Modelling climatic trends for the Zambezi and Orange River Basins: implications on water security

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ABSTRACT

Climate change impacts are dependent on changes in air temperature, rainfall (frequency and amount) and climate indices, which are highly certain. Climate extreme indices are important metrics that are used to communicate the impacts of climate change. The CORDEX African-domain RCM (SMHI-RCA4) run by seven CMIP5 (CCCma-CanESM2, IPSL-IPSL-CM5A-MR, MIROC-MIROC5, MPI-M-MPI-ESM-LR, NCC-NorESM1-M, MOHC-HadGEM2-ES and NOAA-GFDL-GFDL-ESM2M) and two representative concentration pathways (RCP4.5 and RCP8.5) were used in this study. The future climate change is analysed relative to 2020–2050/1970–2000 using a multi-model ensemble projection. Selected climate indices were analysed using a multi-model ensemble of CMIP5 GCMs (GFDL-ESM2G, HadGEM2-ES and IPSL-CM5A-MR). The climate data operators (CDOs) were used in merging and manipulating the modelled (RCM) data and ETCCDI climate indices. The Mann–Kendall was used to compute the trends in time-series data at $p < 0.05$. Results indicate that temperature will increase in the Orange and Zambezi River Basins. Rainfall shows variability in both river basins. The temperature-based indices ($tn90pETCCDI$, $tnnETCCDI$, $txnETCCDI$, $tx90pETCCDI$, $txnETCCDI$ and $txxETCCDI$) were statistically significant with positive linear trends. The $dtrETCCDI$ and $wsdiETCCDI$ were statistically significant with positive linear trends within the Zambezi River Basin. $csdiETCCDI$ and $tn10pETCCDI$ were statistically significant with negative trends in both basins. The change in rainfall, temperature and climate indices will have implications on agricultural production, provisions of various ecosystem services, human health, water resources, hydrology, water security, water quality and quantity. The climate extreme indices can assist in analysing regional and global extremes in meteorological parameters and assist climate, and crop modellers and policymakers in assessing sectoral impacts.

Key words: climate change, climate indices, climate variability, ETCCDI, GCM, RCM, water security, water quality

HIGHLIGHTS

- Extreme weather events are affecting different sectors within the river basins.
- Temperature will increase, while rainfall shows variability in both river basins.
- The number of warm nights and the number of hot days were statistically significant with positive trends in the Orange and Zambezi River Basins for the period 1950–2005.
- Temperature-based indices were statistically significant with positive trends in both river basins.

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Climate change is an important environmental issue (Javadinejad et al. 2020) and is defined as a significant shift in the state of climate identified using statistical assessments by changes in either the mean state of the climate or in its variability, persisting over a long period of time (Intergovernmental Panel on Climate Model (IPCC 2007). The cross-cutting nature of the field of climate change has made it a very topical issue among scientists as well as development experts. Its ability to affect all sectors of life makes it one of the fiercest challenges faced by humanity in recent times.

According to Jain & Singh (2020), river systems are among the most vulnerable and sensitive ecosystems to the impacts of climate change. Once a riverine ecosystem is affected, the impacts will not only be felt through the hydrological regimes within the ecosystem but will also affect human activities that depend on the water resources. This is in addition to the threats to the survival of aquatic systems, wildlife and all organisms dependent on river systems. Other functions of rivers, such as the regulatory functions, habitat functions, water purification or pollution disposal functions, are all likely to be affected by the impacts of climate change. The habitat functions of rivers are such that many other ecosystems are sustained by the existence of major rivers such as the Zambezi and Orange Rivers. These riverine systems support wetlands, riparian areas and flood plains within their course, all of which would be affected by the impacts of climate change. Besides these possible effects, several other consequences are likely to follow if the dynamics of these riverine systems were to change due to climate change. For example, general water resource management (Kundzewicz et al. 2008) would be affected, irrigation schemes dependent on the rivers would be affected, as well as water quality (Delpla et al. 2009). The problems facing riverine systems have been exacerbated by pollution, poor ecosystem health, deteriorating water quality, pollution and climate change. Extreme climate indices, lack of integrated drought and flood management, low adaptive capacity, variability and uneven distribution of rainfall are expected to be amplified in future due to changes in precipitation and temperature (UNFCCC 2007; SADC-WD/ZRA 2008; Chisanga 2019; Chisanga et al. 2020a).

The UNFCCC (2007) noted that developing countries are especially vulnerable to variability in precipitation and increasing temperature. Developing countries have inadequate resources to adapt financially, technologically and socially. Climate model simulations suggest that climate extreme events will become more severe and increase in frequency, affecting an estimated 60–120 million people in Southern Africa (You et al. 2010). Climate change and variability threaten water resources, food production and productivity in sub-Saharan Africa. The Orange and Zambezi River Basins are threatened by floods, droughts, water stress, interannual variability and seasonal variability (SADC-WD/ZRA 2008; Reig et al. 2013). Concerns have arisen that the water resources within the Orange River Basin have not been used sustainably in the past 25 years (Lange et al. 2007).

In recent years, the energy challenges that have faced southern African countries dependent on hydroelectric power generation from the Zambezi and Orange River Basins necessitate the need for a study in the hydrological regimes and climate change impacts on these very important resources. There is a need to understand the impact of climate change on streamflow and the security of the hydrologic conditions of river basins (Oo et al. 2020). Climate extremes often manifest as rare events in terms of surface air temperature and precipitation with an annual reoccurrence period (Yang et al. 2018). Therefore, the study aimed to assess changes in precipitation, temperature and selected Expert Team on Climate Change Detection and Indices (ETCCDI) in the Orange and Zambezi River Basins during the baseline and future climate scenarios using RCPs (RCP4.5 and
This study utilised RCMs to provide a baseline and future climate scenario of the likely climate change in the Orange and Zambezi River Basins. Cooney (2012) pointed out that RCMs have been used to simulate extreme weather events like heat waves, heat stress, heavy rains and droughts, which occur on a regional scale. Furthermore, at a local scale, RCMs have been used to simulate extreme weather events using rainfall, temperature and wind flow as inputs. The impact due to changes in rainfall and temperature is greater when associated with extreme events (floods, heat stress, droughts and heat-waves) and vulnerable populations are at risk (Brown et al. 2010; Mistry 2019).

The structure of this article is organised as follows: description of the Orange and Zambezi River Basins, sources of data, climate scenarios and data analysis are presented in Section 2. Section 3 presents validation statistics, projected changes in temperature and rainfall, changes in selected ETCCDI indices, potential impacts on agriculture production, ecosystem services, health and water resources, and hydrology and implications on water resources. Finally, the conclusion is described.

2. MATERIALS AND METHODS

2.1. Description of the Orange and Zambezi River Basins

2.1.1. Orange River Basin

The Orange River Basin is shared by Lesotho, South Africa, Namibia and Botswana (ANBO 2007) (Figure 1; Table 1), and it covers nearly 3% of the African continent. Furthermore, the Orange River Basin covers an area and a length of 850,000 km² and 2,500 km, respectively. The Orange River starts in Lesotho and receives water from the Makhaleng tributary before entering South Africa (Mohamed 2014). The Caledon tributary between the borders of South Africa and northern Lesotho flows into the Orange River downstream into South Africa. The mean yearly flow from Lesotho to South Africa is estimated at 4.73 km³ year⁻¹. The Orange River is known as the Senqu River as it passes the Lesotho Highlands at about 3,500 m above sea level. It is the primary source of water for the country. In spite of 3% of the Orange River Basin being in Lesotho, Lesotho provides excess flow from the highlands due to high annual mean rainfall. The entire South African plateau is drained by the Orange River and its tributaries. It contributes 22% of the total South African runoff. Furthermore, 64% of the Orange River Basin area is located in South Africa and provides that country’s main water supply.

The Orange River has a lot of tributaries along the Namibia-South Africa boundary. Namibia has many seasonal rivers that are tributaries of the Orange River. One important such tributary is the Fish River where the Hardap Dam was constructed in 1972. Botswana has the smallest part of the Orange River and contributes the least amount of runoff due to its low annual rainfall. The south-western part of Botswana is drained by the Molopo River, which is a tributary of the Orange River. Infrastructure development on the Orange River is extremely high having 29 dams and reservoirs that control its flow, and widespread infrastructure for inter-basin transfer of the water (IRBA 2000). High evapotranspiration and withdrawals from the Orange River have led to a reduction of the natural flow by half (Lange et al. 2007; Mohamed 2014). The dams on the Orange River are used for generating hydroelectric power, regulating channel flows and for irrigation. However, very little water from the river is used for domestic and industrial purposes.

The Vaal River is an important tributary of the Orange River. The average annual runoff from the Vaal Basin is estimated at about 4.27 km³, of which 2.15 km³ is exploitable. It is used to supply water for both domestic and industrial purposes. The Orange River and Vaal River Basins’ water resources are managed independently (Lange et al. 2007). The Orange River is divided into two water management units, upper and lower parts at the point where the Vaal River joins it. The Upper Orange River with its tributaries, the Orange-Senqu River in Lesotho and part of South Africa above the Vaal confluence. The Orange River Basin annual runoff is estimated at 7.59 km³, of which 5.76 km³ is exploitable excluding the Vaal River Basin. The Lower Orange River is below the Vaal confluence and includes parts of Namibia, South Africa and Botswana (Lange et al. 2007).

2.1.2. Zambezi River Basin

The Zambezi River Basin has 13 major sub-basins and is the fourth largest river basin in Africa after the Congo, Nile and Niger (FAO 1997; ANBO 2007). It occupies 4.5% of the total area of the African continent and is shared among eight countries, as shown in Figure 1 and Table 2. The area and length of the Zambezi River Basin are 1,400,000 km² and 2,650 km, respectively (ANBO 2007). From its source in Kalene Hills in the north-western of Zambia and flows northwards for about 30 km. It then runs for nearly 280 km turning west and south through Angola as it re-enters Zambia carrying an annual discharge of approximately 18 km³. After 30 km, it flows southwards through marshy plains in the south-west of
Figure 1 | Relative location and geospatial coverage of the Orange and Zambezi River Basins. The Orange River Basin is shared by Lesotho, South Africa, Namibia and Botswana. The Zambezi River Basin is shared by Angola, Namibia, Botswana, Zimbabwe, Zambia, Tanzania, Malawi and Mozambique.
Zambia as it becomes the border for about 130 km between Zambia and Namibia eastern Caprivi Strip. The river flows for 3,000 km eastward from its sources towards the Indian Ocean. The Chobe tributary of the Zambezi River originates in Angola and crosses the Caprivi Strip carrying 1.3 km$^3$ as its annual discharge. It forms the border between Botswana and Namibia (FAO 1997; ANBO 2007; Beilfuss 2012). As it enters Botswana, it flows for 75 km southwards till it meets the Selinda spillway where spillage from the Okavango arises during high flood years. Thereafter, the Zambezi River turns east forming the border between Botswana and Namibia through a swampy area and flows at the border point of Botswana, Namibia, Zimbabwe and Zambia carrying 4.1 km$^3$ as its annual discharge. An annual discharge of 33.5 km$^3$ has been recorded at this point (FAO 1997; Beilfuss 2012). The river forms the border between Zimbabwe and Zambia as it flows eastward and has its highest width of over 1.3 km, just before its waters drop over the Victoria Falls. After the Victoria Fall, it follows the border between Zimbabwe and Zambia before entering Mozambique. Two man-made lakes are located along the River, Lake Kariba and Cahora Bassa along the border between Zimbabwe, and Zambia and in Mozambique, respectively.

The Kafue River, a tributary of the Zambezi River downstream of Lake Kariba, discharges 10 km$^3$/year into the Zambezi River. The Luangwa River originating from the north-east at the border between Zambia and Mozambique provides an annual flow of 22 km$^3$. The Cahora Bassa dam receives an estimated discharge of 77.5 km$^3$ of water per year. The last tributary of the Zambezi River as it flows south-eastward is the Shire having an average annual discharge of 16 km$^3$ year$^{-1}$. It drains Lake Malawi about 450 km to the north. The southern part is the border between Mozambique and Malawi, while the northern part of Lake Malawi forms the border between Tanzania and Malawi. The total flow into the lake is estimated at about 29 km$^3$ year$^{-1}$, of which 53% is Tanzania, 43% is Malawi and 4% is Mozambique. The total annual outflow from Lake Malawi into the Shire River in the south is estimated at 12.5 km$^3$. The water level in the lake has reduced by 6 m during the last 100 years, with its lowest and highest levels being noted in 1917 and 1980, respectively.

**Table 1 | Orange River Basin represented in area and rainfall by country**

| Country | Total area of country (km$^2$) | Area of country within basin (km$^2$) | Total area of basin (%) | Total area of country (%) | Average annual rainfall in basin area (mm) |
|---------|-----------------------------|----------------------------------|-------------------------|--------------------------|----------------------------------------|
|         |                             |                                  |                         |                          | Min. | Mean | Max.  |
| Botswana| 581,730                     | 71,000                           | 12.2                    | 2.1                      | 35   | 185  | 415   |
| Namibia | 824,900                     | 219,249                          | 26.6                    | 2.1                      | 575  | 755  | 1,040 |
| Lesotho | 30,350                      | 30,350                           | 100                     | 100                      | 35   | 365  | 1,035 |
| South Africa | 1,221,040               | 575,769                          | 47.2                    | 54.5                     | 35   | 325  | 1,040 |
| For Orange Basin | 896,368                   | 100                              | 100                     | 100                      | 35   | 325  | 1,040 |

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**Table 2 | Zambezi River Basin represented in areas and rainfall by country**

| Country | Total area of country (km$^2$) | Area of country within basin (km$^2$) | Total area of basin (%) | Total area of country (%) | Average annual rainfall in basin area (mm) |
|---------|-----------------------------|----------------------------------|-------------------------|--------------------------|----------------------------------------|
|         |                             |                                  |                         |                          | Min. | Mean | Max.  |
| Angola  | 1,246,700                   | 235,423                          | 17.4                    | 18.9                     | 550  | 1,050| 1,475 |
| Namibia | 824,900                     | 17,426                           | 1.3                     | 2.1                      | 545  | 630  | 690   |
| Botswana| 581,730                     | 12,401                           | 0.9                     | 2.1                      | 555  | 595  | 665   |
| Zimbabwe| 390,760                     | 213,036                          | 54.5                    | 54.5                     | 525  | 710  | 1,590 |
| Zambia  | 752,610                     | 574,875                          | 76.4                    | 53%                      | 600  | 955  | 1,435 |
| Tanzania| 945,090                     | 27,840                           | 2.9                     | 43%                      | 1,015| 1,240| 1,785 |
| Malawi  | 118,480                     | 108,360                          | 91.5                    | 45%                      | 745  | 990  | 2,220 |
| Mozambique | 801,590                  | 162,004                          | 20.2                    | 4%                       | 555  | 905  | 1,790 |

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The Zambezi River at its mouth splits into a flat, wide marshy delta. It has been estimated that 106 km³ per annual enters the Indian Ocean. The annual rainfall in the Zambezi River Basin decreases from almost 1,800 mm (northern part) to less than 550 mm (southern part). Namibia and Botswana have dry climatic conditions and only 2% of each country is situated within the Zambezi River Basin. As a consequence, these countries receive an annual precipitation of approximately 600 mm, being higher than the countries’ average of 400 and 280 mm for Botswana and Namibia, respectively.

2.2. Sources of data

2.2.1. Regional climate models

The sources of the RCMs were the Coordinated 15 Regional Climate Downscaling Experiment (CORDEX) and African Domain (AFR-44). CORDEX provides global coordination of high-resolution, historical and future climate projections for improved regional climate change adaptation and impact assessment. It also aims to improve our understanding of climate variability and changes on regional scales by providing higher-resolution RCM simulations for 14 domains around the world (Lee et al. 2018).

One RCM (SMHI-RCA4) driven by seven CMIP5 GCMs (IPSL-IPSL-CM5A-MR, CCCma-CanESM2, MIROC-MIROC5, MPI-M-MPI-ESM-LR, MOHC-HadGEM2-ES, NOAA-GFDL-GFDL-ESM2M and NCC-NorESM1-M) and two scenarios (RCP4.5 and RCP8.5) (Table 3) used in this study were downloaded from the CORDEX and AFR-44 (http://ccocr.tropmet.res.in/cordex/files/downloads.jsp). The CMIP5 GCMs were selected on the basis of having complete data for historical and two representative concentration pathways (RCP4.5 and RCP8.5). The RCM simulation ran at 0.5° spatial resolution of daily precipitation, and the minimum and maximum temperatures covered 1970–2000 (baseline scenario) and 2020–2050 (future climate scenario). The 50 km resolution of CORDEX African-domain RCMs were used to generate a seven-member multi-model ensemble of climate projections for the Orange and Zambezi River Basins. The RCPs depict the greenhouse gas (GHG) concentration trajectory approved by the IPCC in the Fifth Assessment Report in 2014 (Denton et al. 2014). The RCP4.5 and RCP8.5 represent intermediate GHG emissions (650 ppm CO₂ eq.) and very high GHG emissions (1,370 ppm CO₂ eq.).

The World Meteorological Organization quantifies climate over a 30-year period (Dent 2012; Rigal et al. 2019). The observed 30-year climate is used to create new observations and the basis for measuring climatic trends. An ensemble of the RCMs was created for the baseline (1970–2000) and future (2020–2050) climate scenarios under two RCPs (RCP4.5 and RCP8.5).

2.2.2. Observations

The Climate Research Unit time series version 4.03 high-resolution (0.5°×0.5°) gridded datasets of month-by-month variation of precipitation and minimum and maximum temperatures (January 1901–December 2018) were extracted from https://cru-data.uea.ac.uk/cru/data/hrg/cru_ts_4.03/crutics.1905011326.v4.03/ (Harris et al. 2020a, 2020b). The CRU TS4.03 data was produced using angular-distance weighting interpolation and the data is based on gridded monthly fields calculated from sub-daily and/or daily data by the National Meteorological Services and other external agents (Harris et al. 2020a). The extracted NetCDF files contained monthly mean values for temperature and precipitation. The missing value is coded for ‘stn’ as −999.

Table 3 | SMHI-RCA4 Africa CORDEX 50 km matrix

| GCM      | Historical 1950–2005 | RCP8.5 2006–2100 | RCP4.5 2006–2100 |
|----------|----------------------|------------------|------------------|
| HadGEM   | ✓                    | ✓                | ✓                |
| MIROC5   | ✓                    | ✓                | ✓                |
| NorESM   | ✓                    | ✓                | ✓                |
| CanESM   | ✓                    | ✓                | ✓                |
| GFDL-ESM | ✓                    | ✓                | ✓                |
| MPI-ESM  | ✓                    | ✓                | ✓                |
| IPSL-CM  | ✓                    | ✓                | ✓                |
2.2.3. Climate indices

Climate extremes indices as defined by the ETCCDI dataset were downloaded from the Canadian Centre for Climate Modelling and Analysis (CCCMA) (https://climate-modelling.canada.ca/climatemodelfdata/climdex/), and their definitions are presented in Table 4. The ETCCDI were started in 1999 and are co-sponsored by the World Climate Research Programme and JCOMM (Alexander et al. 2013). It is a joint international effort with the participation of Environment and Climate Change Canada among other organisations. The World Climate Research Programme and JCOMM (Alexander et al. 2013) have developed the 27 descriptive ETCCDI climate indices for moderate extremes (Zhang et al. 2011; Alexander et al. 2013; Alexander & Herold 2016; Alexander et al. 2019).

The datasets for assessing climate variability and change are provided by ETCCDI (Dietzsch et al. 2017). The ETCCDI climate indices are based on daily time series of temperature and precipitation. The ETCCDI indices are divided into four categories, namely (i) extreme value indices; (ii) absolute threshold-based exceedance indices; (iii) duration-based extreme indices and (iv) percentile-based indices (Yang et al. 2018; Chapagain et al. 2021). Some indices are based on fixed thresholds that are relevant to particular applications, and others are based on thresholds that vary from location to location. The thresholds are defined as a percentile of precipitation and temperature data (Alexander et al. 2013). The climate extremes were computed using a multi-model ensemble of CMIP5 GCMs (GFDL-ESM2G, HadGEM2-ES and IPSL-CM5A-MR). The CMIP5 GCMs were simulated using observations from 1961 to 1990 (Sillmann et al. 2013a, 2013b). The CMIP5 GCM simulations are run at higher spatial resolution, and the climate models have a complete representation of physical parameterisations (Charron 2014). The analysed and validated simulated baseline and future projected changes in CMIP5 climate extreme indices are presented by Sillmann et al. (2013a, 2013b).

2.3. Data analysis

2.3.1. Climate data operators

The CDOs were used in merging and manipulating the modelled (RCM) data and ETCCDI climate indices. The CDO developed at Max Planck Institute for Meteorology (Schulzweida et al. 2012) represents a set of statistical and arithmetic commands useful for processing atmospherics data in GRIB and NetCDF format. The CDOs were used to generate and

Table 4 | Selected ETCCDI core climate indices and their definitions (http://etccdi.pacificclimate.org/list_27_indices.shtml)

| Type                        | Index          | Name                        | Definition                                                                 | Unit       |
|-----------------------------|----------------|-----------------------------|---------------------------------------------------------------------------|-----------|
| Percentile-based extreme temperature indices | tn10pETCCDI | Amounts of cold nights | Annual % of days when TN <10th percentile | %          |
|                             | tn90pETCCDI   | Amounts of warm nights      | Annual % of days when TN >90th percentile | %          |
|                             | tx10pETCCDI   | Amounts of cold nights      | Annual % of days when TX <10th percentile | %          |
|                             | tx90pETCCDI   | Amounts of warm nights      | Annual % of days when TX >90th percentile | %          |
| Absolute value-based extreme temperature indices | tminETCCDI     | Minimum TX                  | Annual coldest daily TN                                                   | °C         |
|                             | tmaxETCCDI    | Max. TN                     | Annual warmest daily TN                                                   | °C         |
|                             | txnETCCDI     | Annual coldest daily TX     | Annual coldest daily TX                                                   | °C         |
|                             | txxETCCDI     | Max. TX                     | Annual warmest daily TX                                                   | °C         |
| Duration-based extreme temperature indices | csdiETCCDI     | Cold spell duration indicators | Annual no. of days contributing to events where six or more consecutive days experience TN <10th percentile | days       |
|                             | wdsiETCCDI    | Warm spell duration indicator | Annual no. of days contributing to events where six or more consecutive days experience TX >90th percentile | days       |
| Magnitude-based rainfall indices | prcptotETCCDI | Total rainfall              | Sum of daily rainfall >1.0 mm                                             | mm         |
| Percentile-based extreme rainfall indices | r99ptotETCCDI | Contribution from extreme wet days | 100*R99p/PRCPTOT                                                          | %          |
| Duration-based extreme rainfall indices | cddETCCDI    | Consecutive dry days        | Max. annual no. of consecutive dry days                                    | days       |
|                             | cwdETCCDI     | Consecutive wet days        | Max. annual no. of consecutive wet days                                    | days       |
compute the multi-model ensemble from the RCMs and ETCCDI climate indices, respectively. The climate indices were computed using a three-GCM multi-model ensemble from 1950 to 2005 using aerial means for the Orange and Zambezi River Basins. R Programming software was used to manipulate the observations, modelled and ETCCDI climate indices data and for graphing the outputs from the analysis. The Mann–Kendall was utilised to compute trends in time-series data at a 95% confidence interval (\( p<0.05 \)).

### 2.3.2. Trend analysis

The Mann–Kendall, which is a non-parametric statistical test (Butler 2015; McLeod 2015; Pohlert 2016), was used to detect monotonic trends in ETCCDI climate indices on an annual scale (1950–2005). The trends in ETCCDI climate indices (Table 4) were assessed at \( p<0.05 \) (95% confidence level) using the Mann–Kendall Package in R Programming. Other researchers have used Sen’s trend analysis method (Sen 1968; Yin & Sun 2018; Cooley & Chang 2021). The method does not require data to conform to a normal distribution and better estimate the trend changes of extreme rainfall and temperature (Yin & Sun 2018). The Mann–Kendall test statistics were computed using the following equation:

\[
S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{sgn}(x_j - x_k)
\]  

(1)

In Equation (1), \( n \) is the sample size, \( j \) and \( k \) are sequential values of \( X \) and \( \text{sgn}(\cdot) \) is a sign function given by the following equation:

\[
\text{sgn}(x) = \begin{cases} 
1 & \text{if } x > x_j \\
0 & \text{if } x = x_j \\
-1 & \text{if } x < x_j 
\end{cases}
\]

(2)

The mean of \( S \) is calculated using \( E[S] \), while the variance \( S \) is computed using the following equation:

\[
S = \frac{1}{8} \left[ n(n - 1)(2n + 5) - \sum_{j=1}^{p} t_j(t_j - 1)(2t_j + 5) \right]
\]

(3)

where \( n \) is the number of tied groups in the dataset and the number of data points in the \( j \)th tied group is given by \( t_j \). The \( S \)-statistic is distributed normally and used to transform the \( Z \)-statistic. The \( Z \)-statistic (Butler 2015; Mcleod 2015) was used to test the null (\( H_0 \)) hypothesis against the alternative hypothesis (\( H_1 \)). A positive score of the \( Z \)-statistic value represented an upward positive trend and a negative score indicated a downward trend. A \( Z \)-statistic was calculated using the following equation:

\[
Z = \begin{cases} 
\frac{s - 1}{\sqrt{\sigma^2(s)}} & \text{if } S > 0 \\
0 & \text{if } S = 0 \\
\frac{s + 1}{\sqrt{\sigma^2(s)}} & \text{if } S < 0 
\end{cases}
\]

(4)

The \( S \)-statistic is closely related to Kendall’s \( \tau \) as provided by the following equation:

\[
\tau = \frac{S}{D}
\]

where

\[
D = \left[ \frac{1}{2} n(n - 1) - \frac{1}{2} \sum_{j=1}^{p} t_j(t_j - 1) \right]^{1/2} \left[ \frac{1}{2} (n - 1) \right]^{1/2}
\]

(5)

### 2.3.3. Validation of the RCMs

The performance of the models (RCMs) and multi-model ensemble was validated by comparing the observations (CRU TS v4.03) and simulated annual cycles of precipitation and temperature. The metrics used to validate the modelled data were
correlation, standard deviation (SD) and centred root-mean-square error (RMSE). The Taylor diagram (Taylor 2001; Griggs & Noguer 2002; Elvidge et al. 2014) was used to plot the spatial pattern of correlations, RSME and standard deviations with respect to the observations.

3. RESULTS AND DISCUSSIONS

3.1. Validation statistics

Table 5 shows the validation metrics between the RCMs and CRU-TS. The overall evaluation shows a strong correspondence of the modelled (RCMs; CCCma-CanESM2, MIROC-MIROC5, MOHC-HadGEM2-ES, IPSL-IPSL-CM5A-MR, MPI-M-MPI-ESM-LR, NCC-NorESM1-M, NOAA-GFDL-GFDL-ESM2M) data with observed (CRU-TS) based on statistical metrics (SD, RMSE and correlation). The observed (CRU-TS) and modelled (RCMs) data were highly correlated with values being ≥0.70 for the ensemble and considered to be high (Coelho et al. 2018).

3.2. Projected changes in temperature and precipitation

The projected changes in temperature, rainfall, extreme events, climate change drivers, impacts and responses are summarised using a conceptual framework as shown in Figure 2.

Table 5 | Validation of modeled (RCMs) versus observed (CRU) rainfall (PRCP), minimum ($T_{\text{min}}$) and maximum ($T_{\text{max}}$) temperatures

|                | Rainfall | $T_{\text{max}}$ | $T_{\text{min}}$ |
|----------------|----------|-----------------|-----------------|
|                | SD       | RMSE | Correlation | SD | RMSE | Correlation | SD | RMSE | Correlation |
| CRU            | 78.66    | 1.76 | 3.18        | 1.76 | 1.64 | 0.76        | 3.18 | 1.07 | 0.95       |
| CCCma-CanESM2  | 87.39    | 39.78| 0.89        | 2.25 | 1.64 | 0.76        | 3.01 | 2.77 | 0.93       |
| MIROC-MIROC5   | 100.08   | 42.17| 0.93        | 2.12 | 2.39 | 0.71        | 1.22 | 2.77 | 0.93       |
| MOHC-HadGEM2-ES| 92.48    | 45.32| 0.88        | 1.98 | 2.23 | 0.74        | 1.2  | 2.74 | 0.93       |
| IPSL-IPSL-CM5A-MR | 81.67 | 41.52| 0.66        | 2.15 | 1.52 | 0.73        | 1.72 | 2.79 | 0.93       |
| MPI-M-MPI-ESM-LR| 95.78   | 48.49| 0.89        | 2.25 | 2.8  | 0.76        | 1.34 | 2.88 | 0.92       |
| NCC-NorESM1-M  | 99.02    | 42.1 | 0.93        | 2.27 | 2.02 | 0.78        | 1.14 | 2.92 | 0.94       |
| NOAA-GFDL-GFDL-ESM2M | 90.09 | 42.22| 0.88        | 1.83 | 2.77 | 0.68        | 1.56 | 2.33 | 0.88       |
| Ensemble       | 89.13    | 34.42| 0.93        | 2.12 | 2.02 | 0.74        | 1.36 | 2.74 | 0.92       |

Figure 2 | Conceptual framework on the impact of climate change on river basins and implications on water security, biophysical and anthropogenic systems. Reproduced with permission from Belle et al. (2017).
3.2.1. Orange River Basin

The minimum temperature within the Orange River Basin ranged from 1.07 to 1.76 and 1.16 to 1.95 °C under RCP4.5 and RCP8.5, respectively. However, the maximum temperature also increased within the basin relative to 1970–2000 under RCP4.5 (0.96–1.78 °C) and RCP8.5 (1.08–1.95 °C). The projected changes in temperature are below 2 °C as proposed by Maure et al. (2018). The projected changes in precipitation in 2020–2050/1970–2000 range from −1.06 to 0.27 and −0.33 to 0.10 mm under RCP4.5 and RCP8.5 (Figure 3), respectively. The Orange River Basin land cover reveals the wide variation in elevation and precipitation. Furthermore, the largest part of the Orange River Basin is semi-arid and this limits crop production to livestock husbandry (IRBA 2000). Figure 3 displays the projected changes in precipitation, minimum temperature and maximum temperature for 2020–2050/1970–2000 in the Orange River Basin. All areas are projected to experience some degree of warming; however, the largest change in warming is projected in the high latitudes (Gornall et al. 2010).

3.2.2. Zambezi River Basin

The minimum and maximum temperatures will increase in the Zambezi River Basin from 2020 to 2050 relative to 1970 to 2000. The minimum temperature will range from 1.33 to 1.72 °C (RCP4.5) and 1.34 to 1.85 °C (RCP8.5) as shown in Figure 4. The maximum temperature will range from 1.32 to 1.67 °C (RCP4.5) and 1.36 to 1.86 °C (RCP8.5). The increase in temperature is below 2 °C threshold proposed by Maure et al. (2018). The projected changes in precipitation in 2020–2050/1970–2000 range from −2.09 to 0.249 mm (RCP4.5) and −1.64 to 0.27 mm (RCP8.5) (Figure 4). The projected changes are comparable to and are in the same order of degree as those stated by Chota & Jain (2019) and Mpelele (2018) for the whole of the Zambian territory. The Zambezi River Basin experiences variable climates compared to other river basins in the world (Beilfuss et al. 2001). The mean annual precipitation varies from >1,600 to <550 mm/year in the northern highland and water-stressed southern portion of the basin, respectively (You et al. 2010). Rainfall is influenced by water availability and increasing evapotranspiration demand due to rising air temperature. This may increase crop irrigation water requirements by 5–20% globally (Gornall et al. 2010).

3.3. Changes in selected climate indices for the period 1950–2005

The ETCCDI climate indices, as shown in Tables 6 and 7 and Figures 5–8, were selected for analysis due to their relevance and suitability in water resources and hydrology, agriculture, and food security and health.

3.3.1. Percentile-based extreme temperature indices

The number of warm nights (tn90pETCCDI) and the number of hot days (tx90pETCCDI) were statistically significant with positive trends in the Orange and Zambezi River Basins for the period 1950–2005, as shown in Tables 6 and 7 and Figures 5–8. The tn10pETCCDI was statistically significant with decreasing trends in both basins (Tables 6 and 7). This shows that the percentage of days when TN is less than 10th percentile decreased from 1950 to 2005. Yin & Sun (2018) reported similar results in China. The study reviewed that the frequency of cold nights (tn10pETCCDI) and cold days (tx10pETCCDI) significantly decreased during 1961–2017 at 1.75 and 0.93% per decade, respectively (p<0.01). A decrease in tn10pETCCDI and tx10pETCCDI has been observed from the late 20th century to the 21st century under RCP2.6, RCP4.5 and RCP8.5 scenarios (Yang et al. 2018). An increase in tx90pETCCDI increases plant water stress (NCA 2014; Steffen et al. 2014). Other researchers have observed an increase in the frequency of warm nights (tn90pETCCDI; 2.80%) and warm days (tx90pETCCDI; 1.68%) from 1961 to 2017 in China (Yin & Sun 2018).

3.3.2. Absolute value-based extreme temperature indices

The daily temperature range (dtrETCCDI) was only statistically significant with positive linear trends within the Zambezi River Basin. The coldest daily TN (tnnETCCDI), warmest daily TN (txnETCCDI), coldest daily TX (txnETCCDI) and warmest daily TX (txxETCCDI) were statistically significant with positive trends in both river basins for the period 1950–2005, as shown in Tables 6 and 7 and Figures 5–8. The tn10pETCCDI was statistically significant with negative trends in both basins. A study in China shows a warming amplitude intxnETCCDI, tnnETCCDI, txxETCCDI and txnETCCDI, and this has decreased the diurnal temperature range (dtrETCCDI) (Yin & Sun 2018). The dtrETCCDI, tn90pETCCDI, txnETCCDI, txxETCCDI, tx90pETCCDI, tnxETCCDI and txxETCCDI increased at the rate of 0.10, 0.14, 0.01, 0.01, 0.01, 0.16, 0.01 and 0.01 °C per decade, respectively, within the Zambezi River Basin (Table 5; Figures 4 and 5). Yin & Sun (2018) observed an increasing trend in txxETCCDI (0.21 °C), tnxETCCDI (0.29 °C), txnETCCDI (0.30 °C) and tnnETCCDI (0.51 °C) from 1961 to 2017.
at p<0.01. This means that the warming events have increased, while the cold events have decreased (Chisanga et al. 2017a; Yin & Sun 2018; Wazneh et al. 2020).

The warmest daily TN (tnxETCCDI) and warmest daily TX (txxETCCDI) indices were statistically significant with positive trends for the same period. Extreme heat as a result of an increase in txxETCCDI increases plant water stress, resulting in

**Figure 3** | Spatial–temporal variations in (a,b) projected changes in precipitation, (c,d) minimum temperature and (e,f) maximum temperature for 2020–2050/1970–2000 in the Orange River Basin under RCP4.5/8.5.
cessation of plant photosynthesis and death (NCA 2014; Steffen et al. 2014). Long exposure to higher temperatures can cause heat stress, heatstroke, heat exhaustion and ultimately death (Serdeczny et al. 2015). The Orange River Basin has experienced an increased frequency of droughts and floods (IRBA 2000). Drought is described by its characteristics known as duration or severity and is the biggest challenge among natural disasters (Kavianpour et al. 2020).

Figure 4 | Spatial–temporal variations in projected changes in (a,b) precipitation; (c,d) minimum temperature and (e,f) maximum temperature for 2020–2050/1970–2000 in the Zambezi River Basin under RCP4.5/8.5.
3.3.3. Duration-based extreme temperature indices

The cold spell duration indicator (cddETCCDI) was statistically significant with decreasing trends in both basins for the period 1950–2005, as shown in Figures 5–8. The cold spell duration indicator (cddETCCDI) was statistically significant with negative trends for the period 1950–2005 within the Orange River Basin (Table 7). This shows that the cold spell duration has been decreasing from 1950 to 2005.

The warm spell duration indicator (wsdiETCCDI) was statistically significant with positive linear trends for the period 1950–2005 within the Zambezi River Basin. The wsdiETCCDI increased at the rate of 0.17 °C per decade. An increase in wsdiETCCDI has implications on plant growth (NCA 2014; Steffen et al. 2014). An increase in wsdiETCCDI has been observed across Namibia, Botswana, Zimbabwe and Zambia by New et al. (2006). Furthermore, the wsdiETCCDI has increased consistently in Southern Africa at the rate of 2.4 days per decade. The occurrence of extreme weather events is projected to increase in future (Denton et al. 2014).

Climate model simulations have shown that extreme events are anticipated to be more severe and frequent, affecting an estimated 60–120 million persons in Southern Africa (You et al. 2010). Additionally, Africa is susceptible to projected changes in precipitation and temperature due to low adaptive capacity. Researchers have reiterated that the CMIP5 models are capable of simulating climate extremes (Stillmann et al. 2013a).

3.3.4. Magnitude-based rainfall indices

The prcptotETCCDI was statistically non-significant in both river basins (Tables 6 and 7). Other researchers have also reported non-significance in prcptotETCCDI at Mount Makulu (Chisanga et al. 2017a). A study carried out in Portland showed no significant trends in annual observed station data for 1977–2005 (Cooley & Chang 2021). The decrease in prcptotETCCDI increases plant water stress, resulting in cessation of plant photosynthesis and death (NCA 2014; Steffen et al. 2014).

3.3.5. Percentile-based extreme rainfall indices

The total annual PR from very heavy rain days (r99pETCCDI) was statistically significant with decreasing trends in the Zambezi River Basin for the period 1950–2005 (Tables 6 and 7; Figures 5–8). This shows that the amounts of the total annual precipitation decreased from 1950 to 2005. However, a significant increasing trend in r99p at the rate of 6.08 mm per

Table 6 | 55-year trends analysis in consecutive dry days (cddETCCDI); consecutive wet days (cddETCCDI); cold spell duration (cddETCCDI); daily temperature range (dtrETCCDI); annual total wet days (prcptotETCCDI); total annual wet days from very heavy rain days (r99pETCCDI); number of cold nights (tn10pETCCDI); number of warm nights (tn90pETCCDI); coldest daily nights (tnnETCCDI); warmest daily TN (txnETCCDI); number of hot days (tx90pETCCDI); coldest daily TX (txnETCCDI); warmest daily TX (txxETCCDI) and warm spell duration indicator in the Zambezi River Basin

| Statistics          | Z-statistic | n     | P-value | S       | varS   | $\rho$ | $\tau$ | Sen’s slope |
|---------------------|-------------|-------|---------|---------|--------|-------|--------|------------|
| cddETCCDI           | 1.52        | 56.00 | 0.13    | 216.00  | 20,020.00 | 0.14  | 0.10   |
| cwdETCCDI           | −2.00       | 56.00 | 0.05    | −284.00 | 20,018.00 | −0.18 | −0.07  |
| csdiETCCDI          | −4.21       | 56.00 | 0.00    | −596.00 | 20,018.00 | −0.39 | −0.12  |
| dtrETCCDI           | 35,428.00   | 56.00 | 0.00    | 502.00  | 19,997.33 | 0.33  | 0.10   |
| prcptotETCCDI       | 0.00        | 56.00 | 1.00    | 0.00    | 20,020.00 | 0.00  | −0.03  |
| r99pETCCDI          | −2.13       | 56.00 | 0.03    | −303.00 | 20,019.00 | −0.20 | −0.24  |
| tn10pETCCDI         | −3.97       | 56.00 | 0.00    | −563.00 | 20,014.00 | −0.37 | −0.09  |
| tn90pETCCDI         | 4.67        | 56.00 | 0.00    | 662.00  | 20,018.00 | 0.45  | 0.14   |
| tnnETCCDI           | 2.96        | 56.00 | 0.00    | 420.00  | 20,014.00 | 0.27  | 0.01   |
| txnETCCDI           | 4.16        | 56.00 | 0.00    | 589.00  | 20,006.33 | 0.38  | 0.01   |
| tx90pETCCDI         | 4.76        | 56.00 | 0.00    | 675.00  | 20,019.00 | 0.44  | 0.16   |
|txnETCCDI            | 2.04        | 56.00 | 0.04    | 290.00  | 20,012.00 | 0.19  | 0.01   |
|txxETCCDI            | 3.47        | 56.00 | 0.00    | 492.00  | 20,007.33 | 0.32  | 0.01   |
|wsdiETCCDI           | 3.18        | 56.00 | 0.00    | 451.00  | 20,017.00 | 0.29  | 0.17   |
Table 7 | 55-year trends analysis in consecutive dry days (cddETCCDI); consecutive wet days (cwdETCCDI); cold spell duration (csdiETCCDI); daily temperature range (dtrETCCDI); annual total wet days (prcptotETCCDI); total annual wet days from very heavy rain days (r99pETCCDI); number of cold nights (tn10pETCCDI); number of warm nights (tn90pETCCDI); coldest daily nights (tnnETCCDI); warmest daily TN (txnETCCDI); number of hot days (tx90pETCCDI); coldest daily TX (txnETCCDI); warmest daily TX (txxETCCDI) and warm spell duration indicator in the Orange River Basin

| Statistics       | Z-statistic | n   | P-value | S     | varS   | r    | Sen’s slope |
|------------------|-------------|-----|---------|-------|--------|------|-------------|
| cddETCCDI        | 1.92        | 56.00 | 0.06    | 272.00 | 20,020.00 | 0.18 | 0.15        |
| cwdETCCDI        | 0.02        | 56.00 | 0.82    | 34.00  | 20,020.00 | 0.02 | 0.00        |
| csdiETCCDI       | -4.11       | 56.00 | 0.00    | -582.00 | 20,016.00 | -3.38 | -0.04       |
| dtrETCCDI        | -0.16       | 56.00 | 0.87    | -24.00 | 20,000.00 | -0.02 | 0.00        |
| prcptotETCCDI    | 0.00        | 56.00 | 1.00    | 0.00   | 20,020.00 | 0.00 | 0.15        |
| r99pETCCDI       | 1.48        | 56.00 | 0.14    | 210.00 | 20,018.00 | 0.14 | 0.08        |
| tn10pETCCDI      | -3.92       | 56.00 | 0.00    | -555.00 | 20,017.00 | -0.36 | -0.06       |
| tn90pETCCDI      | 4.35        | 56.00 | 0.00    | 617.00 | 20,015.00 | 0.40 | 0.09        |
| tnnETCCDI        | 1.03        | 56.00 | 0.31    | 146.00 | 20,003.33 | 952.39 | 0.00        |
| txnETCCDI        | 3.00        | 56.00 | 0.00    | 425.00 | 20,006.33 | 0.28 | 0.01        |
| tx90pETCCDI      | 3.20        | 56.00 | 0.00    | 454.00 | 20,018.00 | 0.29 | 0.09        |
| txxETCCDI        | 1.37        | 56.00 | 0.17    | 190.00 | 20,013.00 | 0.13 | 0.01        |
| wsdIETCCDI       | 2.79        | 56.00 | 0.01    | 396.00 | 20,012.00 | 0.26 | 0.01        |

Figure 5 | 55-year trends analysis in (a) consecutive dry days; (b) consecutive wet days; (c) cold spell duration; (d) daily temperature range; (e) annual total wet days; (f) total annual wet days from very heavy rain days; (g) number of cold nights; (h) number of warm nights and (i) coldest daily nights in the Zambezi River Basin.
decade was observed in China from 1961 to 2017 (Yin & Sun 2018). However, r99ETCCDI was statistically non-significant at Mount Makulu (Chisanga et al. 2017a). The r99pETCCDI was statistically non-significant within the Orange River Basins.

3.3.6. Duration-based extreme rainfall indices
The consecutive dry days (cddETCCDI) and consecutive wet days (cwdETCCDI) were statistically non-significant for both river basins, as shown in Tables 6 and 7. A statistically non-significant trend in cddETCCDI has been observed in southern Java (Abdila & Nugroho 2021). Other researchers in Zambia have reported non-significant cddETCCDI and cwdETCCDI at Mount Makulu (Chisanga et al. 2017a).

3.4. Potential impacts on agricultural production
Rainfed agriculture production will be highly impacted by climate change and extreme climate indices (Gornall et al. 2010; Chisanga et al. 2020a, 2020b). Higher growing season temperatures can significantly impact soil water content, agricultural productivity, farm incomes and agriculture food security (Gornall et al. 2010). An increase in air temperature will shorten the development and reproductive cycles and eventually crop yield (Chisanga et al. 2020b; Bouras et al. 2019). Higher temperatures can increase heat stress on crops and water loss by evapotranspiration. A 2 °C local warming in the mid-latitudes could increase wheat production by nearly 10%, whereas at low latitudes the same amount of warming may decrease yields by nearly the same amount (Gornall et al. 2010). Variability in rainfall can lead to a considerable decline in crop production

Figure 6 | 55-year trends analysis in aerial means for (j) warmest daily TN; (k) number of hot days; (l) Coldest daily TX; (m) warmest daily Tx and (n) warm spell duration indicator in the Zambezi River Basin.
Rainfall variability under a changing climate will affect soil water holding capacity (Chisanga et al. 2017b). Soils with high water holding would abate the impacts of drought while sustaining crop growth and yield. Crop growth and yield are more sensitive to rainfall compared to air temperature (Kang et al. 2009; Chisanga et al. 2017b).

At the global level, there has been a decline in barley, maize and wheat yield due to an increase in air temperature (Chisanga et al. 2017a). Prolonged extreme temperature (˃32 °C) at a flowering stage for most crops can drastically reduce yield (Gornall et al. 2010). Maize grows well with air temperature being 15–35 °C (Araya et al. 2015). Nonetheless, maize net photosynthesis decreases at temperatures of ˃38 °C (Crafts-Brandner & Salvucci 2002). Adaptation practices include varying sowing dates, varying fertiliser application rates, planting drought-tolerant cultivars, improving water conservation and management practices, using efficient irrigation technologies, crop diversification and improving pest management (Chisanga et al. 2020b; Mall et al. 2017). Extreme temperature and rainfall can prevent crops from growing (Chisanga et al. 2020b).

3.5. Potential impacts on various ecosystem services

Climate change has a profound impact on the provision of ecosystem services. The adoption of the United Nations Sustainable Development Goals and the growing popularity of ‘green economy’ approaches to development have been accompanied by an increasing demand from government decision-makers for ecosystem service information to guide development planning and climate change adaptation at national scales (Mandle et al. 2017). The projected changes in climate are expected to alter ecosystem service provision in multiple ways. Under the high estimate for changes in climate showing increasing rainfall, natural ecosystems are expected to play even greater roles in retaining sediment, regulating dry-season water availability...
and reducing inland flood risk. Reduced rainfall lessens expected erosion with subsequent loss of natural vegetation, resulting in reduced service provision (Mandle et al. 2017).

The wetlands also reduce the impacts of floods. They provide ecosystem services that improve the well-being of local communities (Belle et al. 2017). However, wetlands are vulnerable to projected changes in air temperature, rainfall and climate indices. Integrated management of wetlands that build resilience to the changing climate and extreme weather events should be enhanced.

3.6. Potential impacts on health

Heat waves, which are projected to increase under climate change, could directly threaten livestock (Gornall et al. 2010). Heat waves (periods of extremely high temperature) are likely to become more frequent in the future and represent a major challenge for agriculture. Heatwaves can cause heat stress in both animals and plants and have a negative impact on food production. Extreme events, especially floods, droughts and heatwaves, have affected humans and livestock (Chisanga et al. 2017a). The frequency of extreme rainfall and flooding leads to injuries and increases waterborne diseases such as cholera and dysentery (MTENR et al. 2007).

3.7. Potential impacts on water resources and hydrology

Climate change and climate variability are affecting health, agriculture, food security, energy, water resources and hydrology (Fernandes et al. 2011; Chisanga et al. 2020a). Changes in the frequency and severity of droughts and floods pose challenges...
for farmers and threaten food safety. Extreme events, especially floods and droughts, have affected energy infrastructure and water quality (Chisanga et al. 2017a).

3.8. Implication on water quality

Climate change affects the status of water bodies and thus affects the measures to effectively manage the water resources in meeting policy objectives (Arnell et al. 2015). Reservoir water quality will diminish as a result of rainfall variability, runoff timing and high air temperature (US EPA 2014, 2015). Higher surface air temperature will make it difficult to attain water quality standards (US EPA 2014). Furthermore, the increase in air temperature will affect water quality by changing dissolved oxygen and carbon dioxide. This will impact aquatic flora and fauna negatively. In selected areas, the increase in air temperature will enhance algal bloom and eutrophication, thereby reducing drinking water quality (US EPA 2014, 2015; Radhapyari et al. 2021). The algal bloom will also reduce dissolved oxygen levels (Whitehead et al. 2009).

Extreme weather events such as storm events and floods will increase the sediment load of nutrient inputs into water reservoirs (Delpla et al. 2009; US EPA 2015). Climate change will exert impacts on the water quality of rivers, lakes and reservoirs by modifying physico-chemical parameters, micro-pollutants and biological parameters (Delpla et al. 2009; Radhapyari et al. 2021). The anticipated changes in water quality will also affect the socio-economic aspects and the sustainability of important environmental flows, ecosystems and biodiversity.

3.9. Implication on water security

The increasing trends in temperatures, temperature-based climate extreme indices and increased rates of evapotranspiration in the Orange and Zambezi River Basins will have disproportionately large impacts on river flow and runoff, with implications on water security (Ndebele-Murisa et al. 2020). Muchanga et al. (2019) also observe that extreme change in climate, especially as indicated by increased temperature, reduced precipitation and increased aridity, has implications on water security for livestock within many sub-catchments of the Zambezi Basin. Hughes & Farinosi (2020) show that for the Zambezi River Basin, the greatest impacts of climate changes would be around large natural and man-made open water bodies sensitive to several effects of aridity. Additionally, the projected changes in climatic conditions under both RCP4.5 and RCP8.5 will affect the provision of tree-based, forest, water and soil-based ecosystem services. The increase in temperature and an extremely arid hydro-climate will result in the loss of 83% of precipitation to evapotranspiration in Botswana (IRBA 2000). The increase in air temperature will ultimately increase crop water requirements (Chowdhury et al. 2016). The elevated air temperature will also have a detrimental effect on growth duration and yield (Hossain et al. 2021). Other researchers have argued that plant water requirements could reduce in response to the shortening of the development and reproductive cycle of crops (Bouras et al. 2019).

The water resource in Botswana is under stress and water scarcity is increasing and this will limit its ability to meet future demands. With increasing stress and limited water supply, there is a national concern related to the area of the Orange River Basin within Botswana. Namibia recycles its wastewater to increase usable water resources and desalinises seawater and brackish water. The recycling of wastewater and stormwater should be enhanced and promoted to increase water security in both the Orange and Zambezi River Basins.

4. CONCLUSION

The Zambezi and Orange River Basins have been and are projected to be impacted by impacts of climate change as a result of the changing temperature and rainfall patterns. This research has projected future climatic changes in the Zambezi and Orange River Basins for the period 2020–2050/1970–2000. In the Zambezi River Basin, minimum temperatures are expected to increase from 1.33 to 1.72 °C (RCP4.5) and 1.34 to 1.85 °C (RCP8.5). Maximum temperatures will range from 1.32 to 1.67 °C (RCP4.5) and 1.36 to 1.86 °C (RCP8.5). Over the same period, precipitation will range from –2.09 to 0.2495 mm (RCP4.5) and –1.64 to 0.27 mm (RCP8.5). The minimum temperature within the Orange River Basin will range from 1.07 to 1.76 and 1.16 to 1.95 °C under RCP4.5 and RCP8.5, respectively, for the period 2020–2050/1970–2000. The maximum temperature will also increase within the basin relative to the baseline under RCP4.5 (0.96–1.78 °C) and RCP8.5 (1.08–1.95 °C). The projected changes in precipitation in 2020–2050/1970–2000 will range from –1.06 to 0.27 mm (RCP4.5) and –0.33 to 0.10 mm (RCP8.5).

These identified changes are expected to affect the basins’ provision of different services ranging from contribution to the agriculture sector, ecosystems, health, water resources, hydrology and other regulatory functions. In agriculture, higher
temperatures will significantly reduce soil moisture content, crop yields and increase plant moisture stress. The changing climates will alter ecosystems and hence affect ecosystem service provision. Such important ecosystems as wetlands will likely be affected. The changing climates will also lead to increased heat waves, resulting in heat stress on both humans and animals. Changes in rainfall regimes would also contribute to increase flooding in some parts of the riverine ecosystem as well as droughts in others.

Furthermore, climatic changes will have implications on the availability of freshwater in the regions that utilise these basins. Several threats to the freshwater in the catchments have been mapped. These threats include mining, hydropower and climate variability. Water security will require appropriate water infrastructure, such as dams, to account for the variability, given that the Zambezi Catchment will experience reduced precipitation and increased temperatures particularly in central-eastern and south-western sub-catchment areas. In the Orange River Basin, future climate projections show increased precipitation in the southern areas and increased temperatures, especially in the central-northern sub-catchments. Flooding events may become more prominent in the southern sub-catchments; infrastructure must therefore be built with the appropriate flexibility.

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**AUTHOR CONTRIBUTIONS**
C.B.C. downloaded the regional climate model and climate indices data. C.B.C. analysed the data and drafted the paper. K.H.M. wrote the abstract, conclusion and acknowledgements and reviewed the article, making the necessary changes. H.S., K.B., M.M., L.N., H.J.N., B.Z., A.A.M. and S.K.R. proofread the article and made the necessary corrections and inputs. C.B.C. and K.H.M. generated the figure and tables. L.N., H.J.N., B.Z., A.A.M. and S.K.R. made the necessary changes to figure titles.

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**COMPETING INTEREST**
The authors declare no competing interests.

**DATA AVAILABILITY STATEMENT**
All relevant data are available from an online repository or repositories.

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