and input supply; protectionist agricultural policies in developed countries, decline and unpredictability in the world prices of many major agricultural commodities.

Reference evapotranspiration (ET_o) is an important component of the hydrological cycle, agriculture and the environment. Therefore, assessment of ET_o changes is critical in understanding the impacts of climate change on the agricultural sector and it is necessary for crop water requirement estimations, water balance and ecosystem models used for global change studies. Globally, evapotranspiration (ET) is one of the biggest users of water from catchments and accounts for about 62% of the precipitation (Dingman, 2015). Climate change projections show increases in ET_o worldwide (IPCC, 2008), due to the increases in temperatures caused by the increasing concentration of greenhouse gases and changing land cover patterns. In this study, the impacts of projected increases in ET_o for LRB are expressed as the changes between the projected and current estimates. Reference evapotranspiration was estimated using the Hargreaves-Samani method (Hargreaves and Samani, 1985).

The impacts of projected increases in temperatures (T) and evapotranspiration (ET_o) on farming systems for LRB were expressed as the change between projected and current estimates (Table 16). The combined impact of increases in T and ET_o was estimated as changes in ET_o (see Equation 2):

$$\textit{Potential Impact (ETo) = Exposure of farming systems + Sensitivity} \qquad \text{Eq. (2)}$$

Table 16. Increase in temperatures and evapotranspiration and its impacts on farming systems

Indicator	Variable	Unit	Description
Hazard	Increases in T	°C	Changes between projected and current estimates
	Increases in ET_o	mm	Changes between projected and current estimates
Exposure	Farming systems	Hectares	Different farming systems (dryland farming, irrigated, mixed farming, pastoral farming systems)
Sensitivity	Crop water use Irrigation demand Grazing land		Sensitivity of farming systems to changes in ET_o

4.3.2.2 The Projected Climate on Water Resources: The Drought Impacts

The impacts of climate change were assessed for the LRB and MFCB study sites. These basins, like many others, are frequently exposed to both climate change, whereby precipitation and temperature are the key variables, as well as extreme climate change such as floods and droughts. In the current analysis, drought is used as a climate indicator that is likely to have an impact on both study sites, leading to disruptions of water quality, availability, and supply, for various purposes. The impact of drought on water-linked sectors due to the changing climate is quantified based on two selected determinants, which are sensitivity and exposure.

According to the IPCC (2001; 2007; Engstrom *et al*., 2020), exposure describes the nature and degree to which people, property and systems, among others, are exposed to climatic variations, whereas sensitivity is the degree to which the systems are affected by the changing climate as well as the inherent extreme events. In this analysis, exposure and sensitivity are represented by four metrics, each, summarized in Table 177.

Table 17. Indicators of drought impact and parameters used to calculate the corresponding indicators.

Determinants of Impact	Impact indicator	Indicator/metric	Implication
Exposure	People, property, systems, etc.	Population density	Higher population density, greater sensitivity
		Surface water	More surface water, less sensitivity
		Water access totals	Greater water access, less sensitivity
		Change in streamflow	
Sensitivity	Extremes and change in climate	Drought Frequency	More drought frequency means greater sensitivity
		Drought Severity	The higher the severity the more the sensitivity
		Change in precipitation	Increasing temperature and decreasing precipitation and streamflow increase exposure
		Change in temperature (T_{min})	

The change in temperature and precipitation were calculated based on the change in the projected temperature (minimum) and precipitation from the base period (1976-2006), respectively. Similarly, the change in streamflow was based on the change in the projected streamflow from the base streamflow, all simulated using the mesoscale hydrological model (mHM). On the other hand, the projected change in drought frequency and severity extremes for each period were calculated based on the Standardized Precipitation-Evapotranspiration Index (SPEI), using the baseline reference period. The indicators were each standardized based on the following equation,

$$V_i = \frac{x_i - x_{imin}}{x_{imax} - x_{imin}} \qquad \text{Eq. (3)}$$

where x is the value of a specific indicator for the i^{th} basin, and x_{min} and x_{max} represent the maximum and minimum values of the indicator, respectively. The normalized values (V) range from 0 to 1, where zero represents the least sensitive (exposure), whereas, 1 represents higher sensitivity (exposure). After normalization, sensitivity and exposure indicators were calculated by using Equation 4,

$$Z_{ji} = \frac{\sum_{i=1}^{n} V_i}{n} \qquad \text{Eq. (4)}$$

where *n* is the number of metrics insensitivity or exposure indicators, and Z_{ji} is the value of the indicator *j* (i.e. sensitivity or exposure) for river basin *i*. The combined drought impact (*CDI*) was then calculated as a product function of sensitivity and exposure contributing factors as given in Equation 5:

$$CDI = Sensitivity \times Exposure \qquad \text{Eq. (5)}$$

The sensitivity, exposure as well as the resulting *CDI* were interpreted based on four categories, defined in Table 18. Categories of sensitivity, exposure, and CDI and the corresponding explanation

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Table 18. Categories of sensitivity, exposure, and CDI and the corresponding explanation

Category	Sensitivity (Hazard)	Exposure	CDI (CHWD)
0 < *DI* < 0.25	low risk	low exposure	low impacts
0.25 < *DI* < 0.50	moderate risk	medium exposure	moderate impact
0.50 < *DI* < 0.75	high risk	high exposure	high impact
0.75 < *DI* < 1.0	extreme risk	extreme exposure	Extreme drought impacts

4.3.2.3 The Projected Climate on Human Health: The Heatwave Impacts

There is a well-established link between increased ambient temperatures and adverse health outcomes (Campbell et al., 2018). As evidence in many parts of the world as well as in the LRB and MFCB study sites (Mosase and Ahiablame, 2018), high temperatures and associated extreme heat and heatwave events are natural hazards that can trigger a variety of heat-related illnesses, as well as cardiovascular and respiratory disorders contributing to increased hospital admissions and the risk of mortality (Kravchenko et al., 2013; Wang and Li, 2014; Takaro and Henderson, 2015). Furthermore, there are significant effects on mental health and behaviour (Lõhmus, 2015), particularly in farming communities (Yazd et al., 2019). As seen in some parts of the world (Dessai, 2003), the projected future of intense heat and heatwave events indicates public vulnerability to such events will rise by approximately sixfold by mid-century. Thus, calling for heat-related impacts to be investigated, and appropriate targeted adaptation strategies to combat negative consequences of extreme heat on human health.

In heat impact analysis, the current and projected direct impact of increased temperatures and associated heatwave events on the human population under different climate change scenarios are quantified for the LRB study siteand . The framework recognized by the IPCC (McCarthy et al., 2001) in which extreme heat risk is composed of the three dimensions of heat hazard, exposure, and vulnerability is adopted. Whereby heat hazards, refer to Maximum Temperature (Tmx), Heat Wave Duration (HWD) and Heat Wave Magnitude Index (HWMI) as presented in Table 19**.** .

Table 19. Indicators of heatwave impacts and parameters used to calculate the corresponding indicators

Determinants of Impact	**Indicator/metric**	**Units**	**Implication**
Exposure (people, property, systems, etc.)	Population density	(Pop/km^2)	High population density means more people are exposed to risk
	Total population per district	Millions	A large population means more people are exposed to risk
	Percentage of the elderly	%	Percentage of the population over 65 years old
	Percent of children	%	Percentage of the population under 5 years old
Hazard (change in climate & extremes)	Maximum Temperature	°C	Change in temperature (T_{max})
	Heat Wave Duration (HWD)	Days	Heat wave's length in days
	Heat Wave Magnitude Index (HWMI)	Days	the average magnitude of all yearly heat waves)

The three factors were correlated with direct and indirect impacts on human health, livelihoods, infrastructure, and service provision, while exposure provides information on whether human social systems could be adversely affected by a disaster. Indicators in Table 19. were normalized using equation 3. Equation 4 was used to calculate the exposure and hazard indicators. The combined Heatwave Impacts (CHWI) was calculated as a combination of Exposure and Hazard using Equation 6:

$$CHWI = Exposure \times Hazard \qquad \text{Eq. (6)}$$

4.3.2.4. Climate Change Impacts on the Services Industry: Tourism

In the context of economic development, the tourism industry is one of the sectors affected by climate change. The indirect impacts of climate change include impacts of environmental changes; mobility policies and social change (Brasil, 2008). Tourists from around the globe travel to LRB (Kruger National Park; KNP) and MFCB (Serengeti National Park; SNP) for sports, recreation, religious practices, medical-health activities, and many other reasons. Climate change can affect tourism directly and indirectly in terms of destinations, competitiveness, and sustainability. Geography has a direct link with climate and depending upon the location on the surface of the earth, the climate varies and so does the biodiversity. Depending upon the climate change index, each location has been affected by certain types of climate-induced issues. Extreme weather events such as floods, drought, wildfire, infectious disease, etc. are potential consequences of climate change that can influence tourist activity as well as their safety.

The LRB and MFCB both have national, transnational conservation areas and parks which are rich in biodiversity and support many livelihoods. In Kenya, areas of rich biodiversity that support the tourism sector include the Mau Forest complex (i.e. the largest closed-canopy forest in East Africa), the Serengeti National Park and Masai Mara National Reserve. Biodiversity in the Masai Mara National Reserve comprises grasslands, shrubs and thorny bushes while the Serengeti National Park consists of the most savanna biome and the rangelands are classified as semiarid (Bartzke et al. 2018). The LRB is host to the Kruger National Transfrontier Park and the Mapungubwe National Park a World Heritage Site which supports many communities that also co-own some of the lodges and guesthouses in these conservation areas. Parts of the LRB comprise the Grassland biome which is one of the most threatened biomes and is likely to be replaced by savannah and forest vegetation (DEA, 2013). Savannah ecosystems in both sites support ecosystem-based tourism and provide ecosystem services such as medicinal plants, cultural and religious regulation as well as construction material (Fischlin et al., 2007).

The conceptual framework for assessing the impact of climate change on tourism

An assessment of the impact of climate change on tourism is done in this study by analyzing past, current and projected extreme events; droughts using the SPEI. In particular, Pearson's correlation coefficient is used to establish the correlation between drought and the number of tourist arrivals to the Kruger National Park (KNP). The SPEI at the 6-month drought accumulation period was computed using the SPEI package in R software (Vicente-Serrano et al., 2010) over three weather stations within the KNP, i.e Thohoyandou, Punda Maria and Skukuza (Figure 47). The South African portion of the Kruger national park has long-time weather records and weather data was used from 1982-2020. An Autoregressive Integrated Moving Average with Explanatory Variable (ARIMAX) was developed to assess the impact of projected SPEI under the RCP 8.5 scenario on future visits to the KNP. The RCP 8.5 is probably the most plausible scenario given the current trajectory of greenhouse gas emissions. The developed ARIMAX was used to project the future (30 years) of visits to the KNP. The historical visit was used to regress against the SPEI as the exogenous variable.

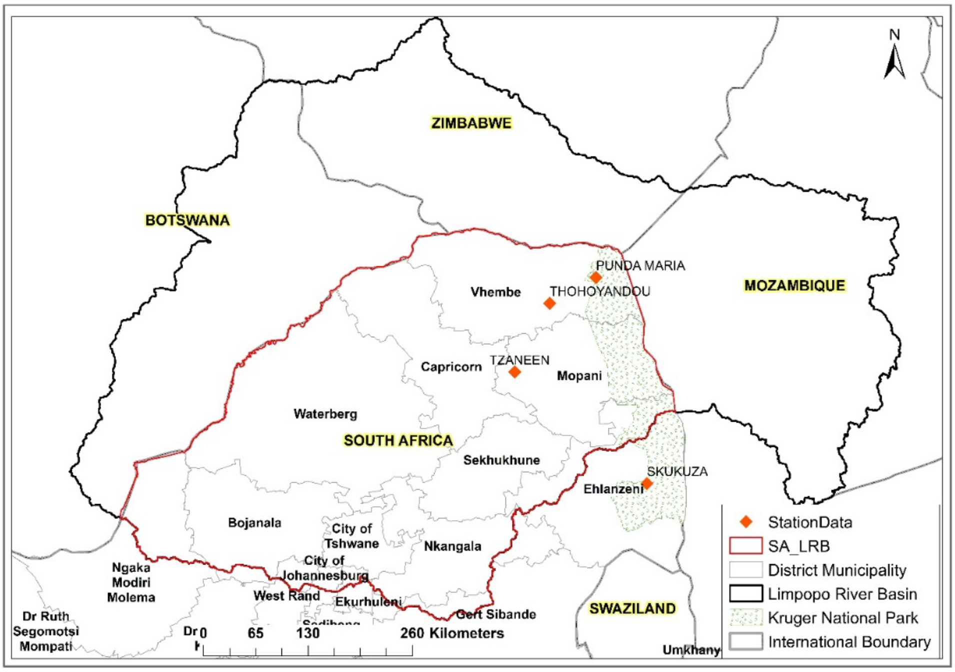

Figure 47. The Limpopo River Basin, showing the South African portion and the Kruger National Park

4.4. Results

4.4.1. Projected Agricultural Impact on Decadal Timescales

Climate change scenarios RCP4.5 and RCP8.5 were used for the periods 2006-2035, 2036-2065, 2066-2095, and for the baseline period (1976-2005). Land use has a critical influence on ET_o rates. Land use classes for the LRB catchment showing different farming systems and other land use classes are presented in Figure 48.

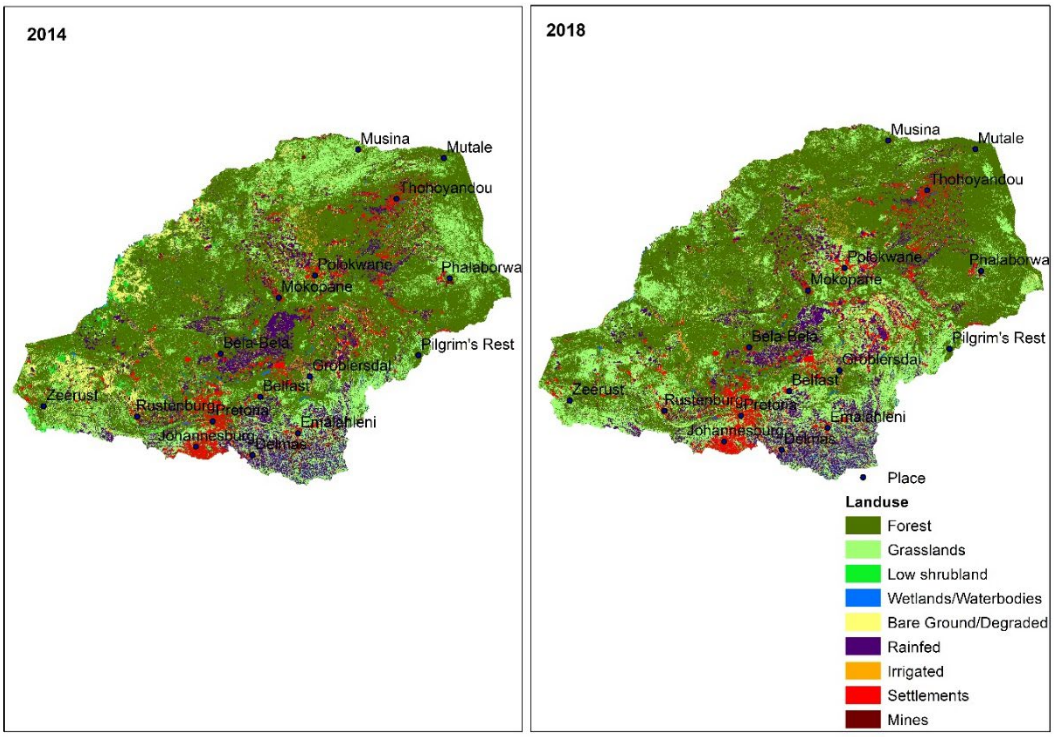

Figure 48. Land use and major land cover classes for the LRB catchment

The mean LRB catchment annual ET_o values for the reference period (1976-2005) ranged between 1000 and 1675 mm as shown in Figure 49. The maximum annual ET_o values (> 1,600 mm) were observed for the north and western parts of the LRB catchment. The lowest mean annual ET_o values for the reference period were in the south and eastern areas of the catchment (Figure 49). The central part of the catchment showed annual estimated values ranging between 1300 and 1500 mm.

Absolute changes in ET_o projections regarding the baseline period (1976-2005) under the RCP 4.5 scenario are presented in Figure 50. Reference evapotranspiration is projected to increase in LRB under RCP4.5 in the future as shown in Figure 50. The highest increases in the ET_o values were observed in the northern, central, and southwestern parts of the catchment for the 2066-2095 period (Figure 50), with mean maximum increases of greater than 110 mm.

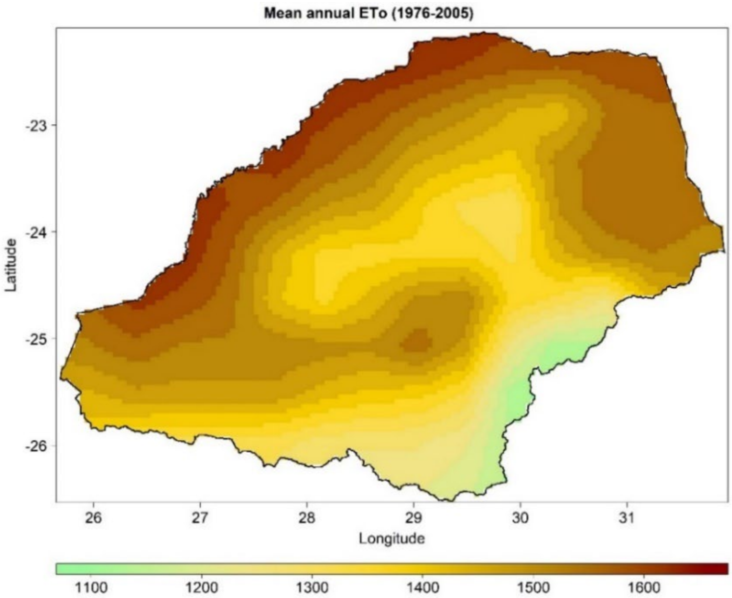

Figure 49. Mean total annual reference evapotranspiration (ETo) estimates (mm) of the LRB catchment for the reference period (1976-2005)

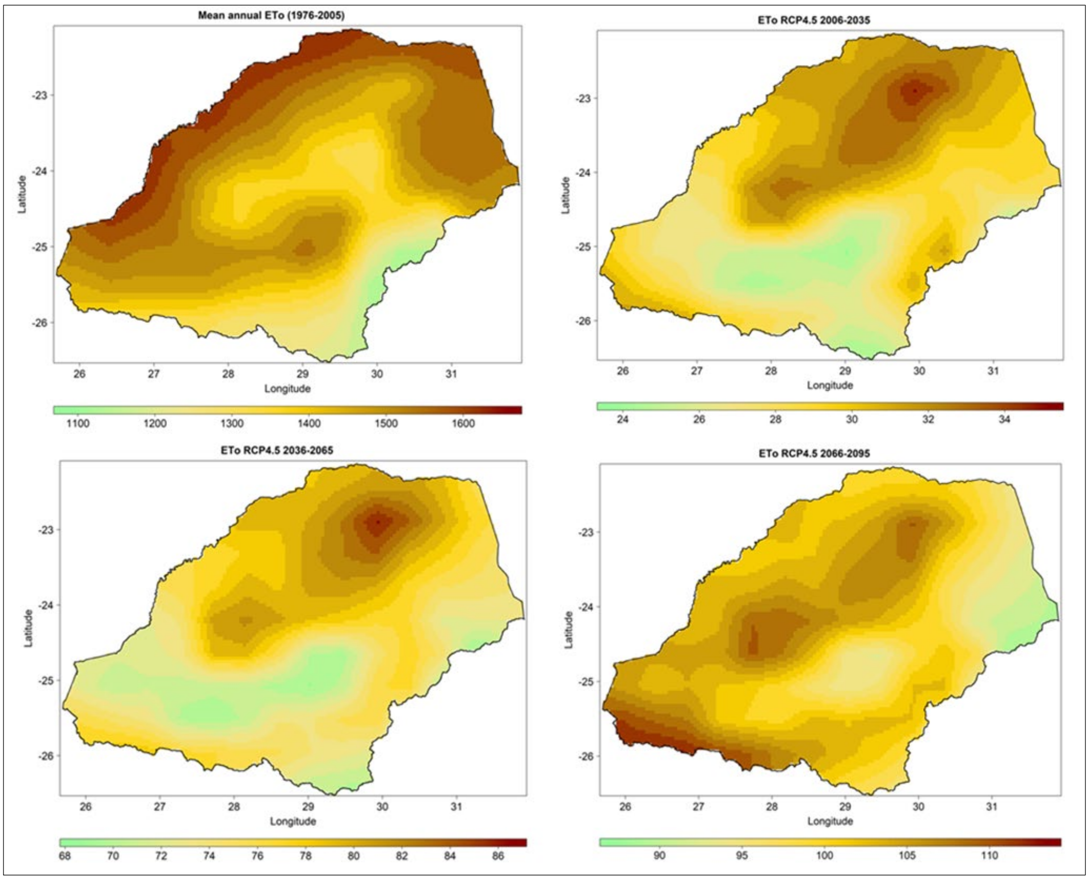

Figure 50. Changes in the spatial distribution of ETo (mm) for the three projection periods for the reference period (1976-2005) for LRB under RCP 4.5 scenario.

Changes in ET_o projections regarding the baseline period (1976-2005) under the RCP 8.5 scenario in LRB are presented in Figure 51. Reference evapotranspiration is projected to increase further in the future periods under RCP8.5. The highest increases in the ET_o values were observed in the central, and southwestern parts of the catchment for the 2066-2095 period (Figure 51), with mean maximum increases of greater than 180 mm.

These future changes in ET_o will impact the different farming systems, summer and winter crops, and livestock production negatively. Changes in rainfall patterns in both catchments compounded with these increases in evapotranspiration due to climate change in the future may directly affect water availability for the agricultural sector. The Increase in projected seasonal ET_o will directly affect dryland farming, grazing and livestock production, and indirectly by increasing irrigation water requirements for most of the irrigated crops grown in the LRB catchment.

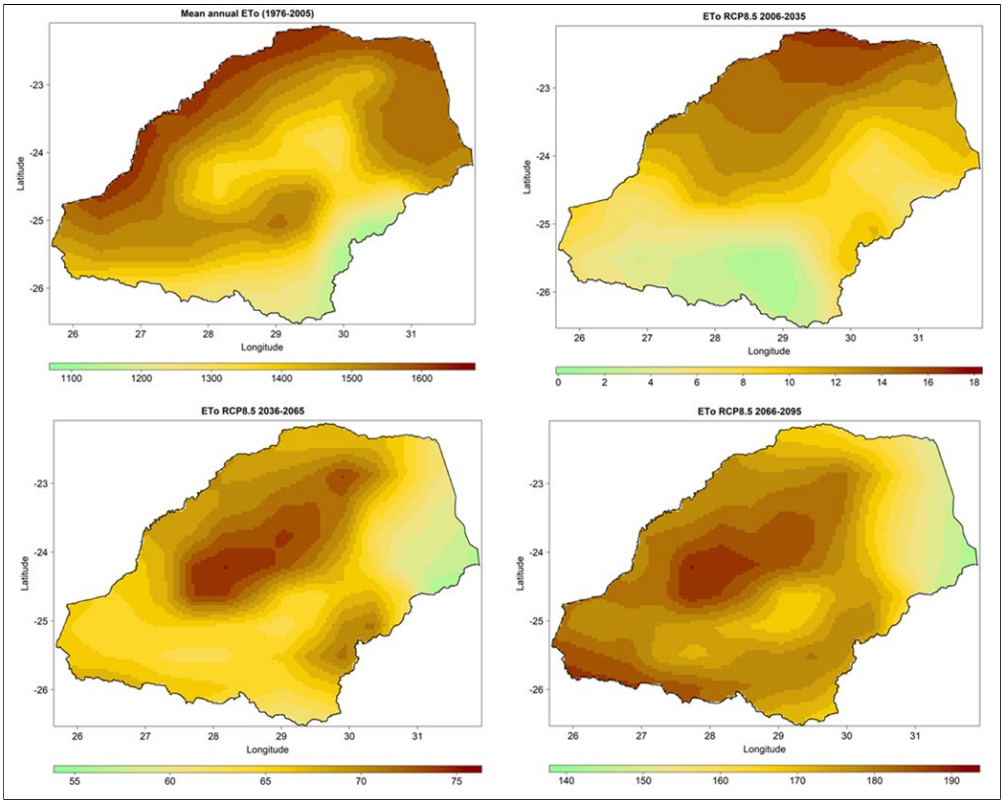

Figure 51. Changes in the spatial distribution of ETo (mm) for the three projection periods for the reference period (1976-2005) for LRB under the RCP 8.5 scenario.

4.4.2. Projected Drought Impact on Decadal Timescales

Results for projected drought impacts for the three-time intervals are shown in Figure 52 (current climatology), Figure 53 (near-future) and Figure 54 (distant-future). In each of these figures, the top and bottom panels correspond to simulations under the RCP8.5 and RCP4.5 emissions scenarios, respectively. The results depict maps for the sensitivity (first column), the exposure (second column) and the combined drought impact (third column) across the projected periods. Furthermore, the labelling (legends) represents the lowest (blue), middle (yellow), and highest (red) numbers for the specified indicator rather than the classified category levels.

As shown in Figure 52 the LRB is moderately sensitive to drought in the present climatology. The northern parts of the basin, covering the Vhembe and Capricon districts, are characterized by the least level of moderate risk, whereas the southern parts (mainly Nkangala and Ehlanzeni) are at the maximum level of moderate risk sensitivity. These regions are also characterized by moderate drought frequency and severity, which exacerbate the sensitivity of drought within the region. The LRB is mostly exposed to drought, with the exposure ranging from moderate in the southern parts (Nkangala and Bojanala) to high category in the northern and central regions. The combined drought impact is in a lower category across the basin. The southern parts of the basin are characterized by the least level category, the north-western parts by the medium level and the north-eastern by the uppermost level of the low drought impact category (based on the RCP8.5 high emissions scenario, top panel).

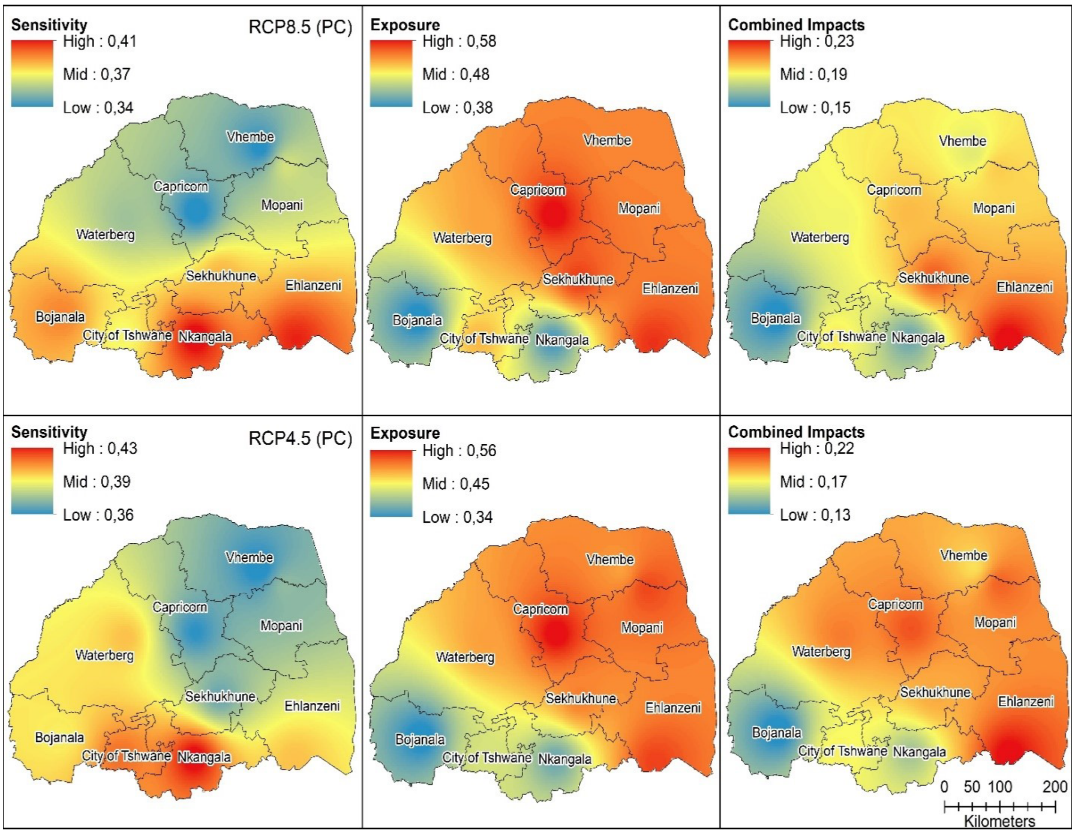

Figure 52. Drought impact layers: Left panel – sensitivity; middle – exposure and right panel – combined drought impacts, top row – RCP 8.5 and bottom row – RCP 4.5, 2006-2035

Near-future projections (Figure 53) indicate that the basin will continue to be moderately sensitive to drought, with a 4% (2%) slight increase (decrease) in the sensitivity values from the present climatology, based on RCP8.5 (RCP4.5) emissions scenarios. There is a slight shift (approximately 6%) in moderate risk sensitivity values in the Vhembe district, from a low level during the present climate to a medium level of moderate risk category in the near future. This is attributed to more frequent drought occurrences projected during the near-future period within the Vhembe district. The exposure pattern observed in the near future is similar to the 2006-2035 projected period, with the northern part, particularly the Vhembe district becoming densely exposed. Similarly, the combined drought impact ranges between 0.16-0.23 (RCP8.5) complementing the low drought impact category in the present climate. However, there is a significant shift in the northeastern parts of the basin, where the regions are likely to be more impacted by drought in the near future.

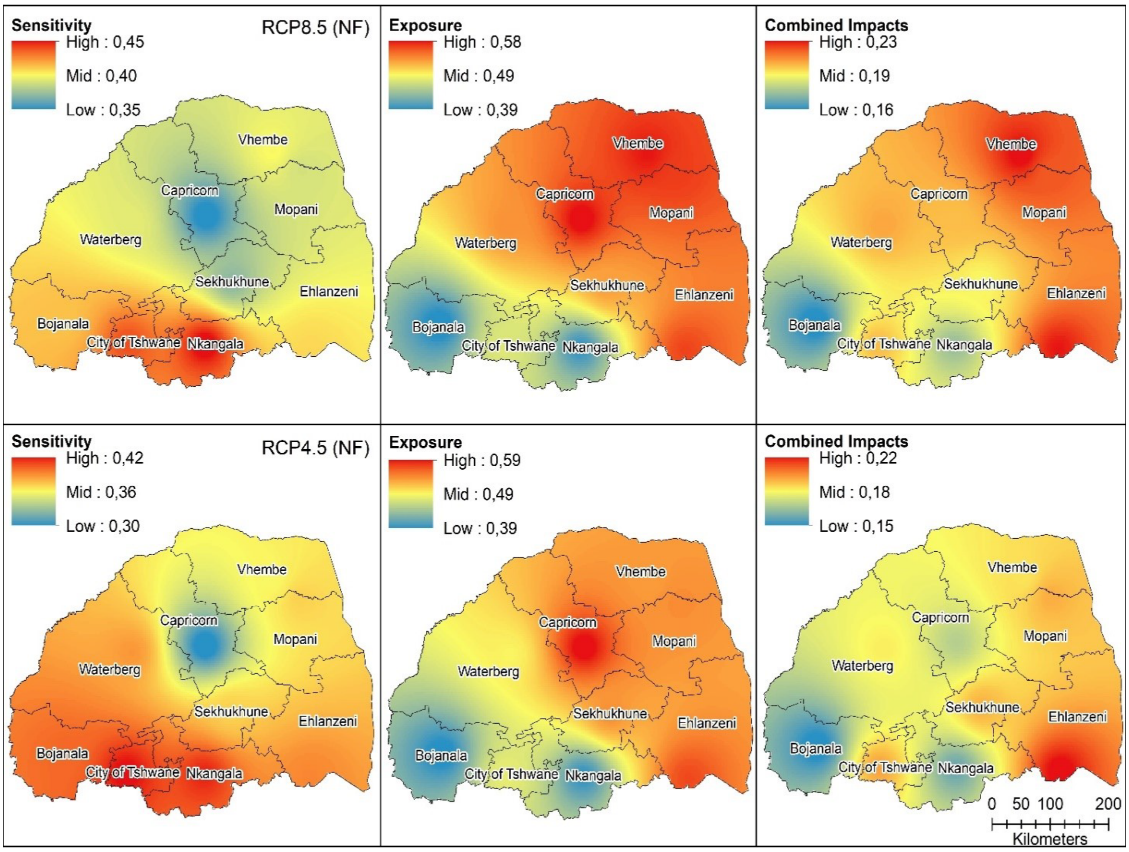

Figure 53. Drought impact layers: Left panel – sensitivity; middle – exposure and right panel – combined drought impacts, top row – RCP 8.5 and bottom row – RCP 4.5, 2036-2065

Persistent moderate risk sensitivity is projected across the basin as we move into the far-future period, see Figure 54. However, based on the RCP8.5 scenarios, there is a 5% shift in moderate risk sensitivity values, concerning the near-future projections. Most of the northeastern and central parts of the LRB are likely to be highly exposed to drought, whereas the southern regions are projected to be moderately exposed to drought. Although the spread of the sensitivity values varies spatially across the basin, the moderate risk pattern is almost similar to the near-future projections. Furthermore, the drought impacts are likely to persist across the basin in the low impact category, during the distant-future period. The projected drought impacts in the far future are likely to be dense and cover more regions in the northeastern and central parts of the basin, contrasting projections observed in the current and near-future periods.

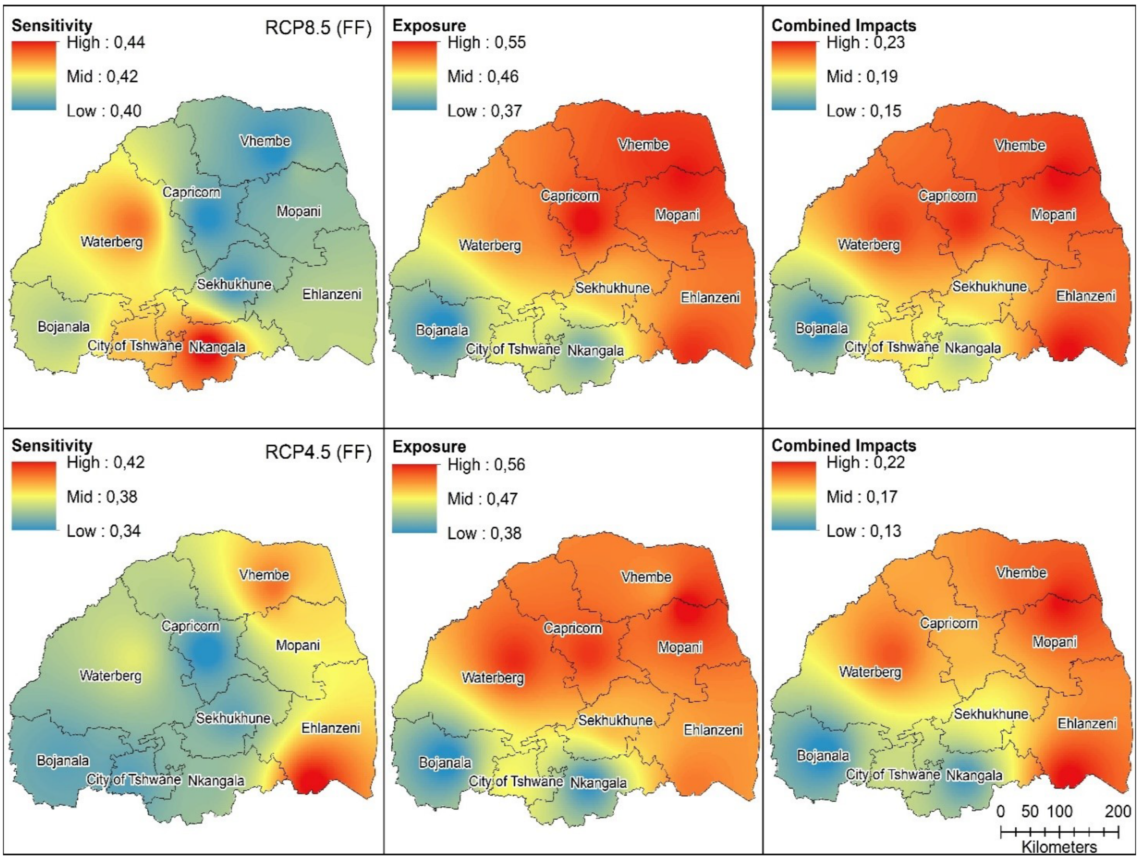

Figure 54. Drought impact layers: Left panel – sensitivity; middle – exposure and right panel – combined drought impacts, top row – RCP 8.5 and bottom row – RCP 4.5, 2066-2095

4.4.3. Projected Heatwave Impact on Decadal Timescales

Figure 55, Figure 56 and Figure 57 show the projected CHWDI in relation to the mean of the reference time (1979-2005) for the current climatology (2006-2035), near future (2036-2065), and far future (2066-2095) period under the RCPs 4.5 and 8.5 scenarios, respectively. The maps portray the hazard, exposure, and combined impacts in panel one to three, respectively whereby the top row on the panel represent the RCP8.5 and the bottom row RCP4.5 scenario.

The dark orange colour corresponds to the high, yellow (middle) and green (low) risk values of each indicator (hazard, exposure and combined impact). The heatwave impacts of each of the indicators are

defined using the same categories as the drought impacts in Table 18. Categories of sensitivity, exposure, and CDI and the corresponding explanation

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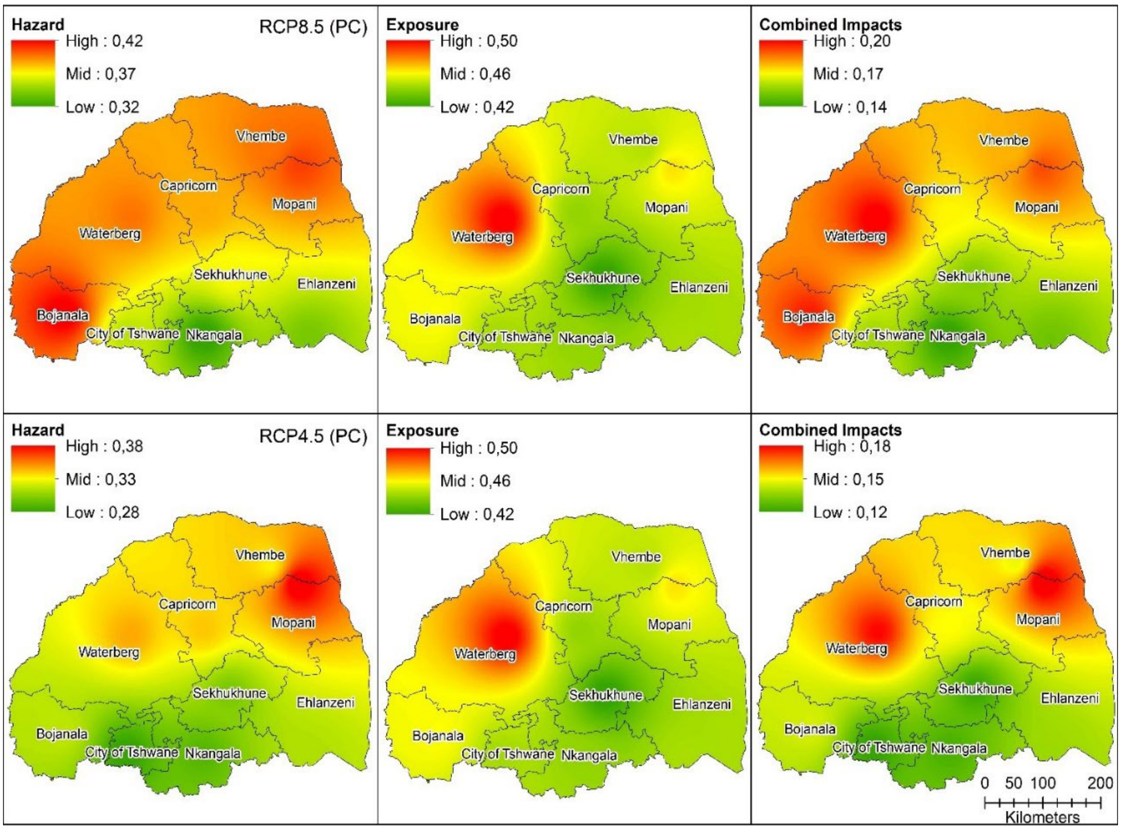


Figure 55. Heatwave impact layers: Left panel – hazard; middle – exposure and right panel – combined heatwave impacts, top row – RCP 8.5 and bottom row – RCP 4.5, 2006-2035

In the current climatology under RCP 8.5, the LRB is vulnerable to heatwave hazards, as shown in Figure 56. The exposure risks are mainly in the medium scale, with the districts of Bojanala and Waterberg comparatively displaying values at the upper end of the medium band. Likewise, the CHWI are relatively pronounced in Bojanala, Waterberg and some parts of Mopane, however, remaining within the low impact range. In addition, the southern parts of the basin (Tshwane, Nkangala, and Ehlanzeni) are generally marked by low values across the hazard, exposure and the combined impacts categories in both the RCP 4.5 and 8.5 emission scenarios.

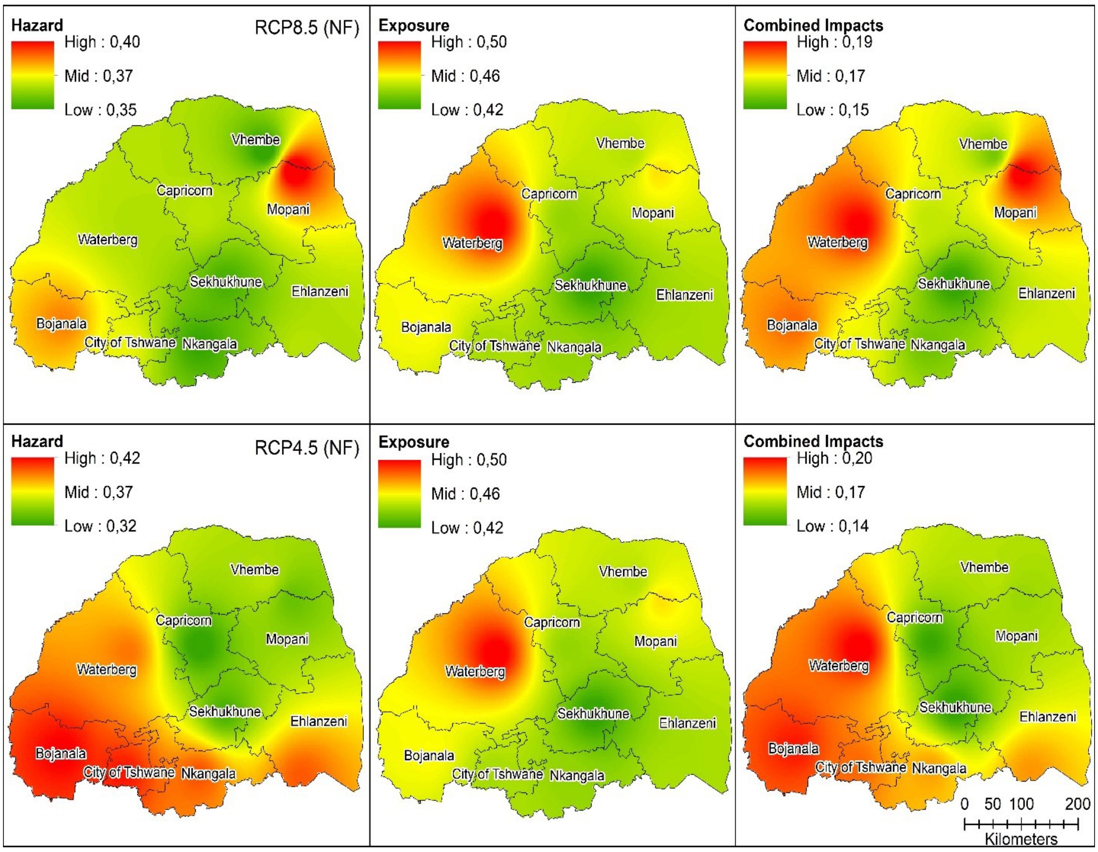


Figure 56. Heatwave impact layers: Left panel – hazard; middle – exposure and right panel – combined heatwave impacts, top row – RCP 8.5 and bottom row – RCP 4.5, 2036-2065

As depicted in Figure 57, progression into the near future (2036-2065) under RCP 4.5, the CHWI is evidently at low category across the basin, with relatively higher values noted in the Waterberg and Bojanala, encompassing parts of the Tshwane and Nkangala district municipalities. Under RCP 8.5, CHWI remains at low impact, however, with relatively higher values observed in the northeastern (Waterberg and Bojanala) and northwestern portion of the basin covering the Mopane district. The heatwave hazard values for the RCP 4.5 are relatively in medium-risk category in the northwestern and southern parts of the basin. This category extends to Mopani under RCP 8.5 for hazard exposure.

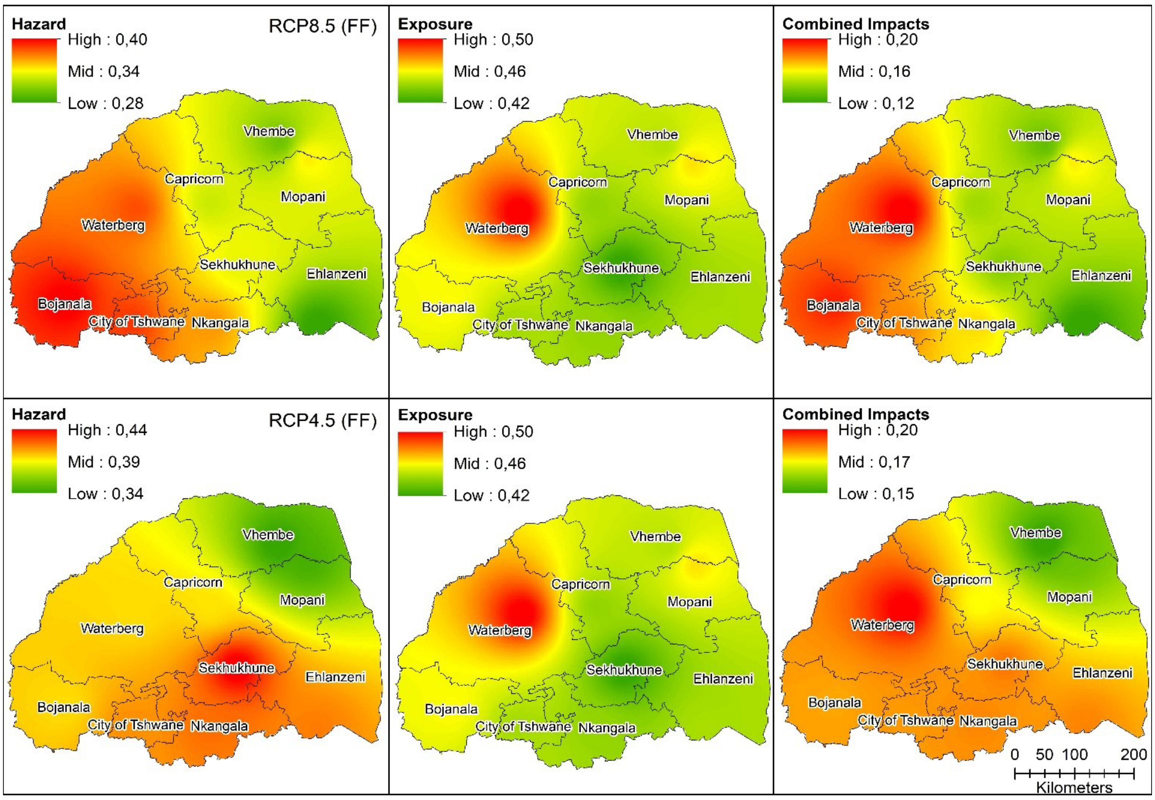


Figure 57. Heatwave impact layers: Left panel – hazard; middle – exposure and right panel – combined heatwave impacts, top row – RCP 8.5 and bottom row – RCP 4.5, 2066-2095

The CHWI for both RCP 8.5 and 4.5 emission scenarios for the far-future epoch (2066-2095) is illustrated in Figure 57 is distinctively at low impact across the basin, with values at an upper end of the impact range observed in the Waterberg and Bojanala districts, extending to the northwestern part of Tshwane. A spatial change and geographical spread in CHWI and hazard are observed in the RCP4.5 emission scenarios covering 7 of 9 districts of LRB. For the two emission scenarios, the exposure risk is in the medium-range Waterberg district. The hazard andCHWI exhibit a similar spatial pattern with relatively higher values in the northwestern and southwestern parts of the basin.

4.4.4. Projected Impacts on Services Industry: Tourism

Tourist visiting data obtained from the South African National Parks (SANParks) for the period (1982-2020) were used to understand the correlation between visitors' numbers and extreme weather events, i.e. drought. The percentage of change in tourist visiting was computed and was used further used for the correlation analysis. Future projections for tourist visit was computed using equation 7.

$$P = P_o \, X \, e^{rt} \qquad \text{Eq. (7)}$$

Where P = Total population after time "t", P_0 = Starting Population, r = % Rate of Growth, T = Time in hours or years and e = Euler number = 2.71828; % Rate of Growth for tourist visit was computed as 4.0%.

An ARIMAX was used to force projected SPEI under the RCP 8.5 scenario to compute the future number of visits to the KNP. The RCP 8.5 scenario is probably the most plausible scenario given the current trajectory of greenhouse gas emissions using an ARIMAX. The outlook of tourist population visits to the KNP for 30 years was projected and compared to a 30-year historical period. Wet and/or drought intensity determined by the SPEI methods can be characterized into 7 groups as shown in Table 20. SPEI categories of drought. A drought event begins when the SPEI reaches a value of -1.0 or less and ends when SPEI becomes positive. It has been determined that SPEI is in normal, moderate, severe and extreme drought conditions 65%, 10%, 5% and 2% of the time respectively.

Table 20. SPEI categories of drought

SPEI	Moisture category	Frequency (%)
≥2.0	Extreme wet	2
1.50 to 1.99	Severe wet	6
1.49 to 1.00	Moderate wet	10
0.99 to -0.99	Normal	65
-1.00 to -1.49	Moderate Drought	10
-1.5 to -1.99	Severe Drought	5
≤-2.00	Extreme Drought	2

As shown in Figure 58 is the SPEI-6 over Thohoyandou, Punda Maria and Skukuza weather stations from 1982-2020. According to Table 20. , all the 3 stations indicated drought occurrences over the KNP in the years 1983/1984, 1991/1992, 1993/1994, 1997/1998, 2004/2005 and 2011/2012 with 2 of the 3 stations (Thohoyandou and Punda Maria) suggesting extreme dry conditions 1991/1992. This result corroborates the findings of Mason and Tyson 2000; Glantz et al., 1997 and Vogel et al., 2000 who reported that the 1991/92 hydrological year has years of a major drought in South Africa.

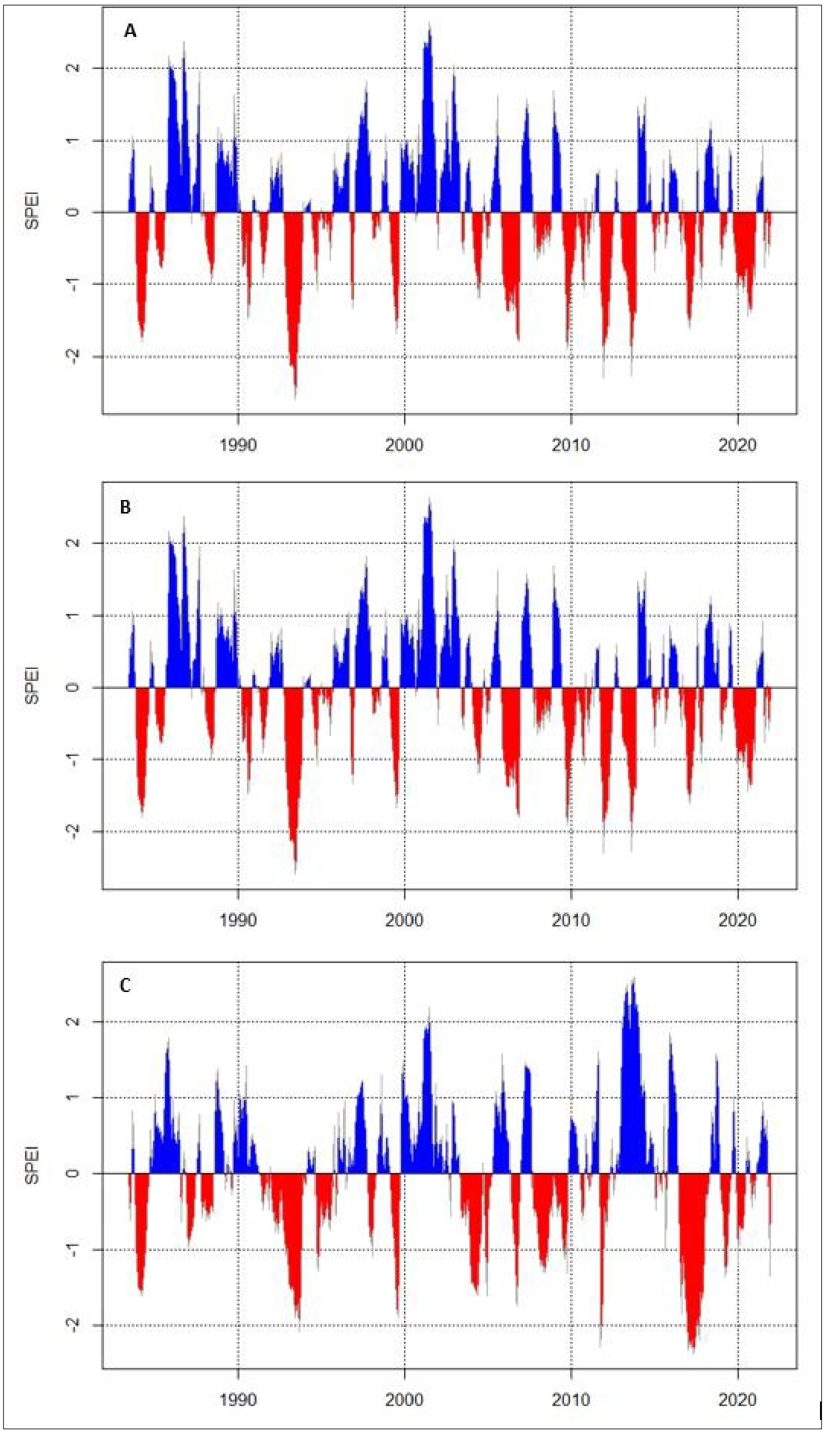


Figure 58. Standardized Evapotranspiration Precipitation Index of 6-month accumulation (A) Thohoyandou, (B) Punda Maria and Skukuza from 1982-2020

The graphical correlation between percentage change in tourist visit and individual stations are shown in. A lag of 4 to 8 months is detected between drought and percentage change Figure 60. Out of the 39 years of investigation, 5 years (12.82%), 7 years (17.95%) and 8 years (20.51%) of the drought years corresponded to the percentage of negative change in tourist visits to the KNP as indicated in Thohoyandou, in Punda Maria and Skukuza respectively.

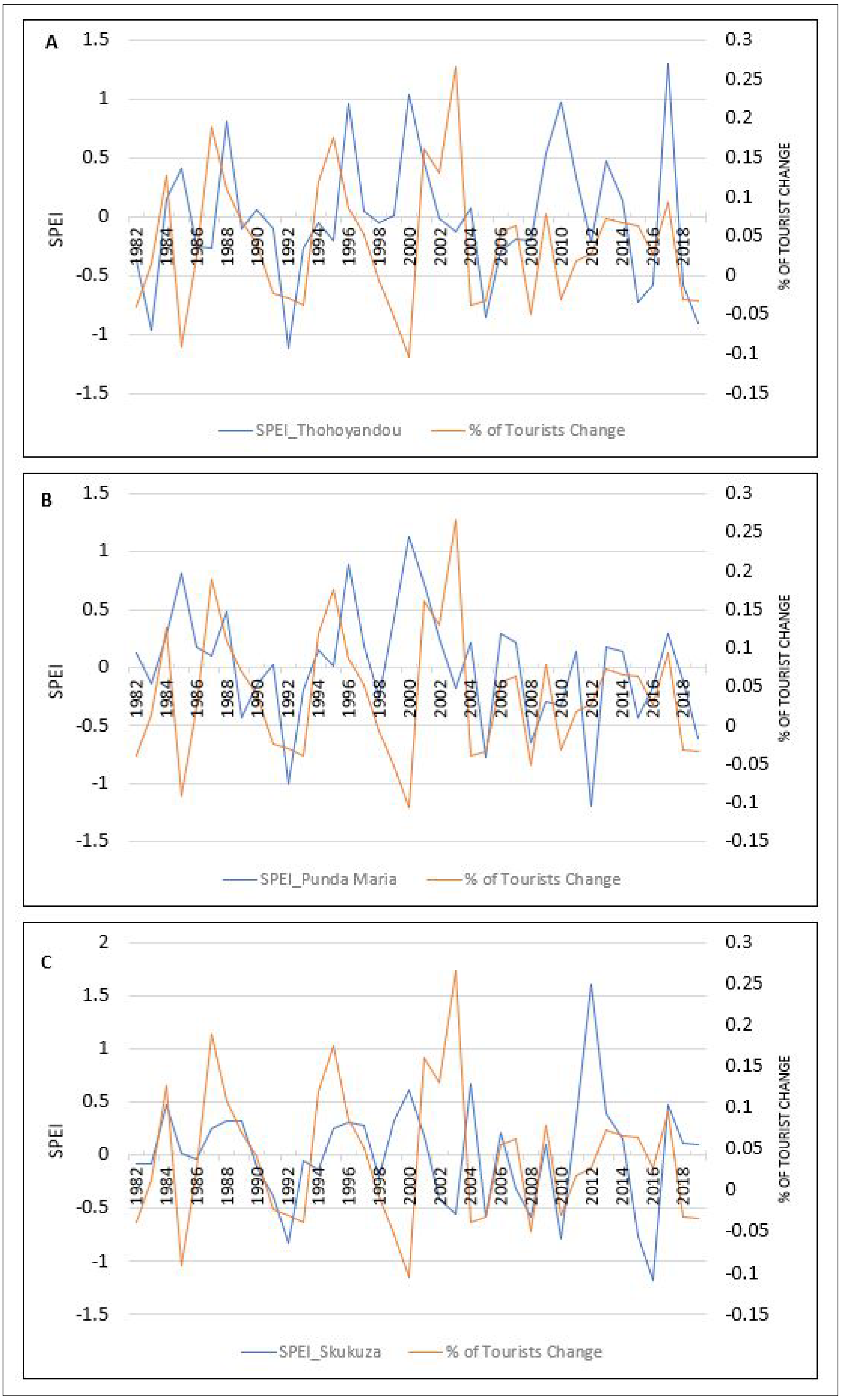


Figure 59. Correlation of computed Standardized Evapotranspiration Precipitation Index with the percentage of tourist change in the Kruger National Park (A) Thohoyandou, (B) Punda Maria and Skukuza from 1982-2020.

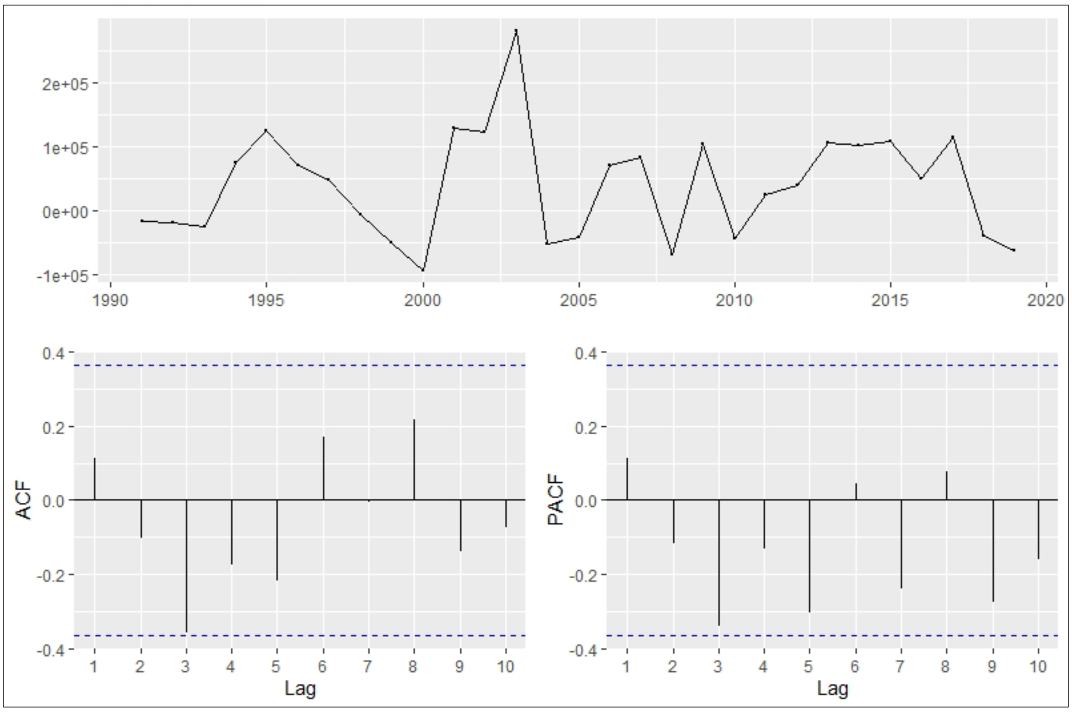


Figure 60. (Top) Time series of differenced tourist visits between 1990 and May 2019, (Bottom right) the Autocorrelation function (ACF), and (Bottom left) Partial Autocorrelation function (PACF) were used to identify the appropriate order of Autoregressive (AR) and Moving Average (MA)

The results of Pearson's correlation suggest a weak but positive correlation between SPEI and tourist visits (Figure 61). Despite the weak correlation, some drought years are associated with a decrease in tourist arrivals in the KNP. For instance, the sharp decline in the number of visitors in 1984/1985 may be attributed to preceding droughts in 1982/1983 and 1983/1984; this is beside other social factors. Years of above-normal rainfall (flood) (2000, 2010) also coincide with years of significant negative change in visiting the KNP.

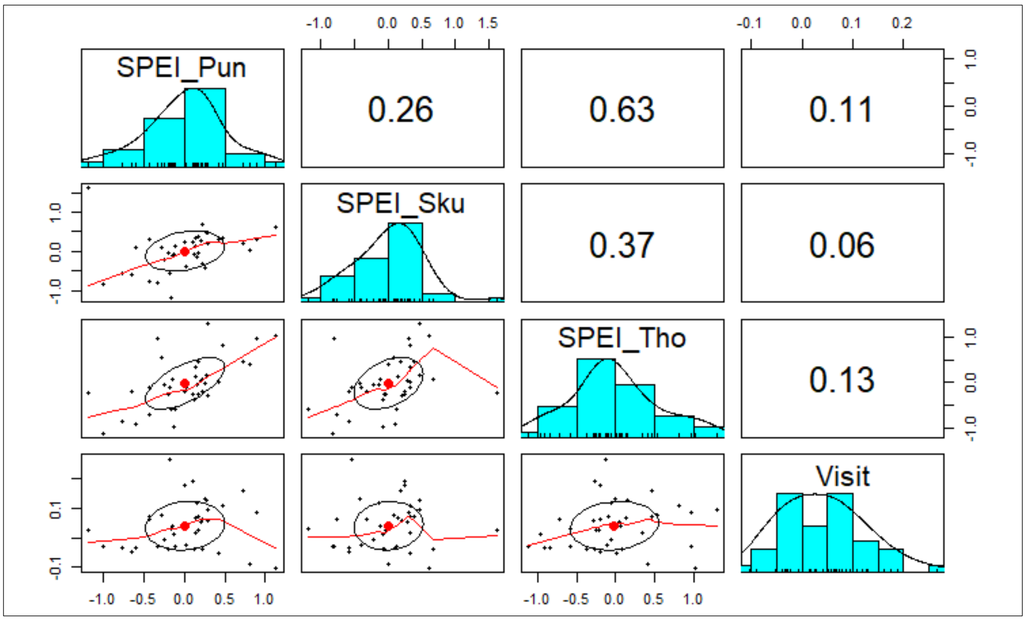


Figure 61. Correlation of computed Standardized Evapotranspiration Precipitation Index with the percentage of tourist change in the Kruger National Park (A) Thohoyandou, (B) Punda Maria and Skukuza from 1982-2020

Future Tourist Population and Climate Change Projection

The results of the ARIMAX model indicated an increase in tourist visits to the KNP at a rate of about 5.6% annually (Figure 62). The result corroborates studies undertaken in KNP which suggested possible tourist increases of about 6% per annum by 2028/2029 (Brett, 2018). The increase in tourist numbers indicates a potential increase in income that can be generated directly and indirectly to benefit the population in KNP where poverty and unemployment continue to be key challenges facing the communities. Water resources in the LRB are already strained and are likely to also be further strained due to projected increases in extreme weather events and an influx of tourists. Other challenges with an increased number of tourists include environmental degradation resulting from a surge in the number of private vehicles as well as visual pollution (de Bruin, 2011). Furthermore, the projected increases in drought can have an impact on wildlife and biodiversity, which are the major attractions to the KNP without which the number of tourists will also decline. During the 1991-1993 drought, the KNP lost about 48% of buffalos and further deaths, i.e. 26% were also recorded during the 2015-2017 drought whilst some migrated in search of grass forage reserves (Swemmer et al., 2018). In the MFCB droughts have also impacted on the migration of wildebeest between the Serengeti National Park in Tanzania and Maasai Mara National park between July and September. This is one of the major tourist attractions in the East African region. Droughts have also been noted to have an impact on savannas destroying trees whilst also increasing the risk of bush encroachment that would change the ecological state which, if possible, may take years to recover (Swemmer et al., 2018). The projected prevalence of extreme weather events would therefore impact revenue generation, human well-being water and food security in the LRB and the vulnerability assessments that were done at the provincial and district levels highlight that there is currently low adaptive capacity to deal with such risks (Vhembe District Municipality, 2016). It is essential therefore to develop adaptation interventions and build the adaptive capacity of key stakeholders including communities to support the tourism sector to ensure the sustainability of the environment and the livelihoods that depend on the sector.

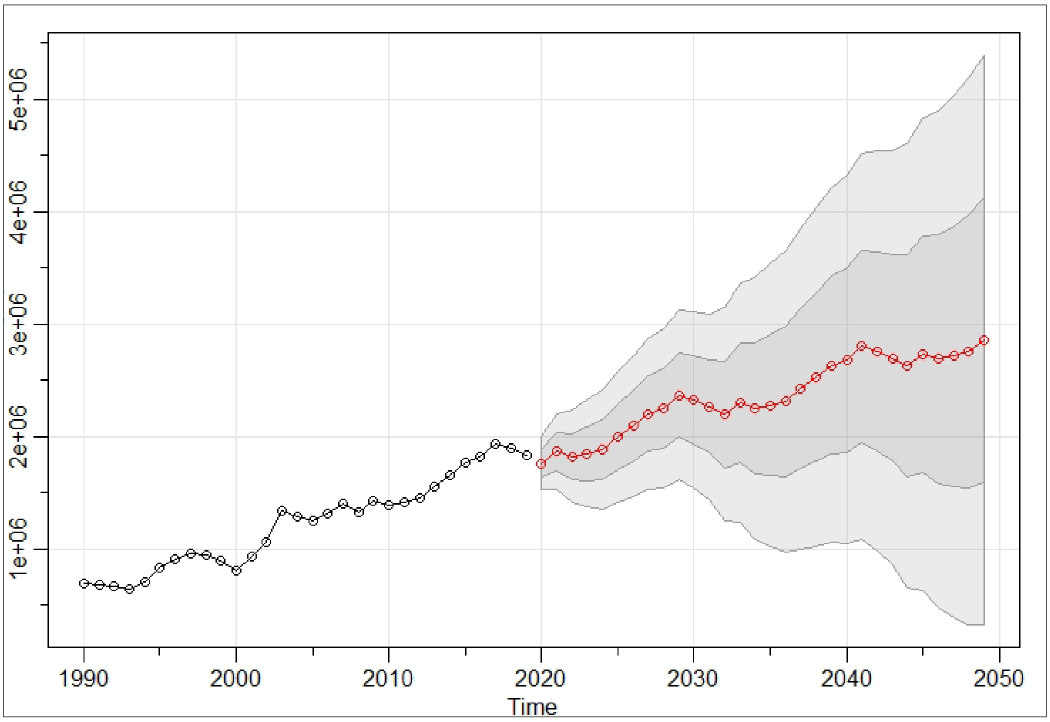


Figure 62. Projected tourists visit in the Kruger national park at 90 (light grey) and 95% (grey) confidence interval

4.5. Concluding Remarks

Extreme climate events (drought and floods) are of prominent occurrence in the LRB. These phenomena have impacts on all sectors, including the socio-economic sector. This report provides a quantified impact of extreme events on the agriculture, water, health and tourism sectors of the LRB. From the impact analysis, it is projected that evapotranspiration will increase owing to increasing temperature values that will affect agricultural production negatively in the process leading to a threat to food security. The drought impacts are projected to increase going into the future. This has a negative outlook on water security as well as food and health security. Heatwave events that are already posing a considerable health threat to the most vulnerable populations in the LRB will continue, with relatively low combined impacts noted in this analysis. Furthermore, connections are made between the sudden decline in tourist visits to the KNP and major drought conditions. However, tourist visits to the KNP are projected to increase in the future.

The following key findings are deduced:

- While the projected drought and heatwave impacts are in the low category in the LRB, the population exposure to hazard indicators remains in the upper notch of the moderate risk categories and will continue into the near- and far-future climate.
- The drought and heatwave impact values in the LRB exhibit noticeable spatial-temporal shifts
- The LRB is likely to continue experiencing water, energy and food resources security threats now and in future.
- The vulnerable population, including small-scale farmers, children, the elderly, and people living in informal households, and having no access to taps, are at risk of heat-stress, vector and water-borne diseases.
- The diminishing productivity and revenue generated from economic activities such as agriculture coupled with increased demand for social support may result in an increased number of populations who are more vulnerable with limited assets to cope and recover from the impacts of extreme weather events now and in the future.
- The study managed to identify evapotranspiration for agriculture, drought, human heat stress impacts and tourism visits which are some of the key steps towards the design of appropriate vulnerability metrics and adaptation interventions.
- The vulnerability metrics are duly suitable for informing targeted adaptation strategies to combat the negative consequences of climate change in LRB and will be developed with inputs from the stakeholders in the study site.

5. A Framework for Developmental Response Options Constrained By Socio-Economic Drivers Under a Changing Climate

5.1. Introduction

Climate is changing in an accelerating space and there is overwhelming evidence showing that such change will significantly impact various climate-sensitive sectors such as water, human health, agriculture, energy, tourism, transport, and urban development, among others. For instance, changes in climatic variables such as temperature and precipitation patterns are likely to significantly affect water resources and crop yields (particularly in rain-fed agriculture), with inherent impacts manifested on water supply and quality, food security and livelihoods (IPCC, 2019). In terms of human health, temperature fluctuations, as well as variations in rainfall features such as the frequency and intensity, are expected exacerbate incidences of vector-borne diseases such as malaria and dengue fever (IPCC, 2019). Frequent occurrences of climate-related extremes such as floods, droughts, heat waves, and storms, among others, have significant impacts on livelihoods, and socio-economic growth, including the destruction of infrastructure and property, particularly in the most vulnerable communities.

Climatic and non-climatic drivers exacerbate the impacts of climate change where interaction between socio-economic, environmental and technological systems from, for instance, cross-sectoral interactions, time delays between climate extremes and behaviour change, and interactions of multiple mitigations and adaptation response options, either create new climate risks or tend to worsen the existing impacts and risks (Helbing, 2013; Matthews et al., 2019). The extent to which the frequency and intensity of climate-related extreme events frequently occur calls for effective climate adaptation efforts and innovative solutions to minimise the inherent impacts of climate change (IPCC, 2012; Noble et al., 2014). Most developing countries have initiated and implemented policy programmes and undertaken comprehensive research projects that led to the development of and implementation of innovative ways of responding to climate change challenges, including adaptation strategies and mitigation measures at local, regional and national scales (Abeysinghe et al., 2017; McEvoy et al., 2021). In addition, numerous frameworks have been conceptualised and implemented for various purposes within the umbrella of climate change impacts and response: e.g. a framework for the assessment of innovation's technical performance to reduce climate-related hazards (Lendering et al., 2018); multi-dimensional environmental performance framework for adaptation innovations (van Loon-Steensman and Goldsworthy, 2022), among others.

In general, climate change is considered a complex and multi-layered problem. Consequently, responses to climate-related issues are dependent on various factors, including both climatic and non-climatic drivers. For this reason, the current study intends to review conceptualised climate-related frameworks and select the most suitable framework for the Limpopo and Mau Forest Catchment Basins.

5.2. Climatic and Non-Climatic Stressors of Water Resources in the Limpopo and Mau Forest Catchment Basins

5.2.1. Selectedwater-linked sectors

From the perspective of IPCC's Climate Change and Water technical paper reported in Bates et al. (2008) and as alluded in USAID (2013a), water-related developmental objectives could be best categorized by considering the following water-linked sectors which are briefly described below:

a) Water supply and sanitation
b) Agriculture, food security, land use, and forestry
c) Human health
d) Settlements and infrastructure
e) Ecosystems and biodiversity
f) Energy

This categorization seems duly suited to the Limpopo and Mau Forest Catchment Basins in the context of analysing the various options for developmental response to climate change as constrained by the socio-economic drivers across the study sites. Climate change has undoubtedly reduced the amount of water that is accessible when and where it is needed. To ensure that water is available in response to both intra- and inter-annual water shortages and locations distant from rivers and lakes, communities across the study sites are supported by the construction of reservoirs, wells, and potho holes. Furthermore, to attain water quality and sanitation treatment of water supplies and wastewater is vital to protect human health and the environment. These constitute an important developmental imperative for these study sites.

The Limpopo and Mau Forest Catchment Basins are characterized by irrigated and non-irrigated agriculture. In particular, a greater amount of water in both river basins is used for agriculture. This suggests that current climate variabilities have significant effects on agriculture and aquaculture. These effects are most severe and immediate for rainfed agriculture, but also pose significant threats to irrigated agriculture and aquaculture. These impacts relate to the sensitivity of physical and ecological processes associated with agriculture production to climate manifestations, including average, seasonal, and extreme temperatures;

precipitation amount and timing; and patterns and intensities of drought. As a result, all these factors (and options) ought to be understood and embedded into a developmental framework.

Literature suggests that access to safe drinking water in sub-Saharan Africa is elusive. This is true for the communities in the Limpopo and Mau Forest Catchment Basins. Notwithstanding the direct health impacts, there are cascading impacts from lack of access to safe water across this study site. The characteristically poor urban households across the study sites are expected to spend a considerable portion of their available time and money obtaining drinking water. Consequently, the resources that ought to be used for other purposes, in support of improving the households' quality of life and health outcomes are diverted to seeking access to this critical resource. In rural areas across the study sites, some households, and especially the vulnerable women and children spend their valuable time seeking portable water, often from remote areas. Undoubtedly, this is an important consideration in any robust impactful developmental framework relevant to these study sites.

The Limpopo and Mau Forest Catchment Basins are known to experience year-to-year climate variability which manifests as floods and droughts and this often impacts developments such as infrastructure and human settlements. As a result, protection against such risks, without a doubt, ought to be considered during the design of the infrastructure and human settlements across these basins. In part, the design of such infrastructures ought to be grounded in an analysis of historical climate based on observed hydroclimatic extremes.

Furthermore, the aquatic and riparian ecosystems across the Limpopo and Mau Forest Catchment Basins are dependent on the available water resources. However, the basins have experienced sustained human water use and/or alteration of the water supplies which have resulted in changes in water quality, and quantity. These impacts are inevitable due to the increased human consumption of water, energy and food resources. Compounding this problem is that these ecosystems and biodiversity will continue to be affected by climate variability and change.

Energy and water are inextricably intertwined. For instance, the extraction, distribution, and treatment of water across the studied basins require the use of energy. Furthermore, irrigation, source water treatment, wastewater treatment, distribution of drinking water, and collection of wastewater and storm water all require extensive inputs of power. Energy is also a key input to development projects such as the fabrication and construction of water infrastructure across the study basins. To achieve sustainable development in the Limpopo and Mau Forest Catchment Basins, adequate energy and water resources will be required, especially in light of the growing population in these regions. The demand for these resources, on the other hand, will be constrained by the projected climate changes resulting from, e.g. increased evaporation rates for surface water, increase agricultural water demand due to higher evapotranspiration rates, and increased peak electricity demand for air conditioning, etc. Additionally, large shifts in rainfall patterns could drive new costly energy-intensive investments to maintain water supply and quality and require energy-intensive investments in water treatment infrastructure across the basins.

5.2.2 Climatic Stressors

As reported in, e.g. USAID (2013a and b), climate change impacts on water resources manifest both as intra- and inter-annual variability and the long-term changes in key climate variables such as precipitation, and temperature. The perspective has to be embedded or mainstreamed into a developmental framework that underpins sustainable development under changing climate. To this end, some of the key climatic stressors relevant to Limpopo and Mau Forest Catchment Basins include;

a) Average and extreme precipitation,
b) Evapotranspiration
c) Soil moisture
d) Runoff and river discharge
e) Heat stress

These hydroclimatic and heat stress extremes ought to be mainstreamed into the climate-resilience framework from the perspective of historical, present, and future climate to derive developmental response options suited for the study sites.

5.2.3. Non-climatic stressors

Non-climatic stressors often impact the sustainability of water resources as well the developmental imperatives of a region. In the context of the Limpopo and Mau Forest Catchment Basins, the following non-climatic stressors ought to be factored into any developmental framework of the study sites.

a) *Population growth:* the increase in population across the study basins will require more water for human consumptive use, growing crops and foods, and economic activities such as industrial production,
b) *Urban development and infrastructure needs:* the study basins will continue to experience population migration to their urban centres thereby putting pressure on water storage, distribution and wastewater treatment facilities. As a result, more investment will be required to ensure the quantity and quality of water are assessable.
c) *Pollution and environmental degradation*: The Limpopo and Mau Forest Catchment Basins' water quality is expected to experience deforestation, land-use change, and practices. These practices

inherently, a) impact on the water storage capacity of soils and vegetation; b) decrease natural filtering of contaminants; c) increase sediment, nutrient, pathogen, and chemical pollutant loading; and d) ultimately decrease groundwater recharge.

d) *Inappropriate government policies and practices*: the study sites are not immune to policies and practices such as poor monitoring of drainage systems (occasioned by flash floods), and poor oversight of industrial operations, which results in adverse effects on the health and environment.

e) *Poor resource governance:* this relates to, e.g. sanitation problems and human health impacts that often result when there is a lack of wastewater treatment and disposal. Additionally, uncontrolled settlement of peri-urban areas in flood- or landslide-prone locations increases the vulnerability of communities to natural disasters.

5.3. A review of developmental response frameworks under changing climate

A framework can be described as a process that incorporates analyses of themes of interest resulting in developmental planning in a specific area of interest at different spatial scales (e.g. local, regional, national and global). For the current study, we have considered aspects of climate change. In this case, the framework addresses climate change themes including conditions that must be met to effectively achieve the goals of such themes. Examples of themes within climate change include climate change impacts, climate risks and vulnerabilities, climate resilience, climate change adaptation and mitigation, climate change response, as well as climate and non-climate drivers, among others. In the developmental process of a framework, priority indicators are identified and incorporated into planning and implementation in support of climate-related decision-making and policies.

Numerous proposed frameworks addressing different climate change themes have been reported in the literature. One such framework was formulated by the Intercontinental Panel on Climate Change (IPCC, 2007) and focused on the anthropogenic causes and impacts of climate change. The framework, as summarised in Figure 63, considers four components, namely (i) climate change characterized by temperature, precipitation, sea-level changes and the occurrence of extreme events, (ii) climate change impacts and vulnerability, (iii) socio-economic developments and (iv) climate process drivers (including greenhouse gas emissions). The framework also recognizes climate change as the key component in mitigating and adapting to it.

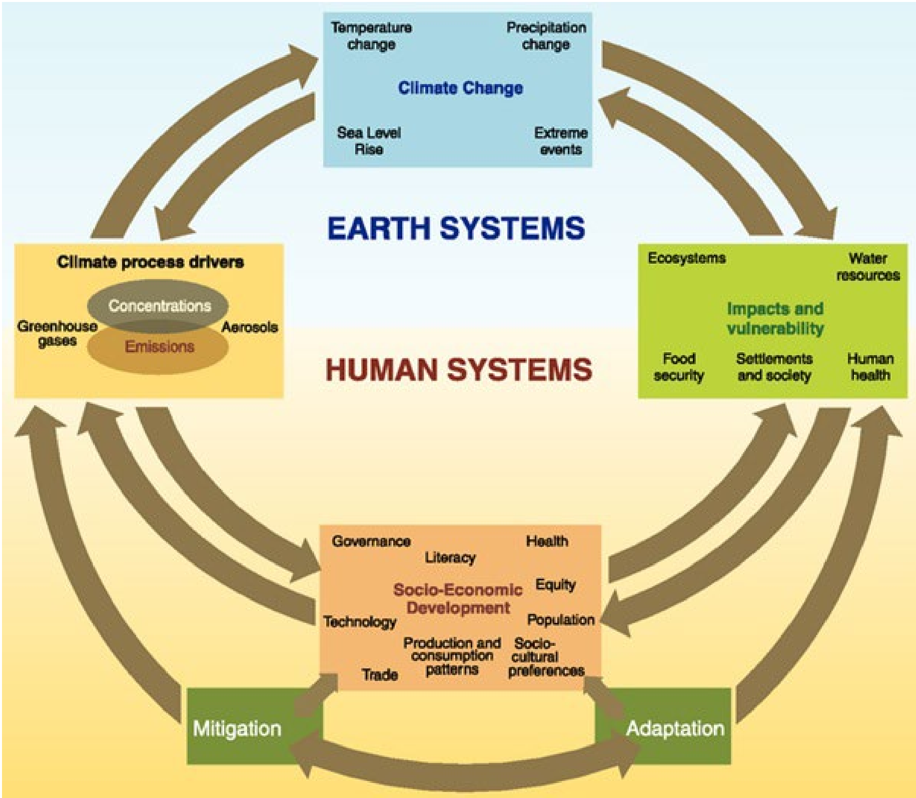


Figure 63. Schematic framework on anthropogenic drivers, impacts of and responses to climate change (IPCC, 2007)

Building on the knowledge derived from the IPCC (2007) framework, a framework to address the complexity of climate change risk assessment was conceptualised by Simpson et al. (2021). The framework was conceptualized on the premise of the need to understand various mechanisms through which climate change creates risks for society. This is important given that climate change risks may be attributes of potential impacts manifested from both climate change and its responses. Consequently, the framework by Simpson et al. (2021) was conceptualized by identifying categories of complex climate change risks, focusing on interactions between multiple climate risk drivers as well as between multiple risks. The approach used motivates sectoral and regional boundaries consultations and partnerships and interrogates physical linkages as well as socio-economic drivers of climate risk.

A similar framework was reported by the United States Agency for International Development Office (USAID, 2014) on understanding and addressing climate change issues, particularly focusing on climate-resilient developmental aspects. Developed to enable the systematic inclusion of climate change factors, the framework concentrates on incorporating climate features into developmental planning in support of decision-making processes, including climate-related policies. The climate-resilient development framework as reported in USAID (2014) consists of five key stages as summarized in Table 21. This framework was successfully applied in an assessment of water security and climate issues in the municipality of Iloilo, Philippines and the upstream Tigum-Aganan watershed.

The framework for water security and climate-resilient development was formulated by the African Ministers Council on Water (AMCOW, 2012) to support the implementation of climate change initiatives, including the goals of the African Water Vision 2025. The framework comprises four phases, (see summary in Figure 64), and it can be applied at sub-national, national and transboundary planning levels.

Table 21. Main stages of the USAID's climate-resilient development framework (USAID, 2014)

Component	**Description**	**Remarks**
Scope	Establishes development context and focus	Identifies climate and non-climate drivers
Assess	Enhances understanding of vulnerability	Formulate vulnerability assessment questions, select methods and assess vulnerability
Design	Identify, evaluate and select adaptation options	Identify and evaluate adaptation options with appropriate evaluation criteria
Implementation and management	Adaptation is put into practice	Builds on established implantation and management practices adopt a flexible approach and incorporates climate information and indicators
Evaluate and adjust	Tracks performance and impact	Measures performance, evaluate impacts of actions on vulnerability and perform adjustments to adaptation strategies

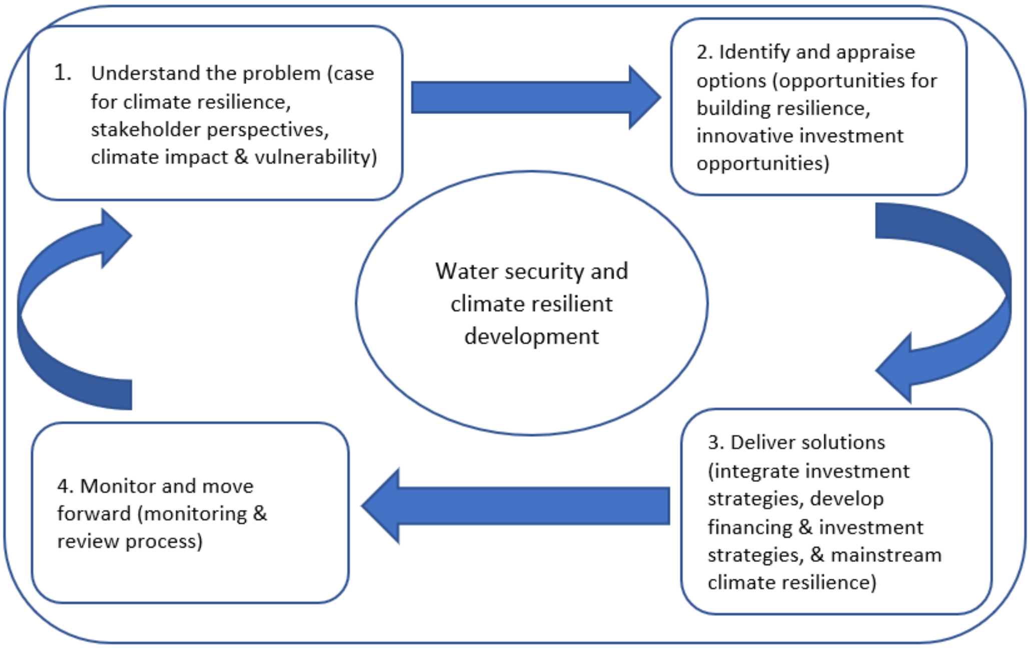


Figure 64. Framework cycle on water security and climate-resilient development (source: AMCOW, 2012)

Widely, researchers have concentrated on understanding and developing frameworks to address and respond to climate change impacts, adaptation, risk and vulnerability themes occurring within the same geographical region. Nevertheless, there are cases where climate change impacts occur remotely from one geographical location to another. This potential outcome has been termed the cross-border climate change impacts. The affected borders may be political or administrative influenced, e.g. between countries or sub-national jurisdictions, respectively or tele-connected through more remote links (Benzie et al., 2019). Consequently, some frameworks have been developed to address the issue of cross-border climate change impacts. For instance, a conceptual framework for cross-border climate change impacts was formulated by Carter et al. (2021). In addressing the issues of cross-border climate impacts, including causal factors, the framework distinguishes an initial impact instigated by climate conditions occurring within a specific region. The proposed framework identifies different key factors that facilitate a better understanding of cross-border climate change impacts and responses. These factors include types of climate instigators, categories of cross-border impacts, the scales and dynamics of impact transmission, the targets and dynamics of responses and the socio-economic drivers (Carter et al., 2021). The proposed conceptual framework is schematically summarized in Figure 65, and detailed information can be obtained in Carter et al. (2021).

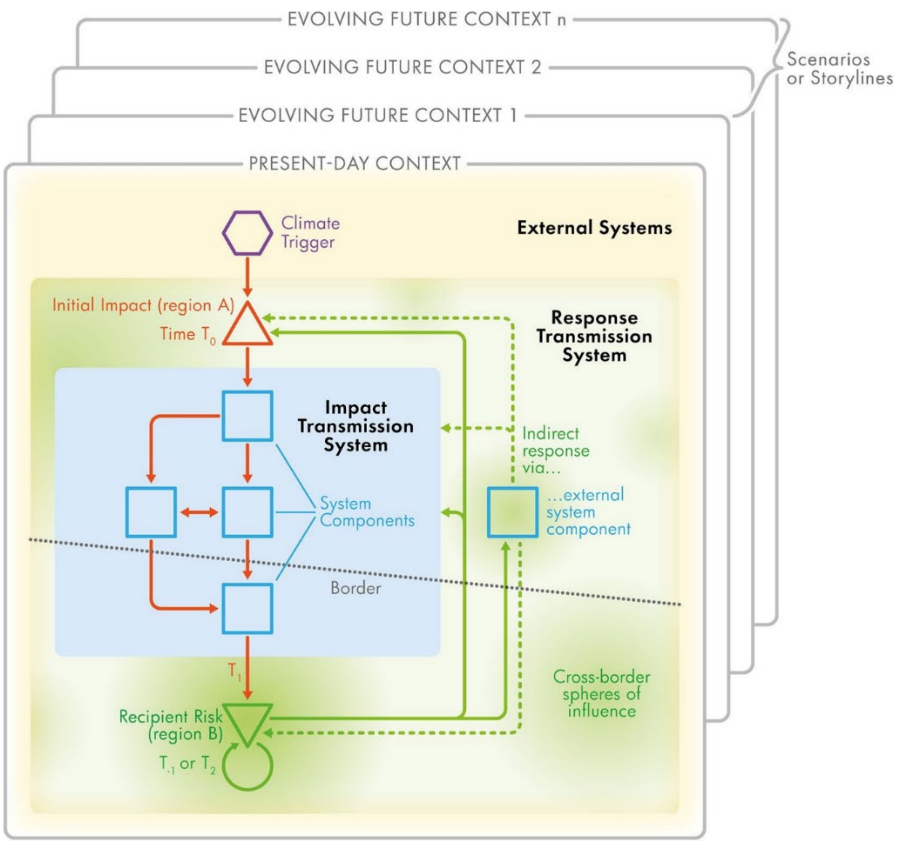


Figure 65. Conceptual framework for cross-border climate impacts (Carter et al., 2021)

5.4. Proposed Framework Relevant for the Study Sites

5.4.1 Introduction

The proposed framework is not an entirely new process rather it strengthens and refines existing processes to build climate resilience into growth and development. Assessment of the impacts of climate change is essential for effective policy and decision-making to mitigate the inherent impacts, including providing supportive measures for proper management and sustainability of key economic resources, and promoting resilience within communities to manage these hazardous conditions. Various framework methods used for climate change impact assessments have been reported in the literature, depending on the identified climate impact, e.g. the drought, flood, agriculture, heat stress/wave, etc. According to the IPCC (2001; 2007), Engstrom et al., 2020), and references therein, climate developmental responses can be structured based on the framework summarized in Figure 66. In general, this process involves 7 steps that can be applied to any sector. Since this report focuses on water, the following steps are proposed as the framework for developmental response options for water security and climate-resilient (1) identify and understand potential water problems attributed to climate change, (2) understand the historical and future trends (3) identify and appraise Vulnerabilities options (4) identify and appraise adaptation options (5) deliver solutions/plans (6) project implementation (7) monitoring and evaluation.

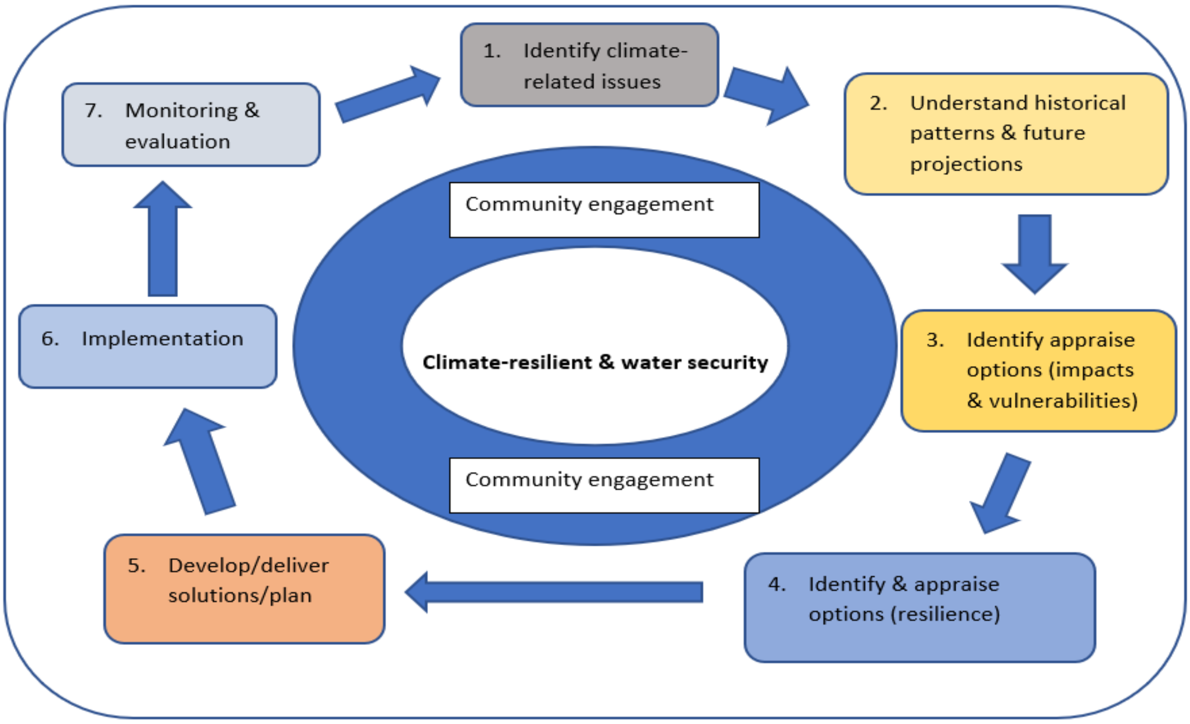


Figure 66. Proposed framework for climate-resilient and water security

5.4.2 Summary of components of the proposed framework

This framework facilitates the systematic inclusion of climate considerations in development planning and implementation.

Step1. What are the climate-related water issues?

This is regarded as the inception phase of the framework. It involves the identification and understanding of the prevailing climate such as temperature, precipitation and non-climate stressors for water such as population, education, urbanization, gross domestic product (GDP), economic growth, rate of technological developments, greenhouse gas (GHG) and aerosol emissions, energy supply and demand, land-use changes. A summary of the water-related issues in the Limpopo and Mau Forest Catchment Basins is described in section 2.

Step 2. Understand historical and future trends.

This stage involves the:

- Analysis of the historical and plausible future characteristics of the identified climate and non-climate stressors.
- Use of the scientific approach of performing statistical and mathematical analysis.
- Improved with a combination of indigenous knowledge.

Step3. Identify and appraise vulnerabilities options

- Define vulnerability assessment questions
- Assess vulnerability
- Provide actionable information

Step 4. Identify and appraise adaptation options

- Identify adaptation options
- Select evaluation criteria
- Evaluate adaptation options
- Select an adaptation option

Step 5. Deliver solutions/plans

- Co-develop integrated low-cost and low risk (sustainable) investment strategies in development planning
- Develop financing and investment strategies

Step 6. Project implementation

- Adopts a flexible approach to account for continuing change
- Mainstream climate resilience in development planning

Step 7. Monitoring and evaluation

- Create evaluation processes
- Measure performance
- Evaluate impacts of actions on vulnerability
- Perform adjustments to adaptation strategies

The whole of the framework is conceptualized on co-creation and co-development drive through structured community engagements and consultation.

5.4.3 Integrating approach to managing water and climate change framework

For effective management of the framework for developmental response options constrained by socio-economic drivers under a changing climate, integrated water resources management must be coordinated across traditional sectoral, political and spatial boundaries. Hence, we propose the nexus approach. There are inextricable interlinkages or nexuses among water and economic sectors such as energy and food (including agriculture), urban systems, landscapes, and ecosystems Figure 67. For example, as urbanization continues around the world, resulting in higher population density and more intense land and water use, reserving urban land for flood alleviation (above or below ground) will likely lead to conflict with other potential uses (such as housing or agriculture), which must be anticipated and addressed. For this reason, it is important to improve overall water resilience, due to the cascading effects it can have on people, economies and natural systems.

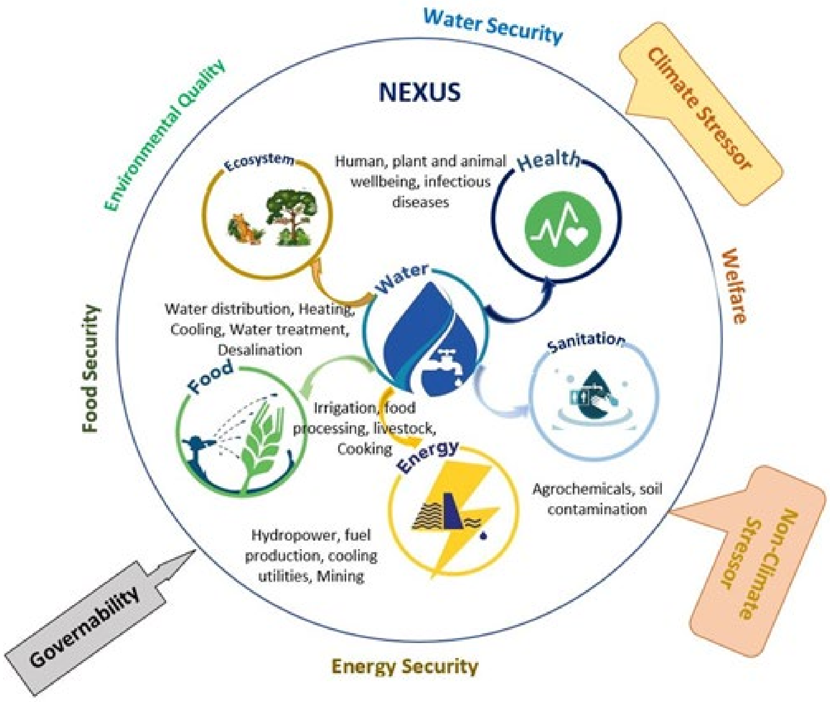


Figure 67. Interlinkages or nexuses among water and other economic sectors

With the expected increase in frequency and intensity of floods, storms, heat-waves, droughts and other weather-related events because of climate change, countries adopted the Transforming our World: the 2030 Agenda for Sustainable Development in 2015 aimed to end all forms of poverty and hunger, fight inequalities and tackle climate change. The 17 Sustainable Development Goals (SDGs) are interlinked and intended to support and complement one another. For instance, "Ensure availability and sustainable management of water and sanitation for all" (SDG 6) supports the attainment of the other 16 SDGs. Realization of SDG 6 and other water- and ecosystem-related targets are essential for society's health and well-being, improving nutrition, ending hunger, ensuring peace and stability, preserving ecosystems and biodiversity, and achieving energy and food security. Water is also an essential component of national and local economies. Water management fosters gender equality and social inclusion, and supports the creation and maintenance of jobs across all sectors of the economy.

The following section illustrates why an integrated approach to water is needed to maximize synergies and help mitigate and adapt to climate change in all sectors.

5.4.3.1 Water, sanitation and hygiene

As a result of climate change, drinking water quality and availability are diminished, as well as sanitation, wastewater, and hygiene performance. As an example, more-frequent combined sewer overflows can inundate and pollute low-lying and/or densely populated areas and receiving waters, while drought can result in peri-urban agriculture using poorly treated wastewater. As a result, adapted water, sanitation and hygiene (WASH) infrastructure and services are crucial to ensure their sustainability, safety and resilience to climate-related risks. At the same time, it is important to ensure investments in resilient WASH systems in areas identified as being at the highest risk contribute to building community resilience to the impacts of climate change, for example, by enabling access to water during times of scarcity or reducing the risk of disease from faecal contamination of water during floods.

Adapting WASH services to climate change requires local implementation approaches, and decisions should be based on the best available local information at the time they were made. For example, there may be limited value in scrutinizing climate projections to the end of the century for rural WASH programmes that prioritize household or community-based systems with a design life of a few years (for example, pit latrines) or decades (for example, wells or boreholes). In these cases, it is advisable to understand risk and base decision-making on observed impacts of climate change at local levels. Major investments in storm drain, wastewater plants and other big infrastructure projects, investments that are long-lived and inflexible will require different analyses (including climate projections) and interventions.

5.4.3.2 Water and health

Climate change has a significant and varied effect on people's right to health. Among the most significant impacts are infectious diseases, many of which are waterborne and already pose a serious burden to vulnerable populations worldwide. Changes in climate variables such as temperature, precipitation, and humidity affect the spread of waterborne diseases like cholera. Through indirect effects, climate change can reduce agricultural productivity, negatively impact nutrition, and lead to an increase in food-borne illnesses.

Extreme weather can increase human exposure to water contaminated by agricultural runoff, flooded water and sewage systems, and standing water that could lead to habitat for toxic algal blooms and a breeding ground for disease vectors that increase malaria risk. On the other hand, drought can decrease the quantity and quality of water available. Additionally, increased temperature and changes in the frequency and intensity of rainfall will likely shift the geographic distribution and prevalence of vector-borne diseases such as malaria and dengue fever. Due to the diversity of impacts over time, proactive planning and adaptation measures are critical for addressing short-term emergencies and long-term stressors. Climate-resilient water and sanitation safety planning are relevant risk-based management approaches for managing health risks associated with climate variability and change.

5.4.3.3 Water and agriculture

The frequency and intensity of rainfall, floods, and droughts are changing due to climate change, resulting in significant implications for agriculture and food production. Although food shocks and stressors affect people of all ages, women, indigenous populations, subsistence farmers, and pastoralists are particularly vulnerable. In regions where basic food production and hunger are significant concerns, addressing climate adaptation, especially through water-related impacts is essential to reduce long- and short-term threats to food security. Climate-resilient water resource management is a potentially powerful mechanism to achieve local and possibly global food security (encompassing food production, preparation distribution, consumption and waste). On the mitigation side, interventions related to the increased utilization of solar pumps, practising conservation agriculture to improve soil organic matter (needed for the soil to retain water), reducing post-harvest losses and food waste, and transforming waste into a source of nutrients or biofuels/biogas can address food security and climate change. The food systems will also need to produce more food with increased nutritional value while becoming more efficient in the use of resources including land, soil, water, energy and chemicals.

5.4.3.4 Water and energy

Most energy generation processes require significant water resources, while the abstraction, transportation and treatment of water require energy (for example, electricity). Population and economic growth are simultaneously increasing energy and water demand, with global energy demand projected to increase by approximately 27 per cent between 2017 and 2045, and water demand is expected to increase roughly 55 per cent over the same period (primarily from manufacturing, electricity generation and domestic use). In addition, climate change and increasing hydrological variability will likely result in a heightened reliance on energy-intensive water supply options, such as transporting water over long distances or desalination.

Renewable energy sources account for a growing portion of the overall energy supply mix and generally have a smaller water footprint than their carbon-based alternatives. Thus, increased investment in renewables such as solar photovoltaics, wind and small hydropower is needed to ensure future energy and water demand can be met. Integrated planning, regulation and management of the energy and water sectors at the national and basin levels can help to ensure trade-offs are accounted for, synergies are maximized and future demand can be met. As mentioned in section IV, efforts to reduce energy demand for water and water demand for energy should be considered, including the provision of alternative cooling systems or combined heat and power plants, as well as revised operations for new and existing hydropower plants.

5.4.3.5 Water and ecosystems

Ecosystems' services provide for climate change mitigation and adaptation, disaster risk reduction, and sustainable development are well recognized. They include: sequestering carbon in forests and peatlands; providing source water, nutrition, livelihoods and medicine; and safeguarding communities from storms, floods, droughts and sea-level rise through coastal forests and wetlands. However, these natural systems remain chronically underutilized and underfunded.

Scaling up community-based natural resource management programmes, green job creation and adopting governance mechanisms for protecting freshwater ecosystems need to be expanded. Ecosystem protection must be fully integrated into climate plans and policies and enforced at all levels. The expanded application of such approaches for transboundary basins is especially relevant, as a basin constitutes a holistic ecosystem.

5.5. Concluding Remarks

The Limpopo and Mau Forest Catchment Basins in South Africa and Kenya, respectively, are characterized by varying climatic conditions. In general, climate change is a complex and multifaceted problem that calls for robust and innovative response solutions to adapt and mitigate future impacts on key socio-economic developmental sectors. While the climate change impacts are felt in the various climate-sensitive sectors, it is simultaneously affecting the socio-economic systems and consequently the livelihoods within the most vulnerable communities in Limpopo and Mau Forest Catchment Basins. This work has identified some climate and non-climate stressors that affect climate-sensitive sectors such as water resources, human health, agriculture, and energy sources in both study sites. Based on the identified stressors, a framework for developmental response options as constrained by socio-economic drivers under a changing climate has been proposed. This framework will be used to assess climate change impacts and to inform policy and decision-making to manage the impacts by drawing aspects from various frameworks in literature.

6. Strategies for Adaptive Response to Mitigate the Impacts of Climate Change on the Water Sector

6.1 Introduction

Progressions of climate change represent a profound threat to both the availability and variability of water resources across local, regional, national, and global spatial scales. Potential climate change impacts at these spatial scales include, but are not limited to, enhanced frequency and magnitude of natural hazards such as droughts, floods, heat waves, storms, changing sea levels, as well as long-term fluctuations in mean renewable water supplies through variations in climatic variables such as precipitation, temperature, humidity, runoff, soil moisture, and wind intensity (IPCC, 2007). Social and climate change linkages, e.g. fluctuations in energy demand for heating and cooling, also influence water use in many regions. In addition to climate change, changes in land cover and land use, water withdrawal and consumption, as well as water resources infrastructure are some of the dynamic processes that have an influence on water resources management (Brekke et al., 2009). These collective influences on water resources have negative effects on communities, ecosystems, biodiversity, and sustainable development. Consequently, climate change coupled with other dynamic processes poses substantial risks for water security, successively enhancing knock-on repercussions on water-linked sectors such as agriculture, health, energy generation and supply, industry, transport, fisheries, forestry, and recreation, among others.

Most African countries are vulnerable to climate change and its influences on several water-linked sectors. This is primarily due to the continent's high susceptibility to water-related hazards, lack of coping capacity, and inability to recover from damages manifested from non-climatic factors (Mitlin and Satterthwaite, 2013; MacAlister and Subramanyam, 2018). In recent years numerous developing countries in Africa have experienced severe droughts, floods, heatwaves, cold spells and other weather-related extreme events, causing major natural disasters in the region (Wahlstrom and Guha-Sapir, 2015). With climate change projected to increase in the future, these events are likely to increase in frequency and intensity (IPCC, 2018). For this reason, comprehensive and integrated water-based interventions and actions are needed to cope and build a society that resiliently adapts to the changing climate, alleviate future impacts on water-linked sectors, as well as support the attainment of Sustainable Development Goal (SDG) 6, "*ensure availability and sustainable management of water and sanitation for all*" and SDG 13 "*take urgent action to combat climate change and its impacts*". A society's vulnerability to climate change depends, among other factors, on the type of initiatives and developments pursued to address climate change related issues. In particular, challenges of climate change call for both medium- and long-term sustainable developments that integrate adaptation strategies to minimize inherent impacts of changing climate, as well as to adapt and build resilience within the poor and most susceptible communities.

Adaptation to climate change and its inherent impacts on the water sector can be facilitated through several water-management adaptation options by integrating various factors such as changes in hydrological variables and regimes, water demand and supply, water conservation, operation and maintenance of water infrastructure, water pricing, use of wastewater and water transfer, as well as water management policies (Loomis et al., 2003; Brekke et al., 2009; Olmstead, 2013). Subsequently, successful mitigation and adaptation strategy in the water sector needs to be evaluated based on both short- and long-term weather and climate related issues within the region. This research study has reviewed multiple dimensions adaptation practices that can be implemented and adopted to combat impacts of climate change on water-linked sectors.

6.2 Review of Adaptation Response Options

Evidence has shown that climate changes are happening at different spatial scales, including global, regional, national and local levels, and such changes are unequivocal (IPCC, 2007). Climate projections indicate that such changes are likely to continue, exacerbating the current status of natural resources (IPCC, 2012). Owing to this, climate change adaptation options have been developed aiming to mitigate the future impacts of climate change at different spatial scales. Adaptation response options are frequently expressed within a framework of increasing climate-resilience, which encourages consideration of broad development objectives that better captures the complex interactions between human societies and their environment. The development of climate-related adaptation practices is dependent on adaptation needs such as environmental, social, institutional as well as information, capacity and resource needs, among others (Noble, et al., 2014). Based on these needs, adaptation practices are developed aiming to reduce risk and vulnerability, seek opportunities and build the much-needed capacity for community groups and natural systems to cope with impacts of the changing climate (Tompkins et al., 2010). Several adaptation options have been identified and reported in the literature. These practices have been categorized into three types, namely, the structural/physical, social and institutional. It is worth mentioning that such categorization is not university agreed upon, however, such the categorization is meant to consider the diversity of adaptation options for different sectors and stakeholders (Burton, 1996).

6.2.1. Structural/Physical Options

Structural options are practices that are discrete, and they provide clear outputs and outcomes well defined in scope, space, and time. Adaptation Fund Board (2013) physical options cover aspects of “concrete activities”, which echo the importance of the Adaptation Fund. Examples include engineering and environment, the application of technologies, the use of ecosystems and their services to aid adaptation needs and the provision of certain services at national, regional, and local levels, see a summary in Table 22.

Table 22. Structural/physical options and examples of adaptation functions/practices

Category	Examples of adaptation options
Engineered & build environment	- Flood control and water diversion, - water storage and pump storage, - sewage works and improved drainage, - storm and wastewater management, - adjusting power plants and electricity grids
Technological	- New crop and animal varieties - traditional technologies and methods - efficient irrigation - water-saving technologies - rainwater harvesting - conservation agriculture - hazard mapping and monitoring technology - early warning systems - renewable energy technologies
Ecosystem-based	- Conservation ponds, small reservoirs, natural wetlands - afforestation and reforestation - bushfire reduction - green infrastructure - adaptive land use management - community-based natural resource management
Services	- Municipal services including water and sanitation - essential public health services - enhanced emergency medical services

6.2.2. Social Options

Social options mostly designed vulnerability of destitute societies, with a focus on vulnerability reduction, gender, unemployment, and inequalities. Examples of this category include education, considered a limitation that contributes to vulnerability (Paavola, 2008), informational (information from early warning systems and its awareness/dissemination forms an integral part of adaptation), and behavioral measures (e.g. behavioral change in drought- and flood-prone areas leading to migration and relocation, which affects human health and security). Examples of social options and their functions are given in Table 23.

Table 23. Same as Table 22 but for social options

Category	Examples of adaptation options
Education	- Awareness raising and integrating into education - gender equity in education - sharing local and traditional knowledge - participatory action research and social learning - community surveys - knowledge-sharing and learning platforms - information dissemination platforms
Informational	- Hazard and vulnerability mapping - early warning and response systems - early warning systems - systematic monitoring and remote sensing - climate services - improved forecasts - downscaling climate scenarios - integrating indigenous climate observations - community-based adaptation plans - participatory scenario development.
Behavioral	- Household preparation and evacuation planning - retreat and migration; soil and water conservation - livelihood diversification - changing livestock and aquaculture practices - crop-switching; changing cropping practices, patterns, and planting dates - reliance on social networks

6.2.3. Institutional Options

Institutional options such as economic instruments (e.g. taxes, subsidies), insurance, social policies regulations, and planning measures (e.g. protected areas, building codes and re-zoning) (Heltberg et al., 2009) are vital in fostering climate adaptation. Examples of institutional categories s and possible adaptation options are summarised in Table 24.

Table 24. Same as Table 22 but for institutional options

Category	Examples of adaptation options
Economic	- Financial incentives including taxes and subsidies - insurance (including index-based weather insurance schemes) payments for ecosystem services - water tariffs - disaster contingency fund
Laws and regulations	- Land zoning laws - building standards - water regulations and agreements - laws to support disaster risk reduction - laws to encourage insurance purchasing - marine protected areas
Government policies and programs	- National and regional adaptation plans - sub-national and local adaptation plans - urban upgrading programs - municipal water management programs - disaster planning and preparedness - city- and district-level plans - sector plans (including integrated water resource management and landscape and watershed management) integrated coastal zone management - adaptive management - ecosystem-based management - sustainable forest management - community-based adaptation

6.3. Limits and Barriers to Adaptation

The anticipated increase of climate change and its inherent impacts on various climate-sensitive sectors across different spatial scales calls for the implementation of suitable adaptation options to mitigate future impacts and the involvement of public policy in facilitating adaptation to the changing climate. Such initiatives are likely to reduce the vulnerability of people and infrastructure, provide information on risks for private and public investments and decision-making, and provide much-needed public goods such as habitats, species, and culturally important resources (Haddad, 2005; Tompkins and Adger, 2005). Consequently, great opportunities and benefits are to be sowed when adaptation practices are implemented as part of governmental planning (Lim et al., 2005). Nonetheless, successful implementation of adaptation practices at national, regional and local spatial scales depends on effective and legitimate actions to overcome limits and barriers to long-term adaptation actions as a response to the changing climate (ADB, 2005).

According to Adger et al. (2007), limits or barriers are conditions or factors that render adaptation ineffective as a response to climate change and are mostly insoluble. Such conditions, which are associated with the rate and magnitude of climate change as well as vulnerabilities, are subjective and reliant on other factors including the values of diverse groups. Examples of limits or barriers to the implementation of adaptation practices often fluctuate in relation to diverse metrics, such as:

- Monetary/financial loss,
- Loss of life
- Biodiversity loss
- Distribution and equity
- Quality of life (e.g. coercion to migrate, resources-related conflicts, cultural diversity and loss of cultural heritage sites, among others) and
- Policy regulations and implementation realms.

6.3.1. Case Study: Online Survey to Assess Limits and Barriers to Adaptation Practices

The current study drew information from the published literature, grey literature, and expert opinions on the various adaptation options relevant for the study sites as summarized in Table 225. Evaluation of the limits or barriers to the implementation and adoption of climate change adaptation options in the Mau Forest Catchment Basin was undertaken using stakeholder participatory methods through a questionnaire survey given in Appendix A. We take note of the recommendation to use multiple participatory methods (Yeasmin and Rahman, 2012) such as informant interviews, focus-group discussions and others when undertaking this kind of study since they reduce the inadequacies of a single method. Nonetheless, the questionnaire survey has given a basic overview of how the participants in the Mara study site understand climate change impacts, the adaptations, and their views on the implementation of various adaptation practices in the area. As indicated in Appendix A, the survey focused on the following key barriers:

- ***Economic limits*** – factors such as micro-economic viability, socio-economic vulnerability reduction potential, employment and inequality limit the implementation and effectiveness of adaptation practices.
- ***Technological limits*** – how technologies are been developed often has limitations on the applicability and development of specific solutions to climate change adaptation.
- ***Institutional barriers*** – limitations are associated with a lack of specialized departments (or institutional capacity), limited knowledge and understanding, administrative feasibility, transparency, and accountability potential.
- ***Social and cultural barriers*** – relate to different ways in which people and community groups experience, interpret and respond to climate change, as well as a lack of interest in issues of climate change. These lead to different risk tolerance and preferences around adaptation practices, depending on individuals' and communities' general views, values, and beliefs.
- ***Physical and ecological (environmental) limits*** – relates to the transformation of the physical environment (including forest ecosystems, sea-level rise, persistent droughts/floods, and land

degradation). Lack of local knowledge about the impacts of climate change on ecological systems limits the implementation and effectiveness of adaptation practices.

Other important barriers that were not included in the survey are:

- ***Financial barriers*** – relate to a lack of financial resources to support local level, individual and community projects to combat poverty and build climate resiliency.
- ***Information and cognitive barriers*** – limitations are associated with factors such as knowledge of climate change processes, impacts and feasible solutions, perceptions of climate change risks, vulnerabilities, and adaptative capacity within community groups as well as the political will to implement adaptation practices.

Table 225. Sectoral adaptation options

Sector	Adaptation options	Remarks
Agriculture	1. Adopt water & soil conservation measures: reduce tillage, mulching, contour ridges 2. Change cropping patterns, sowing and harvesting time, crop diversification, improved crop cultivars 3. Adopt conservation agriculture & climate-smart agriculture: including improved cultivars and agronomic practices 4. Integrate indigenous and Local Knowledge 5. Migration and livelihood diversification 6. Policies, institutions & capacity building to support actors in the sector	• The sector has some inherent mitigation co-benefits, economic, ecological and socio-cultural benefits • There is also potential maladaptation if actions are not well coordinated and implemented • Indigenous Peoples have intimate knowledge about their surrounding environment which should be included in developing adaptation actions • Need flexibility to adopt suitable adaptation measures such as shifting to different crops, changing cropping times or returning to traditional varieties • Effective adaptation in the sector can help secure income and employment , including off-farm employment, reduce temporary or permanent migration • There is need for increased finance including credit, subsidies &/or insurance to limit losses • Training & capacity building is required to improve understanding of the risks and possible actions to build resilience • There is need for well coordinated regulations, including water policies and allocations & incentive instruments aswell as enforcement of policies
Energy & Industrial sectors	1. Changes in cooling water sources & alternative cooling technologies 2. Diversifying energy portfolios: integrating hydro, solar and wind energy 3. Water Intensive Industries (WII) could consider recycling and reusing grey water	• There is potential to reduce freshwater demand by recycling and reusing greywater.
Water, Sanitation and Hygiene (WaSH)	1. Climate-resilient WaSH infrastructure 2. Water conservation, storage and infrastructure, voluntary migration, planned relocation due to flood risk	• Water shortages can exacerbate or lead to new conflicts • Replacement and maintenance of existing infrastructure offer opportunities to implement climate-resilient designs and reduce greenhouse emissions • Limited water can lead to increased competition for water to meet economic development, environmental, political and household demands
	2. Better management of water resources, supply augmentation, and demand management	• Source water protection • Implement effective water demand & supply management • Address potential for areas for maladaptation and gender inequality.

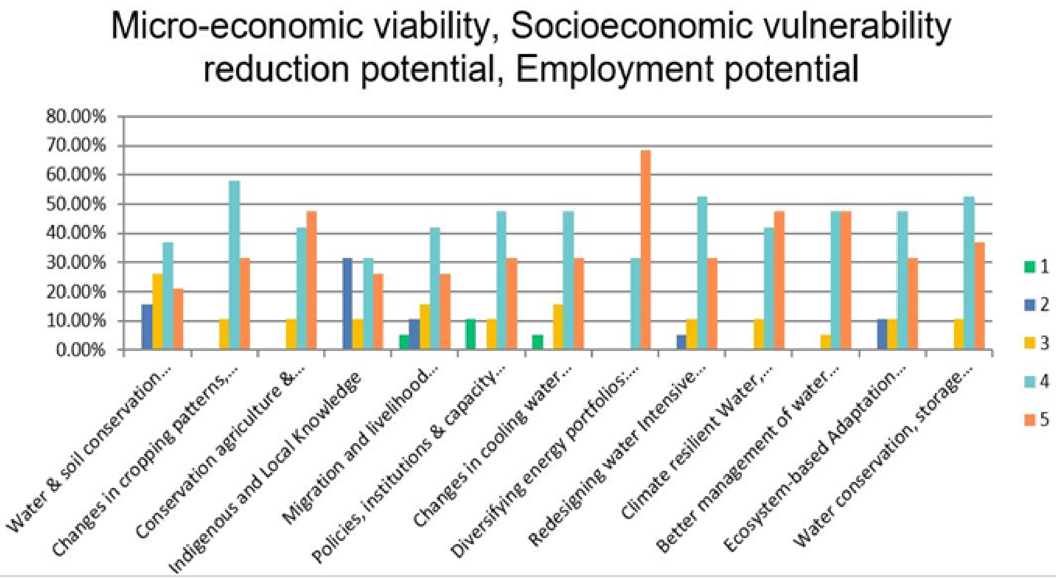
Sector	Adaptation options	Remarks
Rural, Urban & Peri-urban Settlements	1. Adopt a circular economy 2. Ecosystem-based Adaptation (EbA)	• Ensure access to water, sanitation, wastewater treatment, desalination, and water re-use • Implementation can be mpacted by governance, technical, and economic barriers • Efforts should be made to mainstream adaptation across and within all local government departments

6.4. Results

Results from the survey across the five assessed dimensions are presented in Figures 68 to 72. In this survey, 13 metric indicators defined across the following sectors: agriculture, energy and industrial, water, sanitation and hygiene, urban and peri-urban, communities dependent on freshwater ecosystems and water-related conflicts were used to evaluate the influences of economic, technical, legal and legislative, socio-cultural, and geophysical and environmental limitations in the implementation of adaptation practices at the local level, in Mau Forest Catchment Basin. As expected, the results (although vary depending on the respondents' views and knowledge) confirm the consensus presented in the literature regarding the potential barriers to the implementation of adaptation practices at a local level.

6.4.1. Economic Factors

Economic factors influence how communities adapt to climate change, consequently, leading to resistance in acknowledging development adaptation practices. Results in Figure 68 indicate that the energy and industrial and agriculture sectors are the major challenges associated with economic barriers in the implementation of climate-related adaptation options. In this case, 70% and 48% of the participants strongly agree that issues of "*diversifying energy portfolios: integrating hydro, solar and wind energy*" and "*conservation agriculture & climate-smart agriculture: includes improved cultivars and agronomic practices*" within the energy and industrial and agriculture sectors highly influence the adoption of adaptation practices. In general, 57% (i.e. 29% [strongly agree] + 28% [agree]) of the respondents indicated that economic factors influence the implementation and adoption of climate-related adaptation practices. About 25% of the participants had no information hence they selected "don't know" or "not sure" category, whereas 18% (7% [strongly disagree] + 11% [disagree]) of the respondents do not believe that economic barriers influence adaption in their region.



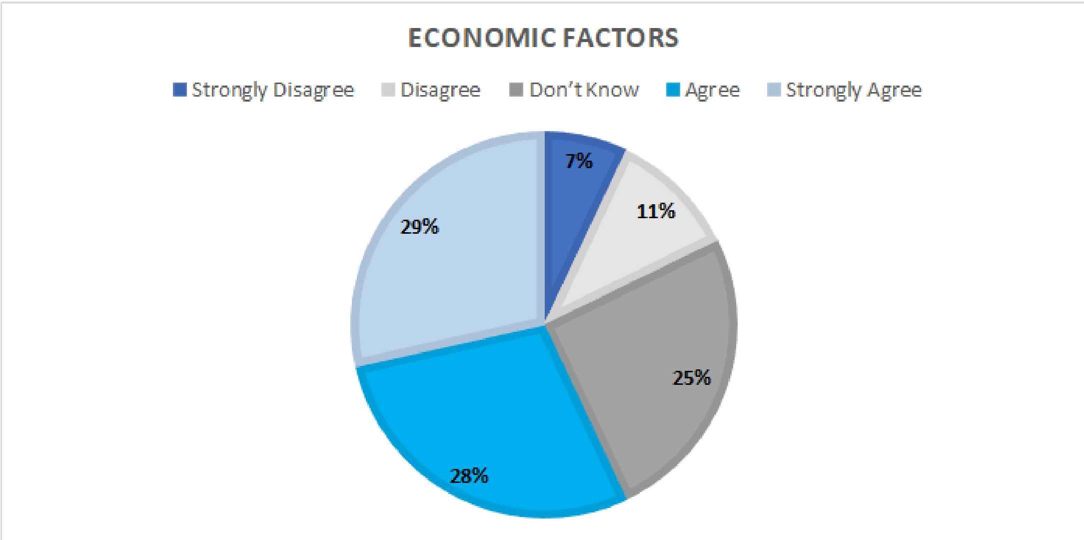


Figure 68. Economic barriers

6.4.2. Technical Factors

The influences of technical factors were confirmed by 47% of respondents (Figure 6969). Similarly, 25% of the respondents were undecided and 28% disputed the concept. Issues such as water conservation, storage and infrastructure, voluntary migration, planned relocation due to flood risk, as well as diversifying energy portfolios, under water-related conflicts and energy and industrial sectors were strongly highlighted by the participants as the major challenge associated with technical barriers.

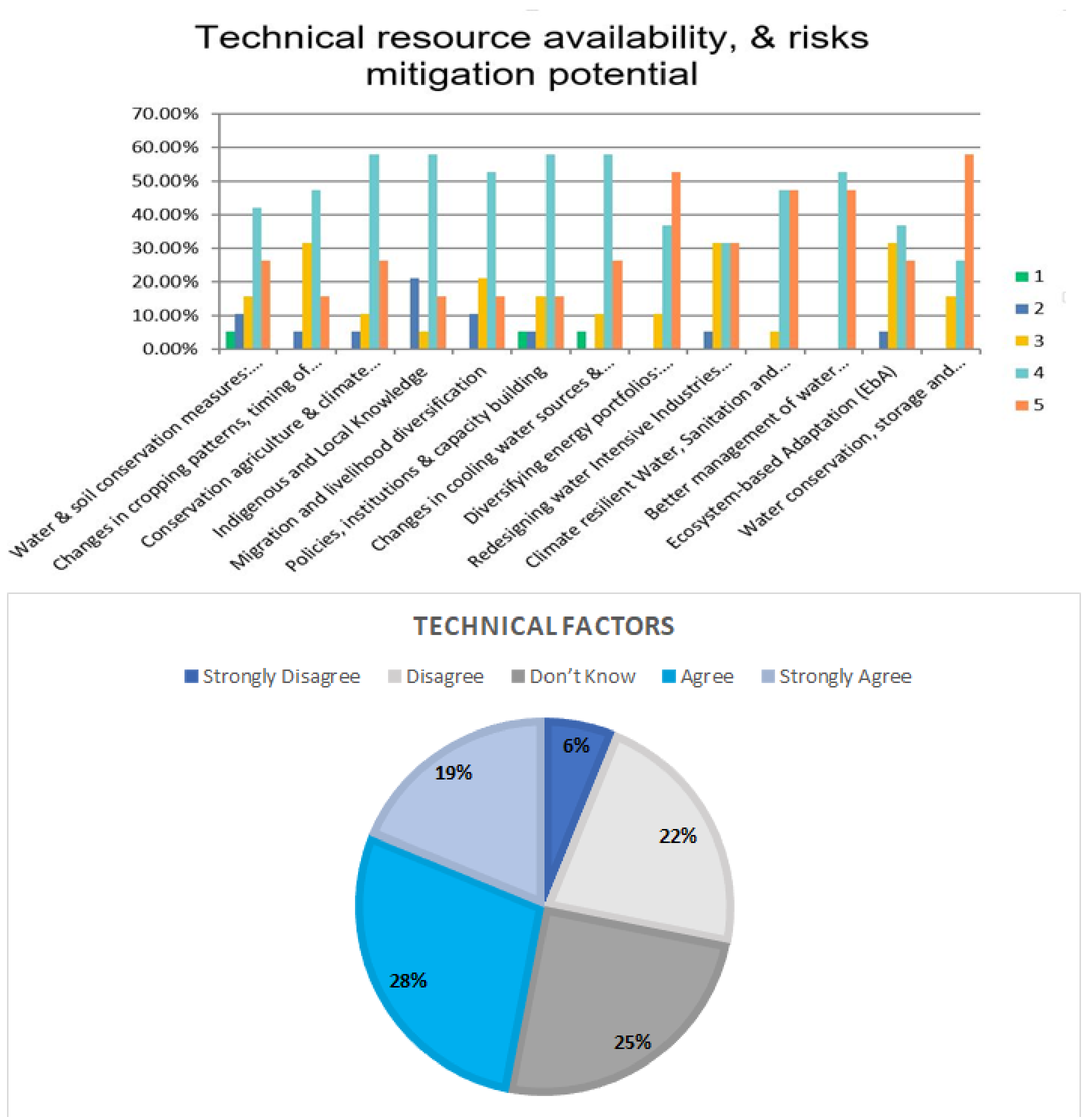
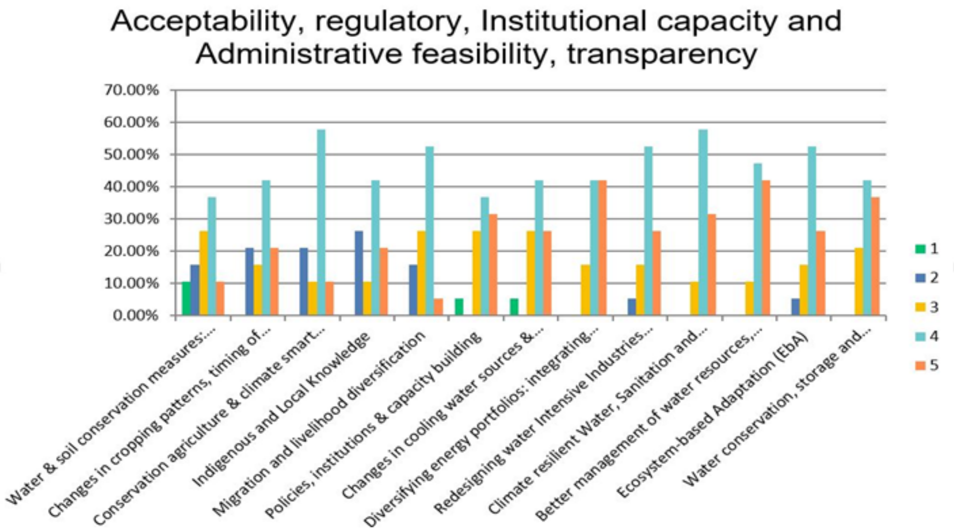


Figure 69. Technical barriers

6.4.3. Legal and Legislative Factors

Similarly, legal and legislative barriers were confirmed by 49% of respondents, with 24% falling under "don't know" or "not sure" category, see Figure 70. About 27% of the participants disputed the idea that legal and legislative factors influence the implementation and adoption of adaptation practices in the Mau Forest Catchment Basin. Issues like conservation agriculture and climate-smart agriculture, migration and livelihood diversification, climate-resilient, sanitation and hygiene infrastructure were ranked as major influences on technical barriers.



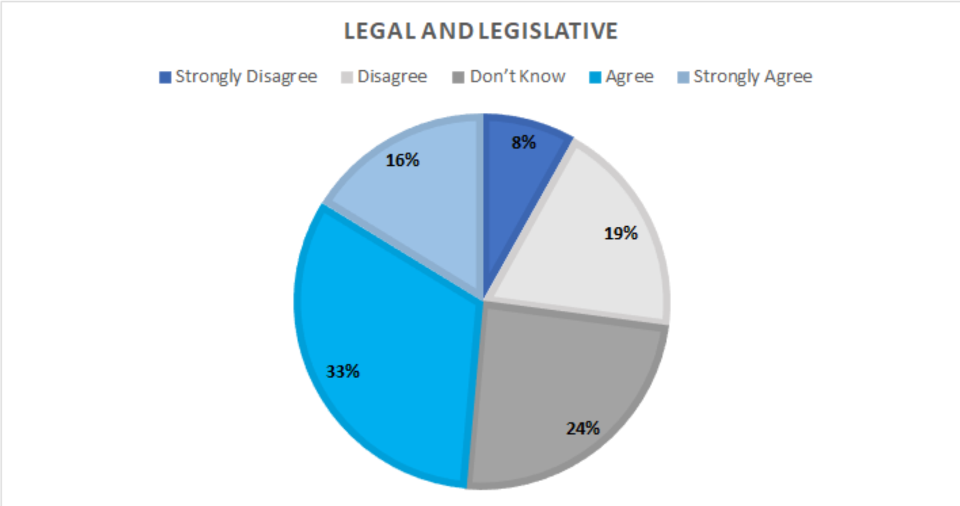


Figure 70. Legal and legislative barriers

6.4.4. Social and Cultural Factors

About 50% of the respondents are of the opinion that social and cultural factors influence implantation and adoption of adaptation practices (Figure 71). In addition, 30% of the participants disagreed with the suggested concept. Major influential factors include conservation agriculture and climate smart agriculture, indigenous and local knowledge, better management of water resources, supply augmentation, and demand management as well as diversifying energy portfolios.

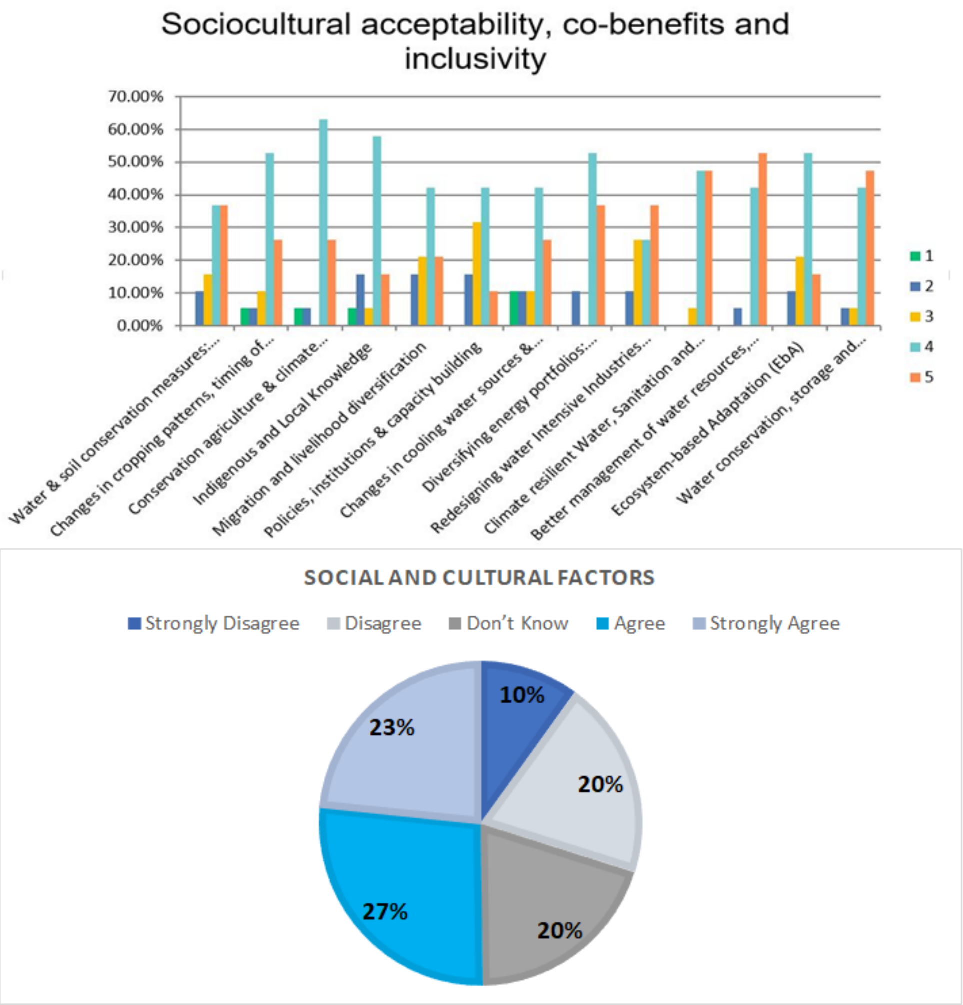
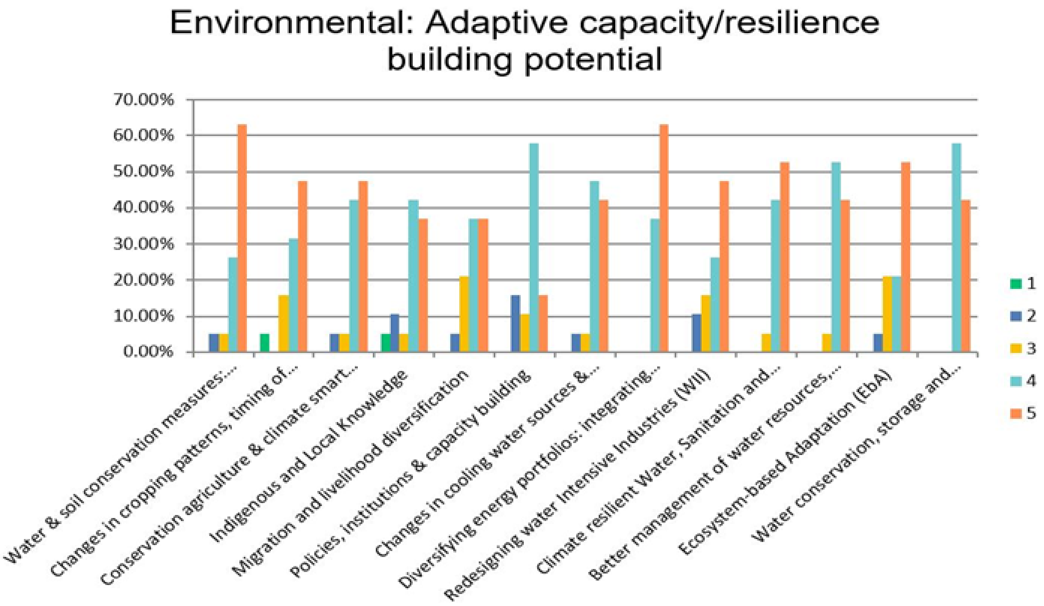


Figure 71. Socio-cultural barriers

6.4.5. Physical and Environmental Factors

Physical and environmental barriers were confirmed by 52% of the respondents, with 31% disputes and 17% undecided (Figure 72). Respondents also ranked the following factors water and soil conservation measures, diversification energy portfolios, climate resilience, sanitation and hygiene infrastructure, and ecosystem-based adaptation as major influences associated with physical and environmental barriers.



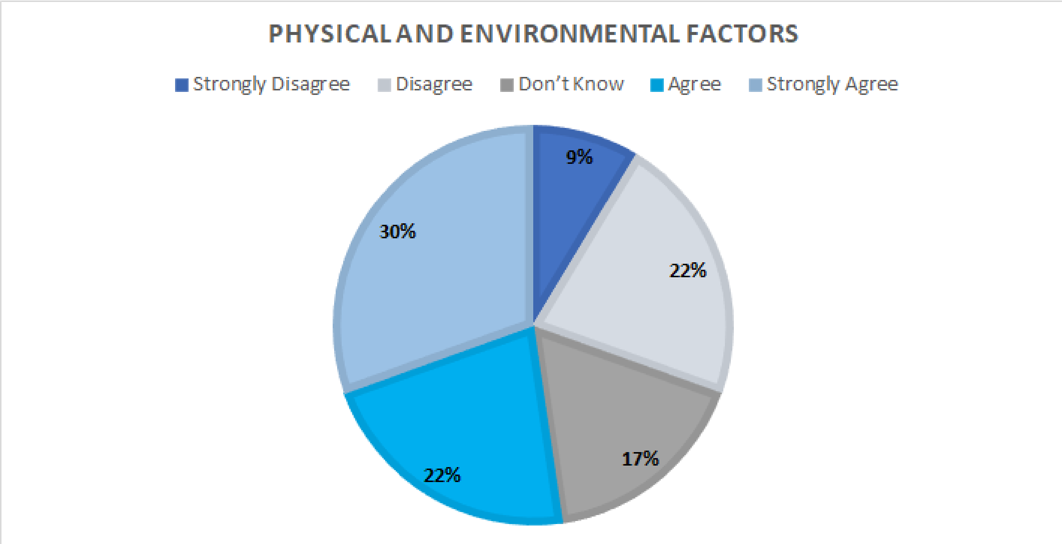


Figure 72. Geophysical and environmental barriers

6.5. Selecting Adaptation Options

As noted in the review section, there are numerous adaptation options defined and categorized to suit different functions and purposes. Selecting the proper adaptation option is therefore crucial for effective decision making and, in the process, circumventing undertaking unnecessary actions or maladaptation. Consequently, it is important to assess and prioritise the adaptation options according to detailed information and criteria. Additionally, adaptation options need to be assessed to ascertain their aptness to the local context, including their efficiency in minimizing vulnerability and building resilience.

Selecting adaptation options is often a challenge due to, for instance, the rate, uncertainty, and collective impacts of climate change as well as limitations such as insufficient local resources, capacities as well as necessary authority and support. According to Fünfgeld and McEvoy (2011), the framing of adaptation influences the selection of adaptation options. In this case, different climate change factors and policies may dominate differently to the impacts of the changing climate, leading to the coupling of adaptation options with other goals, achieving climate-related co-benefits, simultaneously.

Systematic techniques have been developed for selecting adaptation options, e.g. quantification, cost-benefit analysis, risk management, and multi-criterial analysis approaches (UNFCCC, 2011). In addition, numerous considerations have been proposed as essential guidelines for the effective selection of adaptation options. Some of the most common considerations are summarized in Table 226. Using climate information, the reviewed adaptation options and considerations presented in Table 226, a suitable adaptation option aimed to mitigate climate change impacts in the Limpopo and Mau Forest Catchment Basins can be selected.

Table 226. Common considerations for selecting adaptation options (Noble et al., 2014)

Common Considerations	Source/Reference
Effective in reducing vulnerability and increasing resilience	UNFCCC (2007); Brooks et al. (2011)
Efficient (increase benefits and reduce costs)	Stern (2006)
Stakeholder participation, engagement and support	Swart and Raes (2007)
Consistent with social norms, social acceptability & traditions	Alexander et al. (2011)
Environmental and institutional sustainability	Brown et al. (2011)
Flexible and responsive to feedback and learning	Agrawal (2010)
Robust against a wide range of climate and social scenarios	Carmin and Dodman (2013)
Resources available (including information, finance, leadership, and management capacity)	UNFCCC (2007); Brooks et al. (2011); Webb and Beh (2013)
Coherence and synergy with other objectives, such as mitigation	Klein et al. (2007); UNFCCC (2007)

6.6 Concluding Remarks

Climate change impacts on water-linked sectors call for the implementation of effective adaptation options to mitigate future impacts and build community resilience at local levels. In this contribution, we have reviewed numerous adaptation practices that have been implemented at different spatial scales for climate-related adaptation purposes. These adaptation options are categorized into three groups, namely, physical/structural, social and institutional. Examples of each category and functions of these options have been provided in this review. According to the literature, different barriers influence the implementation of adaptation options at the local level. In this review, a survey questionnaire was conducted to test this concept for the Mau Forest Catchment Basin. About 35 respondents participated in the survey. There is overwhelming evidence that factors such as economic, technical, socio-cultural, legal and legislative as well as geophysical and environmental influence the implementation and adoption of adaptation practices at the local level. The review study also highlighted considerations of selecting adaption options for a region. The findings of this review can be used to recommend the best suitable adaptation options for the Limpopo and Mau Forest Catchment Basins to mitigate future impacts of the changing climate.

7. Policy Recommendations

7.1 Introduction

Mau Forest Catchment BasinThe focus on water security and climate change is crucial for the development of adaptation strategies, delivery of immediate benefits to the most vulnerable populations, and advancement of the Sustainable Development Goals while strengthening systems and capacity for longer-term climate risk management. Furthermore, water is a major pathway through which climate change will impact people, ecosystems, and socio-economic activities. The climate change impacts coupled with natural climate variability, exacerbate the frequent occurrences of extreme weather and climate events such as heatwaves, drought, floods, storms, and extreme temperatures among others. Depending on their intensity, duration, and severity, these events pose significant challenges to key socio-economic sectors such as agriculture, water, health, energy, tourism, and transport consequently affecting individuals at local, national, and regional levels.

The most vulnerable communities include small-scale farmers, minority ethnic groups, and female and child-headed households. Climate change-related extreme weather events currently disrupt economic and social development, exacerbating environmental degradation and inequality and poverty. The Ogiek indigenous people in the Mau Forest, for example, are an endangered community who practice a lot of conservation of natural resources in the forest and their livelihoods depend on beekeeping and pastoralism. Deforestation, a decline in rainfall and grazing land has left them more vulnerable as men travel long distances to find grazing lands while women and children are left behind. The assessment of the impacts of climate change is therefore important for effective policy and decision-making to mitigate the inherent impacts, including providing supportive measures for proper management and sustainability of key natural and economic resources as well as promoting resilience within communities to manage climate risks. This project aimed to understand the extent to which climate and extreme events will change and the inherent impacts on water-linked sectors to support the development of effective preparedness measures, including informed policy formulation in the Limpopo River Basin (LRB), South Africa and the Mau Forest Catchment Basin (MFCB), Kenya. Based on information from various literature, projections and community engagements, and transect walks taken in the two study sites, this document provides policy recommendations mainly aimed to assist government policymakers and others who are interested in formulating or influencing policy.

7.2 Climate Change and Its Impacts on the Limpopo and Mau Forest Catchment Basins

Climate change extremes cause a series of social, environmental and ecological problems, particularly in the most vulnerable communities. Climate extreme indices are essential tools useful to assess, monitor and communicate changes in extremes and inherent impacts relating to climate change and variability. The LRB and MFCB have not been spared from climatic variations in temperature, rainfall patterns and the occurrence of extreme weather events, as well as the impacts of climate changes. These unmitigated changes have had direct and indirect effects on public health, agriculture, food security, water resources, biodiversity, human settlements, tourism and energy, to name a few key sectors. The LRB is arid/semi-arid (Trambauer et al., 2014), prone to flood events (during wet seasons and years) and droughts (during dry seasons and years) (Mazibuko et al, 2021). Rainfall in the LRB ranges from 200 mm/year in the west's semi-arid parts to 1,500 mm/year in the south-middle and 600 mm/year in the east towards the Indian Ocean (Legesse Gebre and Getahun, 2016). The basin receives 530 mm of annual precipitation, although most of it is intense (causing flash floods) and intermittent, connected with convective thunderstorms and tropical cyclones (WMO, 2012). Stakeholders in LRB indicate that water availability is a key challenge with many depending on rivers and boreholes some of which have dried up and most smallholder agriculture activities depend on irrigation (See Figure 73).

Figure 73. Smallholder farming using irrigation in Limpopo

Homes and other infrastructure in districts such as the Vhembe District Municipality have been destroyed by floods (Figure 74) caused by intense storms as well as the recent cyclone Eloise. Poor and uncoordinated planning has resulted in villages being built in high-risk areas that are vulnerable to floods.

Figure 74. Bridge destroyed during cyclone Eloise in Limpopo

Mean annual minimum and maximum temperatures in the LRB are 8°C in the south, 20°C in the east, and 23°C in the south, 32°C in the east. High temperatures in the catchment have affected human health due to heat stress and associated illnesses. Other health hazards in the LRB include vector and waterborne illnesses like malaria and cholera, which are exacerbated by a lack of clean drinking water, poor personal hygiene and poor waste management and sanitation (See Figure 75).

Temperatures in the MFCB are highly variable and are mainly modulated by altitude and rainfall distributions. Temperatures are lowest during wet seasons and highest during the dry season and can plummet to 10°C in elevated regions whereas temperatures in lowland areas can rise to 20°C. Stakeholders in MFCB highlighted that the fluctuating temperatures combined with flooding events have increased the incidence of pests and diseases such as locusts and typhoid. The MFCB receives a bimodal rainfall that peaks in April and August and receives the least from January to February (Melesse et al., 2008) and the annual rainfall varies from 650 to 1300 mm with communities indicating high rainfall variability in the last thirty years.

Figure 75. Poor waste management resulting in waste dumped in any open areas in Limpopo causing land and water pollution

Like LRB, MFCB has been affected by floods, heatwaves and drought conditions (Zermoglio et al., 2019) that are exacerbated by rising water demands from different sectors including human settlements and agriculture and have increased conflict for water resources between community members and livestock farmers (Figures 76 to 79). Many households depend on water from the river or rainwater harvesting (Figure 76) however these sources deplete especially in the dry months and the water is often not safe for human consumption. Learners at some boarding schools travel long distances to fetch water to use at their hostels (Figure 77).

Tourism is one of the main economic activities in the MFCB however, conservation areas are at risk due to deforestation for charcoal and firewood, invasion of conservation areas for human settlements and irrigation in the upper Mara River which affects water availability downstream. Table 27 summarizes some of the key changes in climate factors and extreme events, impacts and drivers of vulnerability that have been highlighted in literature and by participants in the LRB and MFCB which shows evidence that the two sites are vulnerable to extreme weather events.

Figure 76. Two examples of water harvesting systems adopted by some households in Narok, Kenya

Figure 77. Learners walking from the borehole to fetch water for personal use in the school hostel in Narok, Kenya

Figure 78. A gulley formed during the floods that learners now have to cross to access their school in Narok

Figure 79. A makeshift bridge constructed by community members when the road was washed of during the floods. The bridge allows communities to cross the river during the rainy season and access homes and grazing lands in the reserve

Table 27. Observed changes in climate, impacts and drivers of vulnerability

	Limpopo River Basin	Mau Forest Catchment Basin
Observed changes in climate	• Intense storms causing floods • Droughts • Increasing temperatures and heatwaves • Increasing rainfall variability	• Intense storms causing floods • Decline in rainfall • Frequent droughts • Heatwaves • Colder winters • Changes in the onset and duration of the rainfall season
Impacts	• Increase in water and vector-borne diseases such as malaria and cholera • Increase in pests and pathogens affecting both people and animals • Destruction of roads and other infrastructure • Water shortages • Increased food insecurity • A decline in crop yields especially for rainfed crops • Heat stress for humans and animals • Loss of biodiversity, biome shifts and soil erosion • Loss of income from tourism, e.g. from Kruger National Park • Loss of traditional medicines used by the community and traditional health practitioners	• A decline in yields and increased food insecurity • Increase in diseases such as typhoid, asthma, TB and HIV/AIDS • Disruption in energy supply • Water shortages • Increased risk of loss of life for learners who cross rivers and gulley's on their way to • Land degradation and loss of biodiversity • Increase in human and animal conflict • A decline in grazing land and migration of pastoralists • A decline in bee farming in the Mau Forest • A decline in air quality • Loss of income from tourism, e.g. Masai Mara National Reserve (migration of wildebeest from Serengeti between July-September) • Loss of traditional plants and medicines used by the Masai
Social, economic and environmental drivers of vulnerability	• Poverty and unemployment • Over extraction of water resources for other economic activities • Deforestation for firewood • Land use change and unplanned settlements • Poor coordination and fragmented decision making in communal lands • Population growth	• Poverty and unemployment • Deforestation of forests for firewood and charcoal • Increase in unplanned settlements and conversion of forests to agriculture and human settlements • Population growth • Political influence and corruption • Illegal sand mining and poor enforcement of environmental laws • Limited financial and human resources to implement and enforce policies

7.3 Future Climate Change Projections and Anticipated Impacts on Water-Linked Sectors

Projected precipitation and temperature-related extreme indices were characterised in this study, for both the LRB and MFCB sites. The results indicate that the variations of the climate indices are localised, for instance, most of the precipitation indices depict an increase in the extremes for the LRB, while the same indices tend to depict both increasing and decreasing patterns for the different parts of MFCB over the same period. Consecutive wet days are projected to increase in parts of LRB and decrease significantly in the MFCB, particularly in the northern parts of the basin. Future projections show that most parts of LRB and MFCB will experience more days of heavy rainfall. On the other hand, consecutive dry days are projected to increase for both LRB and MFCB. Additionally, warm spell days are expected to increase in both the LRB and the MFCB, with different duration periods. In contrast, cold consecutive days are projected to decrease in both river basins, particularly during the near future and towards the end of the century. Agriculture, mining and tourism are some of the key economic activities in the LRB catchment and increased competition for water coupled with droughts may in the future result in conflicts requiring effective management of the scarce resource.

Overall, the findings from this study indicate that both study sites are likely to experience more frequent and prolonged temperature and precipitation extremes throughout the projected period, spanning 2006 to 2095. The projected changes will likely have significant implications for the already strained s sectors, such as water, agriculture, energy and health, among others. Many small-holder agricultural enterprises in the Vhembe District Municipality, for example, currently depend on surface and groundwater for irrigation projected variations in rainfall can impact agricultural production, income and cost of production and food prices. Other potential impacts on the climate-sensitive and water-linked sectors include a further decrease in water quality; increase in evapotranspiration rate; increases in water demand for key sectors such as mining and human settlements; damage to crops, crop displacement, loss of seed production; risk of livestock deaths; land degradation; increased risk of water and food-borne diseases; heat-related mortality; increased demand for power generation reduction in power production efficiency (DEA 2013a,b,c; DEA, 2016a). The current and projected future changes and impacts require that concerted efforts are taken by all stakeholders in the two sites to mitigate short-term and long-term changes through both incremental and transformative adaptation. Stakeholder engagements and literature have highlighted some of the current knowledge, capacity and implementation gaps that have been used to draft the policy recommendations for governance actors and other key stakeholders in both the LRB and MFCB to enhance climate change response.

7.4 Recommendations Related to Existing Strategies or Policies

Legislative action or efforts to respond to climate change in Kenya include the Kenya Climate Change Act (Act 11 of 2016) and other sectoral policies such as the Water Resources Act (Act 43 of 2016) and the Energy Act (Act 1 of 2019) which have been integrated into sectoral plans, however, implementation is still lagging. In 2017, the Kenyan government introduced a ban on single-use plastics to reduce pollution that was also affecting water quality and aquatic life. The policy has been well enforced and implemented in some areas and is being applauded as a global benchmark, but more can still be done to ensure import treaties also comply with these national directives. At the county level efforts to respond to climate change in Narok are driven by community-based organisations (e.g. Narok County Natural Resources Network), NGOs (e.g. WWF) and community members and include replanting indigenous trees, rainwater harvesting and adoption of solar energy at the household level. Such efforts however need to be optimised so that they are more efficient and affordable for most of the population.

In Limpopo, the provincial (Limpopo Provincial Climate Change Response Strategy which is being revised) and district municipalities (Vhembe District Climate Change Response Plan 2016) have developed climate change response strategies as part of the Local Government Climate Change Support Programme by the DFFE. Other national and sectoral policies developed to support adaptation in the LRB include the National Climate Change Response Policy (2011), Climate change Bill, National Climate Change Adaptation Strategy (DFFE, 2020) and the Water and Sanitation Sector Policy on Climate Change (2017). The National Adaptation Strategy provides a common reference point for adaptation in the country that has been missing while implementation of the strategy requires funding and local champions to drive local action (Murambadoro, 2021). Early warning efforts need to be enhanced so that local actors can prepare for and respond to current and future disasters (DEA, 2016b). Implementation of climate change policies in the water-linked sectors and at the local government level is fragmented with predominantly rural municipalities struggling more as they do not have the human and financial resources to take long-term actions. Currently, there are also gaps in alignment and coordination of climate action by key stakeholders in the government resulting in duplication of efforts, redundancy and little or no monitoring of initiatives (Murambadoro, 2021). It is anticipated that the Climate Change Bill will assist in aligning climate change policy and institutional arrangements at various scales, but the bill is yet to be finalised.

7.4.1 Policy Recommendations for Stakeholders in the Mau Forest Catchment Basin

- There is a need for climate change response policy to be shared, revised and implemented with communities and local leaders so that they are aligned with community needs

- Implementation of national policies such as the Energy Act which requires data at the county level and there is a need to make renewable energy alternatives more affordable
- Build the capacity of key stakeholders in government (national and county level) and existing structures such as wildlife groups, women's groups, religious leaders, youth groups, community forest associations and water users association
- Diversify the platforms through which communities, CBOs and other stakeholders can access weather and climate change information, e.g. indigenous women's groups, community radios and community barazas coordinated by chiefs
- Climate change stakeholder engagement needs to be more inclusive of vulnerable groups such as women, children, disabled and minority indigenous groups in the Mau Forest
- Adaptation options need to consider various livelihood activities such as pastoralism, crop production, wildlife and nature conservation to avoid conflict and exacerbating inequality
- Provisions of the Water Act to decentralise water supply to the community level need to be well articulated with clear instructions and resources for implementation by local actors so that they can also manage issues of pollution
- Research and academic institutions in the water sector need to be more visible and empowered to support county governance actors and communities to improve water access for humans and livestock
- Improve management of water used for irrigation in the upper Mau Water tower
- Environmental laws need to be reinforced and penalties instigated to manage illegal sand mining in Narok which is affecting rivers, the availability of water and causing conflict for local communities
- Take advantage of the social and economic opportunities that can be derived from climate change adaptation in sectors such as agriculture, energy and tourism (e.g. job creation through rehabilitation of rivers and wetlands, removal of alien plants and waste to energy and recycling to develop tourist arts and crafts).
- Improve coverage and access to early warning systems in all counties

7.4.2 Recommendations for Stakeholders in the Limpopo River Basin

- Improve monitoring and evaluation of climate action at the local level to ensure effective implementation in all water linked sectors

- Improve coordination of climate change response efforts and learning (vertical and horizontal) for key stakeholders/sectors at national, provincial, and local government levels, traditional leaders and community-based organisations
- Research and academic institutions such as the University of Limpopo, University of Venda, CSIR, and SAWS among others should proactively provide capacity building and useable and relevant information that can be used to support local action
- Land use decision making in communal areas should be done in a coordinated and integrated way (including municipal planning instruments and actors)
- CBOs and NGOs need to collaborate more with government actors and tap into the available climate finance streams
- Protect conservation areas and areas with medicinal plants from overexploitation and invasion including enforcing municipal and traditional bylaws and penalties
- Diversify income and livelihood activities by taking advantage of the opportunities presented by the changing climate, e.g. growing new crops for the local and international market
- Improve access to early warning information and climate literacy at community level
- Encourage community-led climate change initiatives (e.g. outreach and training) as well as the integration of indigenous knowledge in designing local climate change response strategies
- The national government departments such as the Department of Forestry, Fisheries and Environment, the Department of Water and Sanitation and Department of Agriculture, Land Reform and Rural Development should provide support and facilitate access to technical and financial support for long term climate change actions so that local governance actors are proactive than reactive.
- Improved collaboration among disaster managers and SAWS for timely and appropriate dissemination of early warnings of extreme weather events for effective disaster preparedness and management
- Invest in research and technology for effective and efficient early warning systems

7.5 Concluding Remarks

The effects of climate change threaten to undermine food security, poverty eradication, and sustainable development. Climate change affects agricultural productivity through changing rainfall patterns, droughts, flooding, and the geographical redistribution of pests and diseases. Hence, the mechanisms to steer the wheel for adaptation and resilience are imperative to ensure the attainment of the Sustainable Development Goals. This report provides possible policy recommendations that can be implemented to enhance response to climate and climate change through adaptation in the two study areas.

8. Conclusions and Recommendations

8.1. Conclusions

The LRB and MFCB are experiencing climate change-related impacts, manifested in water-linked such as agriculture, tourism, energy and health. Based on the results presented in this report, minimum and maximum temperatures are likely to increase, whereas rainfall will be highly variable in the near- and far future for both study sites. These findings are in agreement with other projection studies reported in the literature. Climate variability will enormously impact rainfall and runoff in the two catchments and thus there is a need to understand this more, especially at a sub-catchment scale. Streamflow simulations for the LRB displayed a consistent decrease in streamflow for both the historical and the present climate, with most of the observed trends being statistically significant at a 95% significance level. Trends in hydrological variables such as baseflow as well as low and high flows also point to reduced streamflow in the LRB over the near- and far-future periods. Consequently, hydrological extremes such as droughts are projected as observed from the derived SSI time series. Similar conclusions are derived for the MFCB, although most of the work was done through desk-top review studies.

Agriculture is one of the major livelihood activities in both Vhembe and Narok with some people depending on rivers for irrigation of subsistence and commercial crops as well as domestic water use. These activities are likely to be impacted negatively in the future by the projected changes in hydrological variables such as streamflow, drought and consecutive dry days. Both study sites are projected to experience more days of heavy rainfall during the near-future projected period which can cause flooding and destruction of physical, social and economic assets. The CWD, for example, is projected to increase in the southwestern and eastern parts of LRB and decrease significantly in the MFCB, particularly in the northern parts of the basin. Most parts of both the LRB and MFCB are projected to experience more days of heavy rainfall during the near-future projected period.

Water management in Kenya has been decentralized to allow regional water supply systems that are managed at the local level. The Water Act provided regulations that enabled community-based water governance however, there has been no guidance for these local actors on how best to manage these resources and there has been limited funding to support implementation. Consequently, challenges have emerged at the county level as governance actors struggle to provide water for all households in Narok. Some rivers are drying up while water quality is also declining due to among other things poor waste management, deforestation and expansion of settlements onto wetlands that provide critical ecosystem services such as purification of water and flood control. Similarly, communities in the Vhembe District Municipality face challenges with water security and waste management which also affects water quality. Current experiences of climate change include a decline in Mopani worms and marula fruits, a decrease in agricultural productivity and increased food insecurity, and damage to roads and other infrastructure by floods. vulnerable groups in the district include small-scale farmers, children, the elderly, people living in communal and informal settlements that have no access to tap water and those in areas with a high risk of heat-stress, vector and water-borne diseases. At provincial and district levels climate change responses have been developed however implementation has been slow with the provincial strategy currently being updated.

Further research is required to profile the social vulnerability of people and communities and identify and understand overall vulnerability to current and future climate risks. While climate change will impact water and its linked sectors there are various opportunities to be explored within the two sites through research to inform local-level adaptation actions that can also meet societal development needs. Adaptation actions need to be informed by stakeholders in the study sites and their success is also dependent on an efficient governance system and the availability of financial and skilled human resources. Participants in the study highlighted that there are some existing policy frameworks in sectors such as water and energy to support climate change response in the study areas however implementation is still lagging and these to be augmented and adopted by all stakeholders to address the inherent impacts on socioecological systems.

8.2. Recommendations

From the findings of the study, the following recommendations are suggested for policy and future research in the two study sites.

- There is a need to build the capacity of stakeholders involved in local-level water management to form coherent and well-coordinated policies to support the sustainable management of water resources that can adapt to current and projected future climate extremes.
- Stakeholders in other water-linked sectors such as environment and agriculture need to coordinate policies and their enforcement to ensure sustainable land use management and minimise land degradation and loss of ecosystems and services
- Raise community climate change awareness including poor and marginalised groups (e.g. women, children and minority ethnic groups) in the two study sites are more vulnerable to current and future projected changes in climate and hence require information and resources to cope with extreme weather events.
- There is a need for further research to understand and build the resilience of communities from the impact of the climate extremes on various water-linked sectors including biodiversity and health
- Early warning at the community level should be issued timeously, through different communication channels and in local languages to improve disaster preparedness and response

- Provide capacity building and information to support communities dependent on agriculture so that they adjust their activities to cope with projected changes as well as take advantage of opportunities presented by the changing climate. This for example includes engaging in other economic activities such as creating products from waste and growing new crops that are more suitable for the new climate, e.g. sorghum
- In the short to medium-term research, development and climate change interventions should integrate indigenous knowledge that communities have to codesign adaptation actions that are relevant at the local level as some current adaptation actions suggested in policy documents have not been informed by the communities at risk.
- In the long term, there is a need for water governance actors to set maximum sustainable limits for water consumption and manage pollution in regional and transboundary river basins to ensure that safe drinking water is accessible to as many people as possible

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APPENDIX 2A:

Appendix 2A provides supplemental information, including figures and tables to Chapter 2 of the report.

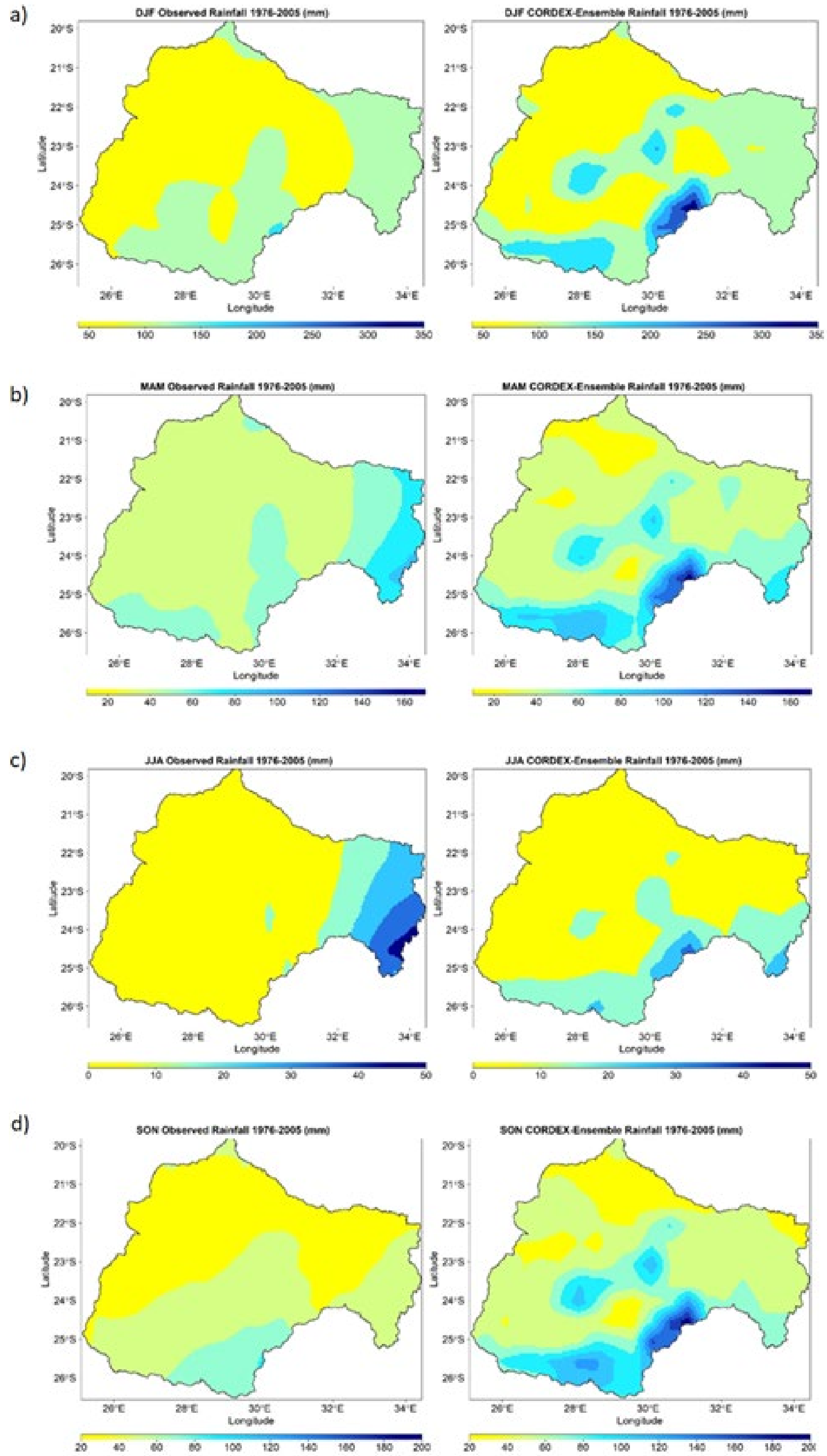

Figure 2A - 1. Seasonal distribution of average totals of observed and CORDEX-ensemble rainfall for historical period in Limpopo River Basin: a) DJF, b) MAM, c) JJA and d) SON

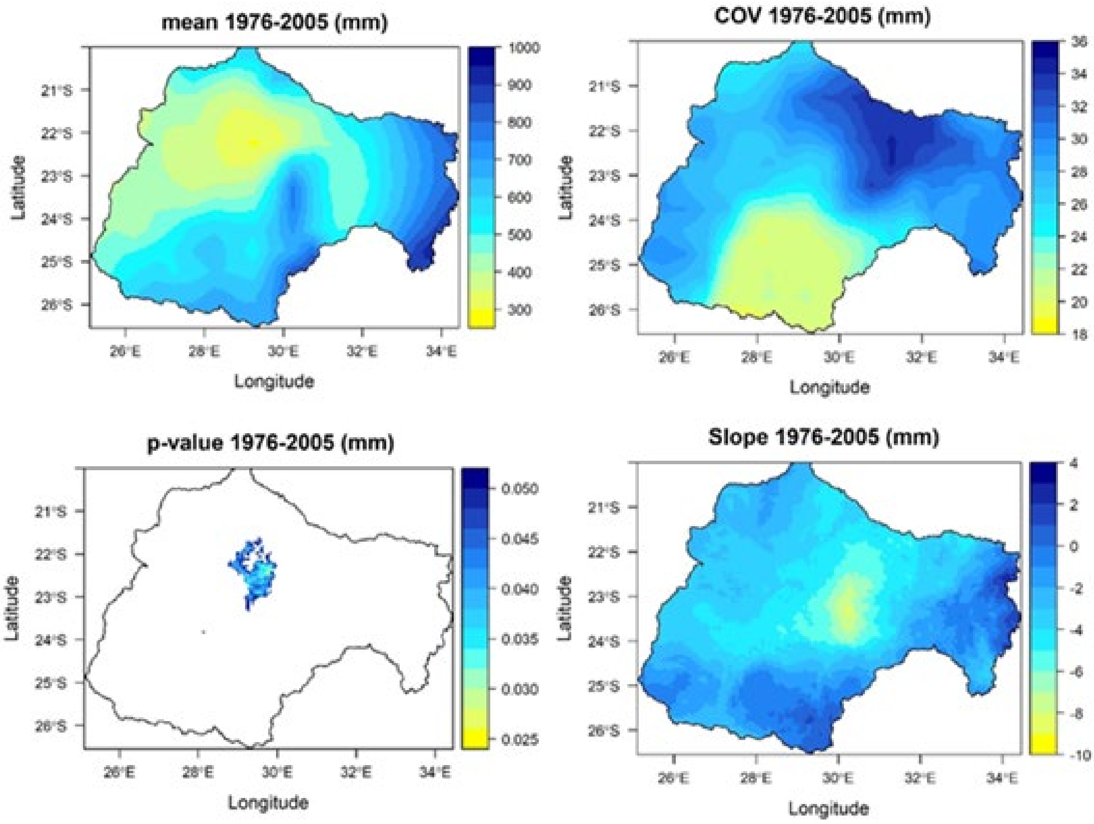

Figure 2A - 2. Spatial statistics of total annual rainfall; mean (top left), Coefficient of Variation (CoV) (top right), p-value of trend (bottom left) and slope (bottom right) over Limpopo River Basin

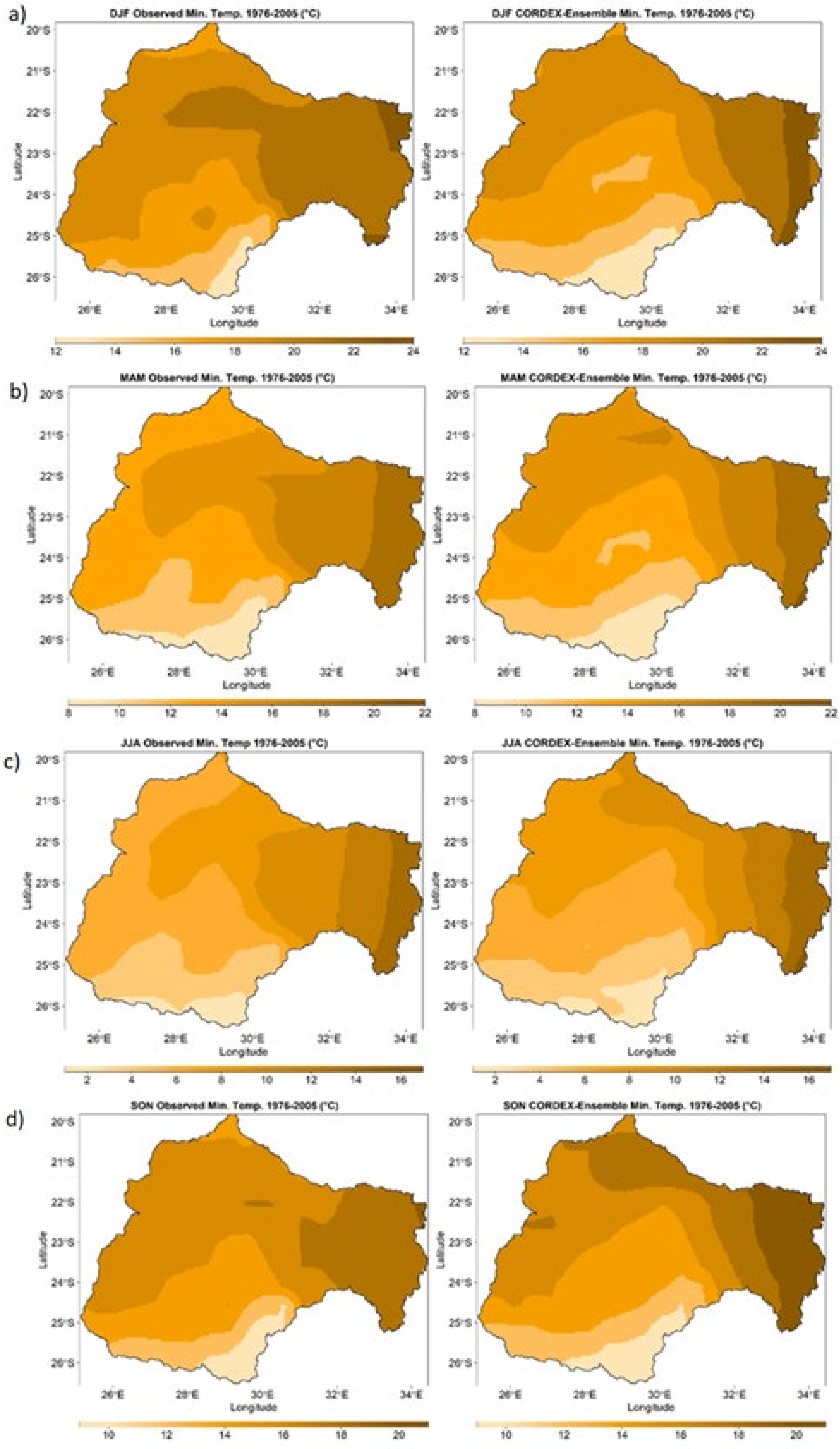

Figure 2A - 3. Seasonal distribution of averages of observed and CORDEX-ensemble minimum temperature for historical period in Limpopo River Basin: a) DJF, b) MAM, c) JJA and d) SON

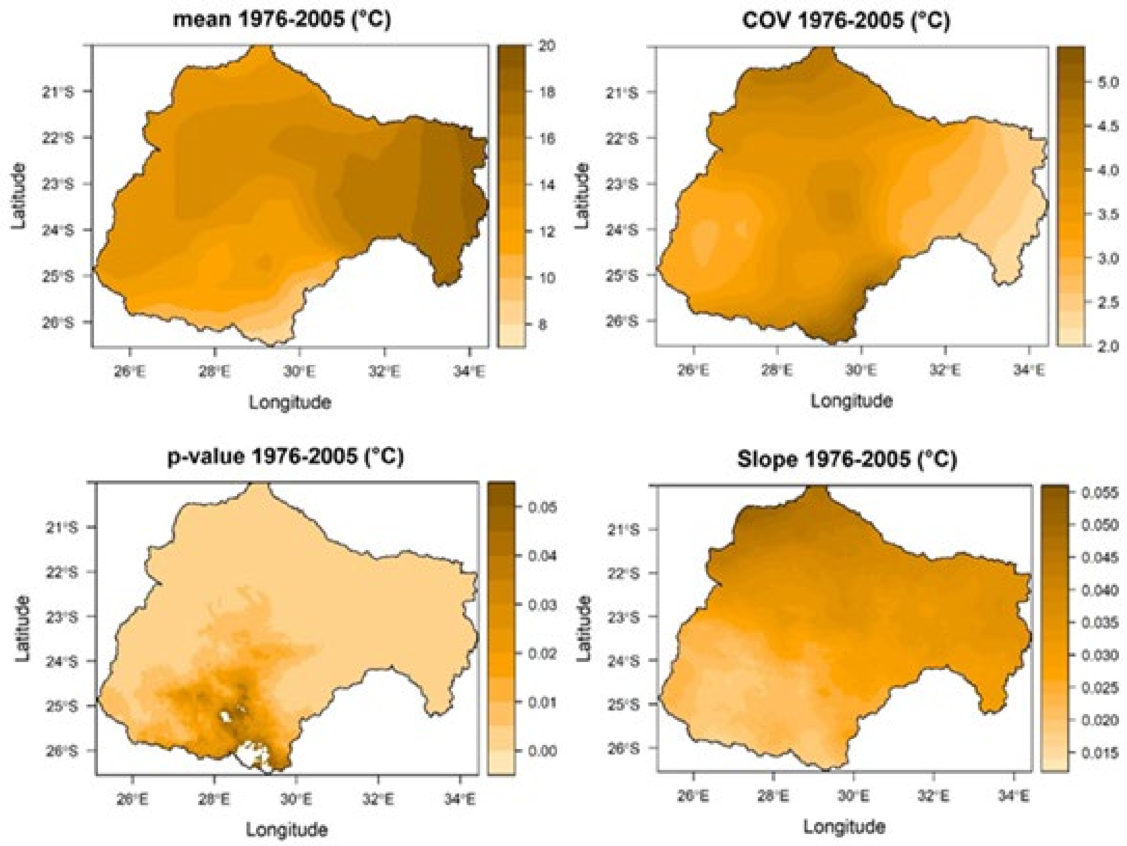

Figure 2A - 4. Spatial statistics of minimum temperature; mean (top left), Coefficient of Variation (CoV) (top right), p-value of trend (bottom left) and slope (bottom right) over Limpopo River Basin

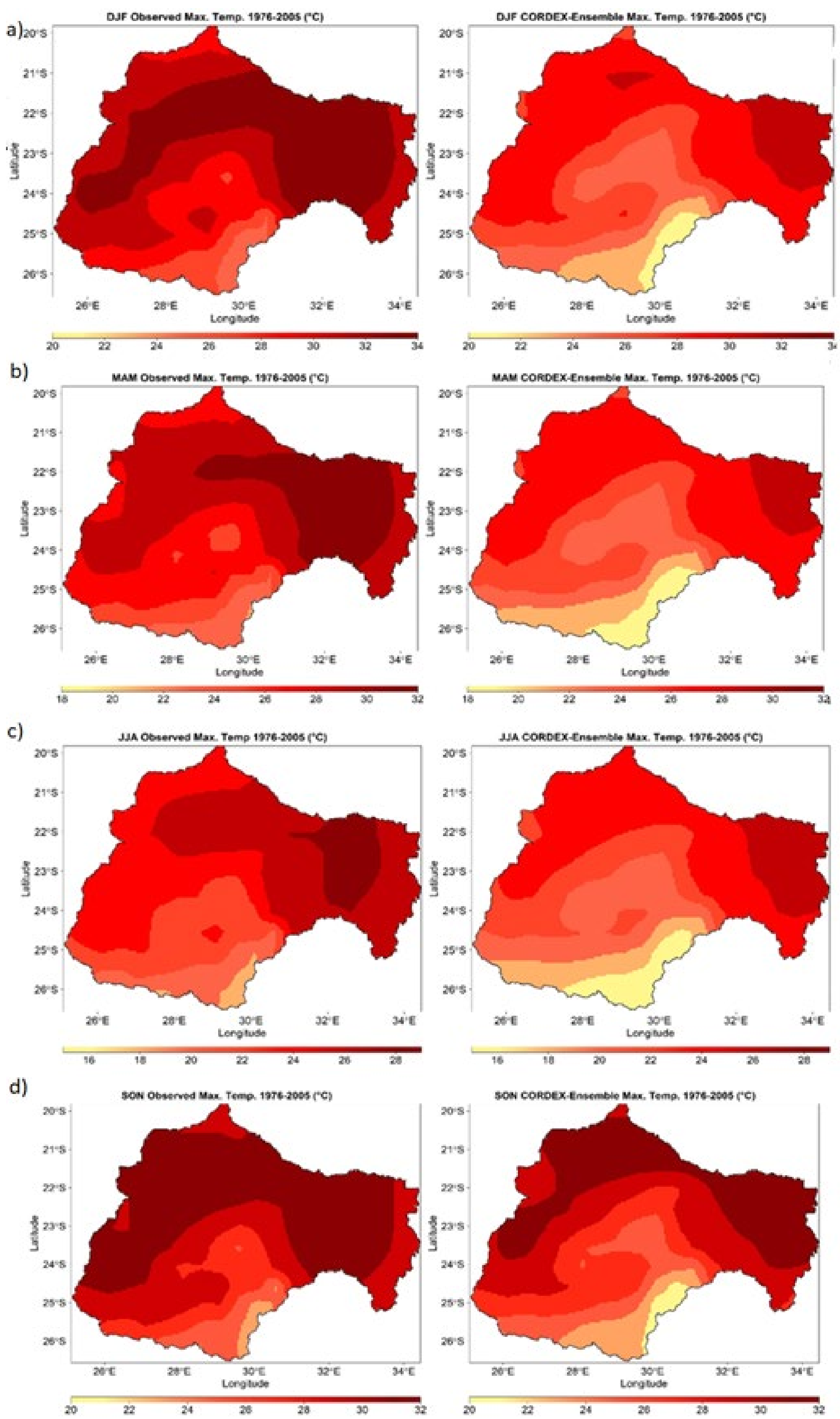

Figure 2A - 5. Same as Figure 2A - 3 but for seasonal averages for the observations and the CORDEX-ensemble model

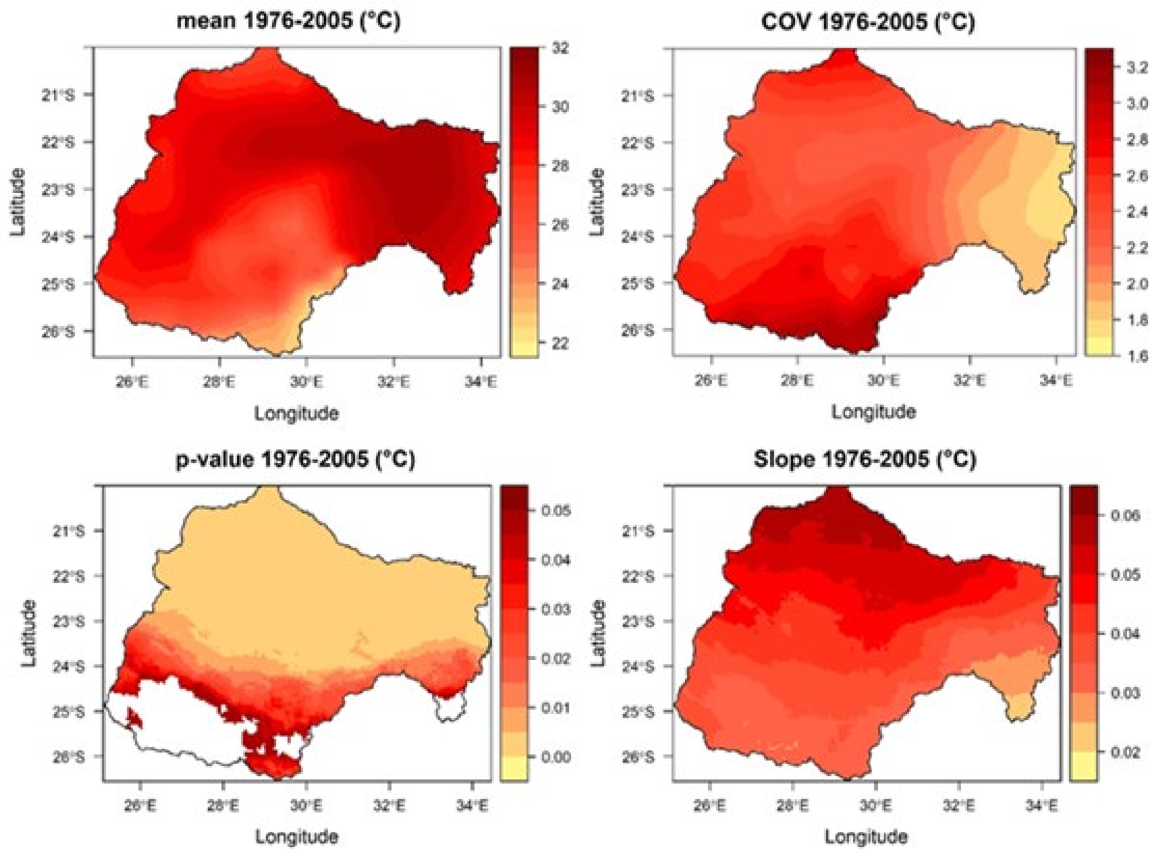

Figure 2A - 6. Spatial statistics of maximum temperature; mean (top left), Coefficient of Variation (CoV) (top right), p-value of trend (bottom left) and slope (bottom right) over Limpopo River Basin

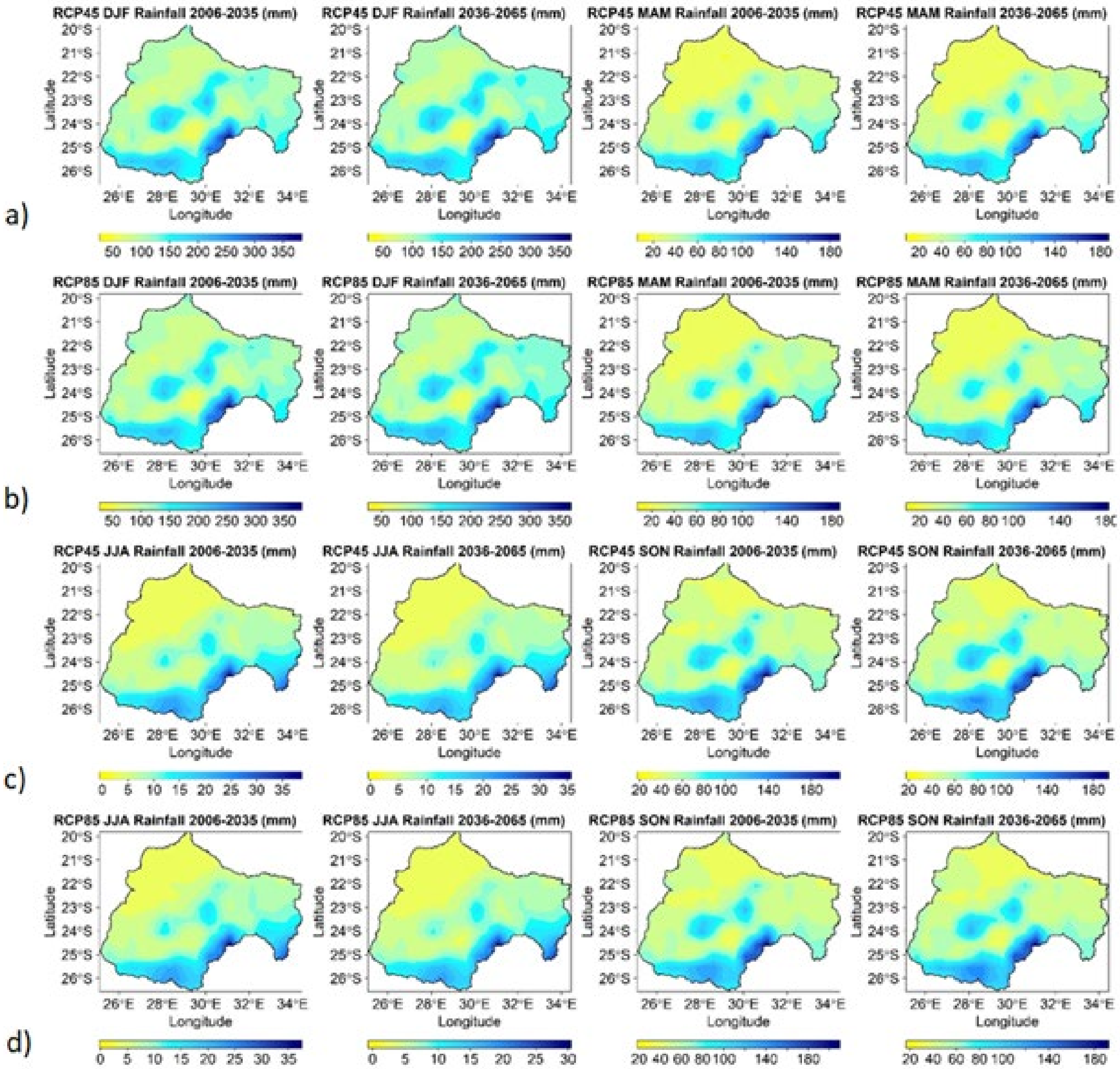

Figure 2A - 7. Seasonal total rainfall: (a) DJF and MAM, under the RCP4.5; (b) DJF and MAM for the RCP8.5; (c) JJA and SON for RCP4.5 and (d) JJA and SON for RCP8.5, across the 2006-2035 and 2036-2065 periods, respectively

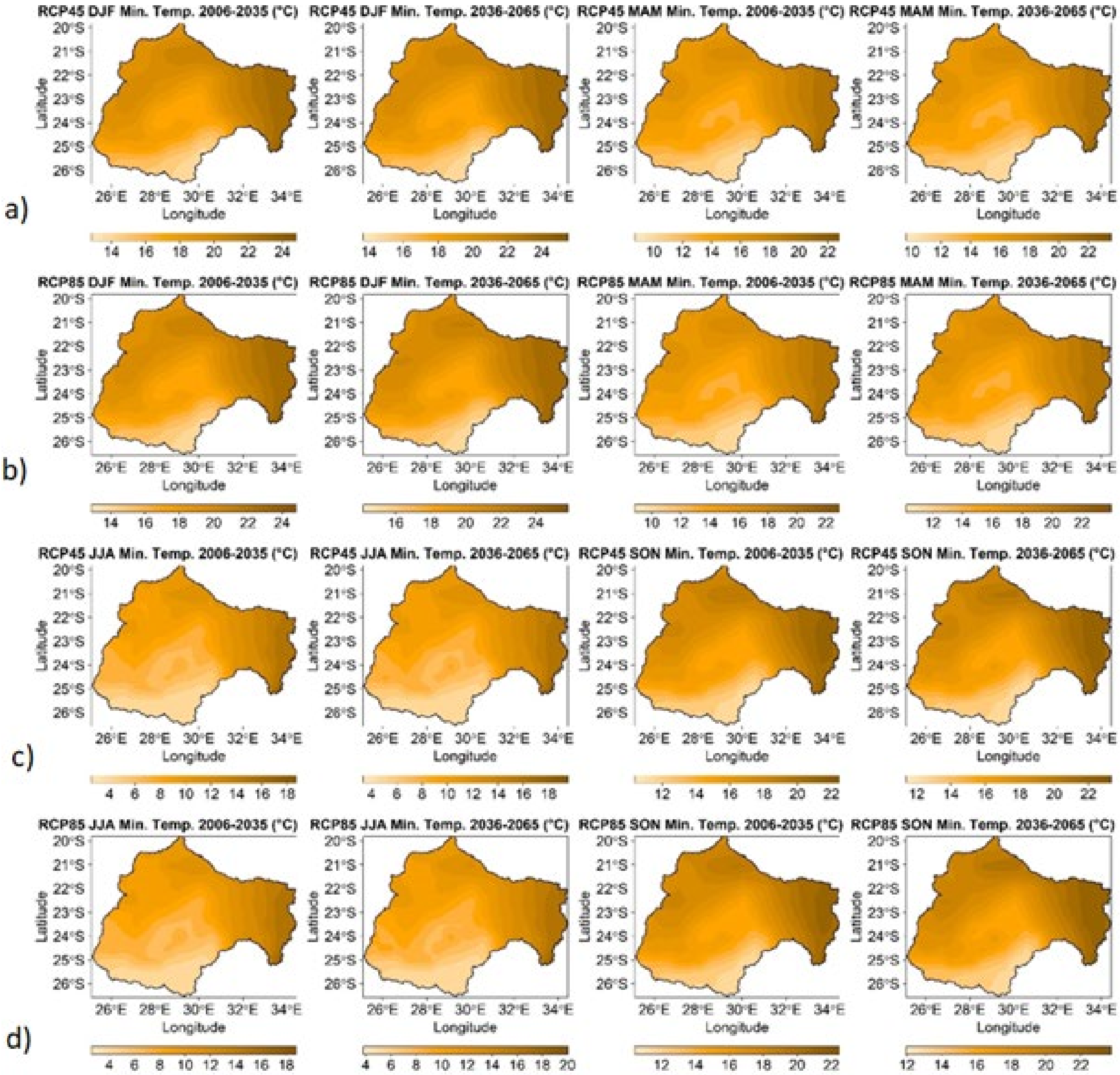

Figure 2A - 8. Same as Figure 2A - 7, but for seasonal minimum temperature

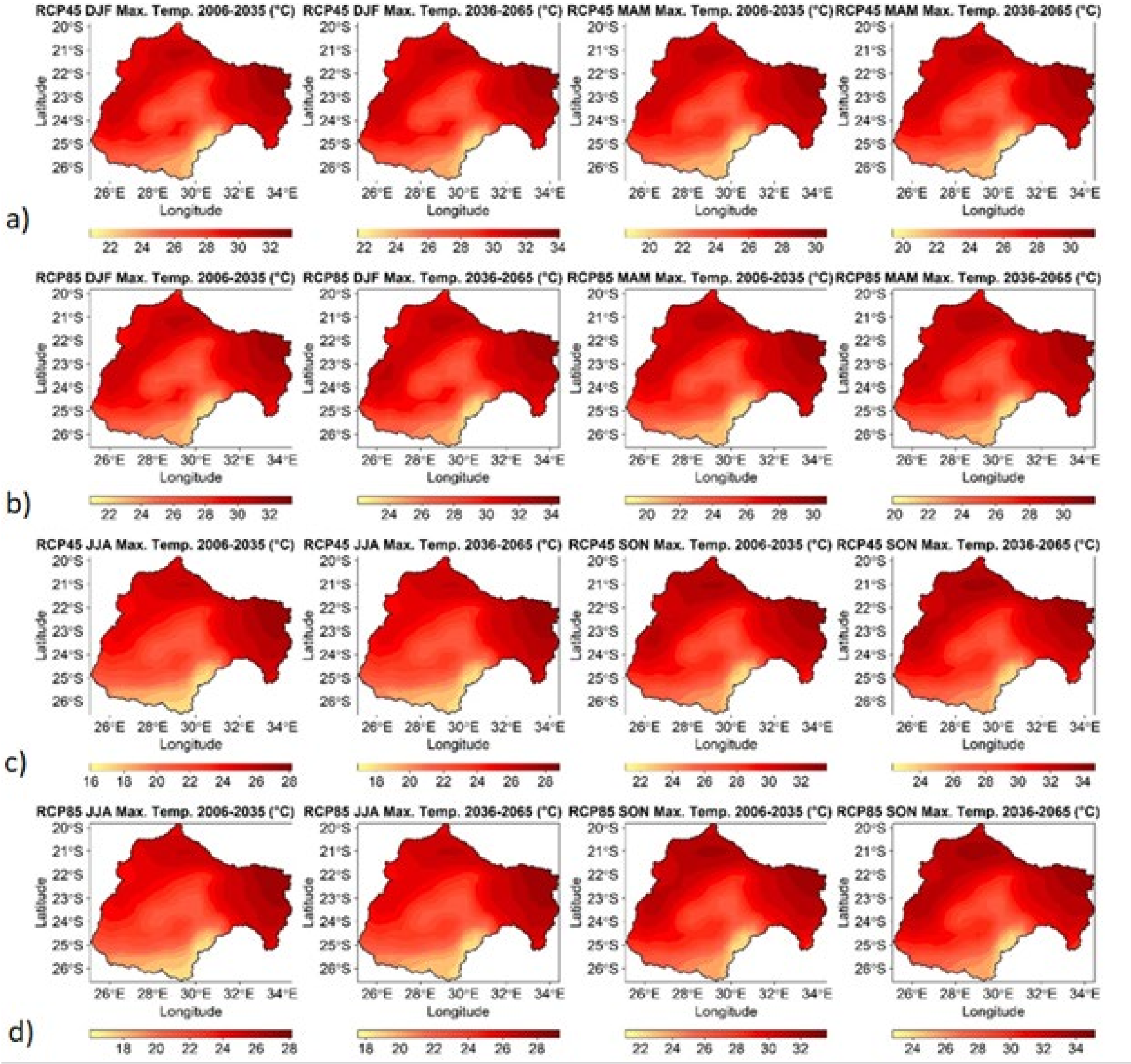

Figure 2A - 9. Same as Figure 2A - 7, but for seasonal maximum temperature

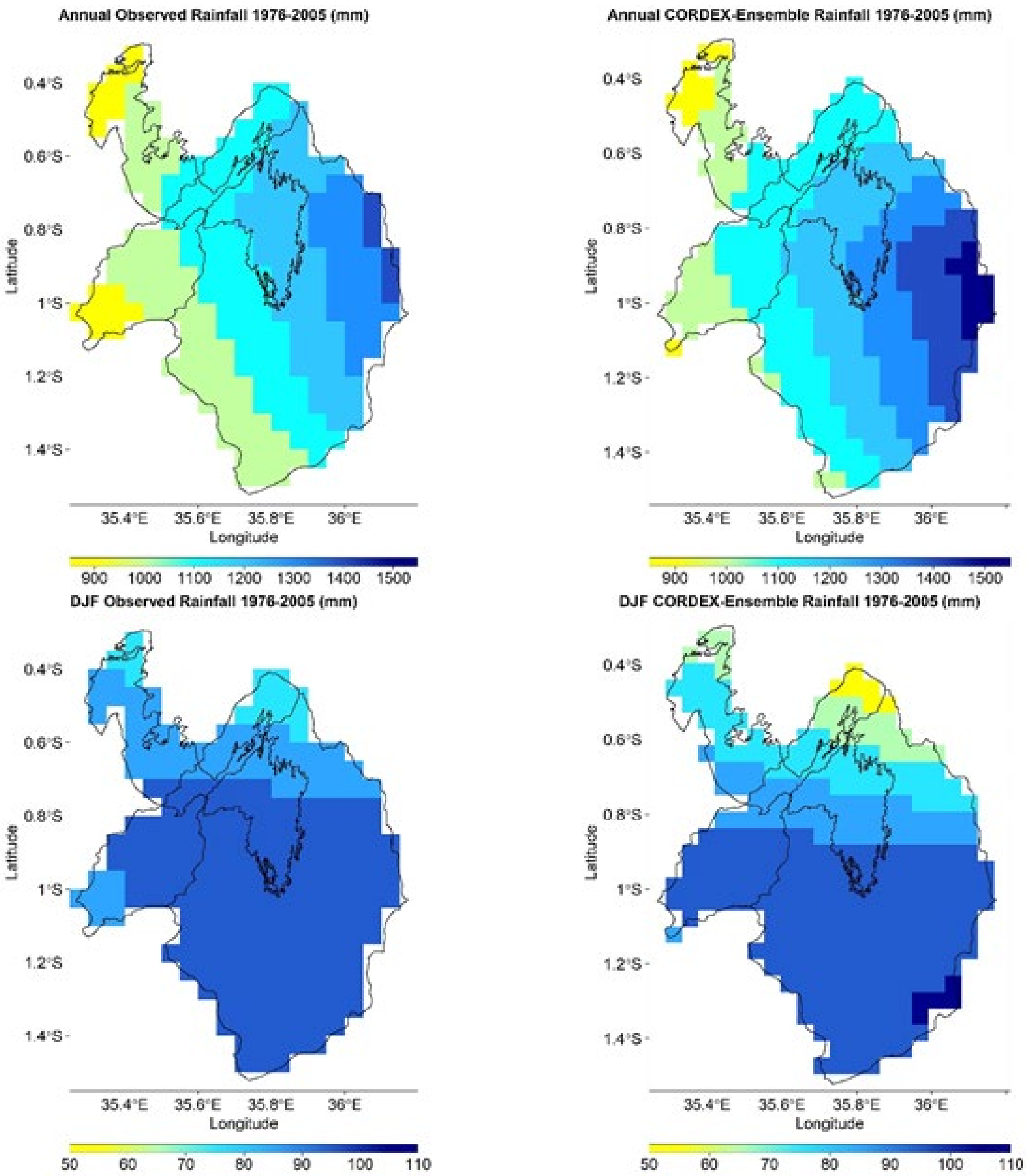

Figure 2A - 10. Annual and DJF average total observed and CORDEX-ensemble rainfall for the baseline year 1976-2005 in Mau Forest Catchment

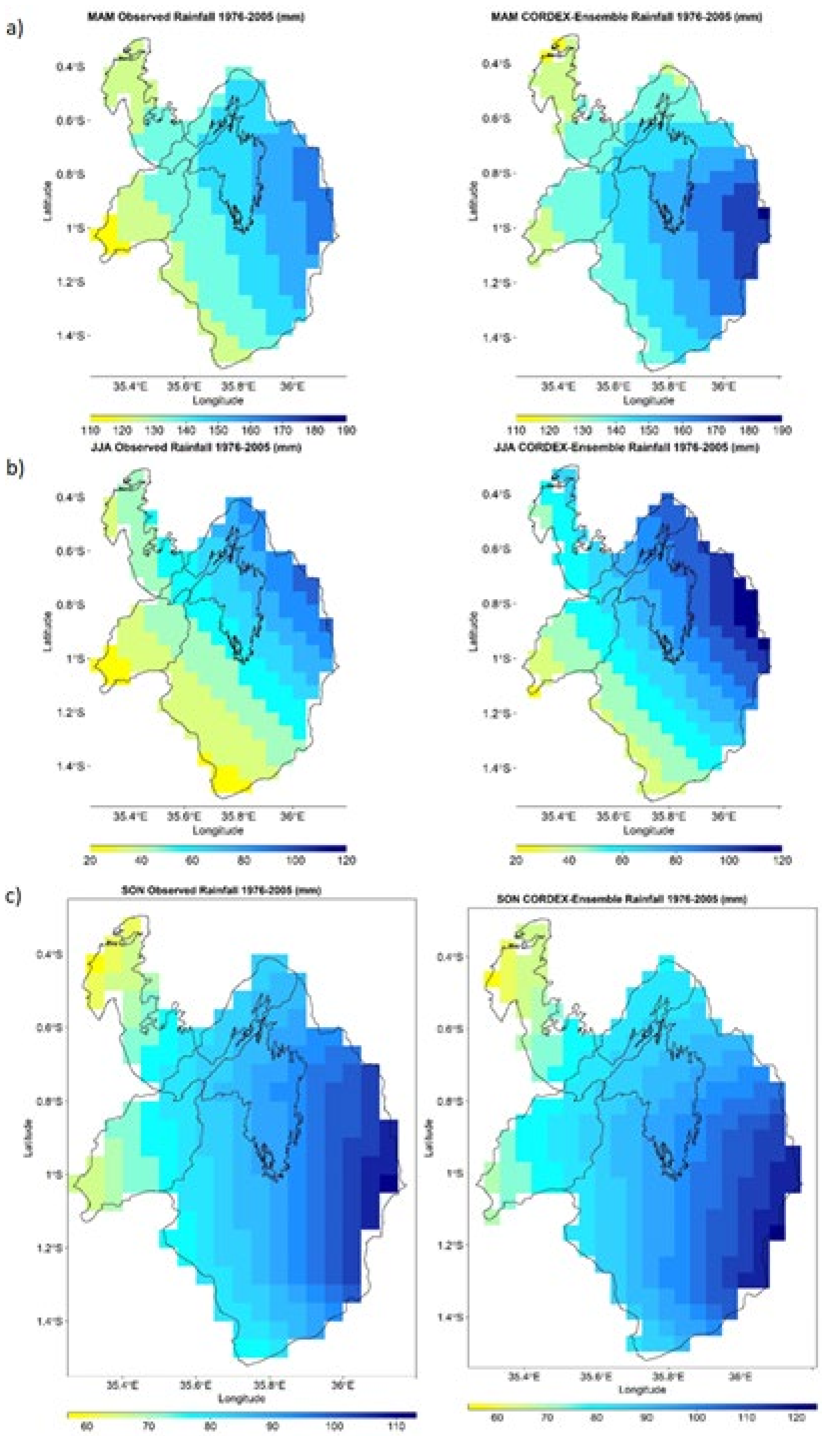

Figure 2A - 11. Seasonal average totals for the observed and CORDEX-ensemble rainfall: (a) MAM, (b) JJA and (c) SON seasons, respectively.

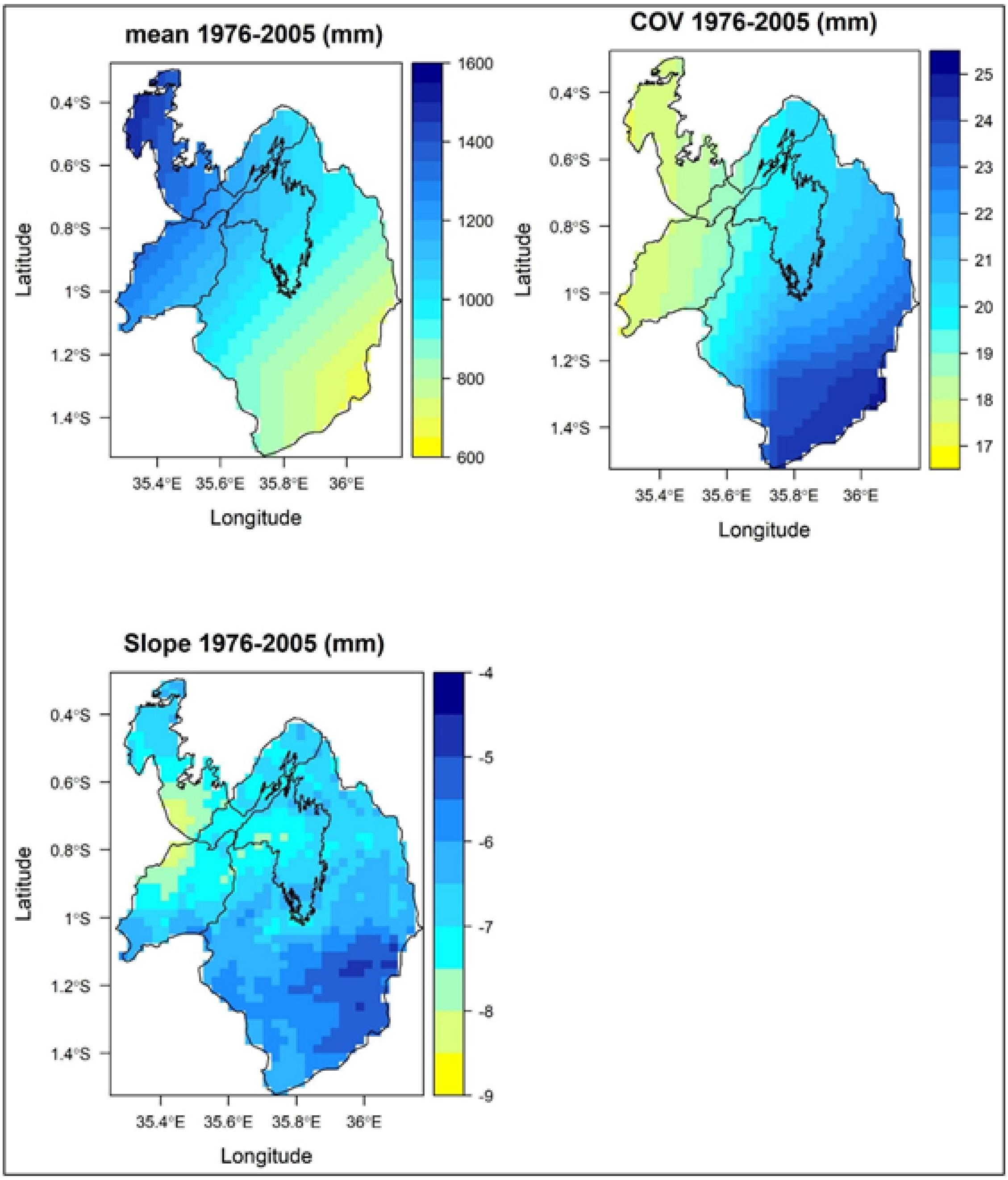

Figure 2A - 12. Spatial statistics of annual total rainfall; mean (top left), Coefficient of Variation (CoV) (top right), p-value of trend (bottom left) and slope (bottom right) over Mau Forest Catchment

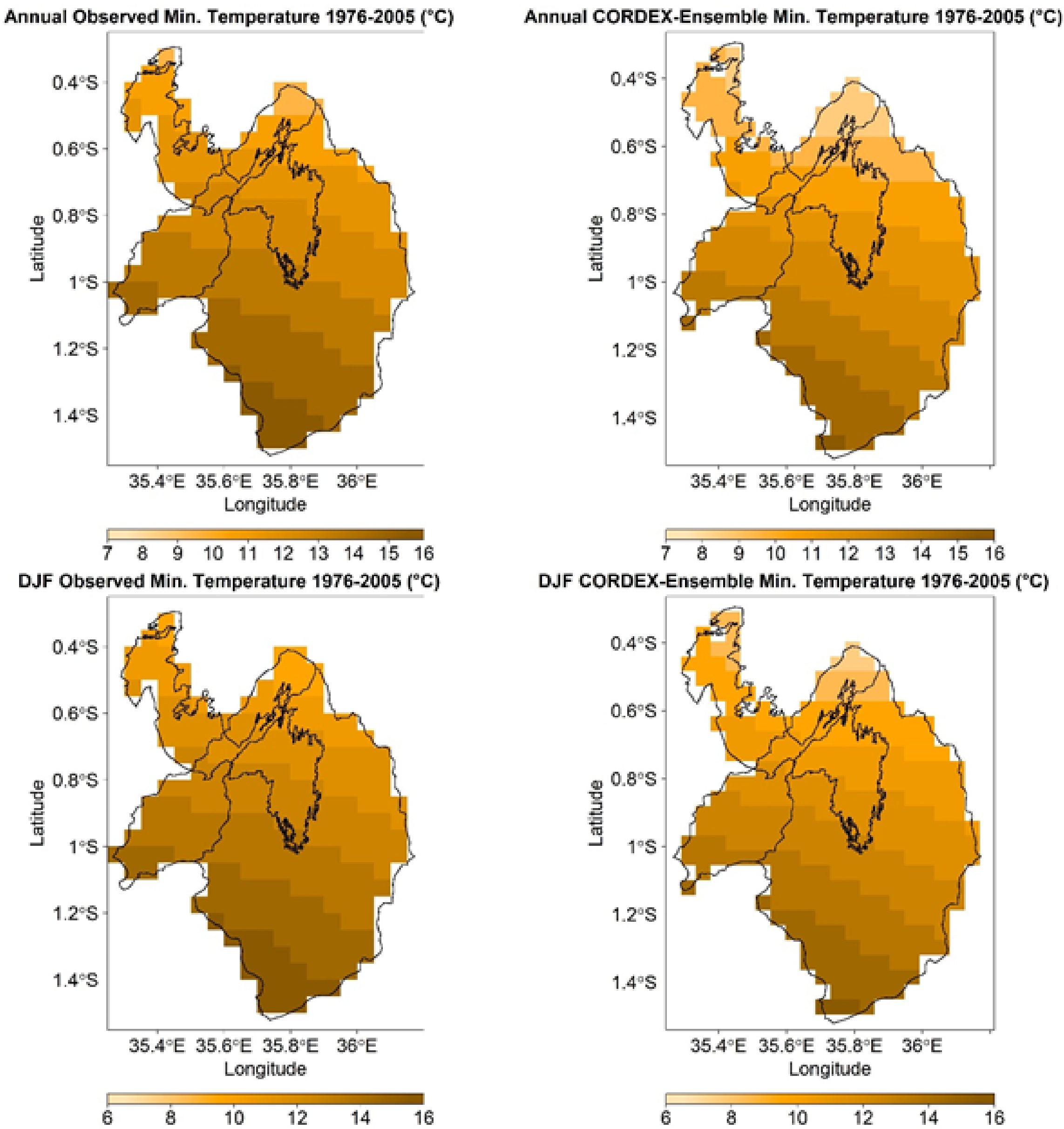

Figure 2A - 13. Annual and seasonal average observed and CORDEX-ensemble minimum temperature for the baseline year 1976-2005 in Mau Forest Catchment, Annual and December to February (DJF).

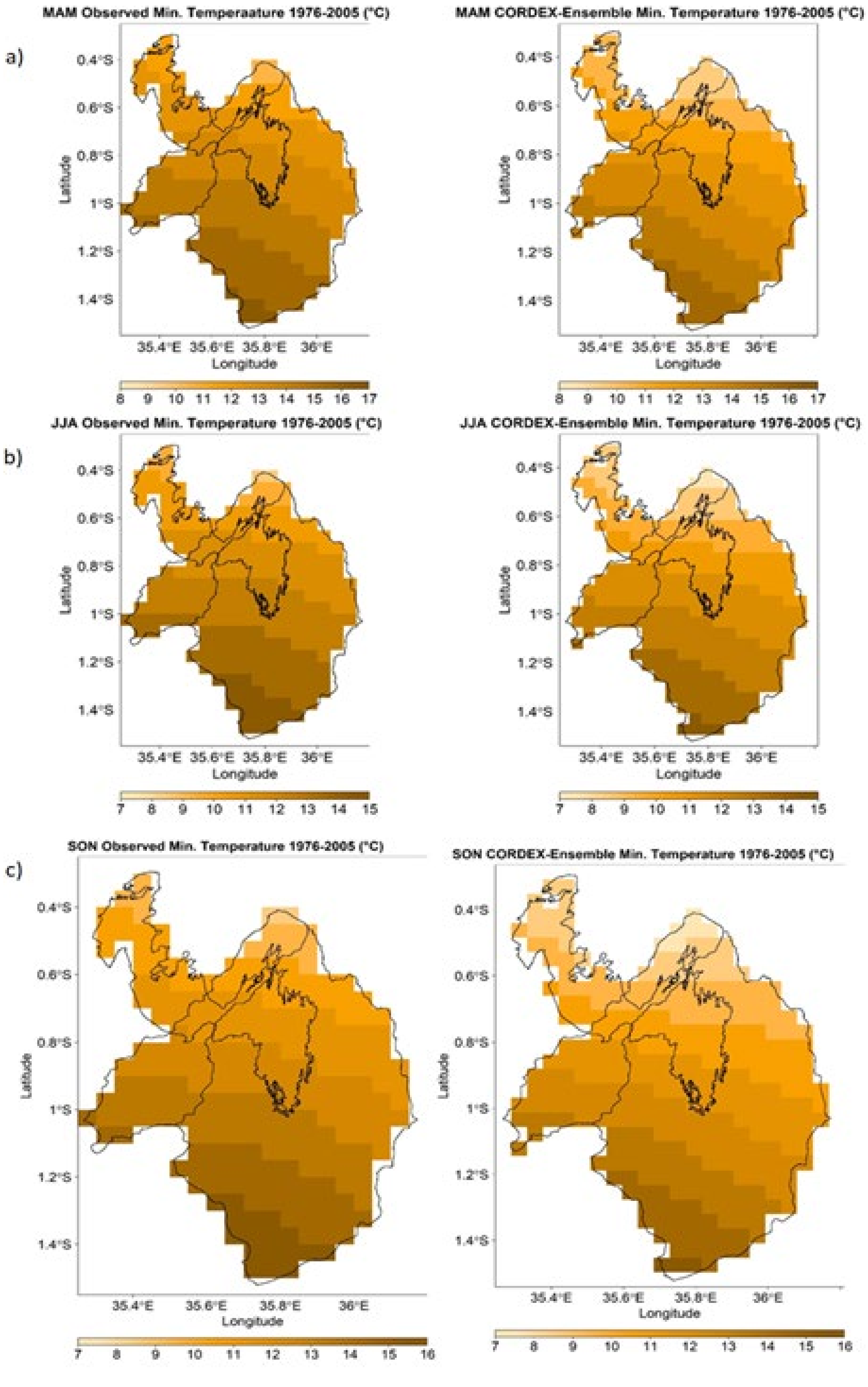

Figure 2A - 14. Seasonal average minimum temperature for the observed and CORDEX-ensemble model a) MAM, b) JJA and c) SON seasons, respectively.

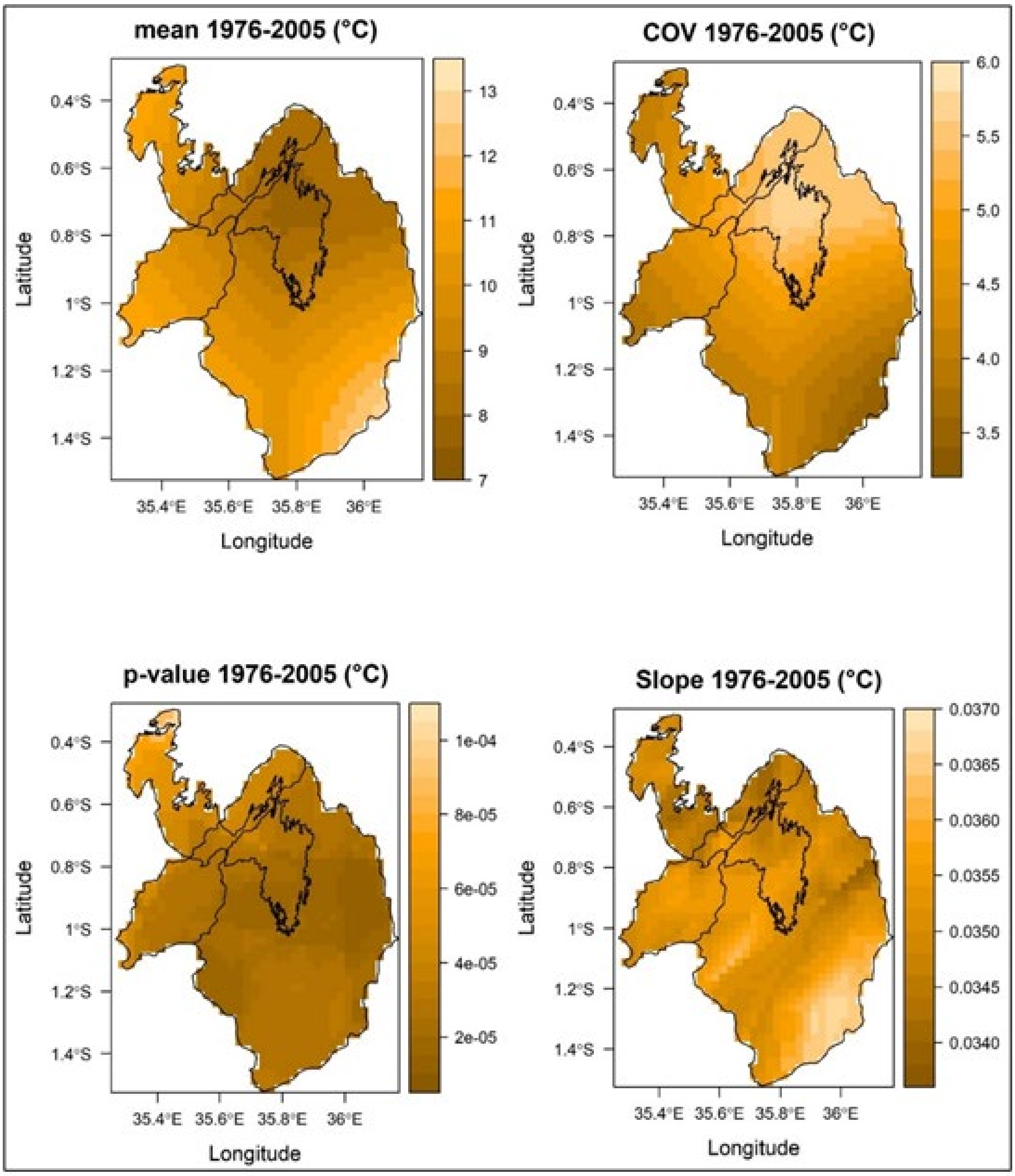

Figure 2A - 15. Spatial statistics of annual minimum temperature; mean (top left), Coefficient of Variation (CoV) (top right), p-value of trend (bottom left) and slope (bottom right) over Mau Forest Catchment.

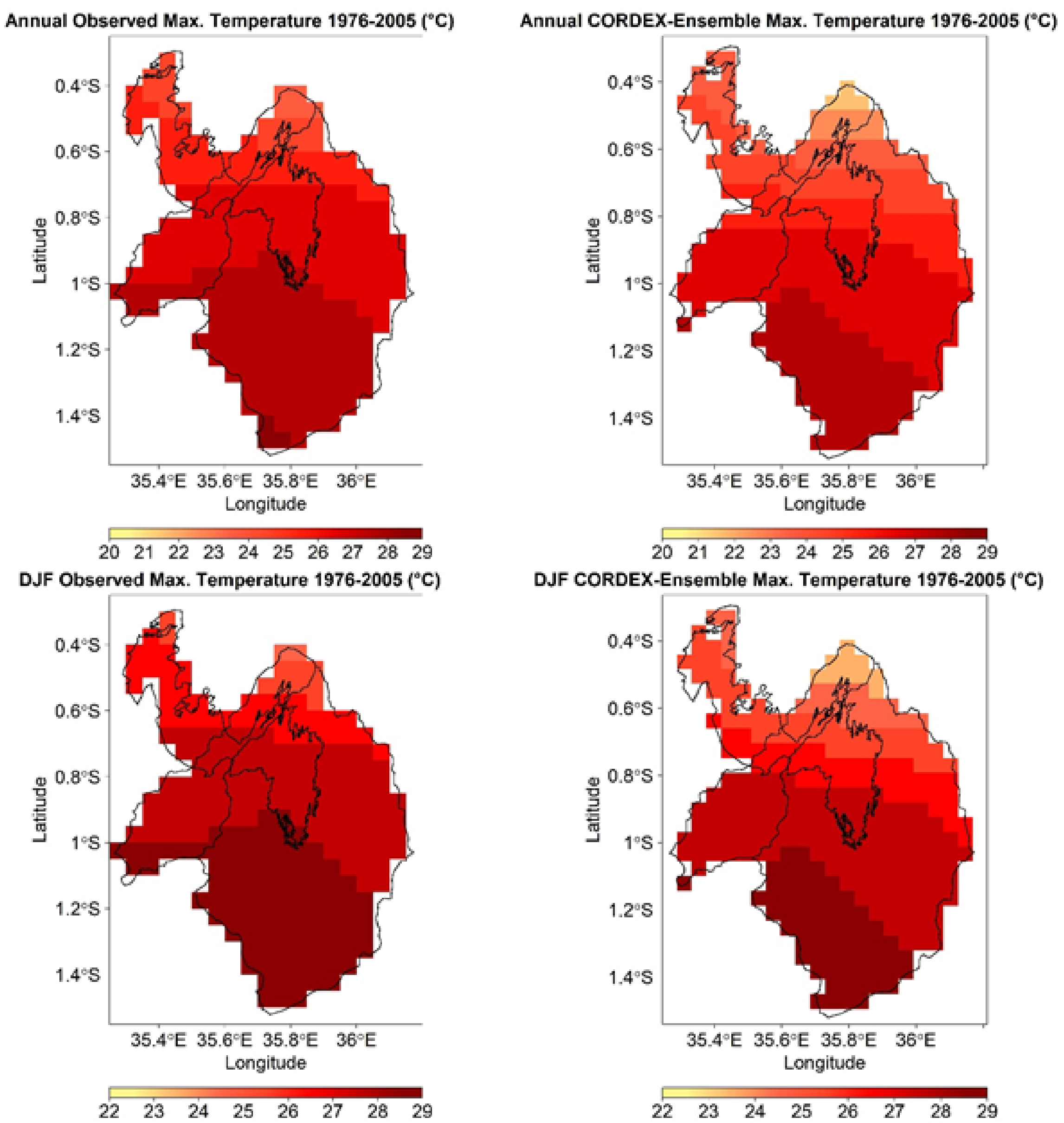

Figure 2A - 16. Annual and seasonal (DJF) average observed and CORDEX-ensemble maximum temperature for the baseline year 1976-2005 in Mau Forest Catchment.

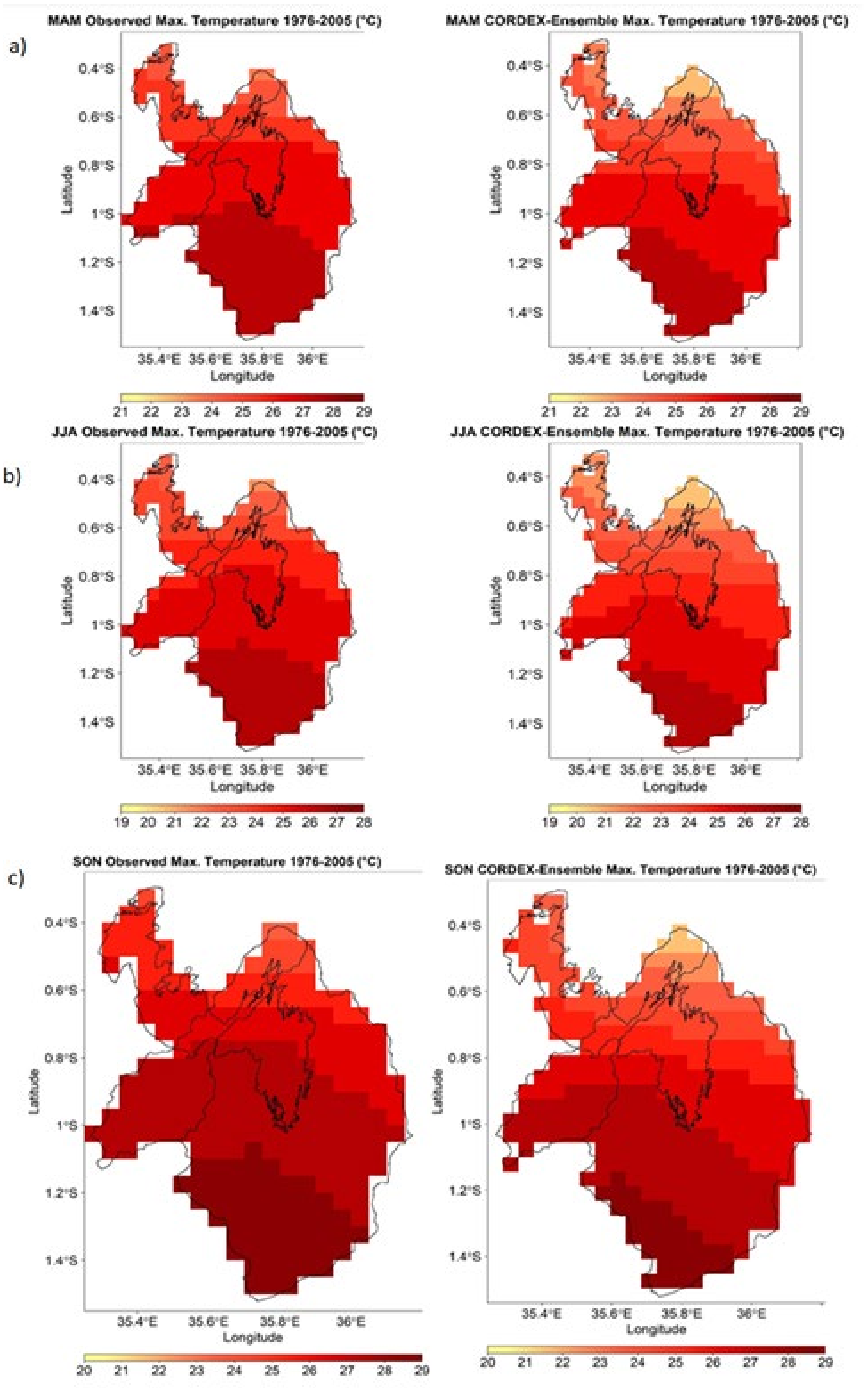

Figure 2A - 17. Seasonal average maximum temperature for the observed and CORDEX-ensemble model for the baseline year 1976-2005 in Mau Forest Catchment, a) MAM, b) JJA and c) SON seasons, respectively.

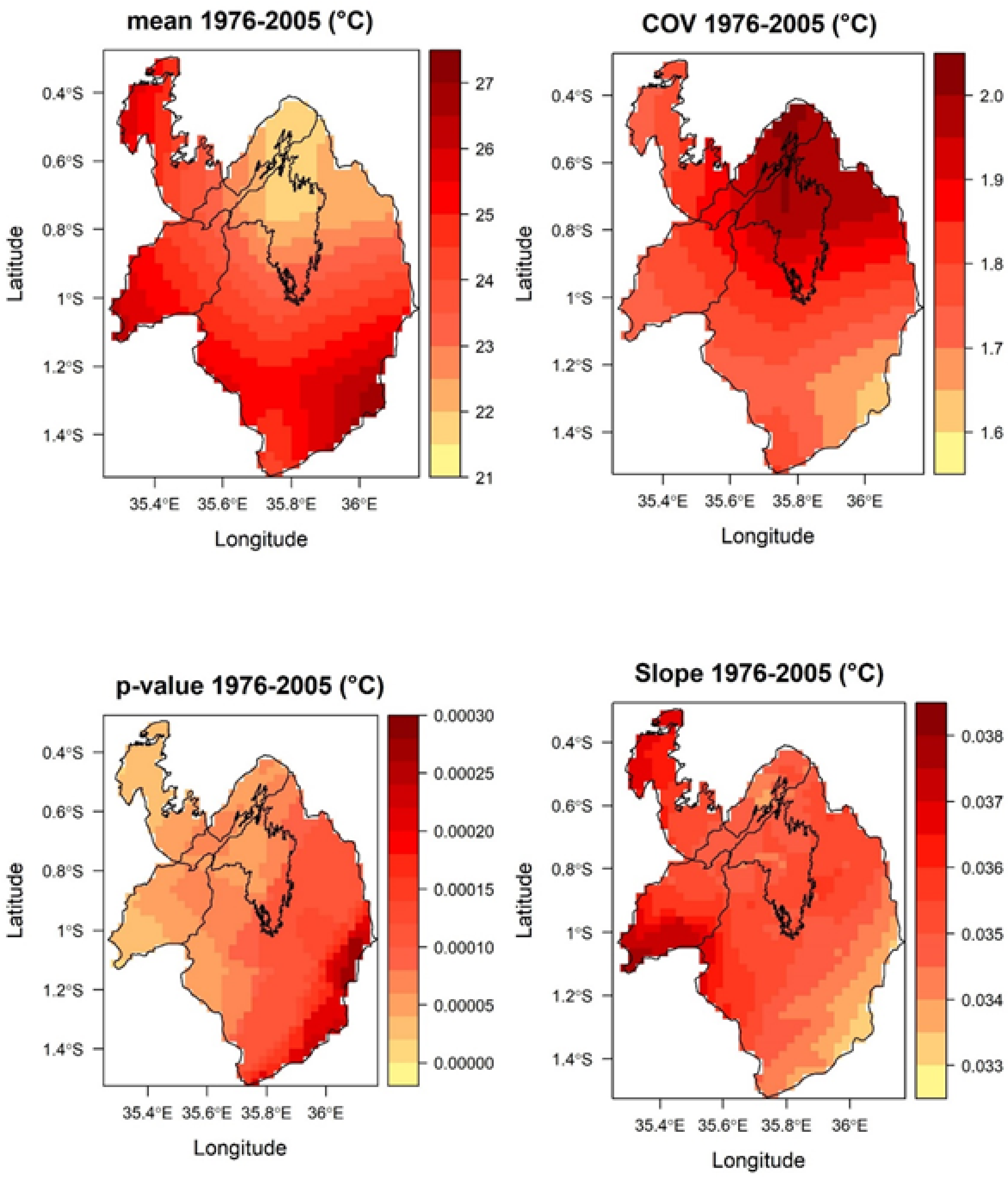

Figure 2A - 18. Spatial statistics of annual maximum temperature; mean (top left), Coefficient of Variation (CoV) (top right), p-value of trend (bottom left) and slope (bottom right) over Mau Forest Catchment.

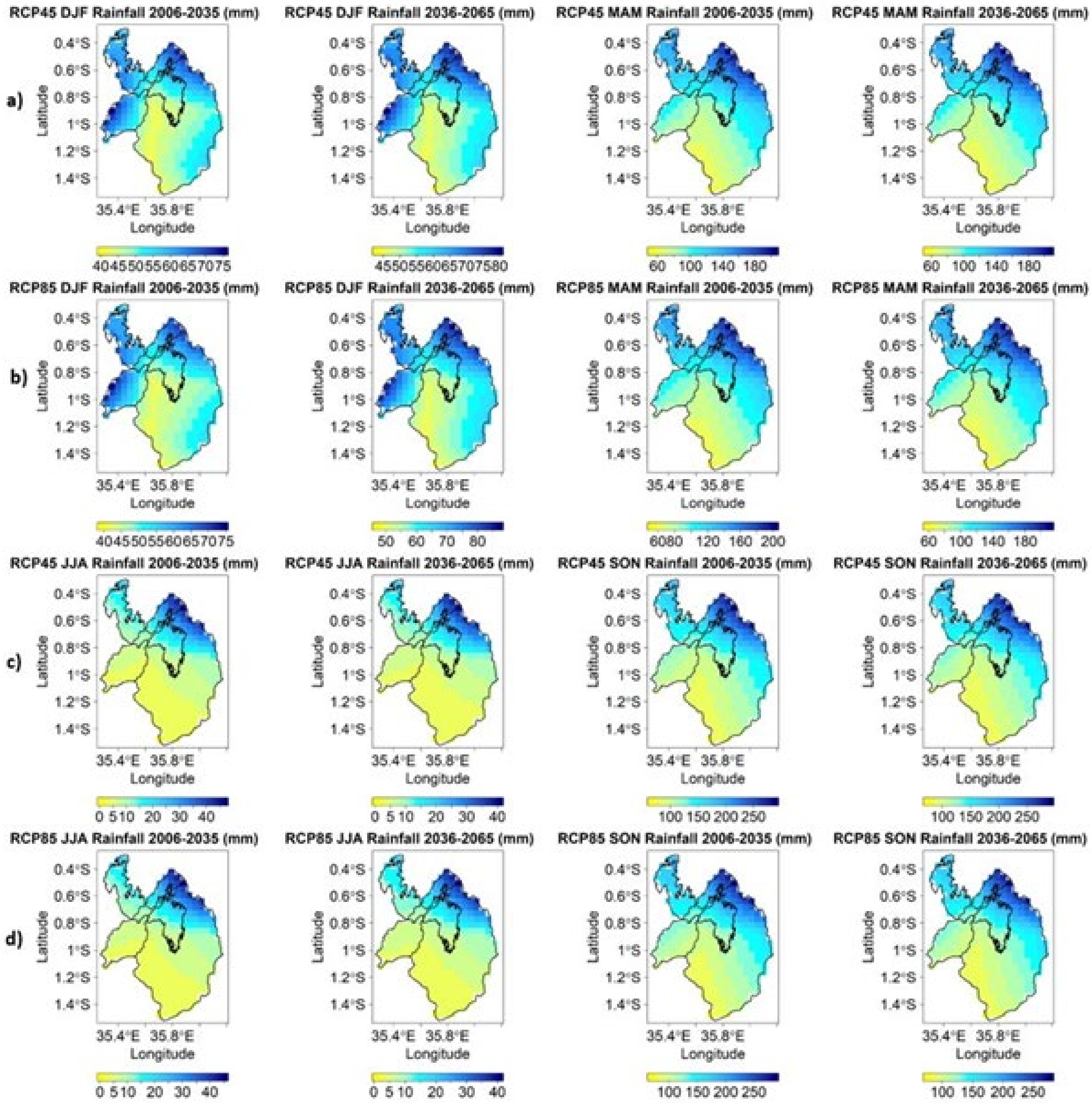

Figure 2A - 19. Seasonal total rainfall: (a) DJF and MAM, under the RCP4.5; (b) DJF and MAM for the RCP8.5; (c) JJA and SON for RCP4.5 and (d) JJA and SON for RCP8.5, across the 2006-2035 and 2036-2065 periods, respectively.

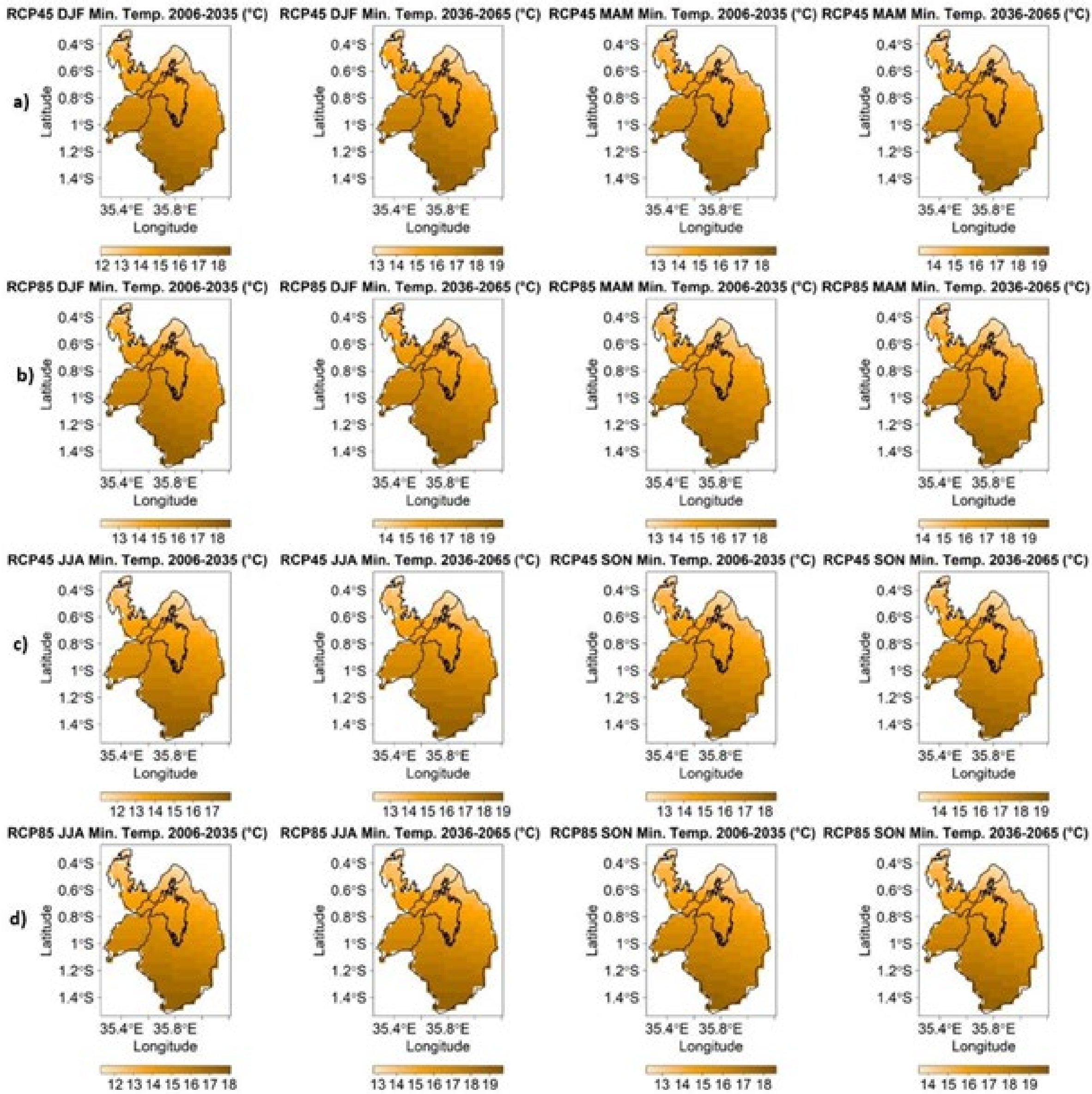

Figure 2A - 20. Seasonal minimum temperature: (a) DJF and MAM, under the RCP4.5; (b) DJF and MAM for the RCP8.5; (c) JJA and SON for RCP4.5 and (d) JJA and SON for RCP8.5, across the 2006-2035 and 2036-2065 periods, respectively.

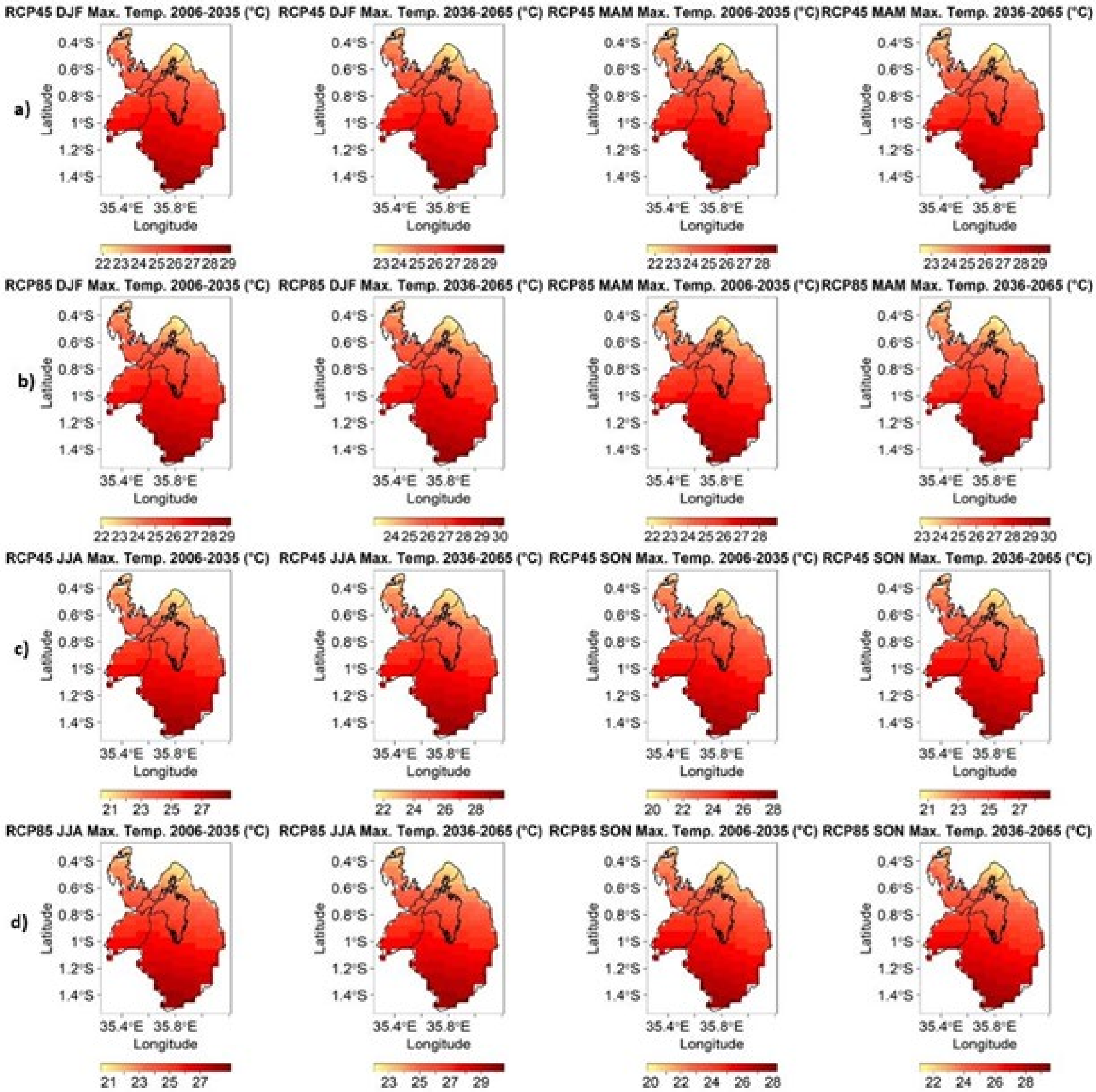

Figure 2A - 21. Annual maximum temperature for 2006-2035 (top left), 2036-2065 (top right) under conditions of the RCP 4.5 pathway and 2006-2035 (bottom left), 2036-2065 (bottom right) under conditions of the RCP 8.5 pathway in Mau Forest Catchment.

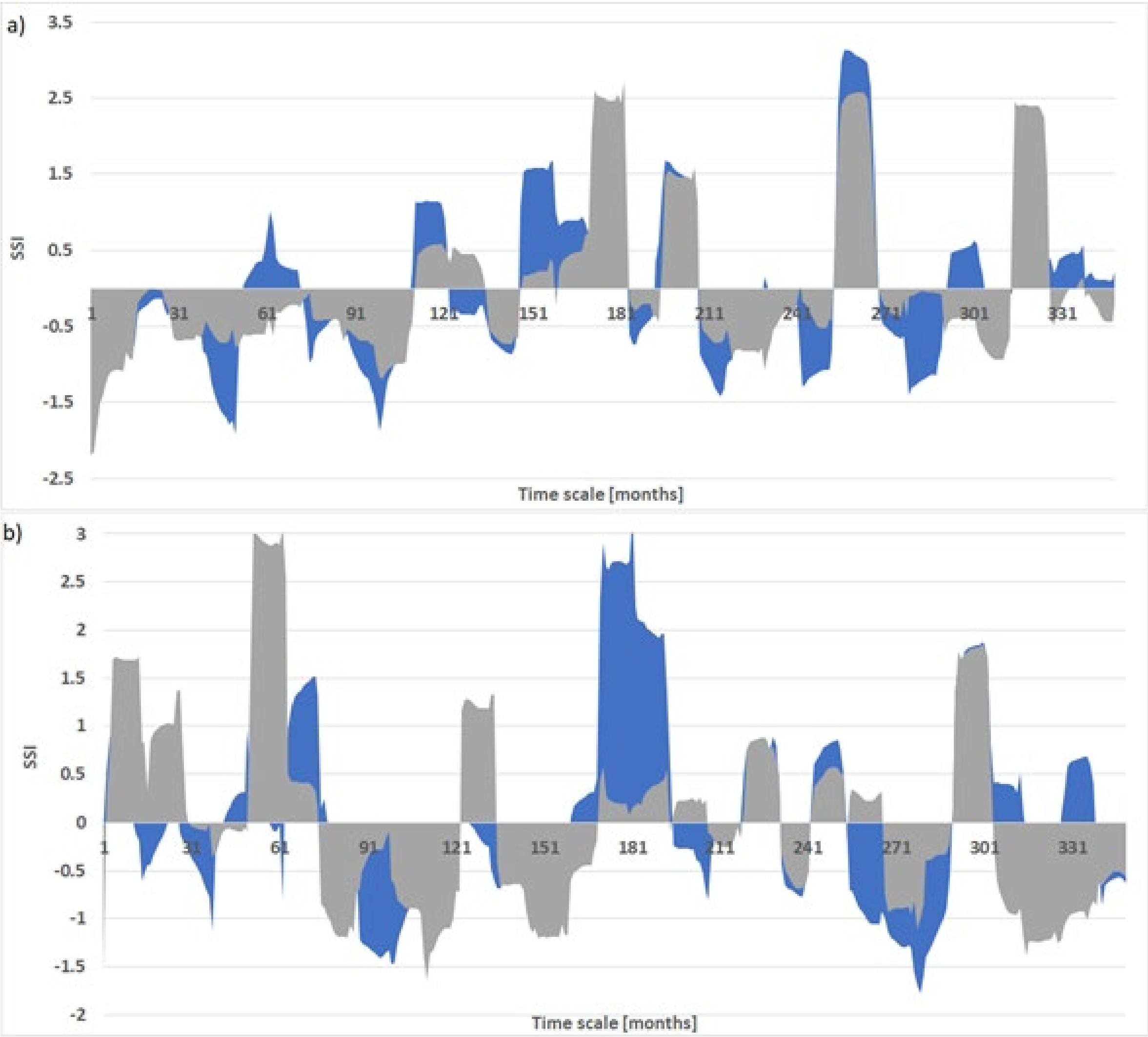

Figure 2A - 22. Standardize Streamflow Index (SSI-12) time series for selected CORDEX models; a) for RCP4.5 and (b) RCP8.5

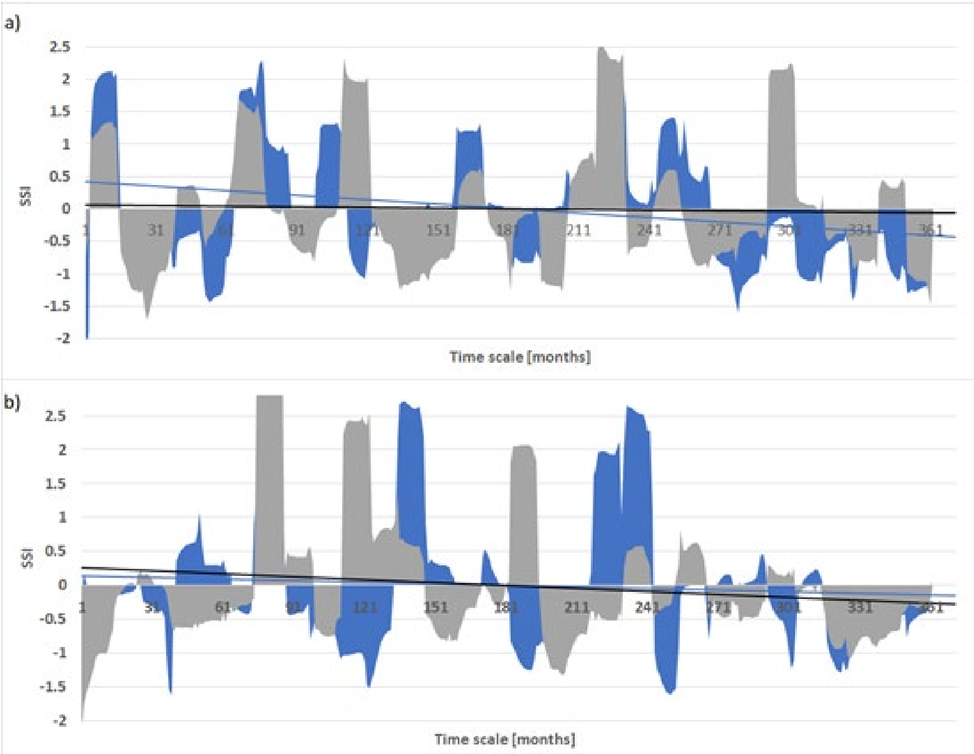

Figure 2A - 23. Near-future SSI-12 time series for selected CORDEX models; a) RCP4.5 and b) RCP8.5 scenarios

Table 2A - 1. Matrix of similarity/dissimilarity based on ACRU streamflow simulations for near-future climate projections (yellow/upper and blue/lower triangles corresponds to RCP4.5 RCP8.5, respectively)

	CanEMS2	CNRM	GFDL-ESM2M	IPSL-CM5A	MIROC5	NorESM1	Ensemble
CanESM2	0	2	2	3	4	3	2
CNRM	2	0	2	3	3	3	2
GFDL-ESM2M	2	3	0	3	4	3	2
IPSL-CM5A	2	2	3	0	3	3	3
MIROC5	3	3	4	3	0	2	4
NorESM1	3	3	3	2	3	0	3
Ensemble	2	2	3	2	3	2	0

Table 2A - 2. Matrix of similarity/dissimilarity based on mHM streamflow simulations for near-future climate projections (yellow/upper and blue/lower triangles corresponds to RCP4.5 RCP8.5, respectively)

	CanEMS2	CNRM	GFDL-ESM2M	IPSL-CM5A	MIROC5	NorESM1	Ensemble
CanESM2	0	2	2	3	2	2	2
CNRM	2	0	2	2	2	2	2
GFDL-ESM2M	2	2	0	2	2	2	2
IPSL-CM5A	2	2	2	0	2	2	3
MIROC5	2	2	2	2	0	2	2
NorESM1	2	2	2	2	2	0	2
Ensemble	2	2	2	2	2	2	0

APPENDIX B:

Appendix B: Questionnaire on barriers to the adoption of climate change adaptation and mitigation options across the Limpopo and Mau Forest Catchment Basins.

Dear Participant,

Through a Water Research Commission Project (#:C2019/2020-00017) titled, "*Climate Change and Water Security: Developmental Perspectives for Water-Linked Sectors in a Future Climate for Africa*", the South Weather Service (SAWS), in partnership with Central University of Technology (CUT), University of Kwazulu-Natal (UKZN), the Kenya Water Institute (KEWI) and Maasai Mara University (MMU) are conducting research to assess the barriers to climate change adaptation and mitigation options across the Limpopo and Mau Forest Catchment Basins. The assessment of the barriers are focused on the five dimensions, i.e. economic, technological, Institutional, socio-cultural and geophysical and environmental systems. We invite you to voluntarily participate in this survey. Please note your responses will be kept confidential.

Instructions

Please select an option that suitably represents your views regarding the existence of barriers in each of the five dimensions to each of the adaptation options across the selected water-linked sectors.

1. Strongly disagree
2. Disagree
3. Don't know
4. Agree
5. Strongly agree

Sector	Adaptation options	**Economic:** Micro-economic viability, Socio-economic vulnerability reduction potential, Employment & productivity enhancement potential	**Technological:** Technical resource availability, & risks mitigation potential	**Institutional:** Acceptability, legal & regulatory, Institutional capacity & Administrative feasibility, & Transparency & accountability potential	**Socio-cultural:** socio-cultural acceptability, co-benefits & inclusivity	Geophysical & Environmental: Adaptive capacity/resilience building potential
Agriculture	1. Water & soil conservation measures: reduce tillage, mulching, contour ridges					
	2. Changes in cropping patterns, timing of sowing and harvesting, crop diversification, improved crop cultivars					
	3. Conservation agriculture & climate smart agriculture: includes improved cultivars and agronomic practices					
	4. Indigenous and Local Knowledge					
	5. Migration and livelihood diversification					
	6. Policies, institutions & capacity building					
Energy & Industrial sectors	1. Changes in cooling water sources & alternative cooling technologies					

	2. Diversifying energy portfolios: integrating hydro, solar and wind energy					
	3. Water Intensive Industries (WII)					
Water, Sanitation and Hygiene (WaSH)	1. Climate resilient WaSH infrastructure					
	2. Better management of water resources, supply augmentation, and demand management					
Urban & Peri-urban	1. resilient circular economy					
Communities dependent on fresh water ecosystems	1. Ecosystem-based Adaptation (EbA)					
Water related conflicts	1. Water conservation, storage and infrastructure, voluntary migration, planned relocation due to flood risk					

Thank you for your participation.

Further enquiries about the project, please contact Dr Joel Botai @ joel.botai@weathersa.co.za