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Climate change hotspots in Africa: spatiotemporal trends of rainfall, temperature, and drought using GIS and statistical modelling

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Despite its minimal contribution to greenhouse gas emissions, Africa faces substantial dangers from climate change repercussions. Using the Climatic Research Unit (CRU) TS 4.06 dataset, this study seeks to investigate climate variability in Africa over the last 120 years (1901–2021). This study also employs climate change data from the revised Meteorological Research Institute Earth System Model version 2.0

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(MRI-ESM2.0) under the Shared Socio-economic Pathway SSP5–8.5 high-emissions scenario to conduct a spatial and temporal analysis of precipitation, temperature, and drought across Africa. The findings reveal that annual precipitation varies spatially and temporally from region to region. Central Africa receives the highest rainfall, followed by the West, East, and South African areas, with the North receiving the least. This study provides a comprehensive continent-wide analysis based on long-term observational and model data, contributing new insights at the Pan-African scale. The findings underscore the urgent need for region-specific climate adaptation and disaster preparedness policies. Policymakers should prioritise resilient water resource management, early warning systems for floods and droughts, and adaptive agricultural practices to safeguard food security, public health, and sustainable development in vulnerable African regions.

Keywords. Climate projections; drought; climate modelling; rainfall patterns; global warming; climate change adaptation.

1. Introduction

Africa is under significant threat from climate change despite contributing negligible amounts of total greenhouse gas emissions (IPCC 2022; Overland *et al.* 2022; Fonjong *et al.* 2024). The vulnerability of the continent to climate change is exacerbated by the interaction of multiple stresses, low resilience, and low adaptive capacity (Zheng *et al.* 2019). Also, the effect of climate change on Africa's major economic sectors cannot be overemphasised, as they are aggravated by existing challenges such as endemic poverty, limited access to capital, rapid urbanisation trends, and complex governance (Lam *et al.* 2012; Baninla *et al.* 2022). Despite the growing concern, there is limited information from scientific research that could be used to quantify the economic costs of the negative impacts of climate change in Africa as a whole (AfDB 2019).

Previous studies on the spatial and temporal analysis of drought, temperature, and precipitation in Africa have largely focused on individual countries and sub-regions (Mekonen *et al.* 2020; Mupepi 2022; Tan *et al.* 2022). In terms of drought analysis, a study conducted a comprehensive investigation on the primary factors contributing to droughts in Africa, the variation in drought occurrences over time, and the geographic extent of severe droughts between 1964 and 1992. Regarding precipitation analysis, a study published in AGU Journals in 2015 analysed rainfall characteristics (amount, frequency, duration, and intensity) over Africa from 1998 to 2012. Another research study analysed changes in monthly potential evapotranspiration, precipitation, and minimum and maximum temperatures across Africa from 1901 to 2015. The objective of the study was to quantify the trends in climatic variables over this extended time frame and assess the correlations between them (Onyutha 2021).

Though observed datasets are the basis for understanding the climate system, long-term climatic data from classical conventional meteorological stations are usually insufficient, labour-intensive, and inaccessible for analysis (Thorne *et al.* 2017). Other limitations also include spatial resolution, accessibility to remote areas, installation and maintenance costs, and data management (Dinku *et al.* 2018; Dinku 2019). Research organisations have striven to develop several interpolation methods and gridded datasets to overcome these challenges, notable among them being the inverse distance weighting (IDW), Natural Neighbor, Kriging, Climatic Research Unit (CRU), Meteorological Research Institute Earth System Model version 2.0 (MRI-ESM2.0), Global Precipitation Climatology Centre (GPCC), and National Oceanic and Atmospheric Administration (NOAA) (Li *et al.* 2010; Becker *et al.* 2013; Schneider *et al.* 2014; Atta-ur-Rahman and Dawood 2017).

Among these, the Climatic Research Unit version 4.06 (CRU TS 4.06) and MRI-ESM2.0 datasets were selected for this study due to their unique suitability for long-term and continental-scale climate analysis in Africa. CRU TS 4.06 offers high-resolution, observationally grounded data covering over a century (1901–2021), making it ideal for capturing historical trends in precipitation and temperature with consistent quality and spatial continuity (Harris *et al.* 2020). In contrast to reanalysis datasets like ERA5, which are limited to post-1979 coverage and incorporate model assimilation that may obscure long-term trends in data-sparse regions, CRU's extensive historical baseline allows for robust trend detection. For future projections, the MRI-ESM2.0 model, part of the CMIP6 family, was chosen based on its improved simulation of tropical climate dynamics and its strong performance over African regions in recent comparative assessments (Yukimoto *et al.* 2019; Ngoma *et al.* 2021a). Its enhanced atmospheric and oceanic resolution offers a more detailed representation of monsoon systems and precipitation variability under high-emission scenarios such as Shared Socio-economic Pathway (SSP) 5–8.5. Together, these datasets provide a complementary framework that allows for both retrospective and forward-looking climate assessments across the African continent.

Considering the low rain gauge station density over Africa (Woldemeskel *et al.* 2013; Schneider *et al.* 2014; Maidment *et al.* 2017; Abdelmoneim *et al.* 2022, 2023), this study used CRU TS 4.06 and MRI-ESM2.0 datasets to conduct a spatial-temporal analysis of drought, precipitation, and temperature over Africa. The CRU dataset is a regularly updated high-resolution monthly grid of land observations from multiple sources covering ten variables from 1901 to the present (Harris *et al.* 2020). The MRI-ESM2.0 is an updated Earth System Model developed by the Meteorological Research Institute of the Japan Meteorological Agency with various improvements, including vertical resolution enhancements of the atmospheric, oceanic, and chemical models, resulting in better performance than its predecessors, Yukimoto *et al.* (2019). Although the model has been widely used locally in Africa and globally, there has not been a study that used the MRI-ESM2.0 dataset in carrying out future climate analysis on Africa as a whole Ngoma *et al.* (2021a).

This study addresses several key gaps in the current literature. First, it provides a rare continent-wide spatiotemporal assessment of climate variability over the past 120 years, whereas most prior studies have been limited to individual regions or shorter timeframes. Second, the study is among the first to integrate long-term observational data (CRU TS 4.06) with high-resolution model projections (MRI-ESM2.0 under SSP5–8.5), offering both historical trends and future climate scenarios in a single framework. Third, the research simultaneously analyses precipitation, temperature, and drought, three critical climate indicators, providing a more comprehensive picture of climate dynamics across Africa. Importantly, the findings contribute directly to ongoing policy efforts to address climate risks in Africa. By identifying regional vulnerabilities and future climate extremes, the study supports the goals of the Paris Agreement, particularly Article 7, which emphasises strengthening adaptive capacity, building resilience, and reducing vulnerability to climate change. Furthermore, the results align with the African Union Climate Change and Resilient Development Strategy (2022–2032), which calls for improved climate data access, early warning systems, and the integration of science into policymaking. This research also provides critical evidence to advance Agenda 2063, the African Union's blueprint for inclusive and sustainable development. Thus, the study serves not only as a scientific assessment but also as a policy-relevant tool to inform African Nations' Nationally Determined Contributions (NDCs), regional adaptation planning, and disaster risk reduction strategies.

2. Study area

The African continent has distinct climatological characteristics. It is the only continent with nearly equal portions in both the Southern and Northern Hemispheres (Collins 2011). Encompassing roughly 30.3 million km^2, Africa constitutes 6% of the Earth's overall surface area and represents 20% of its landmass NourEldeen *et al.* (2020). Africa is renowned for being the hottest continent, with the Sahara Desert covering around 60% of its entire surface area, and temperature variation is a primary driver of plant dynamics, influencing crop species and vegetation distribution Measho *et al.* (2019). Africa is divided into five sub-regions according to the African Union's geographical classification system (West, East, South, Central, and North) as indicated in figure 1. This classification is based on each region's physical, geographical, and climatological conditions (Sahel and West Africa Club 2017).

West Africa has a variety of climates, from humid tropical monsoon conditions near the coast in the south to dry, desert-like conditions in the north. This region experiences the majority of its rainfall from April to September and year-round high temperatures (WMO 2020). With an average annual rainfall of about 1500 to 1800 mm and hot, humid temperatures ranging from 22°C to 30°C, the central region of Africa has an equatorial and tropical climate, as shown in figure 2. Some

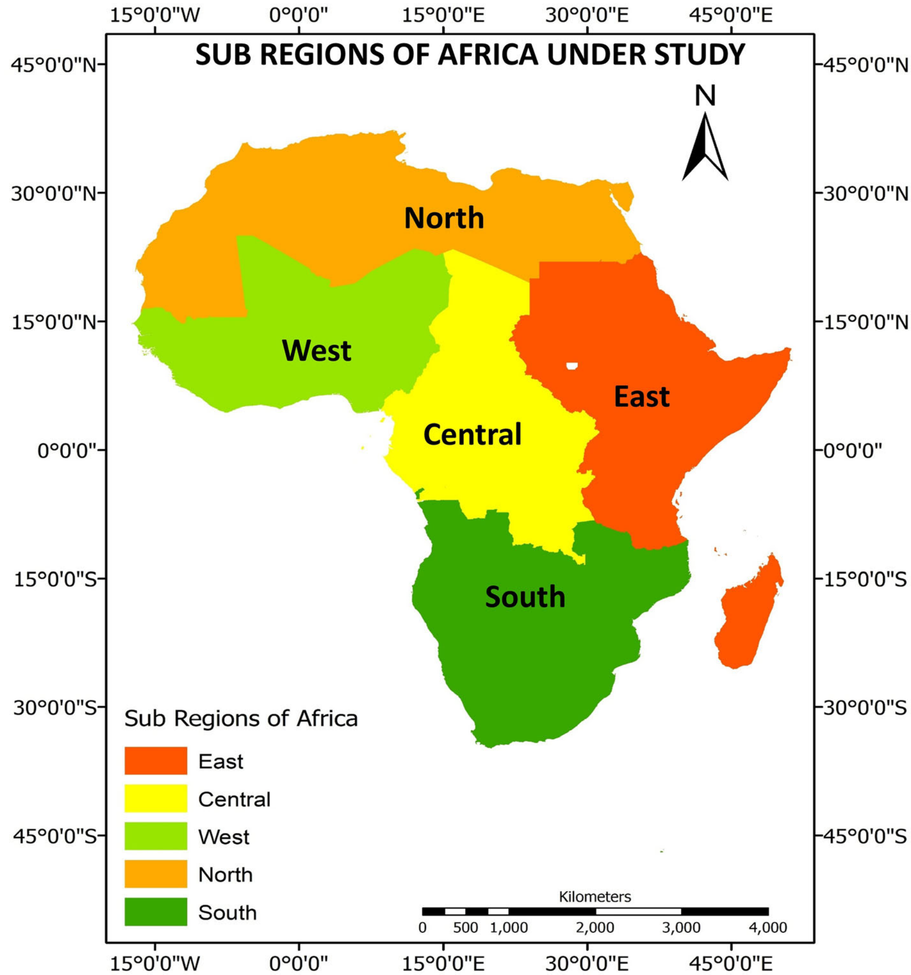

Figure 1. Study area map classifying Africa into subregions (North Africa, East Africa, South Africa, West Africa, and Central Africa).

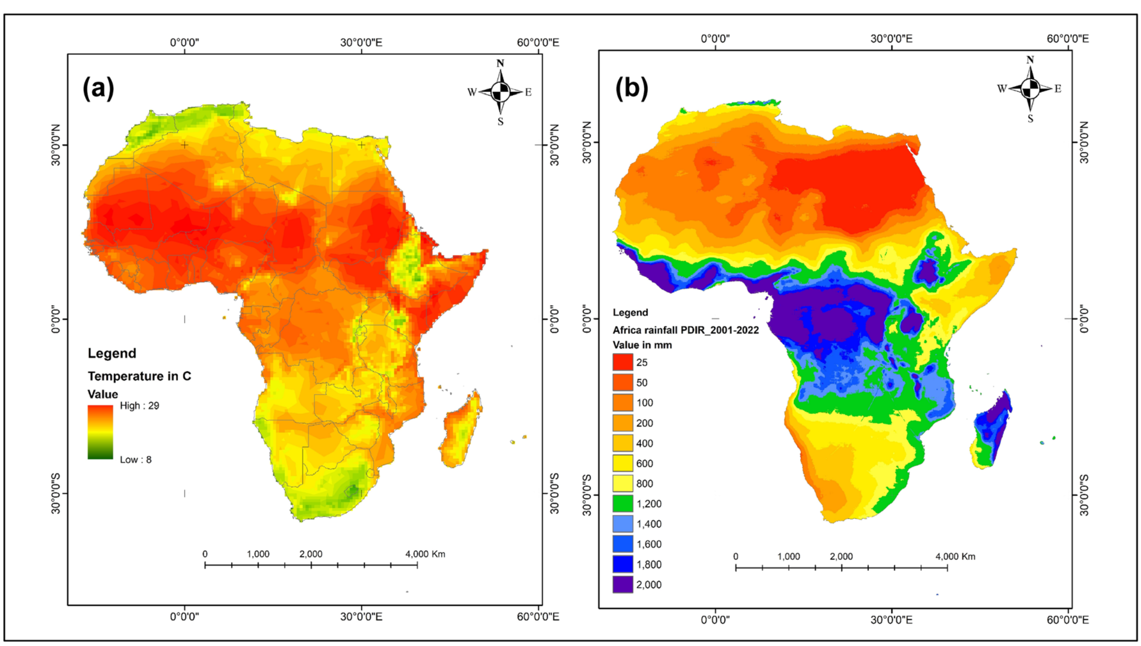

Figure 2. (**a**) Average annual temperature of Africa. (**b**) Average annual rainfall of Africa from 2001 to 2022.

extreme locations, like Debundsha on Mount Cameroon, record up to 10,000 mm of rainfall annually (Tsalefac *et al.* 2015; AFSA 2020).

Along the coast, North Africa experiences a Mediterranean climate with 400 to 600 mm of annual precipitation, mild, wet winters, and warm, dry summers. The region's inland features semiarid and arid desert climates, which are characterised by extreme temperature fluctuations, limited precipitation, and a year-round sirocco wind (Djebbar *et al.* 2020; Tanarhte *et al.* 2024). The East Africa region mostly has bimodal rainfall (March to May and October to December), with rising temperatures in the equatorial and southern regions since the early 1980s Ongoma and Chen (2017).

Finally, the climate in southern Africa ranges from dry to humid subtropical in the north and east, with much of the central region being semi-arid. Except in the southwestern part of South Africa, rains fall between November and March in most of the region. The Kalahari Desert, which spans Botswana, Namibia, and South Africa, has the highest temperatures (Daron 2014; World Bank 2021; Chivangulula *et al.* 2024; Rouault *et al.* 2024).

3. Materials and methods

3.1 *Datasets*

3.1.1 *CRU*

The climatic research unit gridded time series (CRU TS) stands as a commonly employed meteorological data, employing a grid resolution of 0.5° latitude by 0.5° longitude across all terrestrial areas globally, excluding Antarctica. It is obtained through gauge observations and the estimation of monthly climate differences based on wide networks of meteorological station measurements (Harris *et al.* 2014). The CRU TS 4.06 dataset covers the period 1901–2021 and the trends displayed are stronger and more widespread (Harris *et al.* 2020; Bakke *et al.* 2023). In order to determine the historical and future climatic conditions for the African subregions (i.e., North, Central, West, East, and South), temperature and rainfall data were obtained from WorldClim (2022).

The selected metrics for studying Africa's climatic characteristics are temperature and precipitation due to their significant influence on climate extremes. Variations in the average and differences of temperature and precipitation have a direct effect on the frequency and severity of severe weather occurrences. Three categories of datasets were acquired, encompassing information for both temperature and rainfall, organised by month, season, and year. For the historical datasets, the years in focus were 1901–2021, and the years for the consideration of future datasets were 2021–2100. WorldClim is a database of gridded global meteorological and weather information with high spatial resolution for past, current and projected conditions that can be used for mapping and spatial modelling (WorldClim 2022). Previous studies have concluded that WorldClim datasets are accurate, reliable, valuable, and highly useful in climatic evaluations and predictions (Panagos *et al.* 2017; Poggio *et al.* 2018; Wango *et al.* 2018).

3.1.2 *MRI*

MRI-ESM2.0 was created by the Meteorological Research Institute (MRI). It shows improved efficiency than earlier versions of Yukimoto *et al.* (2019), Tsujino *et al.* (2017), and Oshima *et al.* (2020). MRI-ESM2.0 has been utilised in several research over the world, such as Alaminie *et al.* (2021), Kawai *et al.* (2019), Iqbal *et al.* (2021), Klutse *et al.* (2021), Ajayi (2022), Shiru *et al.* (2022), and Niu *et al.* (2023). These datasets exhibit high capability in reproducing historical climate and can be combined with CMIP5 and CMIP6 models to forecast future climate Hamed *et al.* (2022). Models based on MRI-ESM2.0 datasets are the most accurate and show excellent agreement with baseline period observations (Alaminie *et al.* 2021; Ngoma *et al.* 2021a). For this study, the future dataset under SSP5–8.5 was considered.

3.2 *Methods*

The approach is schematically shown in figure 3. All datasets were subjected to both spatial and temporal analysis using ArcGIS version 10.8.2. With Microsoft Excel and R Studio, trend analysis, curves, and graphs for historical data were generated. Drought was assessed using the standard precipitation index (SPI), and the trend in the parameters under observation was examined using the Mann-Kendall (MK) statistical test. To align with standard climate assessment frameworks and enhance policy relevance, the analysis was divided into three time periods: a historical baseline (1979–2018), representing recent observed climate conditions; the near future (2021–2060), relevant

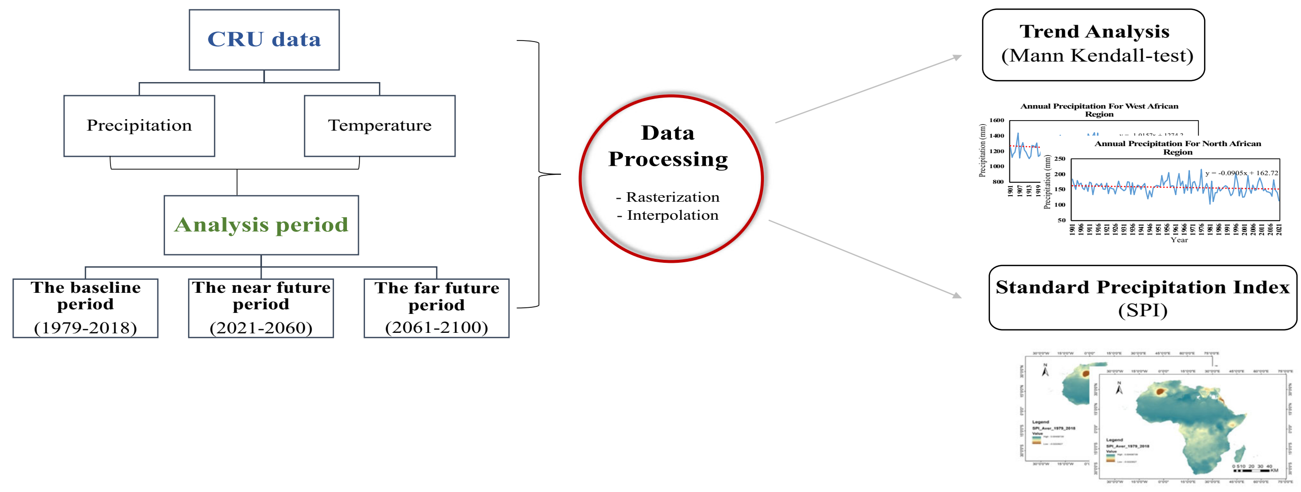

Figure 3. Schematic illustration of the dataset and analysis used in this study.

for short- to mid-term planning and adaptation strategies; and the far future (2061–2100), which supports long-term climate impact assessments and mitigation planning.

3.2.1 *Mann-Kendall test*

MK test is a method of statistical analysis that is commonly utilised for assessing changes in climatology, environment, and hydrologic data series to determine whether any monotonic patterns or statistically significant trends are present or to identify the variation of these trends in long-term (Alhaji *et al.* 2018; Shahfahad *et al.* 2023). This test has two advantages: it is non-parametric, which means that it does not require data that is evenly distributed. Second, due to the irregularity of the time series, the test exhibits low sensitivity to sudden interruptions Alhaji *et al.* (2018). The MK statistic trend test, Z_s, is provided by the following equation.

$$Z_s = \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{Var}(S)}}, & S > 0 \\ 0, & S = 0 \\ \dfrac{S+1}{\sqrt{\mathrm{Var}(S)}}, & S < 0 \end{cases} \quad (1)$$

where

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sign}(X_j - X_i) \quad (2)$$

$$\mathrm{Sign}(X_j - X_i) = \begin{cases} 1 & \text{if } X_j - X_i > 0 \\ 0 & \text{if } X_j - X_i = 0 \\ -1 & \text{if } X_j - X_i < 0 \end{cases} \quad (3)$$

where n numbers of data points, X_j and X_i are annual values in years' j and i, $j > 1$.

3.2.2 *Standardised precipitation index*

SPI relies only on rainfall and is applicable in both arid and rainy periods. It can be calculated for any location based on historical precipitation data for a selected period (Guenang and Kamga 2014; Tefera *et al.* 2019; Zhang *et al.* 2023). According to Guenang and Kamga (2014), SPI has the potential to establish and characterise drought circumstances across various meteorological, agricultural, and hydrological contexts. It is also appropriate for estimating the majority of lack of rainfall occurrence classifications, and its values can effectively describe streamflow (on timescales of 2–6 months), agricultural drought (on timescales of 2–3 months), and groundwater level (on time scales of 5–24 months). SPI is useful in drought analysis by various scholars (Guenang and Kamga 2014; Jiang *et al.* 2015; De Jesús *et al.* 2016; and Zhou *et al.* 2021). The interpretation of the SPI values is clearly presented in table 1 (Alley 1984).

4. Results and discussions

4.1 *Temporal analysis*

4.1.1 *Annual precipitation of the subregions of Africa*

Analysis of annual precipitation data from 1901 to 2021 (figure 4) shows a climatic variability that differs from one region to another. Central Africa receives the most rainfall, followed by the West, East, South, and finally the North in descending order. In West Africa, annual precipitation varies between 906.91 and 1434.79 mm, for the north between 102.58 and 216 mm, for the east between 856.2 and 1313.32 mm, for the south between 541.71 and 936.3 mm, and in central Africa between 1320.46 and 1819.98 mm. This validates the findings presented by Ndebele *et al.* (2020), where they observed an average annual precipitation of 617.3 mm in the Southern area for the period from 1841 to 2016. Gebrechorkos *et al.* (2019) found comparable patterns in East African annual rainfall patterns from 1981 to 2016. According to the study, yearly precipitation in Tanzania was 971.7 mm, while Ethiopia and Kenya received 801.6 and 601.1 mm, respectively. Kabongo *et al.* (2016) observed a comparable outcome in the Democratic Republic of the Congo (Central Africa), where annual rainfall was 1506.3 mm. The likely cause of these heavy rains may be the result of the equator crossing the region Maidment *et al.* (2015).

Table 1. *Drought categories based on SPI values.*

SPI	Category
2 and above	Extremely wet
1.50 to 1.99	Very wet
1.00 to 1.49	Moderately wet
−0.99 to 0.99	Mild drought
−1.00 to −1.49	Moderate drought
−1.50 to −1.99	Severe drought
≤ -2.00	Extreme drought

Additionally, the MKl test and the Sen slope (table 2) demonstrate that the temporal distribution of rainfall in Central, Eastern, and Southern Africa is similar from 1901 to 2021. In contrast, there was a significant decrease in precipitation in the northern and western regions of Africa. Boulmaiz *et al.* (2022) found a decreasing trends in a 30-year period series analysing rainfall in Northern Africa. Similarly, a study undertaken by Ndebele *et al.* (2020) on the spatial-temporal analysis of rainfall over Southern Africa for 176 years discovered that there is no significant trend in the annual series. On the contrary, a 37-year study conducted by Alahacoon *et al.* (2022) indicates an increasing trend in rainfall across all African regions. This variation might be attributed to the difference in timescales.

These contrasting precipitation patterns are likely driven by both large-scale atmospheric circulation and regional land–climate interactions. The observed decrease in rainfall over West and North Africa is consistent with a southward shift and weakening of the Intertropical Convergence Zone (ITCZ), influenced by hemispheric warming asymmetry and persistent SST anomalies in the

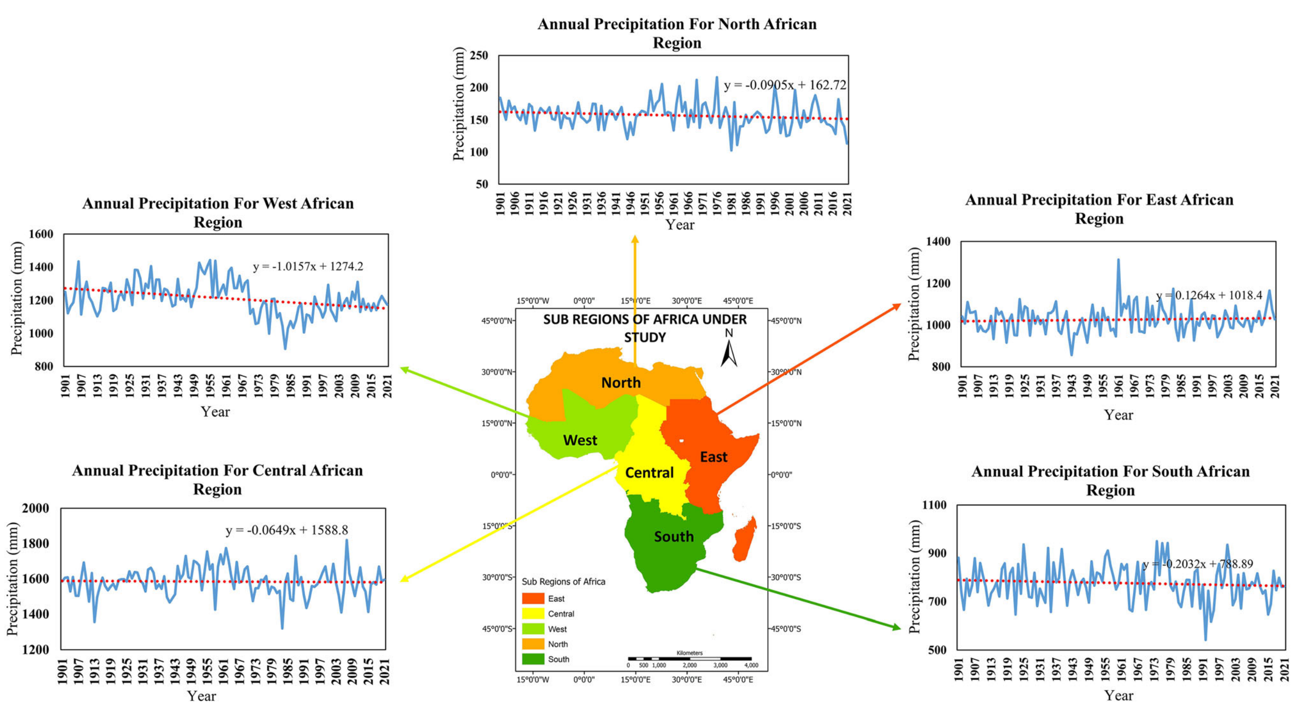

Figure 4. Annual precipitation of the subregions of Africa shown the temporal variability using CRU datasets from 1901 to 2021.

Table 2. *Trend analysis using Mann-Kendall approach for the CRU precipitation and minimum and maximum temperature datasets from 1901 to 2021.*

Sub-regions	Parameters	Trend	P	Z	Tau	Sen slope
Central Africa	Precipitation	No trend	0.69	–0.41	–0.03	–0.08
	Min. T^0	Increasing	0.00	7.21	0.44	0.005
	Max. T^0	Increasing	1.27E-14	7.71	0.47	0.005
East Africa	Precipitation	No trend	0.57	0.57	0.03	0.10
	Min. T^0	Increasing	0.00	8.85	0.54	0.01
	Max. T^0	Increasing	6.00E-14	7.51	0.46	0.008
North Africa	Precipitation	Decreasing	0.03	–2.21	–0.14	–0.11
	Min. T^0	Increasing	0.00	8.98	0.55	0.01
	Max. T^0	Increasing	0.00	9.29	0.57	0.01
South Africa	Precipitation	No trend	0.37	–0.89	–0.05	–0.19
	Min. T^0	Increasing	0.00	6.01	0.37	0.009
	Max. T^0	Increasing	6.66E-16	8.07	0.50	0.009
West Africa	Precipitation	Decreasing	0.00	–3.52	–0.22	–0.89
	Min. T^0	Increasing	0.00	6.37	0.39	0.01
	Max. T^0	Increasing	8.79E-06	4.45	0.27	0.004

Atlantic and Mediterranean basins Boulmaiz *et al.* (2022). Meanwhile, the increased rainfall in East and Central Africa may be associated with enhanced convection near the equator, as well as the modulation of rainfall by the Indian Ocean Dipole and warming of the western Indian Ocean (Nicholson 2018). Additionally, regional deforestation and land-use changes may be altering local moisture recycling and intensifying localised rainfall patterns in some forest-adjacent zones.

4.1.2 *Seasonal precipitation of the subregions of Africa*

To analyse seasonal rainfall behaviour, CRU data were grouped into the seasonal time frames according to the IPCC Atlas classification (IPCC 2013). As shown in figure 5, the season from June to August (JJA) in the Western Area received the most rainfall (600 mm), followed by the SON (September to November) season (400 mm), the MAM (March to May) season (less than 200 mm), and the DJF (December to February) season (less than 50 mm). This result is in agreement with other previous studies (Akinsanola and Ogunjobi 2017; Ilori and Balogun 2021). Also, prior studies have shown a connection between this season's increased precipitation over this region and southwesterly moisture transport from the ocean (Pu and Cook 2010). The DJF, SON, and MAN seasons in North Africa have the most precipitation, with values of 55, 45, and 35 mm, respectively, while the JJA season has the least (20 mm). Babaousmail *et al.* (2021) found similar results, indicating that the DJF season receives the most rainfall in the region. In South Africa, the DJF season is the predominant wet season (800 mm), compared to 200 mm and 100 mm for the MAM and SON seasons, respectively, with the JJA season receiving almost no rainfall (10 mm). The highest rainfall season (DJF) confirms the results of Zebaze *et al.* (2019). According to Simon *et al.* (2015), the availability of adequate moisture and stronger summer insolation intensify atmospheric convection, which accounts for the high precipitation over this region. The SON season received the most rainfall in Central Africa (over 500 mm). This corresponds with the results of Zebaze *et al.* (2019), who observed that SON is the season with the most rainfall in the region. The MAM season received more than 400 mm of rain, the DJF season 300 mm, and the JJA season less than 300 mm. In East Africa, the MAM and DJF seasons each recorded 300 mm of precipitation, while the JJA and SON seasons recorded 200 mm. Anyah and Qiu (2012) confirmed MAM and DJF to be the peak seasons for precipitation in the region.

4.1.3 *Monthly precipitation of the subregions of Africa*

Figure 6 depicts a rainfall trend for the West African region that gradually decreases from November to February and increases from March

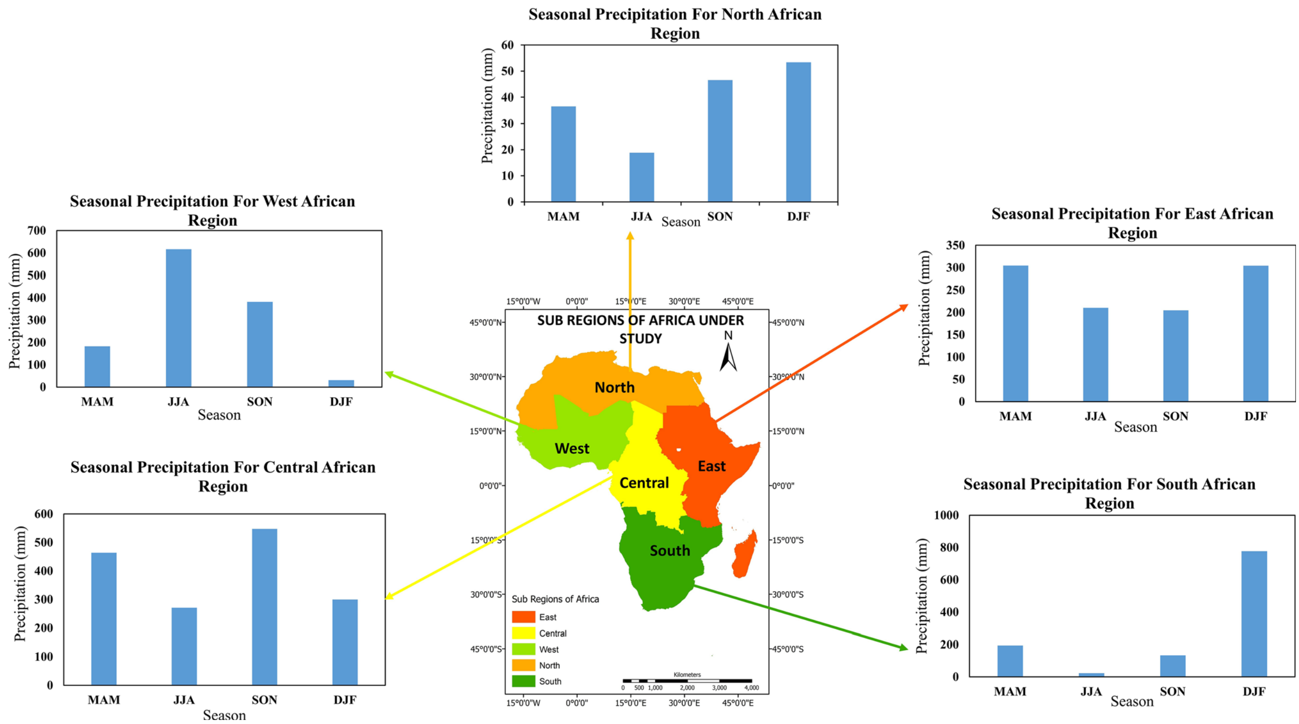

Figure 5. Seasonal precipitation of subregions in Africa using CRU datasets from 1901 to 2021.

to October, peaking in August. This is consistent with research by Muthoni (2020), which found that a 37-year rainfall time series had a substantial positive trend from June to October with a peak in August. In addition, the study found that the months of November, February, and March received minimal rainfall. The rainfall trend in North Africa shows a strong increase from August to January, then steadily decreases from February to July, reaching a minimum in June. The results are consistent with those of Babaousmail *et al.* (2021), who found that the region experiences its peak rainfall in December, and the lowest amount between June and July. In East Africa, the region's rainfall pattern showed a rise from December to May, with April recording the greatest totals for the period under review and June the lowest. The findings agree with a study by Dinku *et al.* (2018) that found the region experiences its maximum rainfall levels between March and May, with April being the wettest month. The study reports that during these months, the ITCZ shifts south, bringing moisture from the Indian Ocean and creating widespread rainfall across the region. The evolution of rainfall in Southern Africa indicates a reduction from March to September, with the lowest value in August, and a significant rise in rainfall from October to March, with the highest value in January. The results are consistent with those of Ambrosino *et al.* (2011), who stated that the region experiences its highest rainfall during the months of October to April. Reason *et al.* (2006) noted that there is a distinct seasonal pattern in rainfall in the area, with a well-defined season spanning from December to April across the majority of the area. Rainfall in Central Africa decreases from November to February and from June to August. Nonetheless, rainfall increases slightly from March to May and significantly from September to October. This is compatible with the results of a study conducted by Camberlin *et al.* (2019), which discovered that Central African subregions have distinct bimodal rainfall regimes, with maximums in April and October and minimums in January and July.

4.2 *Analysis of maximum temperature*

4.2.1 *Annual maximum temperature of the subregions of Africa*

The figures for each region's annual maximum temperature, seasonal maximum temperature, and monthly maximum temperature have been reported as findings (figures 7–9). The results show a trend of increasing annual maximum temperatures

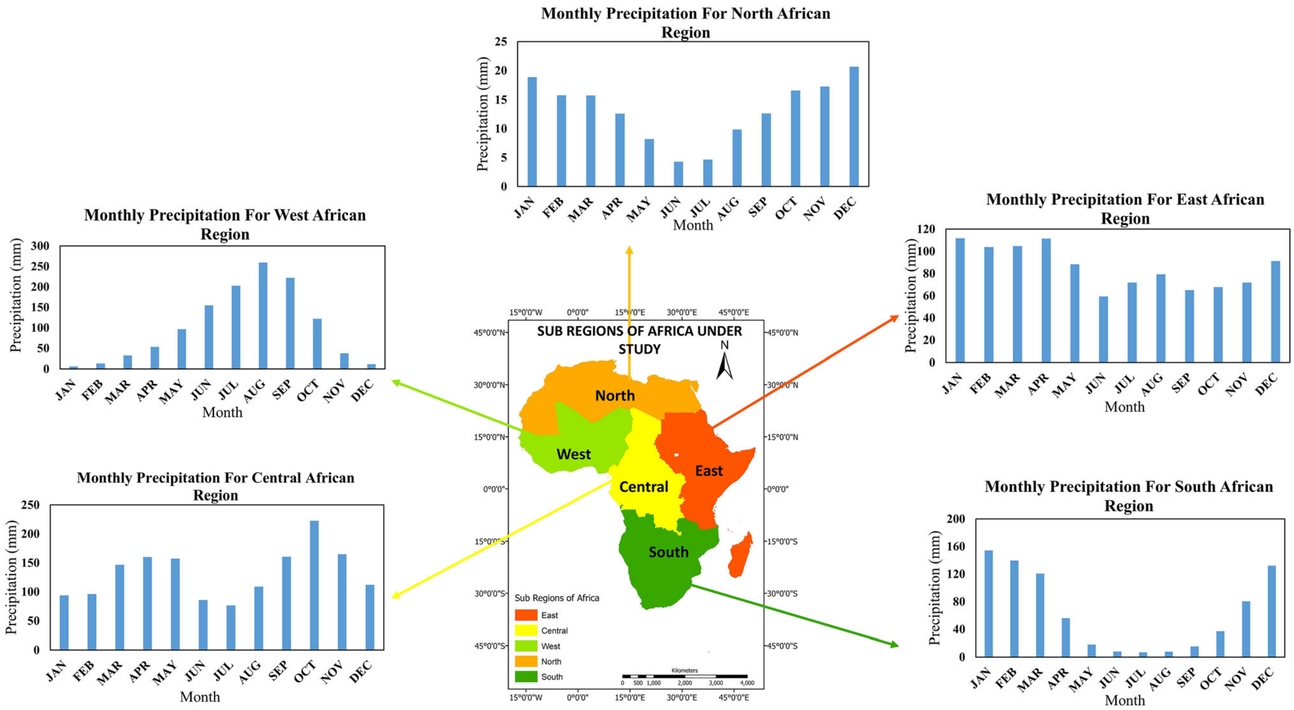

Figure 6. Monthly precipitation for subregions in Africa using CRU datasets from 1901 to 2021.

(from 1901 to 1995 and 2000 to 2021) in all regions of Africa, as indicated in figure 7.

The observed maximum temperature in the northern part gradually increased from 29°C to 29.96°C, over the study period. These findings concur with those of Barkhordarian *et al.* (2012), who found that trends rise each season and each year in terms of mean surface temperatures over North Africa. In the West, the highest recorded temperature was 33.81°C (an increase from 33.54°C), confirming the results of Almazroui *et al.* (2020), who concluded that West Africa is experiencing continuous warming throughout the 21st century. In East Africa, temperatures increased by 0.55°C (from 30.35°C to 30.90°C). Some studies and reports, including those by Trisos *et al.* (2022), have also shown similar results of warming in the region.

Temperatures in Central Africa progressively increased by 0.31°C (from 30.05°C to 30.36°C). Aguilar *et al.* (2009) observed an identical pattern, confirming that this region is warming with an increase in heat extremes. In Southern Africa, similar results of increasing temperatures were observed (an increase from 27.70°C to 28.45°C). Collins (2011), Kruger and Shongwe (2004), and MacKellar *et al.* (2014) found synonymous results stating an increasing trend in annual mean temperatures in most parts of southern Africa experienced over the past decades.

In general, statistics show increasing temperatures in Africa since the late 19th century, making the last 30 years warmer than any previous decade (Ongoma and Chen 2017). Since the 1880s, general warming has been separated only by a period of low temperatures in the middle of the 20th century. The trend of temperature rise seems to be increasing as we approach the end of the 20th century. The few superior resolution simulations that extend to the late 20th century reveal that mean annual temperatures have been 1–2°C higher in recent decades than they were during the medieval climate anomaly Niang *et al.* (2014).

4.2.2 *Seasonal maximum temperature of the subregions of Africa*

Figure 8 shows the seasonal maximum temperature across Africa using the CRU dataset over a 120-year study period. The MAM and SON seasons have the highest maximum temperatures recorded over West, Central, East, and South Africa. The West African region, on the other hand, had a record high of 35.50°C. Zebaze (2019) observed this substantial warming while assessing the CMIP5 multi-model averages of Africa's historical climate.

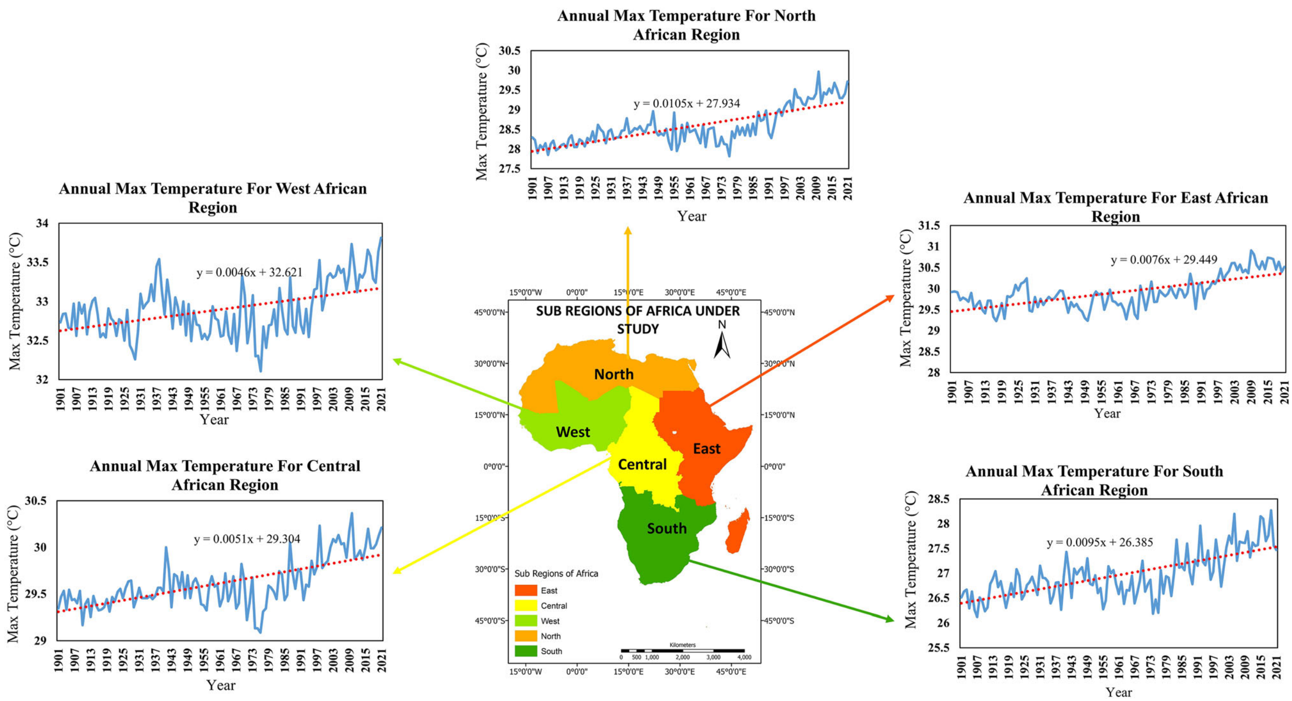

Figure 7. Annual maximum temperature of subregions in Africa using CRU datasets from 1901 to 2021.

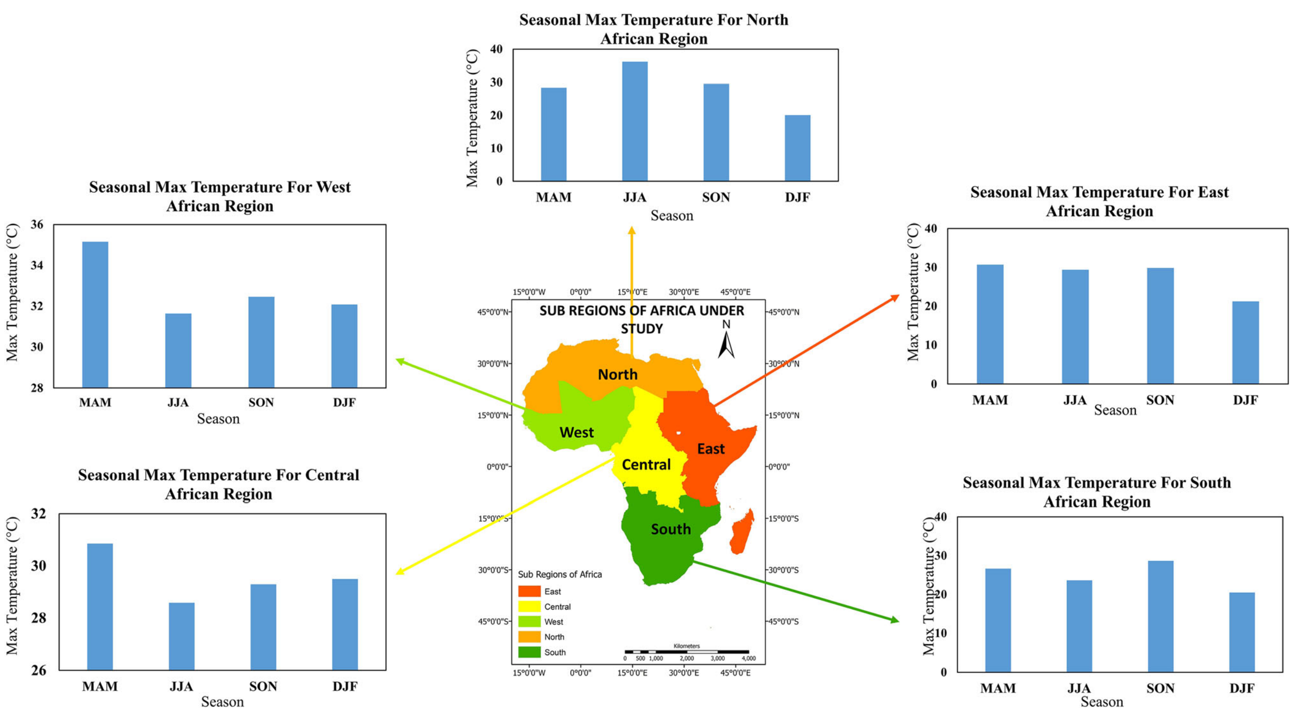

Figure 8. Seasonal maximum temperature of subregions in Africa using CRU datasets from 1901 to 2021.

Sylla *et al.* (2016) also examined into the contemporary trends of seasonal mean temperature (May to September) and precipitation in West Africa, concluding that the region is warming as a consequence of increasing anthropogenic greenhouse gas forcing.

JJA maximum temperatures vary across the continent, with North Africa having the highest record, followed by East and South Africa. East African temperature changes reported during the June–August (JJA) season are consistent with southern hemisphere winters, according to

Ongoma and Chen (2017). Collins (2011) attributes temperature variation to natural climate variability and/or human activity factors.

Figure 8 additionally illustrates that DJF and JJA had the lowest maximum temperatures recorded across the continent, with South Africa having the lowest at 20°C. Zebaze (2019) found that the DJF season had fewer warming trends than other seasons. The rationale for the differences and similarities in monthly and seasonal mean temperature profiles can be explained by investigating slow changes in circulation over decades on a monthly basis using general circulation models, according to Kruger and Shongwe (2004).

4.2.3 *Monthly maximum temperature of the subregions of Africa*

These results show that in North Africa, the month of July is the hottest month. This supports the findings of the World Meteorological Organization (WMO) in 2020, which revealed that in recent years, July experienced exceptionally high temperatures in Morocco and Algeria. The recorded temperatures reached or surpassed 48°C in the majority of Algeria's southern regions (Sahara), with specific instances such as 47.8°C in Hassi Messaoud and Ouargla, and 48.5°C in Adrar (WMO 2020). In the West African region, the analysis indicates that March, April, and May are the warmest months. This finding partially aligns with the results of the United States Agency for International Development (USAID 2018), which identified April, May, and June as the hottest months in the Sahel subregion over the period 1950–2010. The overlap in April and May suggests consistency in the core warm season across both studies, while the difference in the third month of March in our study and June in the USAID study may be attributed to the differing temporal coverage. Our analysis spans a longer period (1901–2021), capturing a broader range of climate variability, whereas the USAID study is limited to 60 years (1950–2010). Similar temperature patterns are observed in the Central and Eastern African regions, where March and April consistently exhibit the highest maximum temperatures. In Southern Africa, temperatures remain relatively stable from October to March, followed by a noticeable decline from April through August, indicating a clear seasonal cycle in thermal conditions.

In addition to anthropogenic climate change, numerous studies have demonstrated that large-scale ocean–atmosphere phenomena significantly influence climatic variability across Africa. The El Niño–Southern Oscillation (ENSO), in both its canonical and Modoki forms, has been linked to interannual anomalies in temperature and precipitation across various African subregions. El Niño events typically lead to reduced rainfall in southern Africa and increased rainfall in equatorial East Africa, while La Niña produces the opposite patterns (Diro *et al.* 2011; Nicholson 2014; Nicholson *et al.* 2018; Ficchi *et al.* 2021). Similarly, the Indian Ocean Dipole (IOD) strongly modulates East Africa's short rain season (October–December), with positive IOD phases associated with enhanced rainfall and flood risk (Black *et al.* 2003; Behera *et al.* 2005; Roy and Troccoli 2024; Zheng *et al.* 2025). Other phenomena, such as the Subtropical Indian Ocean Dipole (SIOD), also affect summer precipitation in southern Africa (Reason *et al.* 2006; Hoell *et al.* 2017). Moreover, land surface changes, including deforestation and land-use conversion, alter regional climate dynamics by modifying surface albedo, evapotranspiration rates, and atmospheric circulation. Measho *et al.* (2019) demonstrated that vegetation dynamics in semi-arid regions are responsive to both climatic fluctuations and land degradation processes. Lelieveld *et al.* (2016) provided further evidence that land degradation and reduced vegetation cover intensify warming and aridity in North Africa and adjacent regions (figure 9).

4.3 *Analysis of minimum temperature*

4.3.1 *Annual minimum temperature of the subregions of Africa*

Variation of the minimum temperature in the five different subregions of Africa over the last 120 years (1901–2021) shows a substantially increasing linear trend curve for each region (figure 10). The West, East, and Central African subregions recorded higher annual minimum temperature variations of 18.4°C, 18.7°C, and 20.3°C to 22°C, 20.2°C, and 20°C, respectively. The Northern region followed with a variation of 15–17°C, while the South recorded the least minimum temperature variation of 13.5–16°C. According to Ogwang *et al.* (2018), subregional temperature analysis from 1950 to 2018 and 1990 to 2018 revealed varying rates of temperature rise, with North, Central, and

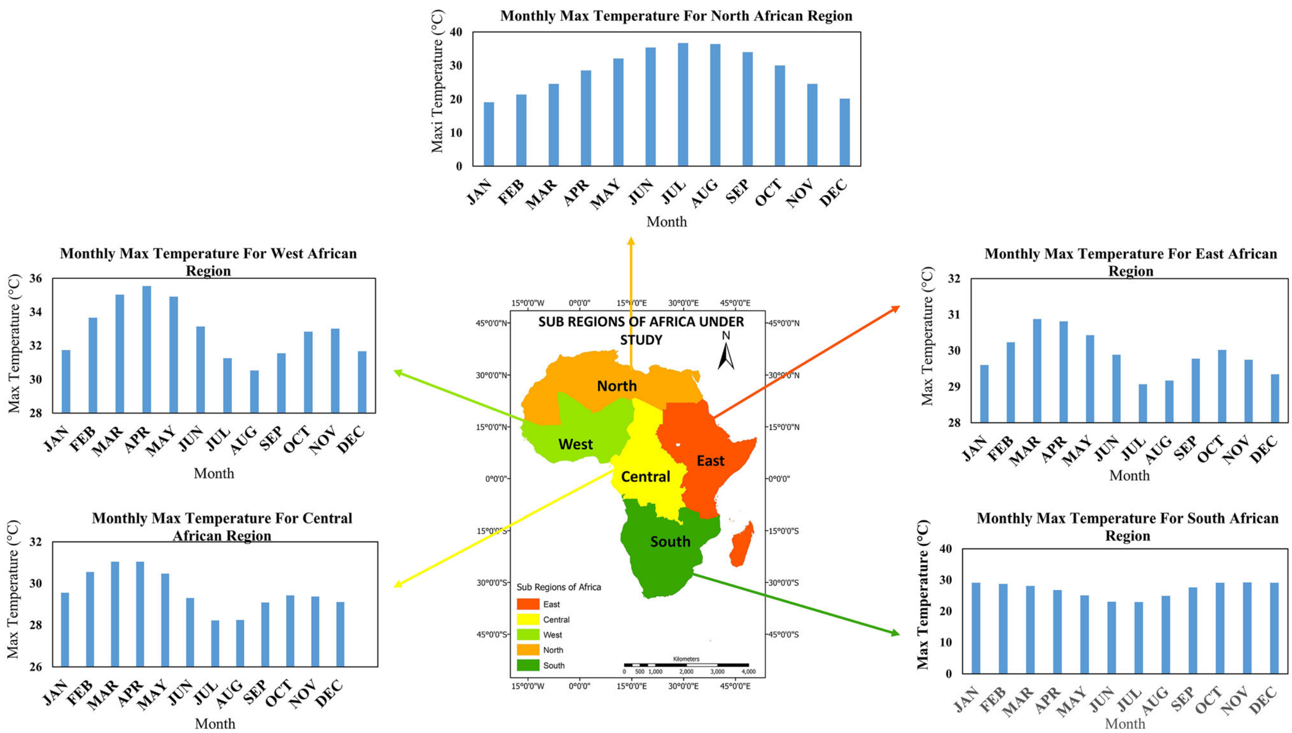

Figure 9. Monthly maximum temperature of subregions in Africa using CRU datasets from 1901 to 2021.

Southern Africa being the third warmest, West Africa seventh, and East Africa fifth. These findings contradict the examined minimum temperature, although this could be because the study's analysis focused on the mean annual temperature cycle.

The temperature increases in West Africa may cause large variations in the region's overall temperature, as a result of the significant temperature increase trend observed globally from the 1950s to the present, owing to global warming. This finding is in accordance with the results of Barry *et al.* (2018), who examined 166 meteorological stations in 13 West African nations across two time periods: 1960–2010 and 1981–2010. All minimum temperature-based indices revealed significant warming trends, according to the findings. Furthermore, the region demonstrated statistically significant warming evidence for the full period as well as for the shorter period 1981–2010. Nevertheless, the longer-term observational tendency shows that warming is substantially higher at night than during the day. Similarly, this temperature variation between day and night was confirmed in another study conducted by NourEldeen *et al.* (2020), where the results showed that the nighttime trend is more significant (>99) than the daytime trend, with majorly significant increasing trends of 8.14% and 3.23%, respectively. Also, the annual temperature increases in East Africa (18.7–22.3°C) are comparable with previous studies (Gebrechorkos *et al.* 2019; King'Uyu *et al.* 2000) that discovered similar growth tendencies in minimum temperature, but the magnitude varied depending on the type of data. Temperatures increased significantly between 1973 and 2021, which can be ascribed to ongoing global warming in conjunction with other mesoscale effects such as changes in land use and land cover.

In addition, the variance of the minimum temperature in Central Africa reveals that the annual linear temperature trend curve increased up to 19.9°C. These results align with those of Almazroui *et al.* (2020) study on the projection of temperature and precipitation changes over Africa from CMIP6, which asserts a continuous increase in temperature in the central African region between 1981 and 2010, even though CRU (1921–2021) data was used in this study. However, according to the climate change and adaptation in Central Africa study (Tsalefac *et al.* 2015), the magnitude of minimum temperature trends varies across the region. Furthermore, the observed differences in the annual minimum temperature in Southern Africa (figure 10) reveal a considerable rise in the warming trend from 14 to 15°C/year, which may be a

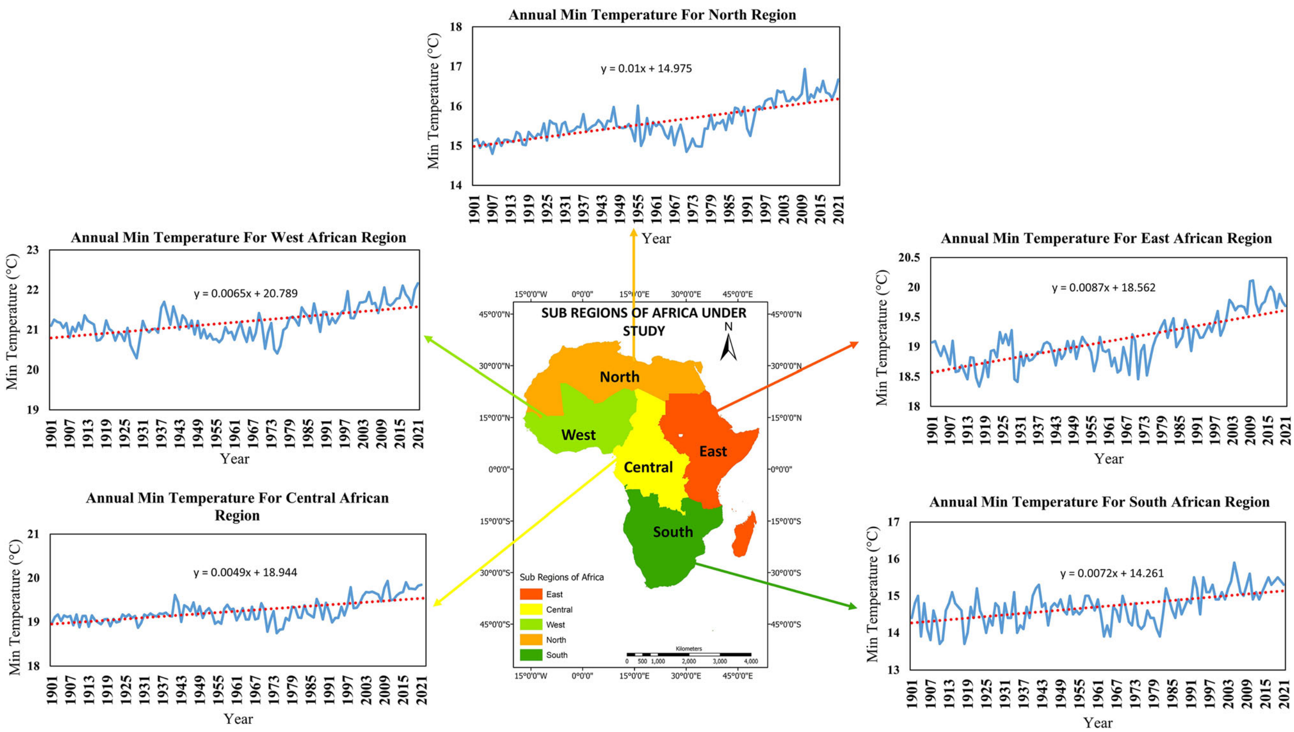

Figure 10. Annual minimum temperature of subregions in Africa using CRU datasets from 1901 to 2021.

result of the substantial warming trend globally since the 1950s as a result of global warming.

4.3.2 *Seasonal minimum temperature of the subregions of Africa*

Figure 11 below shows seasonal variations in minimum temperature for different subregions of Africa over the years 1901–2021. Maximum temperatures in North Africa are near 25°C during the JJA season, with temperatures above 15°C during the SON and MAM seasons, and 10°C or less during the DJF season. The wet, spring, and summer seasons of JJA, SON, and MAM in West Africa all had maximum temperatures around 22°C, however, the winter season of DJF recorded temperatures below 18°C. These findings revealed that the two most critical seasons, wet and hot or dry and cold, have a major impact on the seasonal variation of the region's lowest temperature. This observation is corroborated by a study conducted by Barry *et al.* (2018), which examined 166 meteorological stations in 13 West African countries across two time periods: 1960–2010 and 1981–2010. All seasonal temperature-based measurements, including mean $T_{\min}$, exhibited significant warming trend anomalies. Muthoni (2020) investigated the scope and significance of spatiotemporal patterns in West Africa using gridded data for rainfall and temperatures ($T_{\max}$ and $T_{\min}$) spanning 37 years. All agro-ecological zones (AEZs) and months experienced significant warming and cooling, which were heavily driven by anomalous rainfall fluctuations. This is consistent with the outcomes of this study.

In East Africa, the MAM season records temperatures of 20°C, while the JJA, SON, and DJF seasons record temperatures of 18°C. This finding validates the results of Gebrechorkos *et al.* (2019), which showed minimum temperatures in Kenya and Tanzania increased dramatically (up to +2°C) during the MAM and JJA seasons. However, studies by Ongoma and Chen (2017) reveal the opposite results, with the DJF season between 1951 and 2010 recorded the highest temperature and the JJA season recorded the lowest. For Central Africa, the maximum temperature of 20.19°C is observed in MAM and the least 18.26°C in DJF.

It is worth noting that seasonal precipitation patterns also play a part in determining the temperature trends seen in the region. The wetter seasons of SON and DJF, for example, correspond to milder temperatures, while the drier season of JJA corresponds to the warmest temperatures.

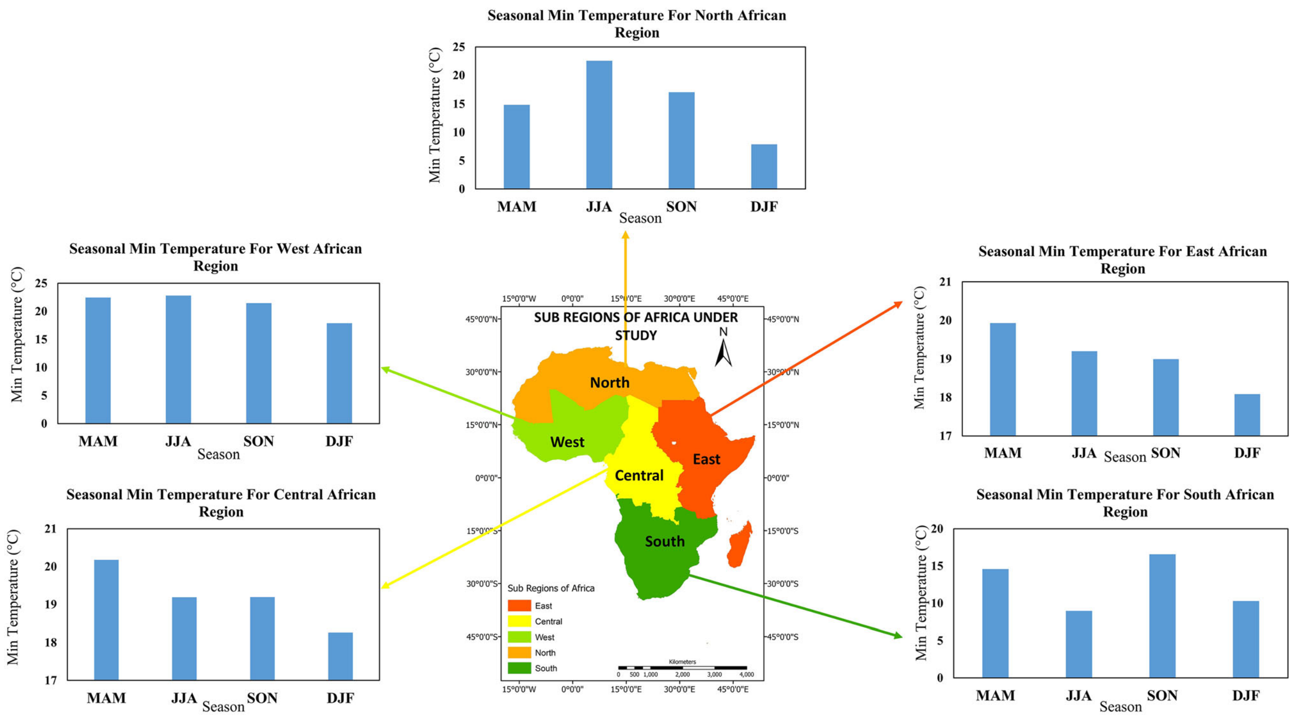

Figure 11. Seasonal minimum temperature of subregions in Africa using CRU datasets from 1901 to 2021.

4.3.3 *Monthly minimum temperature of the subregions of Africa*

From March to October, the monthly temperature in West Africa (figure 12) indicates a persistent trend of high temperatures, with peak values exceeding 22°C. In November, December, January, and February, low temperatures of less than 19°C have been recorded. In contrast, Muthoni (2020) found an exception of localised cooling in August and September over the region's Sahel and Sudan Savanna, which coincided with a positive trend in rainfall.

East Africa experiences high monthly temperatures of around 20°C in April and May. Minimum temperatures in January and December are 18°C. This contradicts the conclusions of a study conducted by Mohamed *et al.* (2021), which revealed that the months of March and April in Ethiopia had high temperatures and July and August had low temperatures. This is due to the limited amount of data points collected from a single region in Eastern Africa. North African temperatures rise steadily from January to May and significantly from April to May. This is consistent with the arrival of summer and the increasing heat in the region, with temperatures peaking in June, July, and August, as expected given that these are the region's summer months. The temperature drops substantially from August to September as the region transitions from summer to fall. The temperature then gradually declines from September to December, with a bigger decrease in November and December, with January being the coldest month in the region, with the lowest temperature. Overall, the monthly temperature trend corresponds to the region's typical seasonal fluctuations. Central Africa has the greatest temperature in April (20.41°C) and the lowest in December (18.17°C), while South Africa has the highest temperature of 19°C (in November, December, January, and February) and the lowest temperature of 9°C (in June and July).

MK trend analysis (table 2) brings significant insight into climate variability across Africa, particularly regarding temperature and precipitation patterns. For precipitation, the MK trend test and Sen's slope estimator were used to detect trends from 1901 to 2021. The results, shown in table 2, indicate a significant decrease in precipitation for North and West Africa, while Central and South Africa experienced an insignificant decrease. These findings align with Almahrouqi's (2020) study, which showed that all countries in North Africa, except Tunisia, exhibited an insignificant decrease in precipitation from 1901 to 2019. Similarly, Lamboni's (2019) research on the Mono River Basin in West Africa and Efon *et al.* (2023) for the

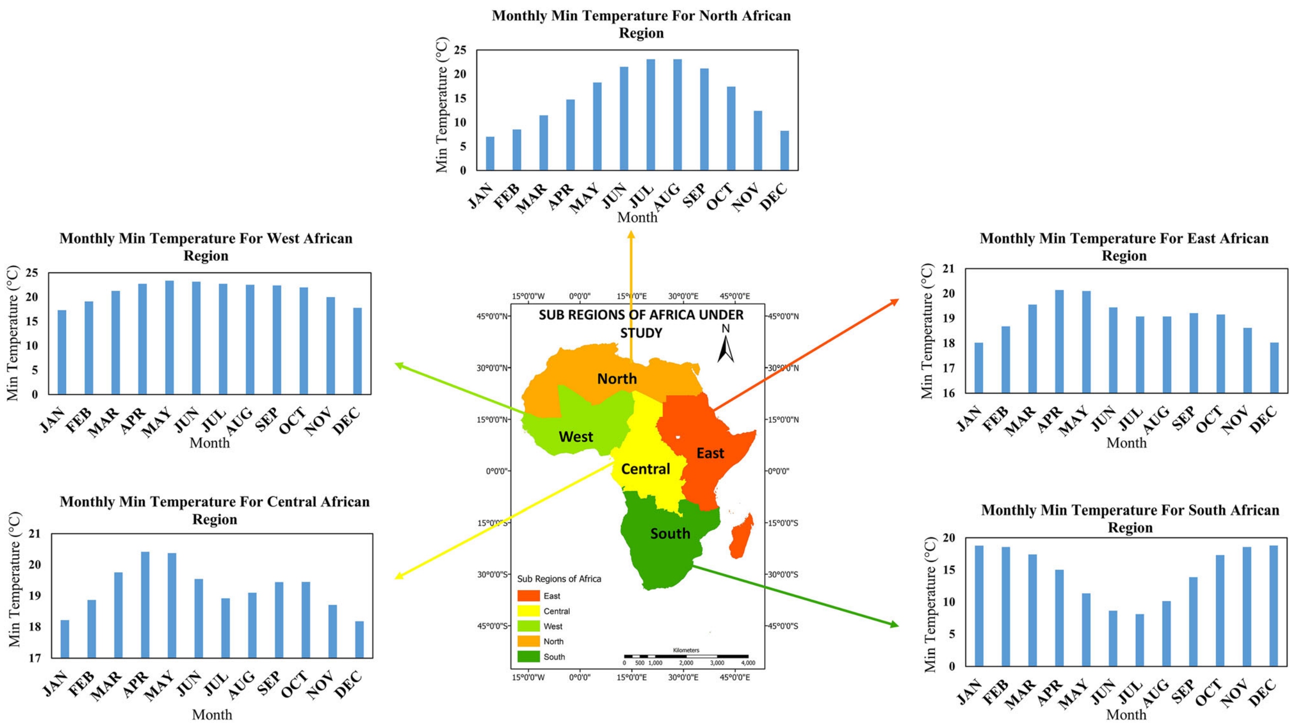

Figure 12. Monthly minimum temperature of subregions in Africa using CRU datasets from 1901 to 2021.

period 1981–2021 also found negative trends in precipitation, particularly in Western and Central Africa. In contrast, East Africa shows an insignificant increase in precipitation, consistent with Ngoma's (2021b) study in Uganda from 1981 to 2019.

MK test was also applied to maximum temperatures across the regions. Table 2 shows an upward trend in maximum temperatures, with North Africa displaying statistically significant increases at the 5% level of significance. These results are consistent with findings from previous studies, such as those by Kruger and Shongwe (2004), Quenum *et al.* (2021), and Almazroui (2017), which documented a substantial rise in maximum temperatures over North Africa. Studies by Vizy and Cook (2012), and Lelieveld *et al.* (2016) also observed similar trends of increasing maximum temperatures in the region, reflecting a broader warming pattern across Africa.

For minimum temperatures, the MK test indicated a significant rising trend across all subregions of Africa, with a *P*-value of 0.00, suggesting a marked increase in minimum temperatures. This aligns with the findings of Chaney *et al.* (2014), who also detected significant changes in climate extremes across Africa between 1979 and 2005. The results suggest a shift toward warmer minimum temperatures, with more frequent occurrences of higher temperatures and a decrease in colder ones. This warming trend is contributing to a noticeable change in the overall temperature distribution across the continent.

4.4 *Spatial analysis for historical and projected climate*

4.4.1 *Spatial precipitation distribution of mean annual rainfall over Africa for the baseline period (1979–2018)*

The spatial precipitation study (figure 13) demonstrates that rainfall amounts in the North, West (a substantial portion), South, and East Africa (including the northern portion) are low, with average annual rainfall ranging from 0 to 50 mm. The remaining eastern region received 50–100 mm of rain on average. Central Africa received 100–200 mm of rain on average. The largest rainfall quantities, however, were recorded in sections of the western region, particularly the southern half of West Africa, with values ranging from 200 to 386 mm.

4.4.2 *Spatial mean maximum temperature distribution over Africa for the baseline period (1979–2018)*

The results of Africa's average maximum temperature from 1979 to 2018 showed variances across the continent (figure 14). Moreover, the continent's central, eastern, and southern regions experienced great variance, but with a dominant mean maximum temperature of 20–30°C. Also, a high maximum temperature was noted in several areas. The highest maximum temperature, however, was recorded in the western part of North Africa, with a maximum temperature ranging from 30°C to 39°C. Figure 14 depicts the trends in the highest temperature recorded throughout time.

4.4.3 *Spatial mean minimum temperature over Africa for the baseline period (1979–2018)*

The analysis of temperature results over Africa (figure 15) revealed that temperatures in North and Southern Africa ranged from 5–10°C to 10–20°C on average. Temperatures in East and Central Africa fluctuate widely, with some areas reporting high (20–28°C) temperatures while others reported low (5–10°C) or moderate (10–20°C) temperatures. The predominant temperature in Central Africa was mild, with high temperatures in some regions. Despite this, West Africa has the greatest average temperature (20–28°C) due to its geographical location in the tropics. Nour Eldeen *et al.* (2020) corroborated this conclusion in a spatiotemporal analysis study of land surface temperature (LST) in Africa. The results show that the annual average LST change was moderate from 2003 to 2017, and the warming trend was notably unequal, with the north and west substantially warmer than the south and east, but mostly in South and Central African areas within the equatorial zone. Nevertheless, higher elevations, like the Atlas Mountain ranges, are colder in the Northern region.

4.4.4 *Spatial difference distribution between future and historical observations over Africa near future maximum temperature (2021–2060) and historical observations*

Figure 16 displays disparities in the spatial distribution of maximum temperature between future projections and historical observations across Africa. Under the SSP5–8.5 high-emissions scenario simulated with the MRI-ESM2.0 model, North Africa is projected to experience a maximum temperature increase of 2–8°C compared to the historical period (1901–2021). Central Africa exhibits a more moderate but still significant increase, while other regions, including parts of East and Southern Africa, show increases between

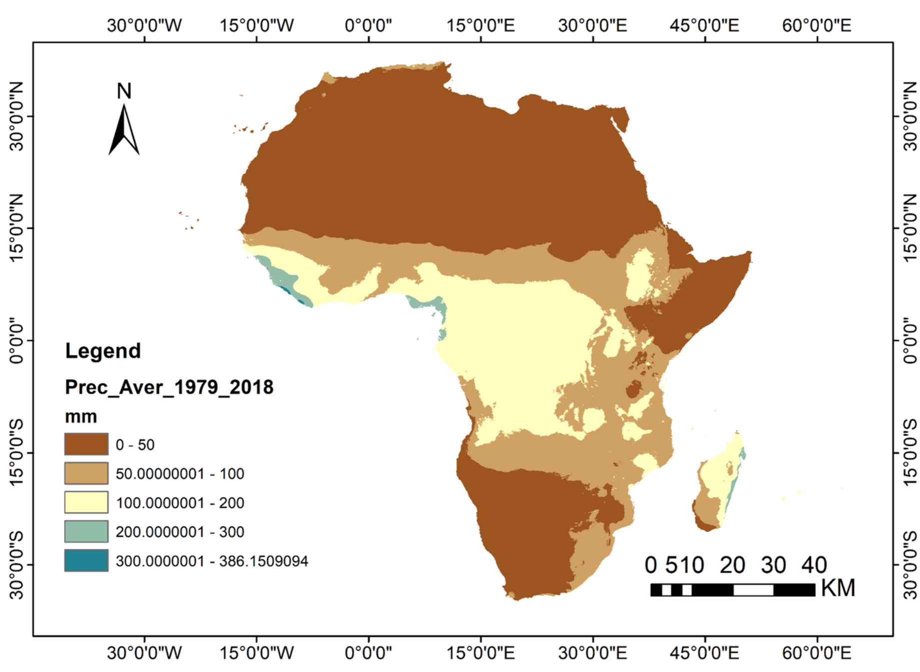

Figure 13. Spatial mean annual precipitation over Africa for the baseline period (1979–2018).

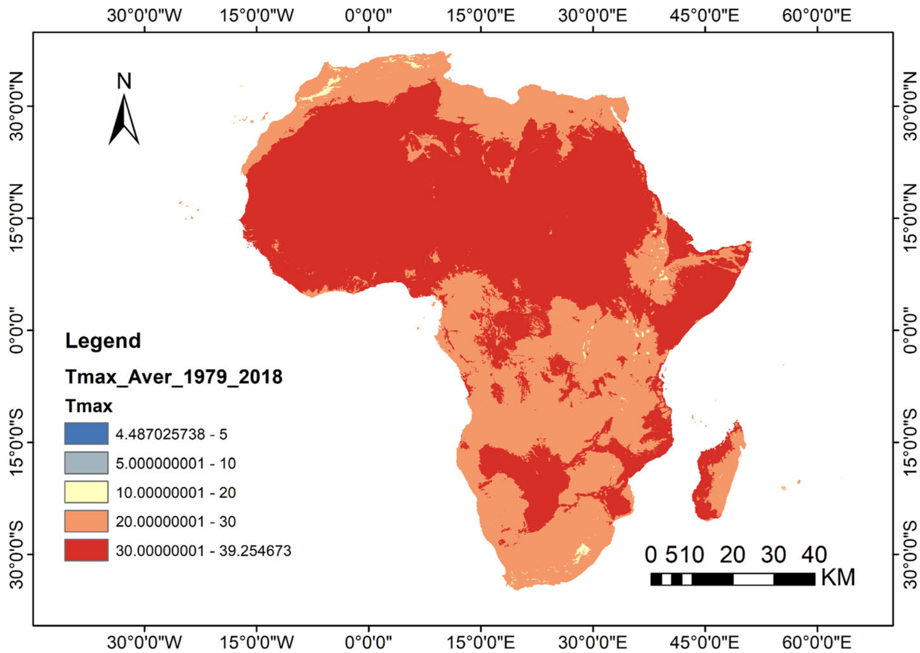

Figure 14. Spatial mean maximum temperature over Africa for the baseline period (1979–2018).

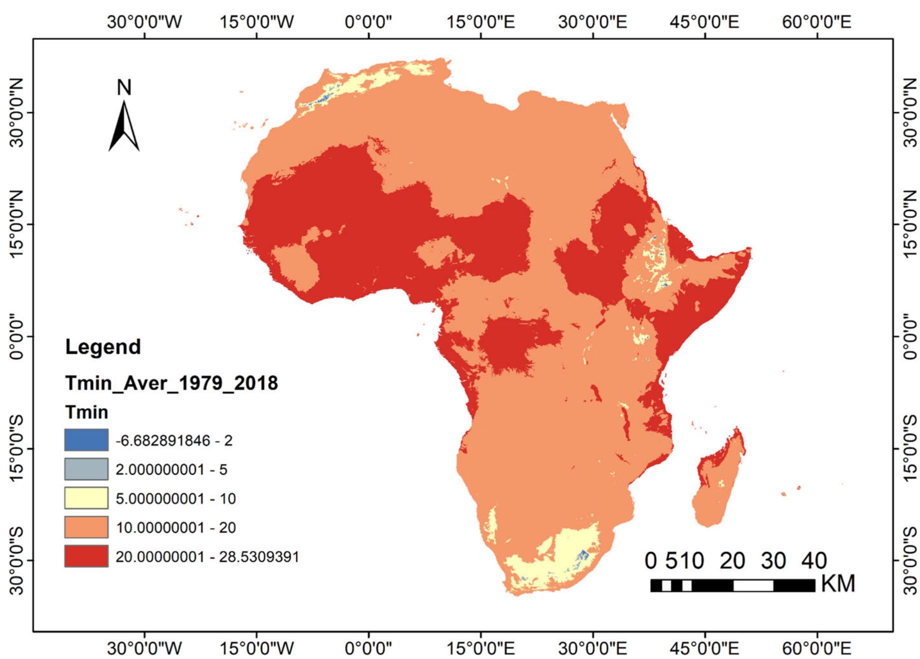

Figure 15. Spatial mean minimum temperature distribution over Africa for the baseline period (1979–2018).

0°C and 2°C. This regional warming pattern aligns with previous studies suggesting that Africa's landmass will warm faster than the global average, particularly in arid and semi-arid zones such as the Sahel and North Africa Niang *et al.* (2014).These results are consistent with, yet slightly more intense than, the CMIP6 ensemble projections under comparable scenarios. For example, Almazroui *et al.* (2020) report projected warming over Africa by the late 21st century ranging from 1.3°C to 3.7°C, depending on the SSP scenario. Our results suggest that the MRI-ESM2.0 model projects stronger warming extremes, particularly in equatorial and arid regions. This discrepancy may be attributed to differences in spatial resolution, model structure, and the longer historical baseline (1901–2021) used in our analysis, which provides a more robust comparison against future periods.

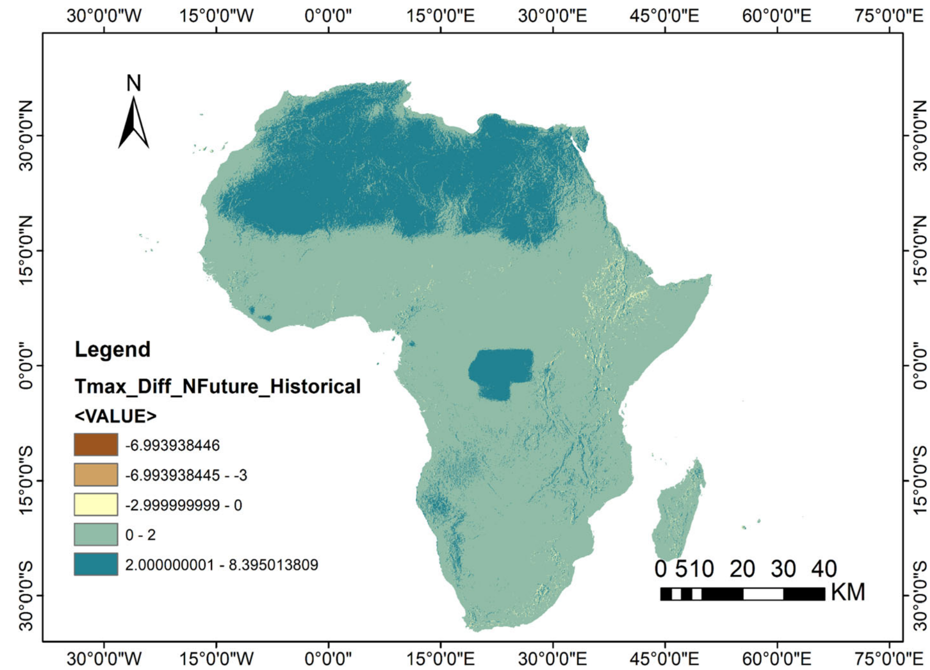

Figure 16. Spatial maximum temperature difference distribution between the near future and historical observations over Africa.

Far future maximum temperature (2061–2100) and historical observations: In the far-future scenario, temperature increases are even more pronounced (figure 17). During the historical period 1950–2008, the background air temperature trend already revealed generalised warming over the Atlantic. These shifts intensified post-1970s, particularly in Northwest Africa, where changes in atmospheric circulation patterns and weakening of anticyclones led to increased surface temperatures Pommier (2005).

Under far-future projections (2061–2100), maximum temperatures are projected to increase by more than 8°C in parts of North Africa and up to 10–12°C in Central Africa, especially in the Republic of Congo. These extreme projections exceed previously reported CMIP6 mean values and highlight the region-specific risks of extreme heat events, particularly under continued high emissions. The findings reinforce the conclusions of Maúre *et al.* (2018) and Almazroui *et al.* (2020), while offering more localised, high-resolution estimates crucial for national adaptation strategies.

Future precipitation (near and far projection) and historical observations: In the near future (2021–2060, figure 18), most of Africa will experience a difference in precipitation of 0 to +10 mm compared to the current scenario. Yet, a considerable area will experience a fall that might reach 59.43 mm. Meanwhile, significant rainfall increases of 10–106.92 mm are forecast in several locations, including northern Mali, southern Benin, central and northern Nigeria, western Chad, northern Cameroon, and the Nile River region. This observation is consistent with that of Fotso-Nguemo *et al.* (2018), who projected rainfall increases in the aforementioned areas from 2006 to 2045.

For the long-term future (2061–2100, figure 18), a large area of African territory will experience precipitation differences ranging from 0 to +20 mm. Significant reductions in rainfall patterns of 0 to –75.6 mm is forecasted over much of southern Africa, northeastern North Africa, and northern portions of central and eastern Africa. In comparison to the findings of Almazroui *et al.* (2020), the projections of the spatial distribution of precipitation in the Central African region show a negative and positive trend. In turn, these authors projected a substantial regional variety during the 21st century, presenting just the positive trend in the indicated region. The inconsistencies in the results are likely caused by the fact that, on the one hand, these scientists began by analysing historical data for a 30-year period (1981–2010) without taking into account the local climate for the previous ten years, while, for the current study, historical data covering a 120-year span was considered.

The expected precipitation trends in Africa are consistent with several prior studies undertaken in various African countries. According to the literature reviewed, a regional variance in mean annual precipitation of the order of –20–25% is expected

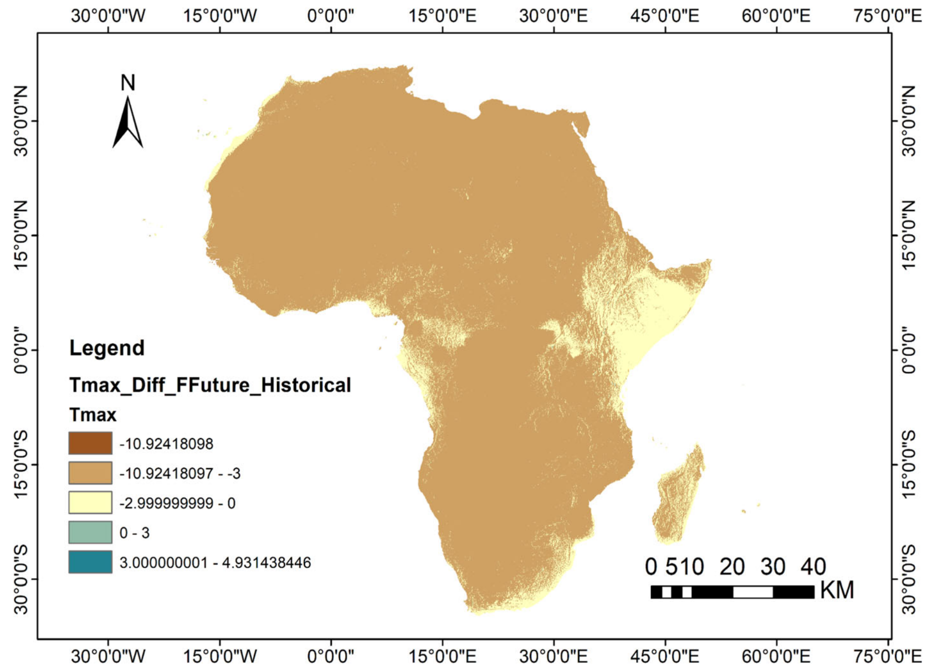

Figure 17. Spatial maximum temperature difference distribution between the far future and historical observations over Africa.

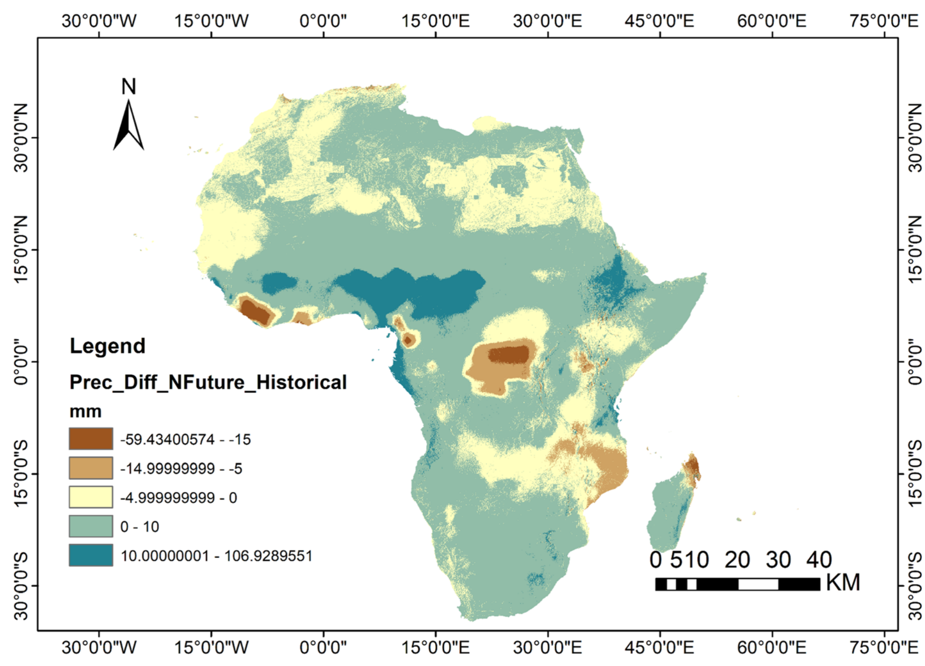

Figure 18. Spatial precipitation difference distribution between the near future and historical observations over Africa.

for 2100 under RCP scenarios (IPCC 2007; Climate Services Center Germany 2016; IPCC 2022).

Hence, it is evident that the anticipated rise in patterns of intense rainfall could aggravate flooding frequencies in the regions concerned. At the same time, the expected decreases in rainfall may accentuate the drought phenomenon. Therefore, strong sub-regional re necessary to facilitate the development of effective adaptation and mitigation measures for the entire continent.

Near future minimum temperature (2021–2060) and historical observations: Projections indicate widespread warming in minimum temperatures across all African sub-regions, ranging from 0°C to 3°C, with some areas of Central Africa, particularly the Congo Basin, experiencing increases of up to 10°C (figure 19). These findings align with those of Maúre *et al.* (2018), who used CMIP5 simulations to project similar trends across the WAFR (West Africa Regional) domain.

Far future minimum temperature (2061–2100) and historical observations: Figures 20 and 21 illustrate a 3°C increase in minimum temperatures during the near future and up to 5°C (and as high as 12°C in parts of Central Africa) in the far future. The Republic of Congo stands out as a critical hotspot, with extreme warming rates in both maximum and minimum temperature projections. Compared to Almazroui *et al.* (2020), who reported maximum projected increases of 3.7°C under SSP5–8.5, our findings suggest higher localised extremes under the same emissions trajectory, reinforcing the need for sub-regional adaptation strategies based on high-resolution modelling.

SPI drought analysis over Africa (1979–2018): The northern region experienced a severe drought occurrence (dry condition) with an SPI value of –0.0226 from 1979 to 2018. Much of Africa's southern region, as well as some parts of its eastern and northern regions, had moderate drought episodes with a value of 0.00459. Nevertheless, the central and western parts of Africa experienced few drought occurrences (wet conditions) between 1979 and 2018 (figure 21).

This finding is compatible with a study by Achour *et al.* (2020) that concluded there will be significant persistent drought occurrences in the near future in the North African Region (Algeria). Also, a study on the West African Sahel by L'hote *et al.* (2002) shows that there will be moderate drought conditions in this region given that there has not been a dramatic change since 1970 and the rainy years in this region are relatively isolated, which is reliable with our findings. A study by Kalisa *et al.* (2020) in the East African region reveals that drought conditions are moderate, producing a result of 96 years (1920–2015) with 41 wet years and 46 drought years, which is also compatible with our analysis, as shown by figure 21.

Impacts on water availability and agricultural systems: The observed decreasing trends in precipitation, particularly over North and West Africa, have substantial implications for water availability in these regions. In these predominantly rainfed regions, reduced rainfall limits both surface and groundwater recharge, thereby constraining water supply for agricultural production and domestic consumption (Niang *et al.* 2014; Dinku *et al.* 2018). These limitations have been linked to declining crop yields, increased food insecurity, and heightened vulnerability of rural populations whose livelihoods are strongly dependent on climate-sensitive sectors (Knox *et al.* 2012; Sultan and Gaetani 2016). Furthermore, growing pressure on scarce water resources may intensify competition among agricultural, domestic, and ecological uses (FAO 2021). Addressing these challenges requires the implementation of adaptive water resource management strategies, including efficient rainwater

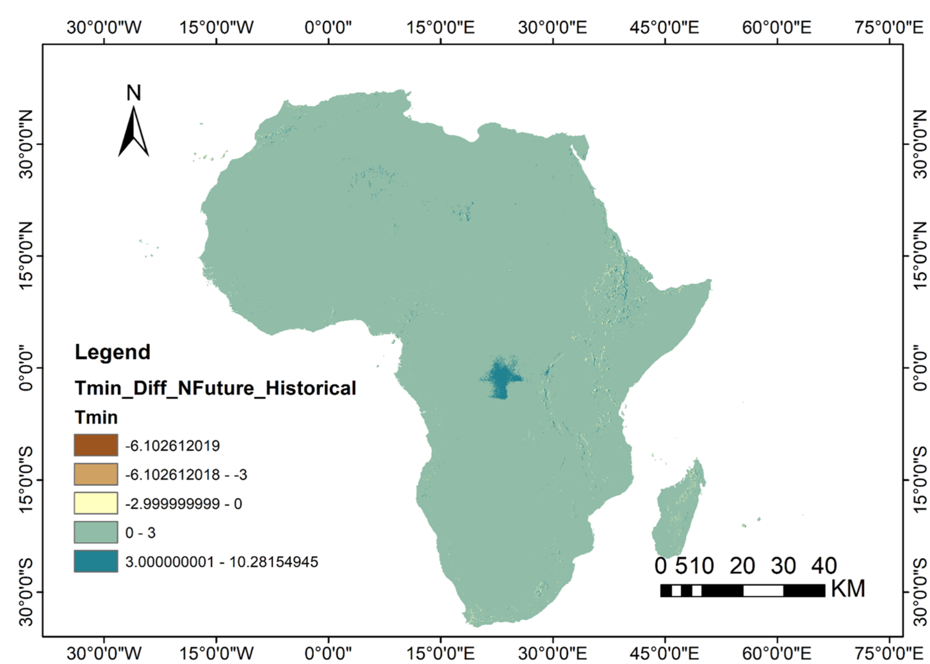

Figure 19. Spatial minimum temperature difference distribution between near future and historical observations over Africa.

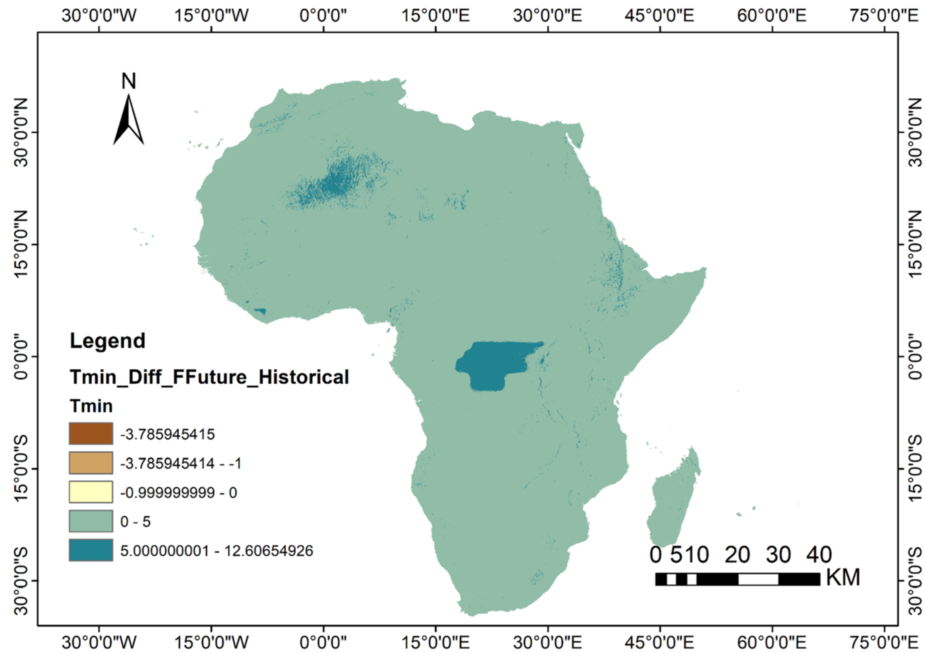

Figure 20. Spatial minimum temperature difference distribution between far future and historical observations over Africa.

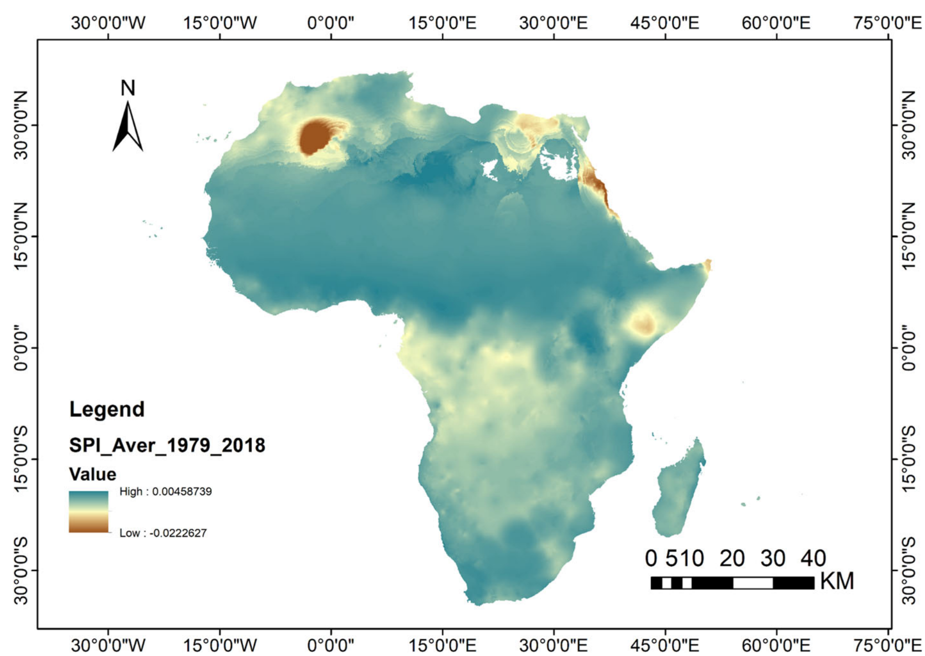

Figure 21. Standard precipitation index (SPI) for drought analysis over Africa (1979–2018).

harvesting, expansion of resilient irrigation infrastructure, and promotion of climate-smart agricultural practices (Rockström *et al.* 2010; Gebrechorkos *et al.* 2019). These responses are consistent with adaptation priorities outlined in strategic frameworks such as the African Union Agenda 2063 and the UNFCCC National Adaptation Plans, which emphasise integrated and resilient approaches to managing climate risks (African Union 2015; UNFCCC 2022).

5. Conclusion

The study highlights significant regional and temporal variations in rainfall and temperature patterns across Africa, with Central Africa receiving the most rainfall and dramatic changes observed in Northern and Western Africa. While most regions may see only slight shifts in precipitation in the near future, more severe changes are expected in certain areas by 2061–2100. Maximum temperatures have consistently risen across the continent, especially in West Africa, underscoring the need for further research on temperature trends. To respond to these observed trends, the following concrete policy actions are recommended: (i) development and implementation of region-specific early warning systems and climate-resilient infrastructure, (ii) mainstreaming climate information into national and local development planning, and (iii) investment in climate-smart agriculture, water harvesting systems, and drought-resistant crop varieties to improve food security in vulnerable zones. In addition, regional cooperation in sharing climate data and best practices can enhance the adaptive capacity of institutions and communities. In terms of mitigation, the study suggests that African countries should prioritise low-carbon development strategies such as forest restoration, clean cooking energy solutions, renewable energy deployment, and improved energy efficiency particularly in rapidly urbanising areas. Strengthening national climate monitoring institutions and integrating traditional knowledge with scientific data can also support long-term mitigation goals.

The study underscores the need for further research using high-resolution regional climate models (RCMs) nested within global models like MRI-ESM2.0 to provide more localised and actionable projections. Future studies should also incorporate socio-economic and ecological datasets, including land use, population growth, and economic vulnerability indicators. Advanced methods such as statistical and dynamic downscaling, machine learning, and ensemble modelling are encouraged to refine climate risk assessments and inform evidence-based policy interventions. This study provides essential insights for both researchers and policymakers to design proactive, science-based strategies for addressing climate variability and extremes across Africa, ensuring that adaptation and mitigation responses are not only timely but also grounded in robust, context-specific evidence.

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