Contrasting hydro-climatic trends and drought dynamics in Ethiopia and South Africa under climate change

Article

Published Version

Mengistu, A., Tesfuhuney, W. A., Woyessa, Y. E., Ejigu, A. A. and Alemu, M. D. (2025) Contrasting hydro-climatic trends and drought dynamics in Ethiopia and South Africa under climate change. Climate Dynamics, 63. 105. ISSN 0930-7575 doi: 10.1007/s00382-025-07588-w Available at https://centaur.reading.ac.uk/122857/

To link to this article DOI: http://dx.doi.org/10.1007/s00382-025-07588-w

Publisher: Springer

Climate Dynamics (2025) 63:105
https://doi.org/10.1007/s00382-025-07588-w

Contrasting hydro-climatic trends and drought dynamics in Ethiopia and South Africa under climate change

Achamyeleh G. Mengistu[1] · **Weldemichael A. Tesfuhuney**[1] · **Yali E. Woyessa**[2] · **Amsalework A. Ejigu**[3] · **Melku D. Alemu**[1,4]

Received: 19 August 2024 / Accepted: 9 January 2025 / Published online: 28 January 2025

Abstract

Climate change profoundly impacts hydro-climatic systems, altering precipitation, temperature, and drought dynamics. This study investigates contrasting trends in Ethiopia and South Africa under historical and future scenarios (SSP2-4.5, and SSP5-8.5) using CMIP6 datasets. The analysis encompasses national averages and regional clusters to capture both spatial and temporal variability. In Ethiopia, annual precipitation increases by 1.2 mm/year under SSP2-4.5 and 2.5 mm/year under SSP5-8.5, potentially benefiting agriculture but elevating flood risks. Conversely, South Africa experiences decline in precipitation of 0.25 mm/year and 0.32 mm/year under SSP2-4.5 and SSP5-8.5, respectively, likely to exacerbate water scarcity and compromising agricultural resilience. Both countries see substantial increases in potential evapotranspiration (PET) and temperature extremes. Ethiopia's PET rises by 0.67 mm/year and 0.97 mm/year, while South Africa's PET increases by 1.14 mm/year and 1.83 mm/year. Temperature increases in Ethiopia are more pronounced in minimum temperatures, while South Africa shows a similar rate of increase in both maximum and minimum temperatures. Drought analysis using SPEI and SPI indices reveals divergent trends: Ethiopia generally experiences decreased drought occurrence, severity and frequency, whereas South Africa faces increased drought occurrences and its properties, particularly under high emissions. These trends vary across clusters, highlighting the need for tailored adaptation strategies in each region. Despite its comprehensive approach, the study acknowledges limitations, including uncertainties in climate model projections and the need for more localized data. Understanding the interplay between hydro-climatic variables and their extremes is essential for effective adaptation. Ethiopia should strengthen flood management and promote soil conservation practices, while South Africa should focus on water conservation. Both nations must integrate climate projections into planning, enhance early warning systems, and foster public–private partnerships for successful adaptation.

Keywords Drought dynamics · CMIP6 datasets · SSP2-4.5 and SSP5-8.5 Scenarios · Ethiopia and South Africa

1 Introduction

Drought stands as one of the most severe climatic adversities globally, posing profound challenges to environmental, economic, and socioecological systems. Particularly in developing countries, droughts threaten sustainable development (UN CCD 2022). Recent reports (e.g., Naumann et al. 2018; Balting et al. 2021; IPCC 2022) indicate that extreme weather events like droughts are projected to increase in frequency, unpredictability, and intensity due to climate change. Understanding the occurrence and characteristics of droughts under future climate scenarios is critical for effective drought management, necessitating robust scientific knowledge to plan early-warning systems and adaptation strategies (Naumann et al. 2018; Balting et al. 2021).

✉ Achamyeleh G. Mengistu
acha.mengistu@gmail.com

[1] Department of Soil, Crop and Climate Science, University of Free State, Bloemfontein, South Africa

[2] Department of Civil Engineering, Central University of Technology, Free State, Bloemfontein, South Africa

[3] School of Agriculture, Policy & Development, University of Reading, Reading, UK

[4] Department of Natural Resources Management, Wolaita Sodo University, Wolaita Sodo, Ethiopia

Comparing Ethiopia's hydro-climatic patterns, shaped by its high elevation and diverse topography, with South Africa's range of climatic zones, from arid to temperate, offers valuable insights into how different climates respond to climate change. This comparison helps identify regional vulnerabilities, informs effective water management strategies, and aids in assessing impacts on food security and economic stability. Additionally, it guides the development of targeted adaptation strategies and policies to enhance climate resilience.

Drought is a pervasive challenge in both South Africa and Ethiopia, profoundly impacting their ecosystems, agriculture, and water resources (Alemayehu and Bewket 2016; Baudoin et al. 2017; Haile et al. 2020; Meza et al. 2021; Orimoloye et al. 2022; Gebrechorkos et al. 2023). South Africa, classified as a water-scarce country (Seckler and Amarasinghe 2000; Du Plessis and Schloms 2017), experiences significant vulnerabilities to even minor rainfall deficiencies, severely affecting ecosystem services and agricultural productivity (Pili and Ncube 2022). Similarly, Ethiopia faces recurrent drought episodes exacerbated by erratic rainfall patterns and climate variability, posing substantial challenges to food security and economic stability (Deressa et al. 2009; Zeray and Demie 2016). Both nations have witnessed severe socioecological impacts from drought, including crop failures, water shortages, and heightened vulnerability to food insecurity (Alemayehu and Bewket 2017; Dube et al. 2022). For example, South Africa's 2015–2018 drought led to significant agricultural losses and water scarcity crises, notably in the Western Cape Province where Cape Town faced the infamous 'Day Zero' scenario, highlighting the imminent depletion of municipal water supplies (Dube et al. 2022). Similarly, Ethiopia has grappled with catastrophic drought events, such as in 2015–2016, which severely affected agriculture and triggered humanitarian emergencies, underscoring the urgent need for robust drought mitigation strategies and sustainable water resource management practices (Haile et al. 2020; Philip et al. 2018).

Climate change profoundly impacts global freshwater ecosystems, intensifying extreme weather events like droughts and heatwaves (Hosseinizadeh et al. 2015; Bharambe et al. 2023; Mengistu et al. 2024). South Africa and Ethiopia, vulnerable to climate shifts, face increased drought risks (Naumann et al. 2018; Balting et al. 2021). Future projections emphasize the need for sustainable development strategies amidst significant spatial and temporal drought variability (Dai 2011; Cook et al. 2014; Naumann et al. 2018; Balting et al. 2021; Chiang et al. 2021). Climate models predict more frequent and severe droughts in both nations, posing challenges for agriculture, water management, and socioecological resilience (Alemayehu and Bewket 2017; Dube et al. 2022). Recent events, such as South Africa's 2015–2018 and Ethiopia's 2015–2016 droughts, highlight vulnerabilities in agricultural sectors and stress the urgency of adaptive measures (Meza et al. 2021; Dube et al. 2022; Haile et al. 2020). Addressing these challenges demands robust adaptation strategies and international cooperation to enhance resilience against escalating climate-induced drought threats in both countries.

Based on the literature and existing research, there are several significant knowledge gaps and critical objectives for future studies. Firstly, there is a gap in understanding long-term trends versus natural variability in hydro-climatic processes which is critical for distinguishing climate change impacts from natural cycles (e.g., El Niño/La Niña events) and making informed projections (Trenberth and Shea 2005). Secondly, current studies predominantly offer broad-scale assessments of climate change effects on hydro-climatic conditions and drought impacts (IPCC 2014, 2022). This underscores the necessity for localized investigations that evaluate the specific vulnerabilities of communities, ecosystems, and infrastructure in Ethiopia and South Africa to projected drought scenarios. Meanwhile, uncertainties persist concerning the accuracy and reliability of the Coupled Model Intercomparison Project Phase 6 (CMIP6) models in predicting regional drought patterns (Knutti et al. 2013). Further validation of these models against historical drought events in both nations could enhance confidence in their projections and support more informed decision-making for drought resilience.

To address these critical gaps, this study set out several objectives. Firstly, it aimed to analyze the long-term trends of hydro-meteorological variables, including precipitation, potential evapotranspiration, and maximum and minimum temperatures, in Ethiopia and South Africa, and to draw comparisons between the two nations. Secondly, it sought to assess drought events and their temporal and spatial variations through detailed analysis for both countries. Thirdly, the study aimed to conduct comprehensive local-scale assessments of drought occurrence, severity, and return periods. By employing CMIP6 climate change scenarios, these assessments provided valuable insights into regional drought impacts and guided the development of targeted adaptation strategies. Ultimately, these efforts are intended to yield actionable insights that support effective adaptation and resilience-building measures, thereby minimizing the adverse impacts of future droughts on water resources, agriculture, and socio-economic stability.

2 Material and methods

2.1 Description of the study area

This study encompasses two distinct regions in Africa: Ethiopia in East Africa and South Africa at the southern tip of the continent. Ethiopia shares borders with Eritrea to the north, Djibouti and Somalia to the east, South Sudan and Sudan to the west, and Kenya to the south (Fig. 1). Its diverse landscape shapes various climates and vegetation types: the south-western, northern, and central highlands feature equatorial rainforests and afro-alpine climates, with average temperatures ranging from 15–20 °C annually. In contrast, the north-eastern, eastern, and south-eastern lowlands experience arid climates, with mean annual temperatures ranging from 25 to 30 °C. This geographic diversity significantly influences rainfall patterns, which vary widely from less than 300 mm annually in the southeast lowlands to over 2000 mm in the southwest highlands. Agriculture is predominant, supporting a primarily rural population engaged in small-scale farming (Shitarek 2012; FDRE 2021).

On the other hand, South Africa is bordered by Namibia, Botswana, Zimbabwe, Mozambique, and Swaziland, with coastlines along both the South Atlantic and Indian Oceans (Fig. 1). Over the period from 1991 to 2020, South Africa recorded an average annual temperature of 18.3 °C and received 456 mm of precipitation annually (World Bank Group 2024). Precipitation varies significantly across the country, with higher levels in the eastern and north-eastern regions compared to the drier western and south-western areas. Conversely, temperatures increase from the cooler eastern and south-eastern provinces to the warmer northern and north-western regions. South Africa's climate diversity includes arid and semi-arid zones (STEP-SA 2024).

2.2 Climate model data

This study utilizes the NASA Earth Exchange Global Daily Downscaled Projections, referred to as NEX-GDDP-CMIP6 (Thrasher et al. 2012, 2022). The Coupled Model Inter-comparison Project Phase 6 (CMIP6) represents the latest set of climate model outputs coordinated by the World Climate

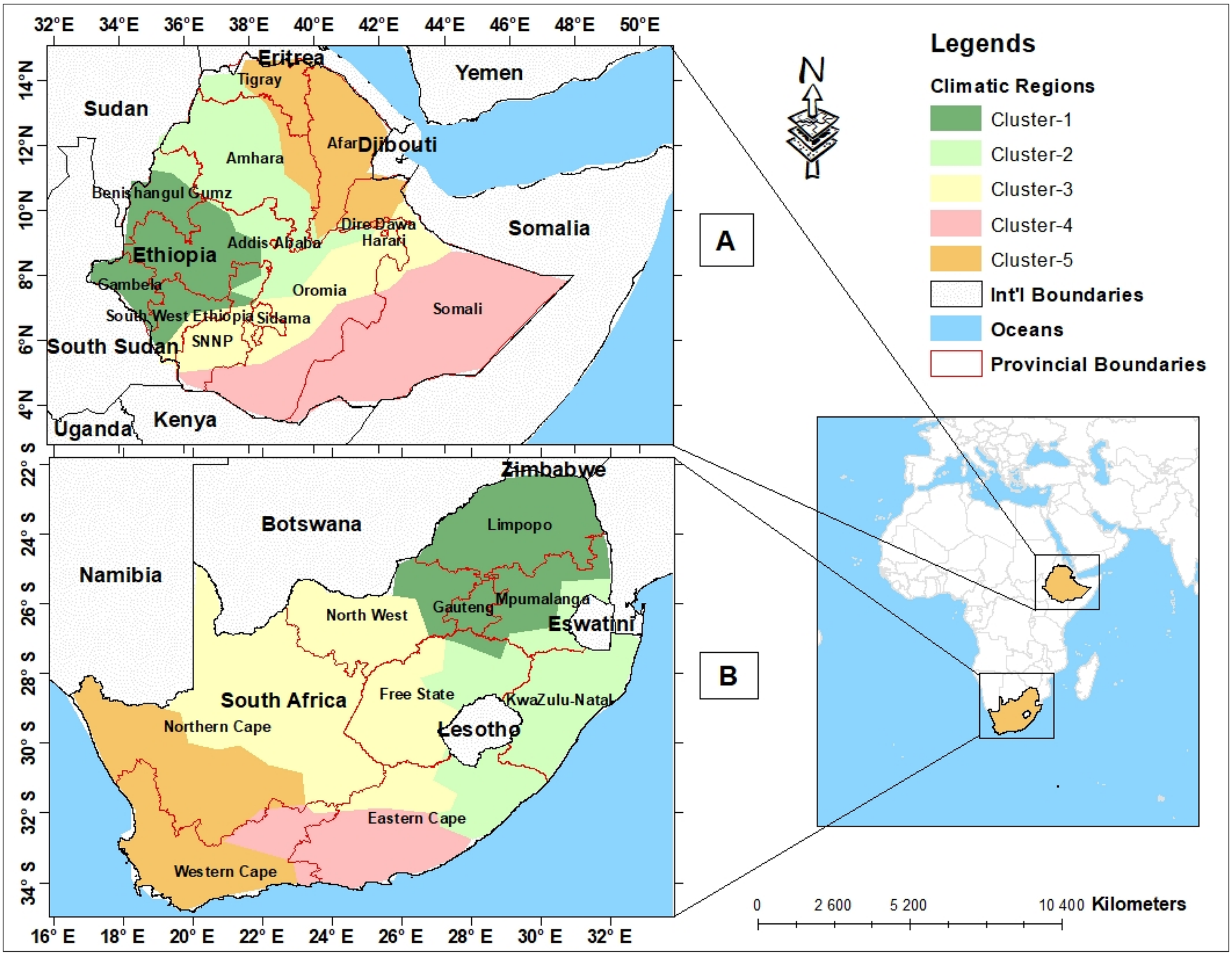

Fig. 1 Location of the study area, showing administrative provinces (bordered in red lines) and the formed climatic regions or clusters (distinguished by different colours) for both Ethiopia and South Africa

Research Program (WCRP). NEX-GDDP-CMIP6 is a dataset that has been downscaled and bias-corrected by NASA, providing higher spatial resolution (0.25 by 0.25 degrees) and daily temporal resolution. This dataset is specifically tailored to support local-scale climate impact studies (Thrasher et al. 2022).

Six global climate models (GCMs) were obtained from the data distribution website (data link: https://ds.nccs.nasa.gov/thredds/catalog/AMES/NEX/GDDP-CMIP6/catalog.html). Although these models cover global data, spatial sub-setting for specific regions of interest was conducted using the R software, by RclimChange package (R Core Team 2023), which is available for download from GitHub (https://github.com/hllauca/RClimChange). Historical data spanning from 1950 to 2014, as well as projections under two climate change scenarios (SSP2-4.5 and SSP5-8.5, from 2015 to 2100), were downloaded for precipitation, maximum temperature, and minimum temperature across all models. Data management tasks, such as merging, creating monthly totals, calculating means, and generating ensembles, were performed using the Climate Data Operator (CDO) software (Schulzweida 2023). Table 1 provides details on the models used and their respective institutions.

This study selected the SSP2-4.5 and SSP5-8.5 scenarios to encompass a range of potential future climate variations that inform policy and planning. The SSP2-4.5, or "middle-of-the-road" scenario, assumes moderate mitigation efforts and socioeconomic shifts, making it ideal for evaluating mid-range impacts. In contrast, SSP5-8.5 represents a high-emission, fossil fuel-reliant pathway with minimal mitigation, illustrating potential extreme outcomes under sustained high emissions (Van Vuuren and Carter 2014; O'Neill et al. 2016). Using both scenarios, this study offers insights across a spectrum from moderate to severe climate impacts, informing how various emission trajectories may affect climate dynamics in the two countries.

2.3 Formation of homogeneous climatic regions (clusters)

Climate variables exhibit significant regional variability, with specific geographic areas responding similarly to particular climatic trends (Badr et al. 2015; Ullah et al. 2029). For effective climate impact management and monitoring, it is crucial to identify and delineate these homogeneous regions.

This study used the R-based package, called HiclimR (Badr et al. 2015) from the Comprehensive R Archive Network (CRAN) to classify regions with similar climatic attributes, for this study, based on the time series historical monthly precipitation. HiclimR calculates similarity metrics, such as correlation coefficients, between adjacent grid cells and then applies hierarchical clustering, merging the most similar cells until a specified number of clusters is reached or each region meets the required criteria, resulting in cohesive, homogeneous climate zones. This method resulted in clusters represented by distinct colours as follows: green for Cluster-1, light green for Cluster-2, light yellow for Cluster-3, light pink for Cluster-4, and light orange for Cluster-5, as shown in Fig. 1A, B for Ethiopia and South Africa, respectively.

The national data for both countries were also cropped according to these boundaries, and zonal means were calculated for each cluster using the Climate Data Operator (CDO) tool (Schulzweida 2023). This approach ensures that the climatic data accurately represents the specific regions, allowing for more reliable and relevant findings. By utilizing such precise and localized data, the study provides actionable insights for regional climate adaptation and mitigation strategies.

2.4 Analysis of hydro-meteorological variables

The study employed multiple methods and tools to analyse hydro-climatic variables across Ethiopia and South Africa. The potential evapotranspiration (PET) was computed using the Hargreaves method with assistance from the SPEI package in R (R Core Team 2023). The Hargreaves method derives PET from maximum and minimum temperature data exclusively. Additionally, R was utilized for spatial data clipping to delimit analysis to the specific area of interest. For aggregating spatial means necessary for time series analysis of precipitation, PET, maximum temperature (Tmax), and minimum temperature (Tmin), the Climate Data Operator (CDO) software was employed (Schulzweida 2023). This integrated approach facilitated comprehensive spatial and

Table 1 List of models, country and running institution used in this study

No	Model	Country	Running institution
1	CanESM5	Canada	Canadian Centre for Climate Modelling and Analysis
2	FGOALS-g3	China	Chinese Academy of Sciences (CAS)
3	GFDL-ESM4	USA	NOAA Geophysical Fluid Dynamics Laboratory
4	GISS-E2-1-G	USA	NASA Goddard Institute for Space Studies (GISS)
5	INM-CM5-0	Russia	Russian Academy of Science
6	NorESM2-MM	Norway	Norwegian Climate Centre

temporal analyses of hydro-climatic variables, enhancing the robustness of the study's findings.

2.5 Calculation of drought indices and characteristics

2.5.1 Drought indices

Drought occurrence and its properties are analysed based on the standardized precipitation index (SPI) and standardized precipitation evapotranspiration index (SPEI) in this study. The SPI is calculated by the difference of each precipitation from the long-term mean precipitation and dividing to the standard deviation (McKee et al. 1993; Agnew 2000). The Standardized Precipitation Evapotranspiration Index (SPEI) assesses drought severity by combining precipitation and potential evapotranspiration (PET). PET is calculated using Hargreaves. Monthly precipitation anomalies are determined by subtracting long-term averages, and these anomalies are then standardized using a fitted probability distribution. SPEI is obtained by dividing the standardized precipitation anomaly by the standard deviation of PET, offering a standardized measure of drought that considers both precipitation deficits and evapotranspiration influenced by temperature (Vicente-Serrano et al. 2010a, b). In this study, only the 3-month time scale was used to analyse drought occurrence and its properties. All these methods are assisted by the SPEI package in R (R Core Team 2023).

2.5.2 Drought properties

In addition to indicating simple drought presence or absence over time, drought indices play a crucial role in assessing characteristics such as severity, duration, and return period (frequency), which are essential for understanding drought behaviour within a region. Drought severity measures the intensity of the drought, duration quantifies the length of the drought period, and return period estimates the frequency of extreme drought events. The calculation of these characteristics typically involves analysing consecutive periods where values fall below a specified threshold in a time series dataset.

In this study, drought characteristics are analyzed using run theory and copula functions (Yevjevich 1967; Hao et al. 2017; EskandariPour and Soltaninia 2022). Drought events are defined using Standardized Precipitation-Evapotranspiration Index (SPEI) values below – 1, identifying periods that meet this criterion, which is a drought category of moderate drought as shown in Table 2. Consecutive drought indices are aggregated to determine the severity of each drought period. The study also identifies the start and end dates for each drought event, calculating the duration as the length of each drought period. The calculation of severity and duration is facilitated by the 'drought' package in R software (R Core Team 2023).

Table 2 Drought categories based on SPEI/SPI values

No	SPEI/SPI value	Drought category
1	0 to – 0.99	Mild drought
2	– 1 to – 1.49	Moderate drought
3	– 1.5 to – 1.99	Severe drought
4	> -2.0	Extreme drought

McKee et al. (1993)

Moreover, the univariate return period, which shows the likelihood of a drought event exceeding a specified threshold value for a single variable, is calculated using the 'drought' package in R. For this study, the variables used in the return period calculation are drought severity and duration, which were determined in the previous analysis steps. The univariate return period is computed using the following formulas (Hao et al. 2017):

$$T_s = \frac{\mathrm{EL}}{\mathrm{P}(S \geq s)} = \frac{EL}{1 - F_s(S)} \tag{1}$$

$$T_d = \frac{\mathrm{EL}}{\mathrm{P}(D \geq d)} = \frac{EL}{1 - F_d(d)} \tag{2}$$

where T_s and T_d refers to the univariate return period calculated from severity and duration, respectively, EL refers to the mean interval between successive droughts, P is a probability level, $F_s(S)$ and $F_d(d)$ are the cumulative distribution functions of drought severity and drought duration, respectively. The mean interval or recurrence time is calculated for both study countries, clusters and scenario separately. A gamma distribution is fitted to estimate the univariate return period from drought severity (T_s) and an exponential function for univariate return period from drought duration (T_d) (Hao et al. 2017; EskandariPour and Soltaninia 2022).

2.6 Data analysis

This study uses ensemble mean data from six global climate models (GCMs) derived from the Coupled Model Intercomparison Project Phase 6 (CMIP6) outputs (Table 1). The analysis was conducted using both temporal and spatial data analysis methods to provide a comprehensive assessment of climate change impacts. For the temporal analysis, the Mann–Kendall (MK) and Sen's Slope method was applied using R software to analyse time series data of climate variables. A significance threshold of $p < 0.05$ were used to identify statistically significant trends over time. This method helped in detecting monotonic trends in the climate data without assuming any specific distribution of the data.

In the spatial analysis, Climate Data Operators (CDO) and R software were utilized. The procedures included boundary cropping, where the data was cropped by geographical boundaries to focus on specific regions of interest. Changes in climate variables (e.g., drought events) were quantified by calculating percent changes over the study period. Raster data manipulation techniques were employed to detect localized changes in climate conditions, allowing for the analysis of spatial variability and patterns. By integrating temporal and spatial analyses, this approach provided a comprehensive assessment of climate change impacts, offering valuable insights for informed decision-making.

3 Results

3.1 Hydro-climatic variables

The annual time series of long-term hydro-climatic variables (precipitation, potential evapotranspiration, maximum and minimum temperature) for Ethiopia and South Africa are illustrated in Fig. 1. Additionally, Table 3 presents the results of the Mann–Kendall (MK) trend analysis for these variables.

In Ethiopia, both the time series plots (Fig. 2A) and MK-trend analysis indicate a significant increase in annual precipitation under both the SSP2-4.5 and SSP5-8.5 scenarios. Specifically, precipitation shows a notable upward trend, increasing at rates of 1.2 mm per annum for SSP2-4.5 and 2.5 mm per annum for SSP5-8.5 scenarios. This demonstrates that the impact of the high emission scenario (SSP5-8.5) is more pronounced, with precipitation increasing at a rate twice that of the medium emission scenario (SSP2-4.5).

Conversely, in South Africa, the results reveal a slight yet significant decrease in annual precipitation under both scenarios (SSP2-4.5 and SSP5-8.5). The trends show decreases at rates of 0.25 mm per annum for SSP2-4.5 and 0.32 mm per annum for SSP5-8.5, indicating a consistent declining trend in precipitation.

Overall, these findings highlight the contrasting impacts of climate change scenarios on precipitation trends in Ethiopia and South Africa. While Ethiopia is experiencing significant increases in precipitation, South Africa is witnessing slight decreases, with the effects of higher emissions scenarios (SSP5-8.5) more pronounced in both regions.

The time series analysis depicted in Fig. 2B reveals significantly increasing trends in potential evapotranspiration (PET) for both scenarios and study areas. The MK trend analysis corroborates these findings. Specifically, PET shows annual increases of 0.67 mm and 0.97 mm in Ethiopia, and 1.14 mm and 1.83 mm in South Africa, for the SSP2-4.5 and SSP5-8.5 scenarios, respectively. This indicates a more pronounced annual increase in PET for South Africa compared to Ethiopia, with increases ranging from 70% under the medium emission scenario to 89% under the high emission scenario.

In accordance with the PET results, Fig. 2C, D illustrate that both Tmax and minimum Tmin exhibit significant increasing trends for both scenarios and study areas. In Ethiopia, Tmin shows a higher rate of increment compared to Tmax. Conversely, in South Africa, both Tmax and Tmin demonstrate almost similar rates of increment across both scenarios. These findings underscore the escalating trends in PET, Tmax, and Tmin across Ethiopia and South Africa under different climate change scenarios.

3.2 Drought occurrence and trends

The analysis of drought occurrence and its characteristics employs the SPEI and SPI indices, as illustrated in Fig. 3 for the monthly time series values of both study areas at the national level. Additionally, Table 4 provides the MK-trend analysis results for the SPEI time series for each study area, including their clusters and scenario levels. In this study, the word 'drought' refers to meteorological drought only.

In Ethiopia, both the time series and MK-trend analysis reveal a significant positive trend in SPEI and SPI values, suggesting a reduction in drought events and occurrences at the national average. Conversely, in South Africa, there is a

Table 3 Man-Kendall trend tests for annual climate variables

Countries	Climate variables	SSP2-4.5			SSP5-8.5		
		z-score	Sen's slope	p-value	z-score	Sen's slope	p-value
Ethiopia	Precipitation	8.97	1.19	< 0.001	12.35	2.49	< 0.001
	Annual PET	13.86	0.67	< 0.001	14.85	0.97	< 0.001
	Max. temp	15.49	0.02	< 0.001	16.2	0.03	< 0.001
	Min. temp	15.45	0.03	< 0.001	16.2	0.04	< 0.001
South Africa	Precipitation	– 5.01	– 0.25	< 0.001	– 5.66	– 0.32	< 0.001
	Annual PET	14.16	1.14	< 0.001	14.85	1.83	< 0.001
	Max. temp	15.16	0.02	< 0.001	15.87	0.04	< 0.001
	Min. temp	15.78	0.02	< 0.001	16.58	0.04	< 0.001

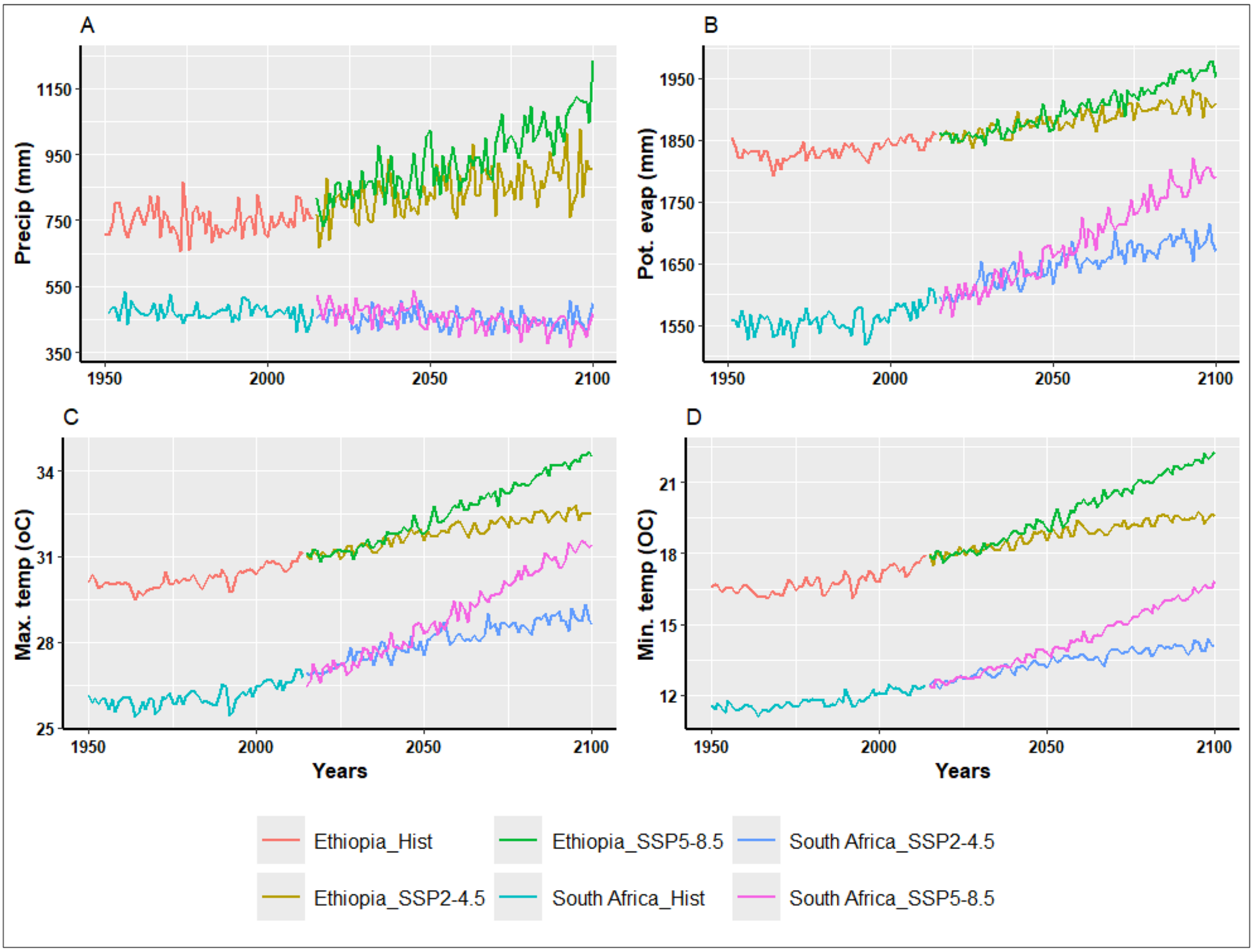

Fig. 2 Annual time series trends of climatic variables for both study areas with historical and two climate change scenarios: **A** Precipitation, **B** Potential evapotranspiration, **C** Maximum temperature, and D) Minimum temperature

notable decrease in SPEI and SPI values, indicating a significant increase in drought occurrences under both SSP2-4.5 and SSP5-8.5 scenarios. The trends exhibit more pronounced negative slopes, especially in the high-emission SSP5-8.5 scenario, suggesting a higher frequency of droughts compared to the medium-emission SSP2-4.5 scenario.

During the historical period (1950–2014), Ethiopia had lower SPEI and SPI values compared to South Africa, indicating more frequent droughts. However, future projections suggest a reversal: South Africa is expected to experience increasingly negative SPEI and SPI values, indicating a rise in drought events. This shift implies that while Ethiopia historically faced more frequent droughts, this trend is expected to decrease, whereas South Africa is projected to see an increase in drought events under both climate change scenarios. This contrasting future trajectory highlights potential shifts in drought patterns due to climate change impacts.

At the national level, Ethiopia's historical trend suggests a tendency for increasing drought severity (Table 4). Nevertheless, projections indicate a significant decrease in drought severity under both the medium (SSP2-4.5) and high-emission (SSP5-8.5) scenarios. Although the national average trends show a significant decreasing trend, variability exists across different climatic regions (clusters). Particularly under the medium emission scenario, some clusters, such as Cluster-4 and Cluster-5, exhibit insignificant but still positive trends. In contrast, South Africa's historical trends show a different picture. Under both SSP2-4.5 and SSP5-8.5 scenarios, all clusters show significant negative trends, suggesting a future increase in drought severity, with the high-emission scenario projecting the most severe conditions. This suggests that South Africa may face more severe drought challenges in the future compared to Ethiopia, which indicates a more diverse pattern across its regions and scenarios.

The spatial variation of drought occurrence for both study areas is illustrated in Fig. 4. This figure depicts the number of drought months (months with SPEI values less than – 1)

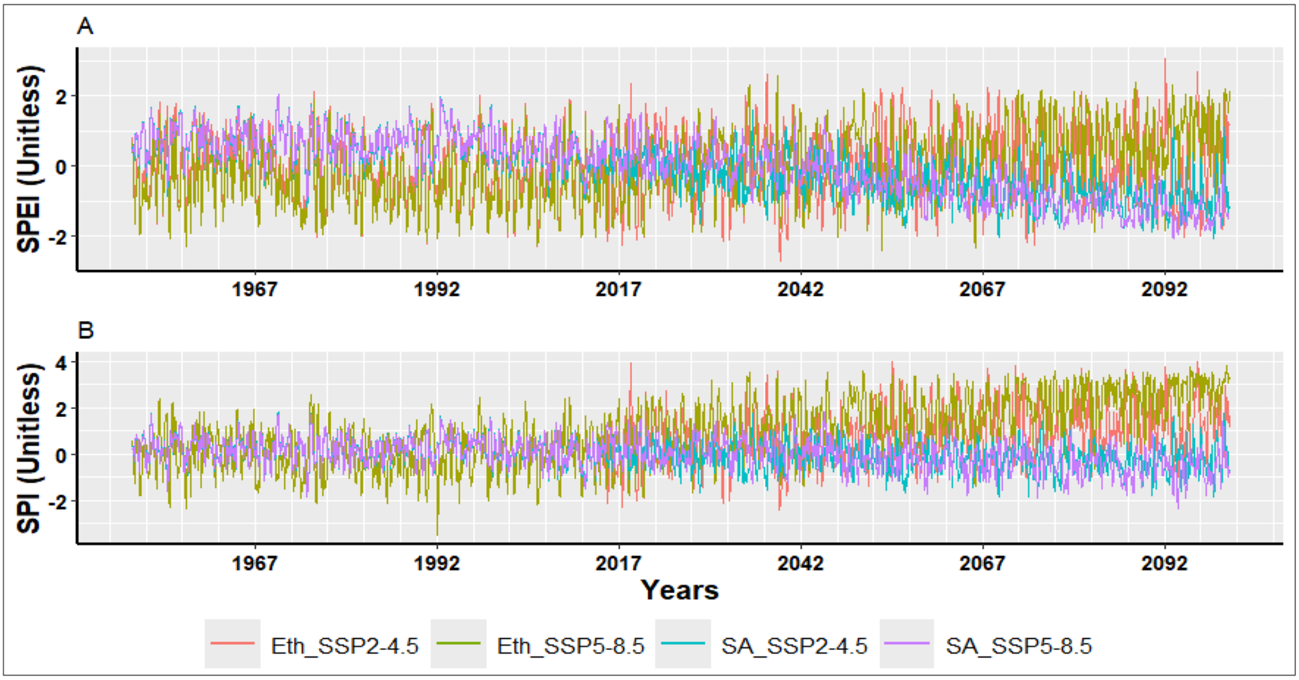

Fig. 3 Comparison of time series drought indices for Ethiopia and South Africa with two scenarios: A) standardized precipitation evapotranspiration index(SPEI), and B) standardized precipitation index(SPI)

Table 4 Mann–Kendall trend tests for SPEI time series in climatic regions and national averages for Ethiopia and South Africa

Study area	Historical			SSP2-4.5			SSP5-8.5		
	Z-score	Sen's slope	P-value	Z-score	Sen's slope	P-value	Z-score	Sen's slope	P-value
Ethiopia	**–2.52**	**–0.0004**	**0.012**	**3.26**	**0.0004**	**< 0.01**	**11.30**	**0.0012**	**< 0.01**
Cluster-1	–0.07	< -0.0001	0.942	4.34	0.0008	< 0.01	9.30	0.0013	< 0.01
Cluster-2	–3.46	–0.001	< 0.01	2.43	0.0005	0.015	5.15	0.0008	< 0.01
Cluster-3	–0.67	–0.0001	0.505	3.50	0.0006	< 0.01	11.02	0.0018	< 0.01
Cluster-4	–0.08	< -0.0001	0.937	1.22	0.0003	0.222	7.37	0.0020	< 0.01
Cluster-5	–1.88	–0.0003	0.603	1.50	0.0001	0.134	8.01	0.0007	< 0.01
South Africa	**–6.48**	**–0.001**	**< 0.01**	**-17.69**	**–0.0012**	**< 0.01**	**–29.08**	**–0.0020**	**< 0.01**
Cluster-1	–3.55	–0.014	< 0.01	–8.21	–0.0211	< 0.01	–10.73	–0.0337	< 0.01
Cluster-2	–1.38	–0.004	0.169	–6.75	–0.0149	< 0.01	–9.33	–0.0259	< 0.01
Cluster-3	–1.66	–0.006	0.097	–7.56	–0.0182	< 0.01	–10.09	–0.0302	< 0.01
Cluster-4	–1.33	–0.004	0.183	–4.40	–0.0098	< 0.01	–8.38	–0.0224	< 0.01
Cluster-5	–3.02	–0.011	< 0.01	–5.97	–0.0144	< 0.01	–9.28	–0.0270	< 0.01

The bold ones are for the country level results. Keeping it as it is will be better

compared to the total number of months within the specified time periods. Specifically, the analysis focus on the percentage of dry months out of the total months for every 20-year period, including the historical period of the last 20 years (1991–2010).

Although the time series analysis (Fig. 3) indicates a general decrease in drought occurrences in Ethiopia, the spatial analysis (Fig. 4A, B) suggests that the trend of drought in Ethiopia is site specific, which is consistent with the results of MK trends for clusters in Table 4. Hence, it indicates that there is an increase in drought occurrence in the northern and eastern regions of the country, particularly after 2060 for both scenarios. Another significant finding is the shift in regions affected by drought in Ethiopia, moving from the western and west-central parts during the historical period to the northern, north-eastern, eastern, and south-eastern regions during the projection periods.

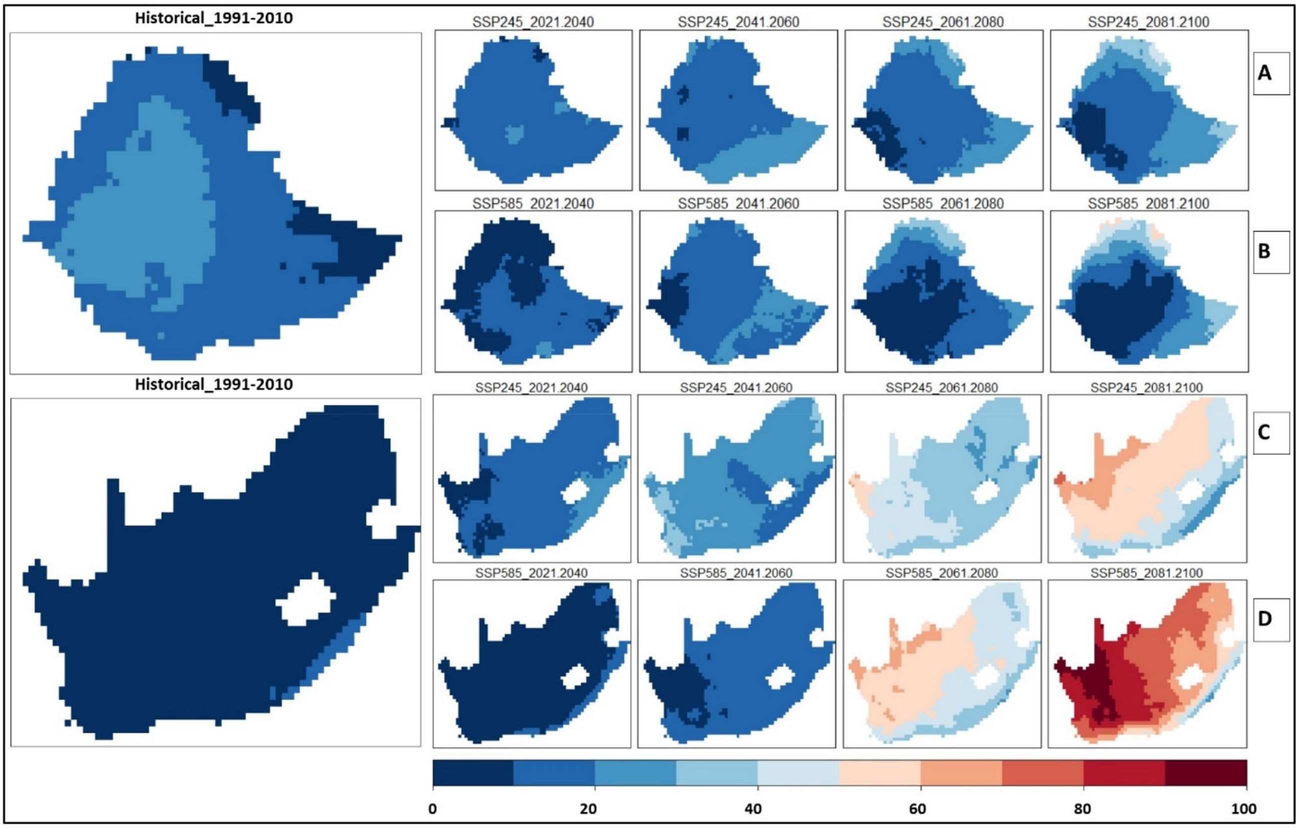

Fig. 4 Spatial drought events comparison (using SPEI): **A** SSP2-4.5 for Ethiopia, **B** SSP5-8.5 for Ethiopia, **C** SSP2-4.5 for South Africa, and **D** SSP5-8.5 for South Africa

In contrast, for South Africa, the spatial drought analysis (Fig. 4C, D) reveals a successive increase in drought events and occurrences from 2021 to 2100 compared to the historical period (1991–2010). Notably, there is also a shift in regions affected by drought from the east (during 1991–2010 and 2021–2040) to the west, particularly after 2060.

3.3 Drought characteristics

Figures 5 and 6 illustrate the relationship between the univariate return period and drought severity for Ethiopia and South Africa, respectively. Similarly, Figs. 7 and 8 depict the relationship between the univariate return period and drought duration. The analysis covers one national average and five climatic regions in each country. Generally, the relationship between drought severity vs. return period and duration vs return period is non-linear. This means that changes in drought severity/duration do not occur at a constant rate as the univariate return period increases. Lower return periods correspond to less severe or short-duration droughts for both nations and across all climatic regions.

In Ethiopia (Fig. 5), the high emission scenario (SSP585) shows longer return periods, indicating less frequent droughts compared to the medium emission scenario and historical data. However, there is also an indication that the severity of drought increases during the medium emission scenario than the historical event. This finding may seem contradictory to the MK-trend analysis results in Table 4, but it could be due to the severity-duration-return period analysis considering only events with a SPEI value below – 1. There could be many SPEI values during historical periods ranged between 0 and – 1, which were not included in the severity-duration-return period analysis, but included in the MK-trend analysis.

The trends for severity versus return period vary among different climatic regions. All clusters, except Cluster 5, show that drought severity increases during the medium emission scenario (SSP2-4.5) compared to the historical and high emission (SSP5-8.5) scenarios, consistent with the national average. Two clusters (Cluster 1 and Cluster 3) exhibit trends which is similar to the national average, where drought becomes less severe during the high emission scenario and more severe during the medium emission scenario. In Clusters 2 and 4, historical droughts were less severe than during the high and medium emission scenarios. Comparing historical and medium emission scenarios, all clusters,

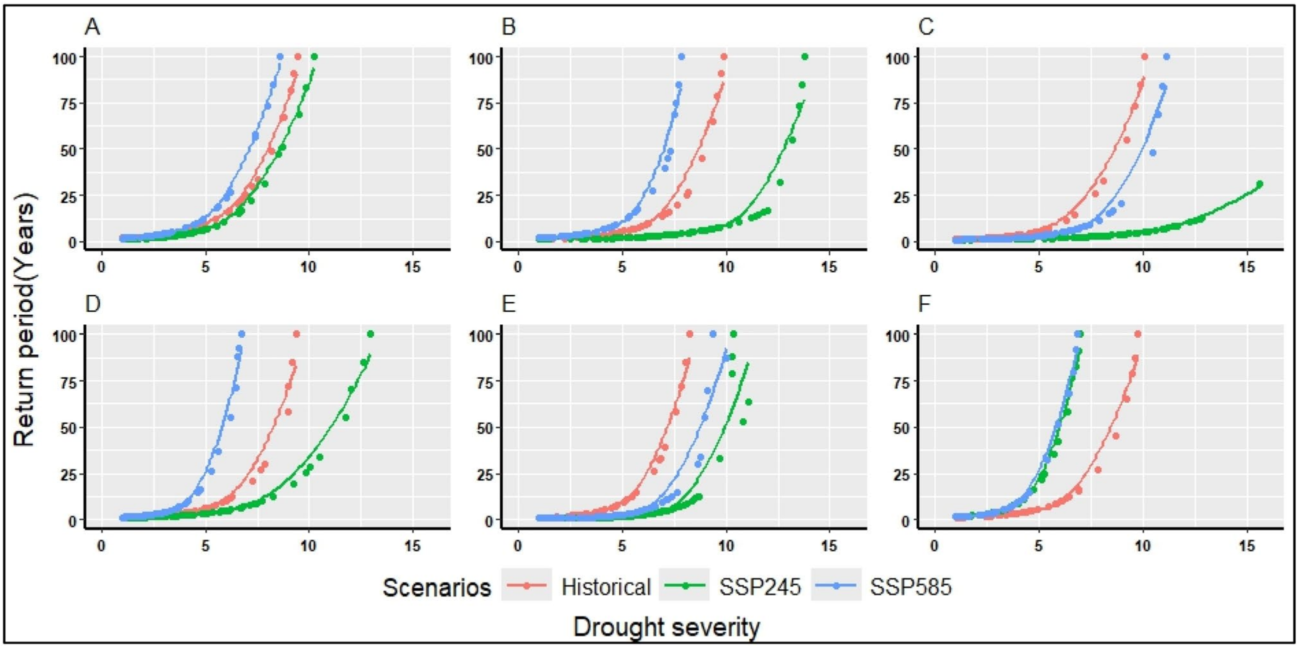

Fig. 5 Relationship between drought severity and return period during historical and future climate change scenarios in Ethiopia: **A** National average, **B** Region-1, **C** Region-2, **D** Region-3, **E** Region-4, and **F** Region-5

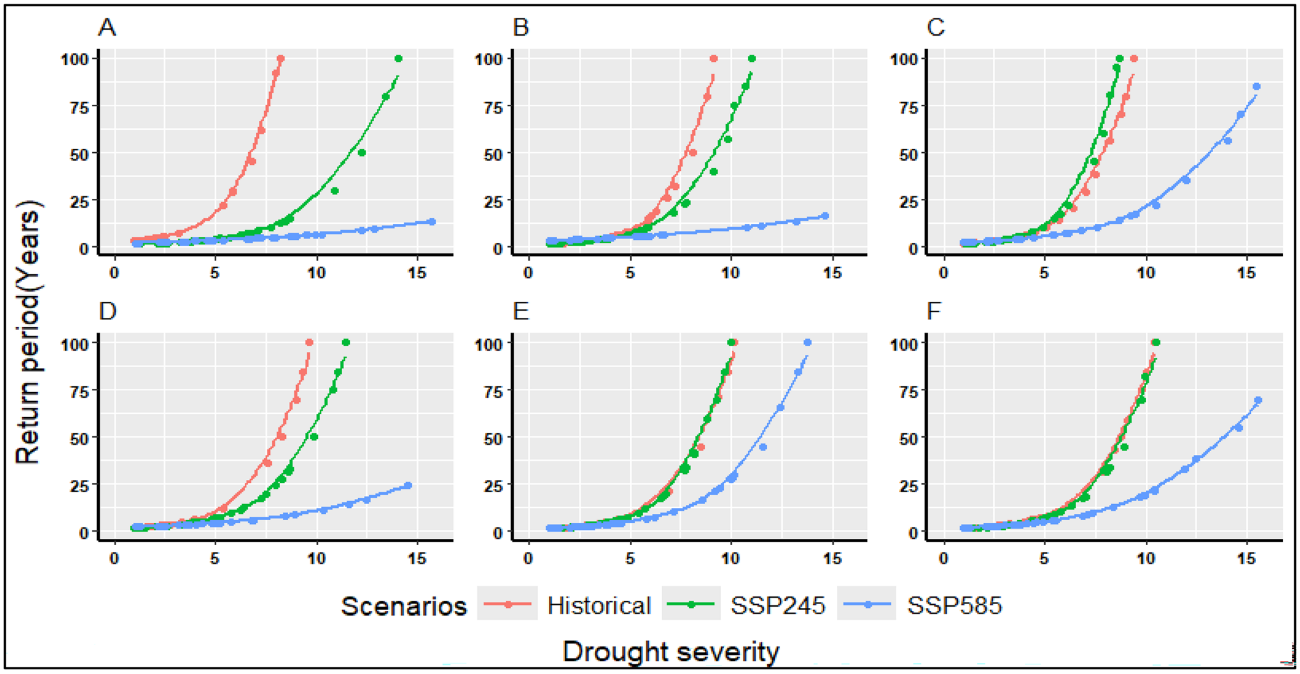

Fig. 6 Relationship between drought severity and return period during historical and the two climate change scenarios in South Africa: **A** National average, **B** Region-1, **C** Region-2, **D** Region-3, **E** Region-4, and **F** Region-5

except Cluster 5, show increasing drought frequency and severity during the medium emission scenario. In Cluster 5, the historical trend indicates more severe droughts than the medium and high emission scenarios, suggesting that drought severity is decreasing for both future scenarios for that specific cluster.

For South Africa (Fig. 6), the impact of climate change contrasts with Ethiopia. The high emission scenario

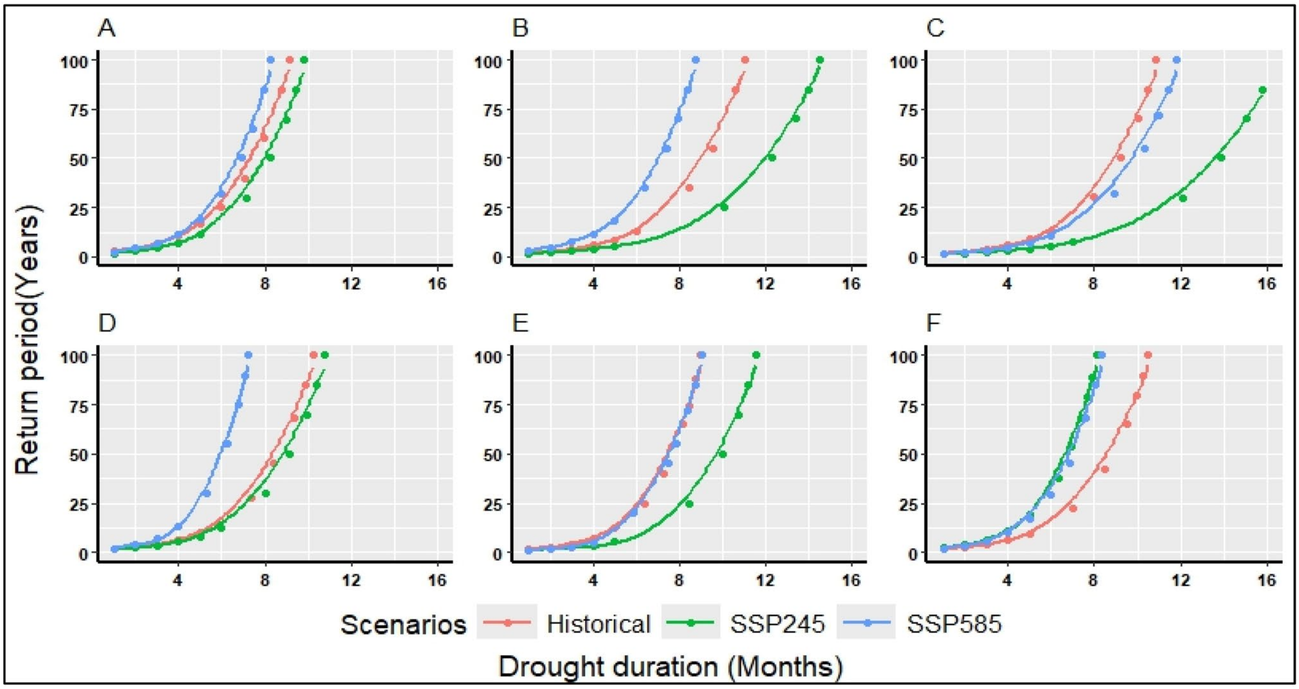

Fig. 7 Relationship between drought duration and return period during historical and future climate change scenarios in Ethiopia: **A** National average, **B** Region-1, **C** Region-2, **D** Region-3, **E** Region-4, and **F** Region-5

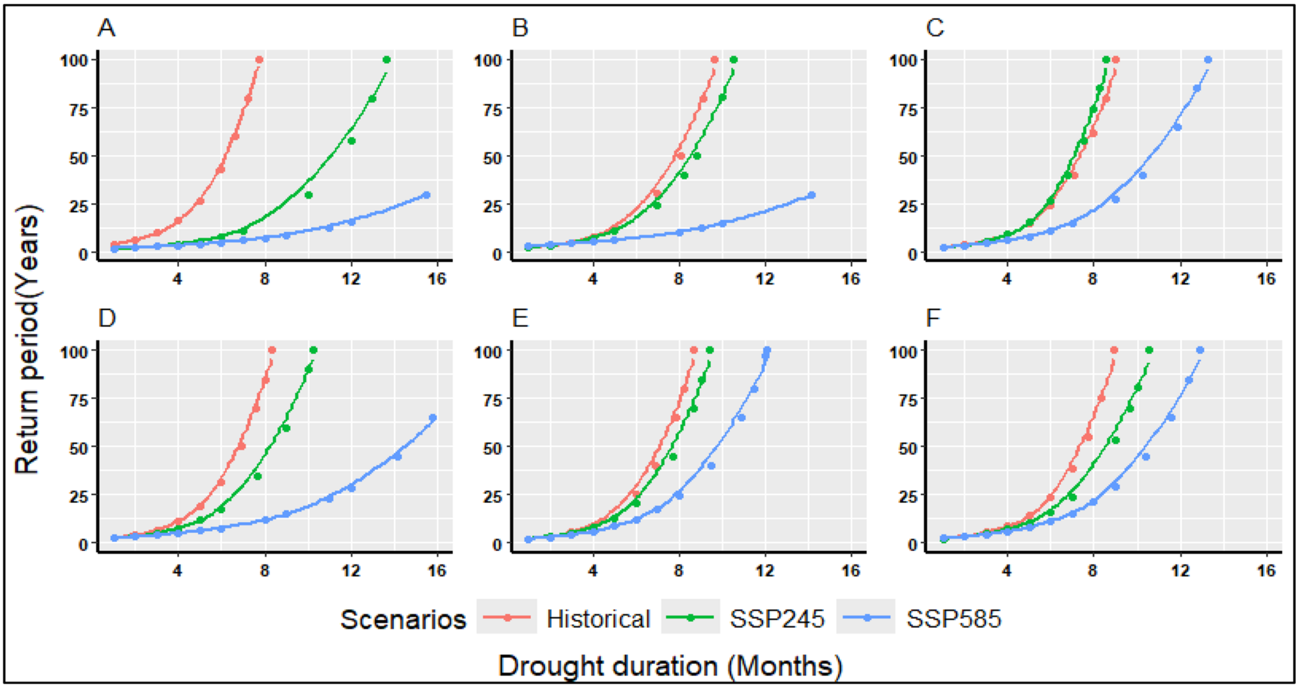

Fig. 8 Relationship between drought duration and return period during historical and the two projected climate change scenarios in South Africa: **A** National average, **B** Region-1, **C** Region-2, **D** Region-3, **E** Region-4, and **F** Region-5

(SSP585) shows shorter return periods (more frequent droughts) compared to both historical and medium emission scenarios. Unlike Ethiopia, there is no apparent reduction in drought severity under future scenarios; instead, the high emission scenario (SSP5-8.5) indicates even more severe droughts at shorter return periods compared to the medium emission scenario. There is some variation in clusters, particularly for the historical and SSP2-4.5 scenarios. Clusters 1 and 3 show similar results to the national average. However, for Cluster 2, the medium emission scenario indicates less severe and less frequent droughts than the historical scenario. In Clusters 4 and 5, the response to the historical and medium emission scenarios is almost identical.

In both Ethiopia and South Africa, the patterns of drought duration relative to return periods are broadly consistent with the patterns observed for drought severity. In Ethiopia (Fig. 7), longer-duration droughts are becoming less frequent under the SSP5-8.5 scenario, suggesting a reduction in the frequency of prolonged drought events with changing climatic conditions. However, under the SSP2-4.5 scenario, there is an expectation of more frequent long-duration droughts, except in Cluster 5, which does not follow this trend.

In South Africa (Fig. 8), the high emission scenario (SSP5-8.5) projects more frequent with longer-duration droughts compared to both the historical and medium emission scenarios. This trend is consistent across all climatic regions, indicating a broader pattern of increasing drought duration under more severe climate change conditions. Further analysis across different regions and scenarios show that the high emission scenario consistently results in longer-duration droughts with increased frequency compared to both historical and medium emission scenarios. The medium emission scenario also generally predicts longer-duration droughts compared to historical conditions, with Region 2 being an exception to this pattern.

4 Discussion

Climate change poses significant challenges to global hydro-climatic systems, profoundly impacting precipitation patterns, temperature regimes, and drought dynamics across diverse regions. Ethiopia and South Africa are two pivotal countries in Africa with distinct climate challenges and socio-economic contexts that make them crucial subjects for climate change and variability studies. Ethiopia, with its diverse topography and reliance on rain-fed agriculture, faces varying hydro-climatic impacts that affect its water resources, agriculture, and food security. South Africa, on the other hand, is experiencing increasing frequency and severity of droughts, which have significant implications for its water supply, agriculture, and energy production. Thus, this study focuses on the contrasting trends observed in Ethiopia and South Africa, highlighting the implications of changing hydro-climatic variables and drought occurrences under various climate change scenarios.

In Ethiopia, the analysis reveals a notable increase in annual precipitation under both moderate and high emission scenarios, with precipitation rates rising more prominently in the latter. This positive trend suggests potential benefits for agricultural productivity and water resources, which are essential for sustaining livelihoods in a predominantly agrarian economy (Zenebe et al. 2011; Sinore and Wang 2024). While additional rainfall may boost crop growth and water availability, careful management is needed to prevent soil erosion, crop flooding, and waterlogging. Additionally, this increase may enable recession farming in lowland floodplain areas, taking advantage of receding waters to grow crops. This may support year-round agricultural productivity and water resources. However, this rise in rainfall could also significantly increase the risk of flooding, particularly in regions prone to heavy rainfall events and lowland areas.

As such, while the immediate benefits of increased precipitation could enhance crop yields, the potential for flooding and soil erosion raises concerns about long-term agricultural sustainability and infrastructure resilience.

Conversely, South Africa experiences a slight yet significant decline in annual precipitation, exacerbating existing water scarcity challenges and negatively impacting agricultural resilience (Meza et al. 2021). Similar studies corroborate these findings, indicating that regions with increasing precipitation trends, like parts of Ethiopia, may face challenges related to soil erosion and nutrient runoff (Tullu 2024). In contrast, regions with declining precipitation trends, such as South Africa, are likely to encounter intensified water scarcity issues, which can lead to reduced crop yields, increased competition for water resources, and heightened vulnerability among rural communities (Meque and Abiodun 2015).

The study also examines changes in potential evapotranspiration (PET) and temperature variables (Tmax and Tmin), indicating significant increases across both countries. Elevated PET rates in South Africa highlight heightened water demand, compounding the effects of declining precipitation. Rising temperatures pose risks to ecosystem health and agricultural viability in both regions, as they can lead to increased stress on crops and livestock (IPCC, 2022). Additionally, the rising temperatures associated with climate change pose significant health risks in both Ethiopia and South Africa, disproportionately affecting vulnerable populations and exacerbating existing health challenges. The increases in Tmax and Tmin observed in recent studies (Mbokodo et al. 2020; Kapwata et al. 2022) have multifaceted implications for public health, including heightened risks of heat-related illnesses and the spread of vector-borne diseases.

The higher rates of temperature and potential evapotranspiration (PET) in South Africa, compared to Ethiopia, could be primarily influenced by the distinct oceanic and atmospheric conditions. South Africa's proximity to the warm Agulhas Current and the Indian and Atlantic Oceans makes it more susceptible to sea surface temperature (SST) anomalies, which amplify warming and drying, especially during El Niño events (Rouault et al. 2019; Gore et al. 2020; IPCC 2022). These conditions, combined with the country's vulnerability to the El Niño-Southern Oscillation (ENSO), elevate PET through intensified heat and reduced humidity. Furthermore, South Africa's subtropical high-pressure systems reduce cloud cover and increase solar radiation, contributing to more extreme seasonal warming (MacKellar et al. 2014; Rouault et al. 2019). In contrast, Ethiopia, located further inland and at higher elevations, is relatively less influenced by SST anomalies and ENSO, with the Ethiopian highlands moderating temperature extremes and dampening PET increases.

The analysis of drought occurrence using the Standardized Precipitation-Evapotranspiration Index (SPEI) and Standardized Precipitation Index (SPI) reveals divergent patterns between Ethiopia and South Africa. Ethiopia shows a significant decrease in drought occurrences, as indicated by more positive SPEI and SPI values, particularly under the SSP5-8.5 scenario. This decrease suggests a potential reduction in drought frequency and severity, although localized increases may occur in northern and eastern peripheral regions post-2060. Similar results are reported by Haile et al. (2020), IPCC (2022), Gleixner et al. (2022), Gebrechorkos et al. (2023). In contrast, South Africa experiences a pronounced increase in drought occurrences, evidenced by more negative SPEI and SPI values under both scenarios. The high emission scenario (SSP5-8.5) indicates shorter return periods for drought events, suggesting a more frequent occurrence compared to historical data and medium emission scenarios. This aligns with projections from similar studies predicting escalating drought risks in regions vulnerable to climate variability (He and Ding 2023; IPCC 2014, 2022; Engelbrecht et al. 2024). Spatial analyses further reveal shifting drought patterns, with Ethiopia anticipating increased drought occurrences in its northern and eastern regions, while South Africa faces a westward shift in affected areas (Zenebe et al. 2011; He and Ding 2023; Engelbrecht et al. 2024).

This study found that both indices effectively captured drought events in Ethiopia and South Africa, aligning with findings from related research while acknowledging certain limitations. The SPEI, which accounts for both precipitation and temperature (via evapotranspiration), is particularly robust in regions where warming intensifies drought conditions, such as the semi-arid zones in South Africa and Ethiopia (Vicente-Serrano et al. 2010a, b; He and Ding 2023). Meanwhile, the SPI, focused solely on precipitation (is reliable for meteorological drought), offers a straightforward measure of rainfall deficits but may underestimate drought severity in warming climates. Together, SPI and SPEI provide complementary perspectives, with SPEI capturing broader climate-driven droughts and SPI giving direct insights into rainfall deficits, leading to a more comprehensive understanding of regional drought dynamics.

A multitude of complex factors, spanning regional/global scales, contribute to the occurrence of extreme precipitation events. Global climate drivers, such as elevated greenhouse gas concentrations and changes in atmospheric circulation patterns, significantly impact regional climates. Increased greenhouse gas levels intensify the hydrological cycle, leading to greater evaporation and precipitation (Haile et al. 2020; IPCC 2022). Shifts in the Intertropical Convergence Zone (ITCZ) and phenomena such as the Indian Ocean Dipole (IOD) and the El Niño-Southern Oscillation (ENSO) further modulate rainfall patterns (Wolde-Georgis 1997; Korecha and Barnston 2007). ENSO, in particular, plays a key role in drought conditions for both nations; El Niño typically reduces rainfall, exacerbating drought, while La Niña often increases precipitation, potentially alleviating drought but sometimes resulting in flooding (Wolde-Georgis 1997; Korecha and Barnston 2007; Meque and Abiodun 2015; Gore et al. 2020; Engelbrecht et al. 2024). Regional climate models underscore ENSO's significant influence on drought prediction, highlighting the necessity of integrating ENSO forecasts into effective drought management strategies (Meque and Abiodun 2015; Gore et al. 2020).

The climatic disparities between Ethiopia and South Africa, along with their regional variabilities, indicate that tailored strategies are necessary for effective management. Each country faces unique challenges and opportunities due to their distinct hydro-climatic conditions. Ethiopia's strategies must address both the increased risk of flooding and localized droughts, while South Africa should focus on mitigating water scarcity and adapting to the increasing drought occurrence. For Ethiopia, strategies should include strengthening flood management infrastructure, promoting climate-resilient and sustainable agriculture, and implementing water resource management to conserve resources and reduce runoff. In South Africa, recommended actions include advancing climate-smart agriculture, reforestation, conservation agriculture, improving water-use efficiency, efficient irrigation, and cultivating drought-tolerant crops (FAO 2013; IPCC 2022). Developing region-specific management plans that foster an inclusive green economy, encourage cross-level government collaboration, and establish early warning systems tailored to diverse climatic impacts will be critical for enhancing resilience and sustainability in both nations.

Policymakers can integrate these strategies into national and regional frameworks by embedding climate resilience as a core priority within development agendas. Both countries should adopt climate projections in long-term planning, promote intergovernmental collaboration, and enhance early warning systems to ensure timely responses to extreme events. Encouraging public–private partnerships can aid effective strategy implementation, while incentives for private sector investment in sustainable infrastructure will further support resilience efforts. Leveraging climate data for informed decision-making allows policies to be adaptive, responsive, and aligned with evolving environmental challenges.

5 Conclusion

This study is driven by the need to gain a deeper understanding of the diverse impacts of climate change on two crucial African nations, with the aim of guiding effective adaptation and mitigation strategies in response to evolving climate conditions. The research highlights shifting hydro-climatic patterns and drought dynamics in Ethiopia and South Africa under various climate scenarios. Ethiopia faces the challenge of balancing the benefits of increased precipitation with the risks of flooding and localized droughts, while South Africa grapples with declining precipitation and increasing drought frequency amid rising water demands. Addressing these challenges requires tailored, region-specific strategies to effectively manage impacts, enhance resilience, and promote sustainable practices in agriculture and water management.

However, the study does have limitations. Reliance on climate models and indices introduces uncertainties due to the assumptions and projections inherent in these models. Additionally, the spatial resolution of the data may not fully capture localized climate impacts, and a more detailed analysis of regional variations could provide deeper insights into specific vulnerabilities.

Overall, understanding the climate change impacts on Ethiopia and South Africa offers valuable insights into broader regional effects across Africa. By examining their contrasting hydro-climatic trends and drought dynamics, this study aims to illuminate both unique and shared vulnerabilities, contributing to the development of targeted adaptation strategies and policies that address each country's specific needs while supporting broader climate resilience efforts across the continent.

6 Availability of data

The dataset used in this research is publicly available and can be accessed from the following link: https://ds.nccs.nasa.gov/thredds/catalog/AMES/NEX/GDDP-CMIP6/catalog.html.

Acknowledgements We express our gratitude to the World Climate Research Program (WCRP) and its Working Group on Coupled Modelling for their coordination and promotion of the raw CMIP6 dataset. Our sincere thanks also go to the Climate Analytics Group and the NASA Ames Research Center for preparing the NEX-GDDP-CMIP6 dataset using the NASA Earth Exchange, which is distributed by the NASA Center for Climate Simulation (NCCS).

Author contributions (1) Achamyeleh G. Mengistu conceived and designed the analysis, collected the data, contributed data or analysis tools, performed the analysis, and wrote the paper. (2) Weldemichael A. Tesfuhuney conceived and designed the analysis and participated in editing and proofreading. (3) Yali E. Woyessa conceived and designed the analysis and contributed to editing and proofreading. (4) Amsalework A. Ejigu contributed to data management, analysis, and participated in proofreading. (5) Melku D. Alemu participated in proofreading.

Funding Open access funding provided by University of the Free State. This research was conducted independently without specific funding, with all associated costs covered by the authors.

Declarations

Conflict of interest The authors declare no competing interest.

Ethical approval Not applicable.

References

Agnew CT (2000) Using the SPI to identify drought. University of Nebraska-Lincoln, Lincoln

Alemayehu A, Bewket W (2016) Vulnerability of smallholder farmers to climate change and variability in the central highlands of Ethiopia. Ethiopian J Soc Sci Hum 12(2):1–24

Alemayehu A, Bewket W (2017) Determinants of smallholder farmers' choice of coping and adaptation strategies to climate change and variability in the central highlands of Ethiopia. Environ Dev 24:77–85

Badr HS, Zaitchik BF, Dezfuli AK (2015) A tool for hierarchical climate regionalization. Earth Sci Inf 8:949–958

Balting DF, AghaKouchak A, Lohmann G, Ionita M (2021) Northern Hemisphere drought risk in a warming climate. NPJ Clim Atmos Sci 4(1):61

Baudoin MA, Vogel C, Nortje K, Naik M (2017) Living with drought in South Africa: lessons learnt from the recent El Niño drought period. Int J Disaster Risk Reduct 23:128–137

Bharambe KP, Shimizu Y, Kantoush SA, Sumi T, Saber M (2023) Impacts of climate change on drought and its consequences on the agricultural crop under worst-case scenario over the Godavari River Basin, India. Clim Serv 32:100415

Chiang F, Mazdiyasni O, AghaKouchak A (2021) Evidence of anthropogenic impacts on global drought frequency, duration, and intensity. Nat Commun 12(1):2754

Cook BI, Smerdon JE, Seager R, Coats S (2014) Global warming and 21st century drying. Clim Dyn 43:2607–2627

Dai A (2011) Drought under global warming: A review. Wires Clim Change 2:45–65. https://doi.org/10.1002/wcc.81

Deressa TT, Hassan RM, Ringler C, Alemu T, Yesuf M (2009) Determinants of farmers' choice of adaptation methods to climate change in the Nile Basin of Ethiopia. Glob Environ Change 19(2):248–255

Du Plessis JA, Schloms B (2017) An investigation into the evidence of seasonal rainfall pattern shifts in the Western Cape, South Africa. J S Afr Inst Civ Eng 59(4):47–55

Dube K, Nhamo G, Chikodzi D (2022) Climate change-induced droughts and tourism: Impacts and responses of Western Cape Province, South Africa. J Outdoor Recreat Tour 39:100319

Engelbrecht FA, Steinkopf J, Padavatan J, Midgley GF (2024) Projections of future climate change in southern africa and the potential for regional tipping points. Sustainability of Southern African Ecosystems under Global Change: Science for Management and Policy Interventions. Springer International Publishing, Cham, pp 169–190

EskandariPour M, Soltaninia S (2022) Analyzing the duration frequency and severity of drought using copula function in the Yazd city. J Water Clim Change 13(1):67–82

Federal Democratic Republic of Ethiopia (FDRE) (2021) Updated nationally determined conditions (NDC). Ministry of Environment, Forest and Climate Change.

Food and Agriculture Organization of the United Nations (FAO) (2013) Climate-Smart agriculture: sourcebook. FAO

Gebrechorkos SH, Taye MT, Birhanu B, Solomon D, Demissie T (2023) Future changes in climate and hydroclimate extremes in East Africa. Earth's Future 11:e2022EF003011

Gleixner S, Lüttringhaus S, Kaufmann J, Smytzek P, Gornott C (2022) Assessment of climatic impact drivers in Ethiopia. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, p 9

Gore M, Abiodun BJ, Kucharski F (2020) Understanding the influence of ENSO patterns on drought over southern Africa using SPEEDY. Clim Dyn 54(1):307–327

Haile GG, Tang Q, Hosseini-Moghari SM, Liu X, Gebremicael TG, Leng G, Kebede A, Xu X, Yun X (2020) Projected impacts of climate change on drought patterns over East Africa. Earth's Future 8(7):e2020EF001502

Hao Z, Fang H, Singh VP, Ouyang W, Cheng H (2017) An integrated package for drought monitoring, prediction and analysis to aid drought modeling and assessment.

He B, Ding KJ (2023) Global greenhouse gases emissions effect on extreme events under an uncertain future: A case study in Western Cape, South Africa. PLOS Clim 2(1):e0000107

Hosseinizadeh A, SeyedKaboli H, Zareie H, Akhondali A, Farjad B (2015) Impact of climate change on the severity, duration, and frequency of drought in a semi-arid agricultural basin. Geoenviron Disasters 2:1–9

Intergovernmental Panel on Climate Change (IPCC) (2014) Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press

Intergovernmental Panel on Climate Change (IPCC) (2022) Chapter 9: Africa. In Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Kapwata T, Gebreslasie MT, Wright CY (2022) An analysis of past and future heatwaves based on a heat-associated mortality threshold: Towards a heat health warning system. Environ Health 21(1):1–12

Knutti R, Masson D, Gettelman A (2013) Climate model genealogy: Generation CMIP5 and how we got there. Geophys Res Lett 40(6):1194–1199

Korecha D, Barnston AG (2007) Predictability of June–September rainfall in Ethiopia. Mon Weather Rev 135(2):628–650

MacKellar N, New M, Jack C (2014) Observed and modelled trends in rainfall and temperature for South Africa: 1960–2010. S Afr J Sci 110(7-8):1–3. https://doi.org/10.1590/sajs.2014/20130353

Mbokodo I, Bopape MJ, Chikoore H, Engelbrecht F, Nethengwe N (2020) Heatwaves in the future warmer climate of South Africa. Atmosphere 11(7):712

McKee TB, Doesken NJ, Kleist J (1993) The relationship of drought frequency and duration to time scales. In: Proceedings of the 8th Conference on Applied Climatology, Boston, MA, USA, 17–22 January 1993 (Vol. 17, No. 22, pp. 179–183)

Mengistu AG, Woyessa YE, Tesfuhuney WA, Steyn AS, Lee SS (2024) Assessing the impact of climate change on future extreme temperature events in major South African cities. Theoret Appl Climatol 155(3):1807–1819

Meque A, Abiodun BJ (2015) Simulating the link between ENSO and summer drought in Southern Africa using regional climate models. Clim Dyn 44:1881–1900

Meza I, Rezaei EE, Siebert S, Ghazaryan G, Nouri H, Dubovyk O, Gerdener H, Herbert C, Kusche J, Popat E, Rhyner J (2021) Drought risk for agricultural systems in South Africa: drivers, spatial patterns, and implications for drought risk management. Sci Total Environ 799:149505

Naumann G, Alfieri L, Wyser K, Mentaschi L, Betts RA, Carrao H, Spinoni J, Vogt J, Feyen L (2018) Global changes in drought conditions under different levels of warming. Geophys Res Lett 45(7):3285–3296

O'Neill BC, Tebaldi C, Van Vuuren DP, Eyring V, Friedlingstein P, Hurtt G, Knutti R, Kriegler E, Lamarque JF, Lowe J, Meehl GA (2016) The scenario model intercomparison project (ScenarioMIP) for CMIP6. Geosci Model Dev 9(9):3461–3482

Orimoloye IR, Belle JA, Orimoloye YM, Olusola AO, Ololade OO (2022) Drought: A common environmental disaster. Atmosphere 13(1):111

Philip S, Kew SF, van Oldenborgh GJ, Otto F, O'Keefe S, Haustein K, King A, Zegeye A, Eshetu Z, Hailemariam K, Singh R (2018) Attribution analysis of the Ethiopian drought of 2015. J Clim 31(6):2465–2486

Pili O, Ncube B (2022) Smallholder farmer coping and adaptation strategies for agricultural water use during drought periods in the Overberg and West Coast Districts, Western Cape, South Africa. Water SA 48(1):97–109

R Core Team (2023) R: A language and environment for statistical computing. R Foundation for Statistical Computing. https://www.R-project.org/. Accessed 1 May 2024).

Rouault M, Monyela B, Kounge RAI, Stella A, Njouodo N, Dieppois B (2019) Ocean impact on southern African climate variability and water resources. Water Res Comm Rep. Report No. 2425/1/18. Pretoria, South Africa

Schulzweida U (2023) Climate Data Operator (CDO) - User Guide (ver. 2.3.0). Zenodo. https://doi.org/10.5281/zenodo.10020800

Seckler D, Amarasinghe U (2000) Water supply and demand, 1995 to 2025. IWMI Annual Report 1999–2000. IWMI

Shitarek, T (2012) Ethiopia Country Report. Department for International Development, UK

Sinore T, Wang F (2024) Impact of climate change on agriculture and adaptation strategies in Ethiopia: a meta-analysis. Heliyon. https://doi.org/10.1016/j.heliyon.2024.e26103

Spatial and Temporal Evidence for Planning in South Africa (STEP-SA). (2024). *Climate indicators: Aridity.* An online database of a collaborative research initiative between CSIR, HSRC & DST.

Available from: http://stepsa.org/climate_aridity.html. Accessed 29 June 2024

Thrasher B, Maurer EP, McKellar C, Duffy PB (2012) Technical note: Bias correcting climate model simulated daily temperature extremes with quantile mapping. Hydrol Earth Syst Sci 16(9):3309–3314. https://doi.org/10.5194/hess-16-3309-2012

Thrasher B, Wang W, Michaelis A, Melton F, Lee T, Nemani R (2022) NASA global daily downscaled projections, CMIP6. Sci Data 9:262. https://doi.org/10.1038/s41597-022-01393-4

Trenberth KE, Shea DJ (2005) Relationships between precipitation and surface temperature. Geophys Res Lett 32(14). https://doi.org/10.1029/2005GL022760

Tullu KT (2024) Assessment of soil erosion response to climate change in the Sululta catchment, Abbay Basin, Ethiopia. H2Open J 7(1):23–37

Ullah H, Akbar M, Khan F (2029) Construction of homogeneous climatic regions by combining cluster analysis and L-moment approach on the basis of Reconnaissance Drought Index for Pakistan. Int J Climatol 40(1):324–341

UN CCD (2022) *COP-15 Côte d'Ivoire - Drought in Numbers 2022 - Restoration for Readiness and Resilience*. United Nations Convention to Combat Desertification. https://policycommons.net/artifacts/3155564/cop-15-cote-divoire/3953436/. Accessed 10 Jan 2024

Van Vuuren DP, Carter TR (2014) Climate and socio-economic scenarios for climate change research and assessment: reconciling the new with the old. Clim Change 122:415–429

Vicente-Serrano SM, Beguería S, López-Moreno JI (2010a) A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. J Clim 23(7):1696–1718

Vicente-Serrano SM, Beguería S, López-Moreno JI (2010b) A multiscalar drought index sensitive to global warming: The Standardized Precipitation Evapotranspiration Index-SPEI. J Clim 23(7):1696–1718. https://doi.org/10.1175/2009JCLI2909.1

Wolde-Georgis T (1997) El Niño and drought early warning in Ethiopia (March 1, 1997). Internet J Afr Stud 2. Available at SSRN: https://ssrn.com/abstract=1589710

World Bank Group (2024) Climate Change Knowledge Portal: Current Climate: Climatology. Available at: https://climateknowledgeportal.worldbank.org/country/south-africa/climate-data-historical. Accessed 28 June 2024

Yevjevich VM (1967) An objective approach to definitions and investigations of continental hydrologic droughts, vol 23. Colorado State University, p 25

Zenebe ZG, Stage J, Mekonnen A, Alemu A (2011) Climate change and the Ethiopian economy: A computable general equilibrium analysis. Discussion Paper Series, Environment for Development, EfD DP 11–09.

Zeray N, Demie A (2016) Climate change impact, vulnerability and adaptation strategy in Ethiopia: a review. J Earth Environ Sci 5:45–56