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The Impact of Climate Change on Water Security in The Agroecological Zone of The Sudd Wetland, Jonglei State-South Sudan.

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Abstract:
Climate change posed a significant global challenge, characterized by long-term alterations in climate patterns. This study evaluated the impact of climate change on water security in the Sudd region, with a focus on Jonglei State, South Sudan. Utilizing historical and projected climate data, including the SSP1-1.9 and SSP3-7.0 scenarios, the study examined temperature and precipitation trends, highlighting substantial changes over several decades. The results revealed an upward warming trends and erratic rainfall patterns, represented by the regression equation $y = 0.1126x+29.292$, and $y = 6.1977x+159.45$ for the historical climate data from 1901 to 2020, respectively (figure 3.3). Annual and 5-year average temperature trends analysis from 1951 to 2020 revealed annual increase of approximately 0.0315°C, totalling around 0.1575°C over five years (figure 3.2 (a)). Climate projections indicated continued warming, with mean temperature increases ranging from 0.5°C to 0.67°C for the period 2020-2039, rising to 0.77°C to 0.95°C by 2040-2059 under the SSP1-1.9 scenario, and 1.21°C to 1.51°C under SSP3-7.0. Rainfall patterns exhibited moderate uncertainty; however, positive correlations were observed in both scenarios. Approximately more than 80% of rural households in the Sudd region depended on rain-fed agriculture, with future projections suggesting potential yield reductions of up to 50%. This underscores the vulnerability of local communities, particularly women, who face disproportionate impacts due to socioeconomic factors. The findings emphasize the need for Integrated Water Resource Management (IWRM) to enhance resilience against climate variability. The study advocates for robust policies and multi-stakeholder coordination to address the interconnected challenges of water security and socioeconomic stability. Ultimately, the study offers actionable recommendations to improve resilience and promote long-term stability in the Sudd region.

Keywords: **Climate Change, Water Security, SSP1-1.9, SSP3-7.0, Sudd Region, Climate Scenarios, IWRM.**

1.0.Introduction

Climate change has emerged as one of the most pressing global challenges of the 21st century, characterized by long-term shifts in temperature, precipitation patterns, and the frequency of extreme weather events. According to the Intergovernmental Panel on Climate Change (Fay et al., 2016; IPCC, 2013, 2021; Vicente-Serrano et al, 2024)**,** these changes are intensifying, with profound implications for ecological systems, socioeconomic stability, and human livelihoods. Among the most vulnerable regions to these impacts are fragile ecosystems and low-income countries, particularly in Sub-Saharan Africa.

The effects of extreme climate events in South Sudan are especially pronounced in the agroecological zone of the Sudd Wetland, a globally significant ecosystem. The Sudd is one of the largest tropical wetlands in the world, with a fluctuating area ranging from 30,000 to 130,000 square kilometres, depending on seasonal flooding (Davidson et al., 2018). It plays a pivotal role in the hydrological and ecological stability of South Sudan, offering critical ecosystem services such as water purification, flood regulation, and biodiversity conservation. Moreover, it supports the livelihoods of approximately 86% of rural households, who rely on its resources for agriculture, fishing, and livestock grazing (Howell, 1988; UNEP, 2018).

The Sudd Wetland agroecological zone faces significant environmental and socioeconomic challenges due to the adverse impact of climate, these changes occur in the form of slow-onset and sudden climate events, including drought, erratic rainfall, flooding, and heat stress, posing threats to water resources and complementary ecological and socioeconomic systems. Historical climate data reveal a decline in summer rainfall by 15-20% and a temperature increase exceeding 1°C over the past two decades (Hulme, 2001; NUPI & SIPRI, 2021, 2025). These changes are projected to continue and intensify, with regional temperature increases expected to reach 1.5°C to 2.5°C by the 2050s, potentially rising to 6°C by the end of the century (Hulme, 2001; IPCC, 2014a, 2021; Niang et al, 2014). Fay et al. (2016) indicates that increased evaporation, coupled with altered precipitation regimes, can significantly disrupt the hydrological cycles of wetlands, leading to challenges in water resource management.

Empirical studies have further demonstrated the consequences of these trends for communities, ecosystem and agricultural productivity (IPCC, 2023; Murphy & Walsh, 2019; Taye et al., 2015; UN-Water, 2021; WMO, 2024). As the Sudd region is heavily dependent on rain-fed agriculture, fluctuations in rainfall and rising temperatures have led to reduced crop yields, heightened food insecurity, and increased competition for water resources (Maria et al, 2015; USAID, 2019). Projected yield reductions of up to 50% threaten the economic foundations of agropastoral communities in the Sudd region, where local populations are highly dependent on natural resources for survival. The social implications are equally significant. Climate-induced water insecurity disproportionately affects women and marginalized groups, who often have limited access to resources, land ownership, and decision-making power in agricultural systems (Mai, 2018; UNEP, 2018). In this context, climate change not only exacerbates environmental stress but also deepens existing socioeconomic inequalities, potentially driving migration, conflict, and displacement (IPCC, 2014b; Nicholson, 2017).

To address these multifaceted challenges, scholars and practitioners have increasingly advocated for Integrated Water Resources Management (IWRM) as a framework for enhancing climate resilience. IWRM promotes the coordinated development and management of water, land, and related resources to maximize social and economic welfare without compromising the sustainability of vital ecosystems (GWP, 2004). Effective implementation of IWRM requires localized knowledge, stakeholder participation, and adaptive strategies that are responsive to the specific ecological and socio-political contexts of regions like the Sudd Wetland agroecological zone.

Given the ecological importance of the Sudd and the socioeconomic vulnerabilities of its inhabitants to climate extremes, there is a critical need to assess how climate change is altering water security in this region. This study aimed to evaluate the historical and projected impacts of climate change on water resources in the Sudd region from 1901 to 2059, with a focus on Jonglei State. It examined temperature and precipitation trends using both observed data and future scenarios under SSP1-1.9 and SSP3-7.0, and assessed the implications for agricultural productivity, livelihood security, and gender equity. Furthermore, the study proposed an IWRM based strategy tailored to the unique environmental and socioeconomic characteristics of the Sudd Wetland, offering policy relevant recommendations to enhance resilience and promote long-term sustainability in the region.

2.0.Materials and Methods

2.1. Study area

Jonglei State spans across universal transverse mercator (UTM) zone 36N within the Sudd region, a largest State in South Sudan covering an area of 123,070 km². The Sudd wetland begins to widen north of Bor town, Jonglei State, where the White Nile flows and expands into a vast floodplain. As part of the Jonglei Plains, the agroecological zone of Sudd wetland constitutes one of the largest intact savannah ecosystems in Africa.

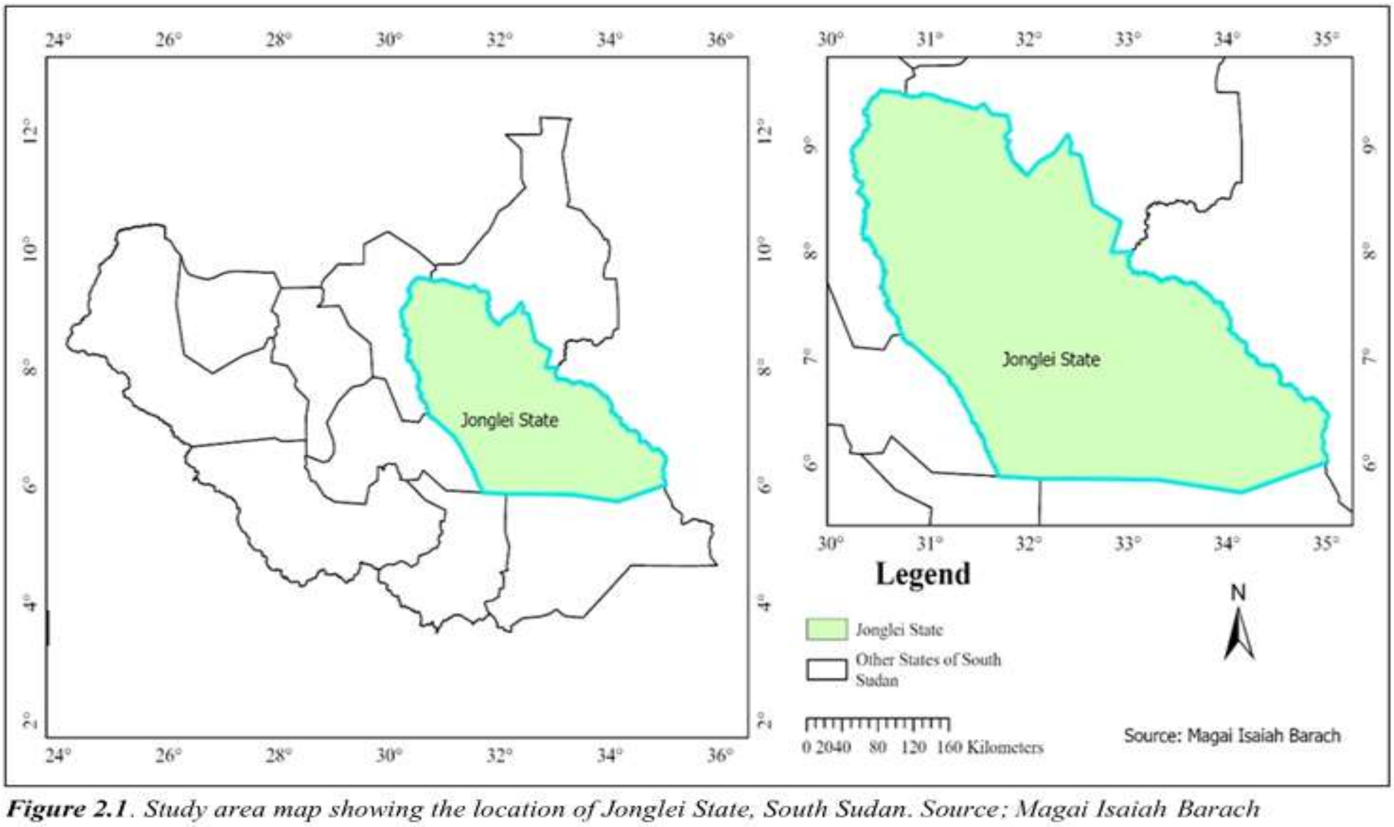

Figure 2.1. Study area map showing the location of Jonglei State, South Sudan. Source: Magai Isaiah Barach

The Sudd wetlands supports diverse wildlife, including endemic fish, bird, and mammal species. It serves as a crucial habitat for migratory mammals during the dry season and as a wintering ground for numerous bird species of regional and international conservation importance (Rebelo et al., 2008).

According to the 2021 Population Estimation Survey (PES) by the National Bureau of Statistics' (NBS), the Sudd region is home to approximately four million people who rely on its ecosystem services for their livelihoods. The traditional inhabitants of the Sudd region are primarily agropastoralists. Subsistence agriculture accounts for over 80% of employment and income generation, supplemented by fishing. Rainfall in the Sudd region is highly seasonal, following a unimodal distribution. Most precipitation occurs between May and October, peaking in July and August, with annual rainfall ranging from 800 mm to 1,200 mm. The agroecological system of the Sudd region is characterized by cycles of drought and flood, which significantly influence pastoralism, crop production, and supplemental livelihood activities such as fishing.

1.1. Sources of data

1.1.1. Primary data

The historical climate data focusing on average temperature and rainfall was collected from the South Sudan Meteorological Department, supplemented by online satellite data. Historical climate data and trends in this study was used as the baseline for mapping hazards, assessing monthly, seasonal, annual and inter annual trends, identifying relationships with historical impacts, and providing a reference against which to compare current and anticipated climate conditions, providing valuable information in distribution shifts in average mean temperature and rainfall. The rainfall and temperature data were used for indicating potentially impactful weather and climate events, such as the occurrence of flooding or droughts, or anticipated extreme climate events under way.

1.1.2. Secondary Data

The key sources for secondary data included research studies on climate change impacts, government reports on water resource management, biodiversity conservation and environmental assessments and reports from international organizations such as the United Nations, World Bank, IPCC and others. The secondary data was use in this study to provide critical context to support the interpretation and analysis of the primary findings.

1.2. Data Analysis

1.2.1. Quantitative Data Analysis

In this study, we analyse mean temperature and rainfall data to examine long-term climate trends. A variety of charts and graphs are employed to illustrate the patterns and variations in the climate of the study area across different timeframes including monthly, annual, interannual, and decadal periods. To quantify changes in climate, IBM SPSS Statistics is used for the statistical analysis of climate data. Descriptive statistical measures such as means, and frequency distributions are applied to summarize key climate characteristics. In addition, correlation and regression analyses are conducted to assess the relationships between climatic variables and other observed phenomena. These statistical methods enable the evaluation of both the strength and direction of the relationships between temperature and rainfall across the specified periods. Graphical representations including charts, histograms, and line plots enhance the clarity and interpretability of the data, allowing for a more effective presentation of climate trends and distributions. Furthermore, ArcGIS Pro is utilized to delineate and visualize the spatial characteristics of the study area.

1.2.2. Qualitative Data Analysis

The analysis of qualitative data collected through Key Informant Interviews (KIIs) and focus group discussions (FGDs) follows a systematic approach to ensure thorough understanding and validity of the findings. Key Informant Interviews were conducted with selected individuals who possess specialized knowledge relevant to the study. Focus group discussions were held to gather diverse perspectives from participants on the topic. Both methods provided rich, in-depth insights into the interconnected impact of climate change on the ecological, social and economic systems in the study area. To enhance the validity of the qualitative data, triangulation methods were applied. This involved cross-checking findings from KIIs and FGDs against each other, as well as comparing them with existing literature to establish the reliability and validity of our qualitative findings, providing a robust understanding of the climate trend and impacts in the agroecological zone of the Sudd wetland.

1.3. Climate Models and Projections

In this study, the shared socioeconomic pathways (SSP's), SSP1-1.9 and 3-7.0 climate model and scenarios were used to analyze the trends and the anticipated climate hazards in the study area. The SSP scenarios were analysed to align with regional and global efforts aimed at planning long-term climate adaptation and environmental sustainability. This involved identifying positive indicators for policy direction focused on mitigating climate change impacts and promoting environmental health, as well as examining scenarios that reflect a world characterized by high greenhouse gas emissions driven by a fragmented approach to development and a lack of coordinated climate action.

2.0.Results and Discussion

2.1. Climate Trends in the Sudd Region, Jonglei State, 1990-2020.

2.1.1. Temperature trends

Figure 3.1. presents the average mean temperature and rainfall for the Sudd region, Jonglei State. March records the highest temperature (32.09°C), followed by February (30.64°C) and April (31.94°C), marking the dry season with minimal rainfall and high evaporation rates, leading to water scarcity.

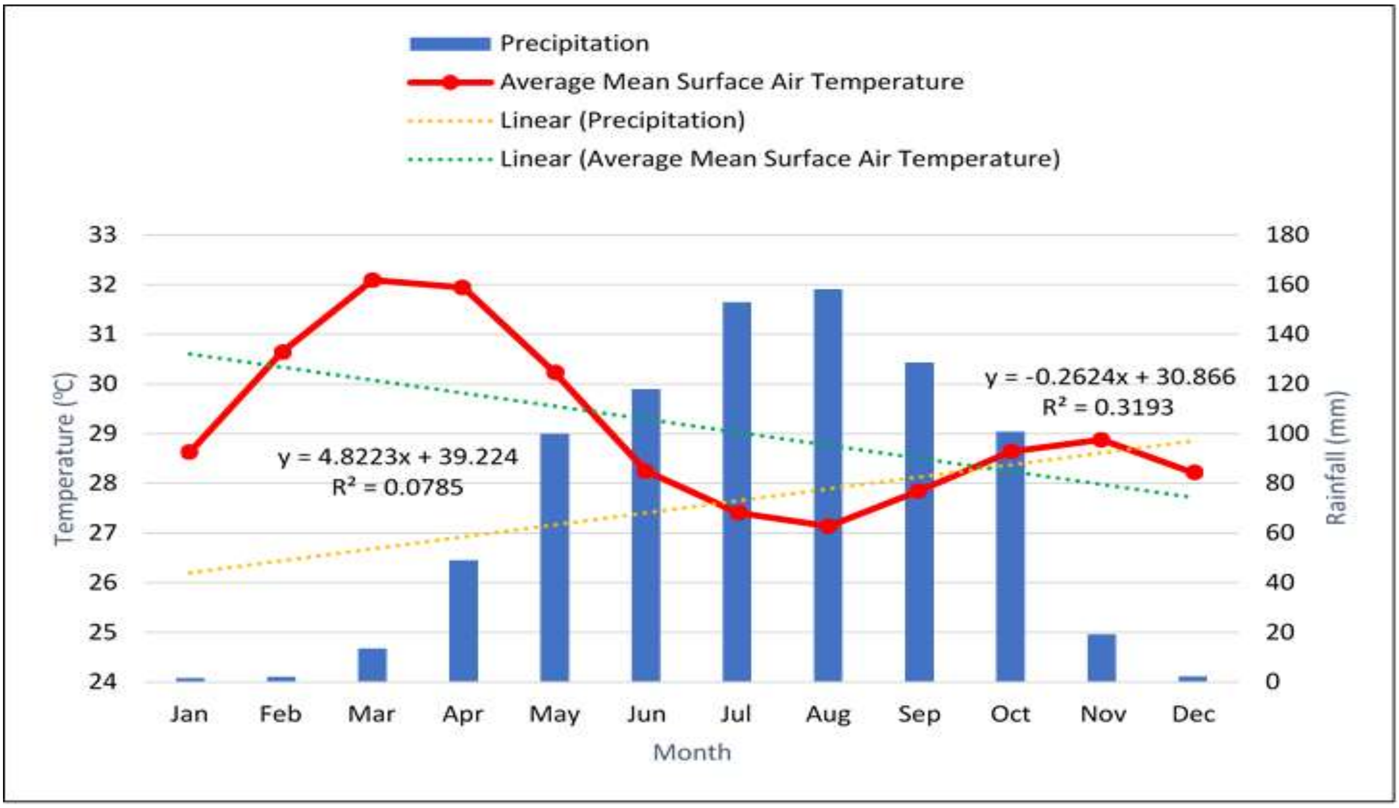

Figure 3.1. Average mean temperature and rainfall in the Sudd region, Jonglei State, 1990-

The coolest months during this period are July (27.41°C) and August (27.14°C), coinciding with the wet season, where increased cloud cover and precipitation reduce temperatures and evaporation. The dry months (November-March) feature average temperatures above 28°C, posing challenges for water availability, agriculture, and livestock. Regression analysis indicates an annual warming trend of 0.2624°C ($R^2 = 0.3195$), reflecting significant risks of evaporation and water stress due to climate change. This trend aligns with global observations reported by the IPCC (2021), and confirms findings by Vicente-Serrano et al. (2024) and NUPI & SIPRI (2021, 2025), which point to anthropogenic factors as key drivers of regional warming. The temperature rise has already had tangible impacts, such as school closures in April 2024 and 2025 due to extreme heat, highlighting climate change's direct effects on social structure across South Sudan.

2.1.1. Rainfall Pattern

Rainfall upsurges during the wet season (May-September), with August receiving the highest rainfall (158.21 mm), essential for replenishing wetland water levels and supporting biodiversity. Rainfall increases from May (100.03 mm) and declines gradually after September (128.7 mm). The dry season (November-March) sees minimal rainfall, with January (1.64 mm) and February (2.23 mm) recording the lowest levels. Despite a slight annual increase in rainfall (4.82 mm), the trend shows weak correlation with time ($R^2 = 0.0785$), indicating high variability influenced by complex climatic factors like the Intertropical Convergence Zone and El Niño Oscillations. Despite a slight increase in average rainfall, irregular distribution remains a concern. Rainfall in wet months has increased by 15-20%, while dry season precipitation has declined by up to 20% (Hulme, 2001; NUPI & SIPRI, 2021). These erratic patterns complicate agricultural planning, heightening vulnerability among the 80% households' dependent on rain-fed farming (Maria et al., 2015). As Nicholson (2017) and the IPCC (2014b) highlight, such variability severely disrupts ecosystem services and affects agropastoral livelihoods. Advanced climate models and integrated adaptation strategies are essential to manage water resources and ecosystem services effectively, ensuring the region's sustainability amidst increasing hydrological challenges.

2.2. Change in Distribution of Average Mean Temperature in the Sudd Region, Jonglei State, 1951-2021.

Long-term temperature data (1951-2020) further support the warming narrative. From 1951 to 2020 the Sudd region experienced a clear warming trend, with average temperatures gradually increasing across three distinct periods (Figure 3.2(a) and (b). During the earliest period (1951-1980), the mean temperature ranged from 25.33°C to 30.34°C, with mid-range temperatures (26.11°C to 27.84°C) dominating.

The highest frequencies were concentrated between 27.12°C and 27.72°C. Lower temperatures (below 26°C) were prevalent, indicating a cooler climate during this period. The second period 1971-2000 showed a noticeable shift toward higher temperatures, with concentrations between 27°C and 28.91°C. Notable frequencies were observed at 27.12°C (0.702876) and 27.30°C (0.74303). The frequency of lower temperatures (below 26°C) diminished significantly, highlighting a clear warming pattern.

The warming trend intensified during the most recent period 1991-2020, with average temperatures consistently exceeding 26°C and peaking at 30.34°C. Most average mean temperatures fell within the range of 27.28°C to 29.03°C, with notable values at 27.72°C (0.368913), 28.38°C (0.608234), and 29.03°C (0.368913). Lower temperatures (below 25.5°C) disappeared entirely, confirming long-term warming. Across the three periods, frequencies of lower temperature ranges (below 26°C) gradually vanished, while higher ranges (above 28°C) became dominant, confirming a shift toward a hotter climate. Regression analysis (y=0.0315x + 27.393, R^2=0.7933) confirms an annual average temperature increase of 0.0315 ºC, highlighting threat to wetland ecosystem. These findings mirror those of Taye et al. (2016), who emphasized the vulnerability of East African wetlands, like the Sudd, to temperature-driven hydrological stress.

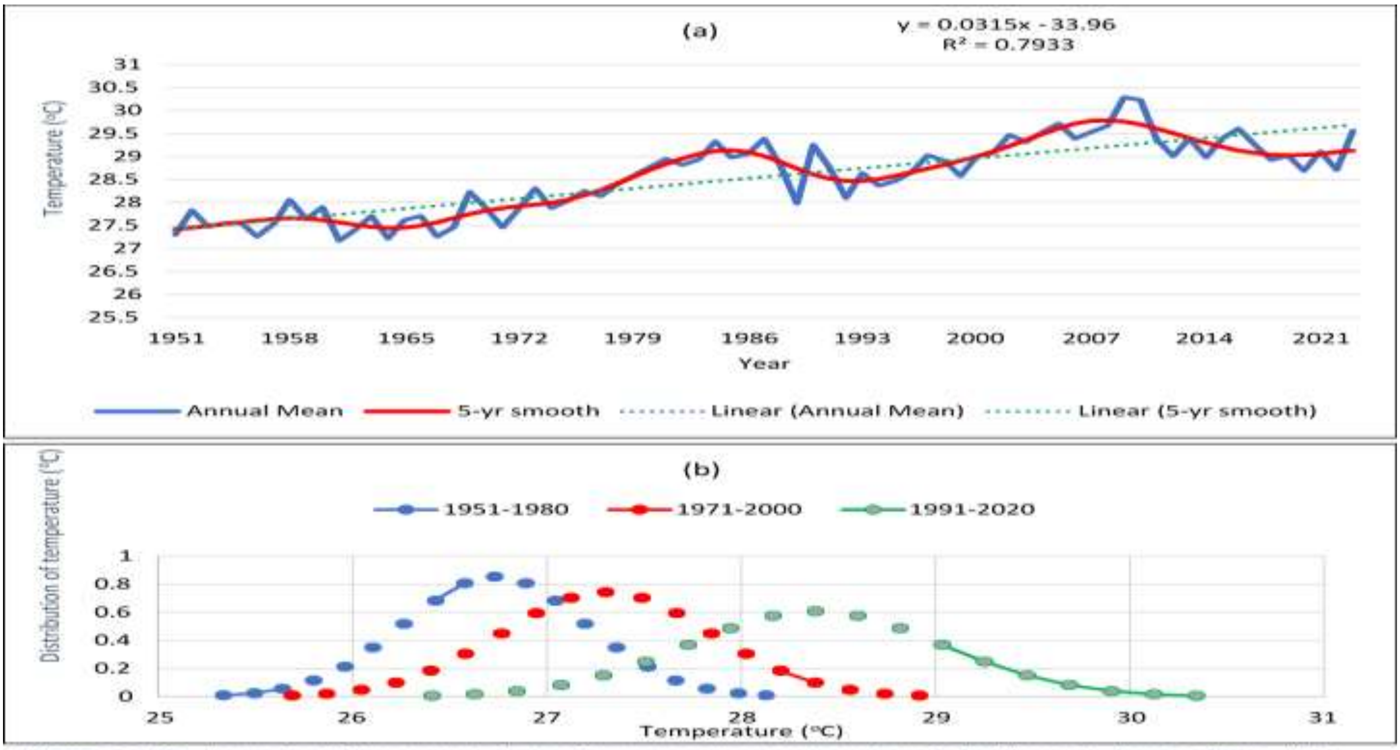

Figure 3.2 (a). Annual and interannual change in average mean temperature in Sudd region, Jonglei State, 1951-2020. (b). Observed change in distribution of average mean temperature, Jonglei State, 1951-2020.

2.3. Change in Seasonal Average Mean Temperature and Rainfall in the Sudd Region, Jonglei State, 1901-2020.

As shown in Figure 3.3, the temperature and rainfall trends from 1901 to 2020 shows a consistent warming pattern across all seasons, particularly notable in the March-April-May (MAM) and December-January-February (DJF) seasons. The average MAM temperature increased from 29.92°C in 1901-1930 to 31.41°C in 1991-2020, while DJF temperatures rose from 27.94°C to 29.12°C over the same period. The June-July-August (JJA) and September-October-November (SON) seasons also exhibit gradual temperature increases.

Rainfall patterns reveal that the JJA season consistently records the highest rainfall, with 429.3 mm in 1991-2020, while DJF sees the lowest, at 6.07 mm. Although JJA precipitation has slightly increased from earlier periods, DJF precipitation has declined marginally. The MAM and SON seasons show moderate precipitation increases, with MAM rising from 159.11 mm (1961-1990) to 162.58 mm (1991-2020).

A regression analysis indicates an average annual temperature increase of approximately 0.1126°C, although only 14.19% of temperature variation is linked to time, suggesting that other factors like greenhouse gas emissions are significant. Conversely, rainfall shows a slight annual increase of about 6.2 mm, but with a weak correlation to time (3.47%), indicating high variability influenced by external factors. These climatic changes pose serious implications for agriculture, water resources, and ecosystems. The findings echo previous studies (Taye et al., 2015; Junk et al., 2013), which emphasize that rising temperatures and erratic rainfall significantly affect the hydrological cycles of wetlands, leading to reduced water availability, habitat loss, and increased flood risk. The unpredictability of rainfall complicates water management, highlighting the necessity for adaptive strategies to mitigate climate variability impacts.

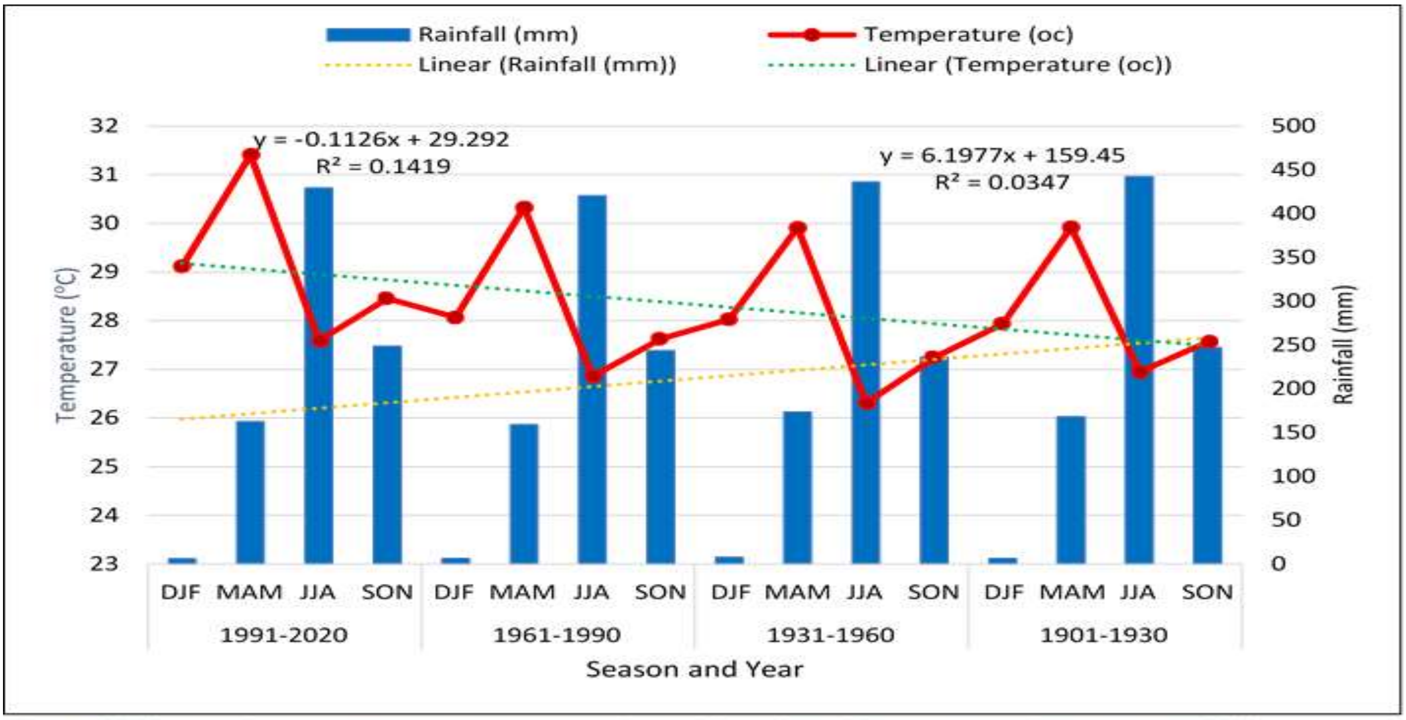

Figure 3.3. Seasonal average mean temperature and rainfall in the Sudd region, Jonglei State, 1901-2020

2.4. Projected Climate Change Scenarios, 2020-2059.

2.4.1. Projected Change in Temperature Under SSP1-1.9: A Low Emission Pathway

Figures 3.4 and 3.5 presents the projected trends in average mean temperature for the SSP1-1.9 scenarios during the periods 2020-2039 and 2040-2059. Under SSP1-1.9, temperature increases are modest, ranging from 0.5°C to 0.67°C, with the highest warming occurring in March (0.67°C) and February (0.63°C).

April to June temperatures increase slightly, peaking in May (0.65°C) with narrower variability ranges, for example (April: 0.39°C to 0.75°C). Cooler months (October-December) show lower increases, such as November (0.52°C) and December (0.5°C), with negative lower bounds in November (-0.02°C) and December (-0.06°C), reflecting possible cooling in some cases. Variability is higher during warmer months, especially February (0.29°C to 0.95°C), indicating moderate uncertainty.

The projected scenarios for the period 2040-2059, under the SSP1-1.9 pronounced more warming, with increases in average temperatures ranging from 0.77°C to 0.95°C as shown in figure 4.5. March (0.94°C) and May (0.95°C) experience the highest warming, while January (0.77°C) and December (0.78°C) show the least. Variability is moderate, with warmer months like June (0.60°C to 1.32°C) and July (0.46°C to 1.18°C) showing wider ranges. Cooler months, such as November (0.22°C to 1.10°C) and December (0.25°C to 1.10°C), display narrower variability, suggesting more predictable conditions.

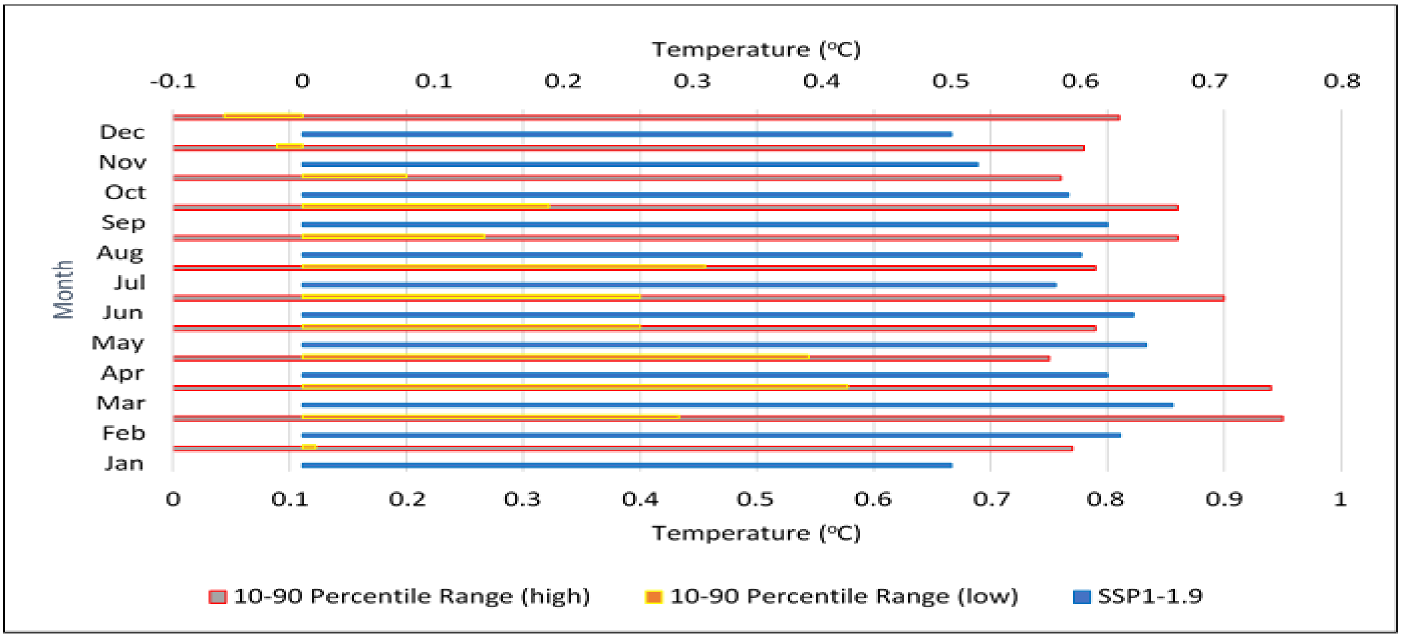

Figure 3.4. Projected average mean temperature under SSP1-1.9 scenarios in the Sudd region 2020-2039

Moderate variability and predictability under the SSP1-1.9 scenario make it favourable for planning and adaptation, confirming conclusions drawn by (van Vuuren et al., 2011) with regard to the benefits of coordinated global climate action. Low-emission pathways align with global climate targets, as highlighted in the IPCC's Sixth Assessment Report (IPCC, 2021). These scenarios reduce precipitation variability, mitigate extreme weather risks, and enhance climate adaptation strategies.

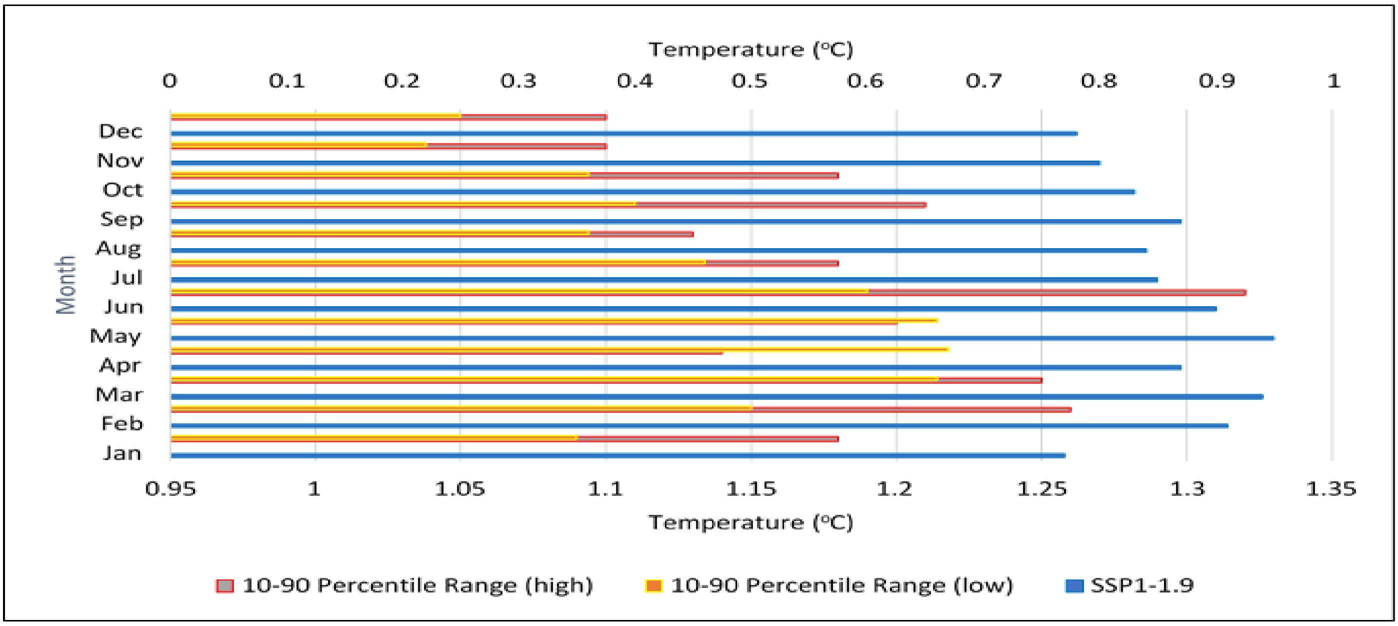

Figure 3.5. Projected average mean temperature projection under SSP1-1.9 for Jonglei State, 2040-2059

1.1.1. Projected Change in Temperature Under the SSP3-7.0: A High Emission Pathway.

The projected temperature trends under the high-emission SSP3-7.0 scenario suggest a significant warming trajectory for the Sudd region, with clear seasonal and decadal variations. The period 2020-2039 shows moderate mean temperature increases, ranging from 0.43°C to 0.74°C. The highest warming is projected in March (0.74°C) and August (0.67°C) months that typically correspond to the late dry and peak rainy seasons, respectively (Figure 3.6). These increases are consistent with findings by Niang et al. (2014) and USAID (2019), who emphasized that warming in sub-Saharan Africa is expected to be more pronounced during transitional seasons, exacerbating hydrological stress and agricultural vulnerability.

Cooler months, January (0.43°C) and December (0.46°C) show more modest warming. However, the variability in projections is higher during these months, with lower bounds extending into negative percentiles (for example, January: -0.4°C to 1.14°C; December: -0.42°C to 1.09°C), suggesting episodes of potential cooling relative to baseline values. This range of uncertainty aligns with previous studies, for example IPCC (2021) and van Vuuren et al. (2011) highlight the complexity of climate responses under high-emission scenarios, particularly in regions influenced by multiple climatic drivers such as the Intertropical Convergence Zone (ITCZ) and El Niño-Southern Oscillation (ENSO).

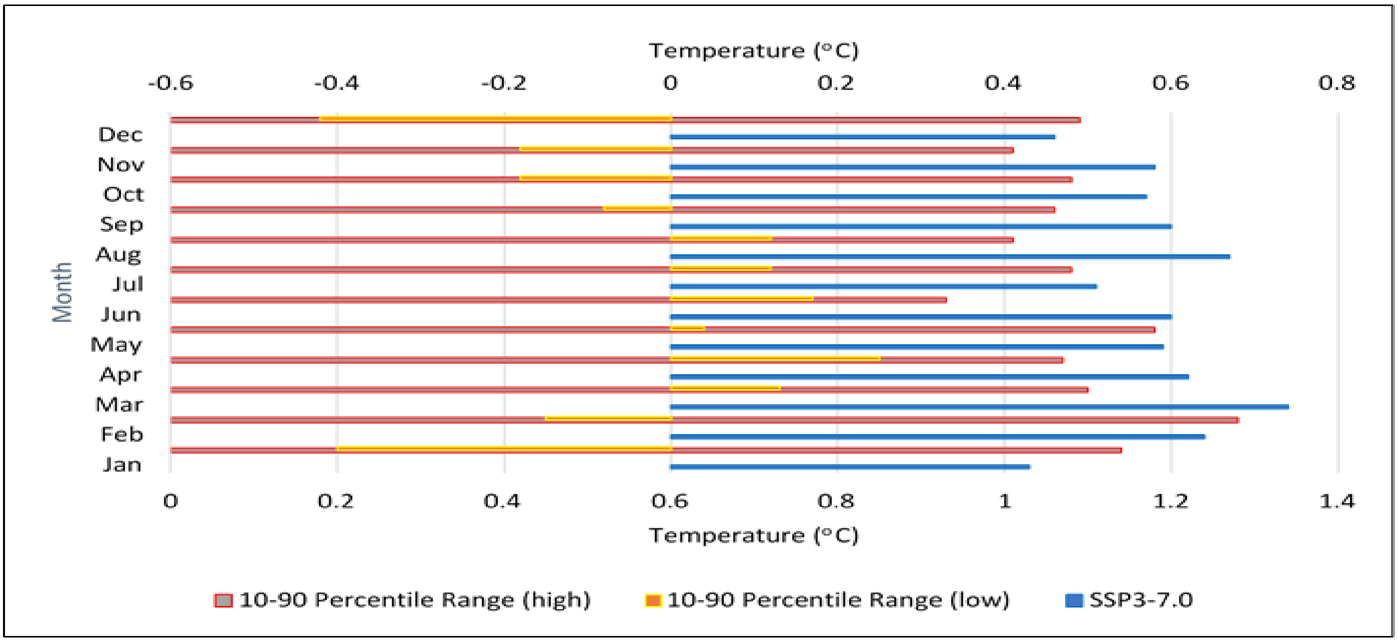

Figure 3.6. Projected average mean temperature under SSP3-7.0 for Jonglei State, 2020-2039.

In deviation, warmer months (March-August) display more consistent warming, with narrower variability bands, particularly in June (0.17°C to 0.93°C) and August (0.12°C to 1.01°C). These trends are indicative of a steady warming pattern during the core agricultural season, which may lead to increased evapotranspiration, soil moisture deficits, and crop stress. Research by Taye et al. (2016) and Maria et al. (2015) supports these findings, emphasizing that temperature increases of even 0.5°C-1.0°C during growing seasons can significantly impact rain-fed agricultural productivity in wetlands and floodplains across tropical Africa. The high-emission pathways compromise regional resilience by amplifying variability and undermining sustainable development efforts.

The projected warming for 2040-2059 under SSP3-7.0 marks a more intensified thermal trajectory, with mean temperature increases ranging from 1.21°C to 1.51°C (Figure 3.7). March (1.51°C) and May (1.46°C) record the highest warming, reinforcing the trend of seasonal intensification in the dry months. This level of warming exceeds the 1.5°C threshold identified by the IPCC (2018) as critical for avoiding the most severe impacts of climate change, particularly in fragile ecosystems like tropical wetlands.

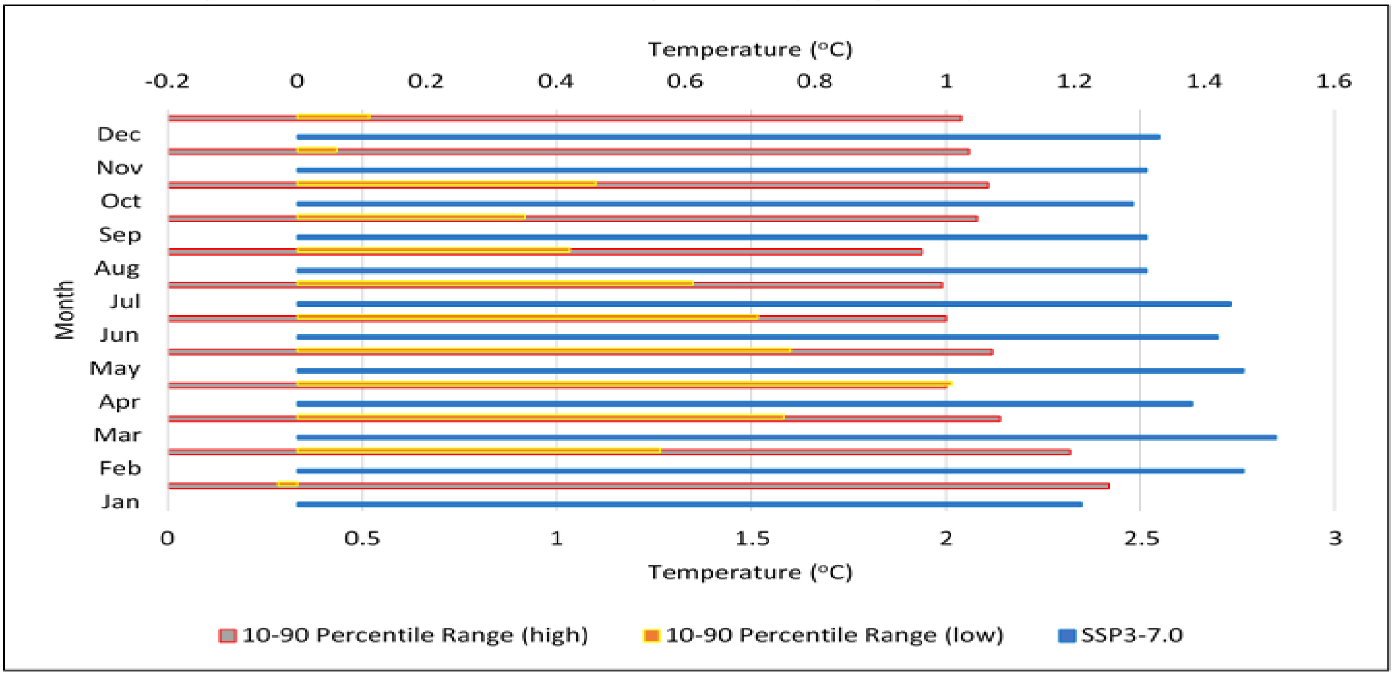

Figure 3.7. Projected average mean temperature under SSP3-7.0 scenarios in Jonglei State 2040-2059.

Cooler months such as January (1.21°C) and November (1.31°C) show slightly lower warming, but also exhibit substantial variability with January projections ranging from -0.03°C to 2.42°C and November from 0.06°C to 2.06°C. The high variability in cooler months underscores the uncertainty and potential for extreme temperature anomalies, which could manifest as either short-lived cold snaps or heatwaves, both of which pose distinct risks to agriculture, water storage, and livestock health (Nicholson, 2017; UNEP, 2018).

In contrast, warmer months (March-July) show narrower and more consistent warming bands, particularly in April (1.01°C to 2.00°C) and June (0.71°C to 2.00°C). This consistency may offer some predictability for seasonal planning, but the absolute warming levels forecasted could lead to severe hydrological shifts in the Sudd Wetland. Consistent with studies by Junk et al. (2013) and Howell et al. (1988), sustained warming during this period may contribute to wetland desiccation, reduced seasonal flooding, and loss of biodiversity, especially if not mitigated through effective water governance.

1.1.1. Projected Change in Seasonal Rainfall Under the SSP1-1.9 and SSP3-7.0 Scenarios, 2020-2059.

Figure 3.8 presents the projected percentage change in seasonal rainfall in the Sudd region, Jonglei State under the SSP1-1.9 and SSP3-7.0. The projections, which span key future periods (2020-2039 and 2040-2059), highlight notable seasonal and inter-decadal variations in precipitation patterns, with implications for water resources, agriculture, and climate resilience in the region.

Precipitation is projected to increase during the DJF season to 75.28% of the baseline, with a range of 42.98% to 134.68%. The MAM (March-May) period shows a significant increase to 101.95%, with a range of 81.17% to 124.31%, reflecting enhanced rainfall during this season. Rainfall during JJA (June-August) is projected at 102.31%, with variability ranging from 92.01% to 112.77%, indicating a consistent increase during the wettest months. The projected rainfall for SON increases to 104.63%, with a range of 89.25% to 120.67%, showing stable wet-season rainfall. The period 2020-2039 shows a general increase in rainfall across all seasons, with the highest percentage increase in SON (104.63%), suggesting improved wet-season rainfall. The variability in DJF (42.98%-134.68%) and SON (89.25%-120.67%) indicates moderate interannual fluctuations, particularly during the dry and transition periods. These findings are broadly consistent with the IPCC AR6 Working Group I report, which projects an increase in East African rainfall under low-emission scenarios (SSP1-1.9), particularly during the long and short rainy seasons (IPCC, 2021). The increase in precipitation, especially during SON and JJA, suggests that the region may experience more reliable wet-season rainfall, improving water availability and agricultural productivity under the SSP1-1.9 scenario.

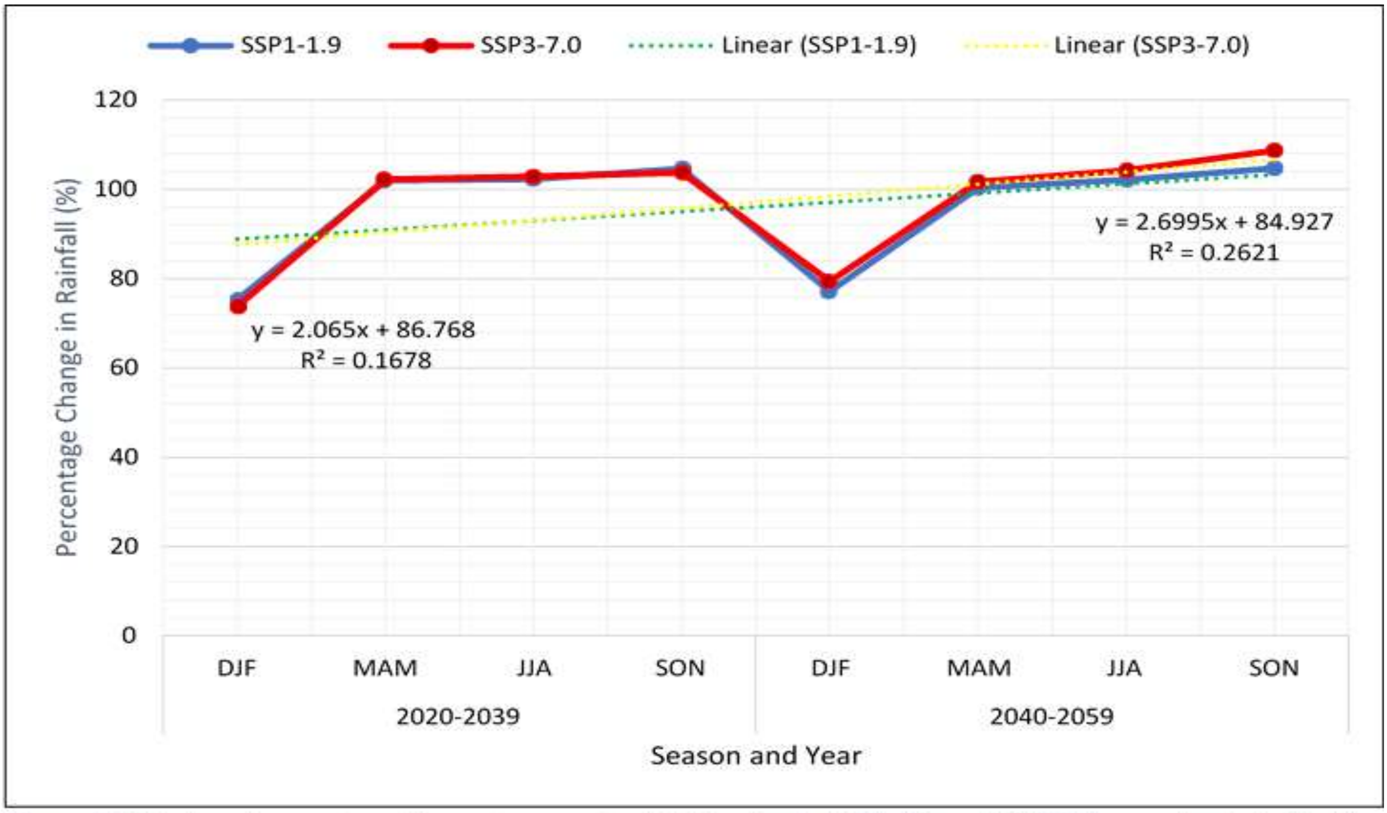

Figure 3.8. Projected percentage change in seasonal rainfall under the SSP1-1.9 and SSP3-7.0 scenarios in the Sudd region, Jonglei State, 2020-2059.

In the mid-century period from 2040-2059, projected rainfall under the SSP1-1.9 scenario in the Sudd region remain stable, with only slight seasonal variations. DJF sees a modest increase to 77.13%, and SON maintains its positive change at 104.69%. MAM and JJA remain near baseline levels at 100.34% and 102.15%, respectively. Notably, variability remains moderate to high, especially during DJF (45.90%-138.53%), reflecting uncertainty in dry-season precipitation projections. These results demonstrate the potential benefits of the SSP1-1.9 pathway, which emphasizes sustainability, international cooperation, and aggressive mitigation efforts. As highlighted in the IPCC AR6 Synthesis Report (2023), SSP1-1.9 is aligned with the 1.5°C global warming target under the Paris Agreement, and is associated with slower rates of climate change, reduced extreme weather events, and more stable hydrological cycles (IPCC, 2023).

1.1.1. Projected Change in Seasonal Rainfall Under the SSP3-7.0 Scenarios, 2020-2059.

Under the high-emissions SSP3-7.0 scenario, rainfall in the Sudd region is projected to increase across all seasons (figure 3.8) between 2020 and 2059, though with considerable seasonal variability. During DJF (December-February), precipitation is projected to rise to 73.76% of the baseline, with a wide variability range from 40.72% to 141.75%, indicating moderate rainfall increases but high interannual variability during the dry season. The high variability in DJF underscores greater uncertainty in future dry-season precipitation, a concern noted in the IPCC AR6 Working Group I report (IPCC, 2021), which highlights greater unpredictability in precipitation extremes under higher warming scenarios.

In MAM (March-May), rainfall increases to 102.22%, with variability ranging from 75.27% to 130.07%, suggesting a moderate but more stable increase during the early rainy season. This projection supports findings from IPCC AR6 that suggest changes in seasonal rainfall patterns in East Africa may lead to longer rainy seasons or shifts in onset and cessation dates, particularly under higher emission pathways. For JJA (June-August) the peak of the wet season rainfall is projected at 102.86%, with a relatively narrow variability range (90.79% to 115.99%), indicating stable and consistent increases during the most agriculturally important season. Similarly, SON (September-November) rainfall is expected to rise to 103.74%, with a range of 89.31% to 121.61%, reflecting robust wet-season precipitation and lower uncertainty compared to DJF and MAM. The period 2020-2039 shows a general increase in rainfall across all seasons under the SSP3-7.0 scenarios, with the most consistent gains observed in JJA and SON. However, DJF exhibits the highest variability, posing challenges for water availability and dry-season crop production.

By the mid-century period (2040-2059), rainfall projections under SSP3-7.0 suggest further increases. In DJF, rainfall is projected to reach 79.40%, with an even broader variability range from 42.61% to 172.27%. This reflects higher potential rainfall totals but significant interannual variability, reinforcing the IPCC's findings that climate extremes particularly droughts and short-term intense precipitation events are more likely to intensify under high-emission scenarios (IPCC, 2021, 2023).

MAM rainfall slightly decreases to 101.69%, with variability between 77.51% and 129.23%, suggesting continued stability but potential early-season uncertainties. For JJA, precipitation increases to 104.24%, with a range of 88.55% to 119.23%, confirming the trend of consistent and reliable rainfall during the peak wet season. This is promising for agriculture and wetland hydrology, especially in the Sudd region, which is highly dependent on the Nile's seasonal flood dynamics. The most notable increase is observed in SON, where rainfall rises significantly to 108.69%, with a variability range of 86.95% to 138.35%. This suggests stronger and more prolonged wet-season conditions, aligning with IPCC projections for intensified rainfall in tropical regions due to increased atmospheric moisture capacity and altered monsoonal patterns (IPCC, 2021, 2019).

1.2. Implication for Climate Change and Adaptation Under SSP1-1.9 and SSP3-7.0 Scenarios in the Sudd Region.

The observed trends suggest that seasonal rainfall in the Sudd region is projected to increase moderately under future climate scenarios, with notable stability during the key wet seasons JJA (June-August) and SON (September-November). These projections are particularly promising under the SSP1-1.9 low-emission scenario, which is associated with reduced climate extremes, more stable hydrological cycles, and enhanced adaptive capacity (IPCC, 2023). The consistent increases in rainfall during agriculturally significant periods may bolster food security, reduce drought risk, and support the achievement of sustainable development goals (SDGs) in the region. However, the high variability in DJF (December–February), observed across both near and mid-term projections, underlines the need for flexible adaptation strategies to manage potential dry season anomalies. As emphasized in the IPCC Special Report on Climate Change and Land (IPCC, 2019), managing seasonal water variability is essential in regions where communities and ecosystems are heavily dependent on rainfall.

Under the SSP3-7.0 high-emissions scenario, the Sudd region is projected to experience overall wetter conditions, particularly during the core rainy seasons (JJA and SON). However, this improvement is offset by increased variability in dry season rainfall, especially in DJF. These trends align with the IPCC AR6 Working Group II (2022) findings, which warn that high-emission pathways are associated with greater hydrological extremes, creating the dual challenges of flood and drought risk. This variability has significant implications for climate adaptation and resource planning in South Sudan. While increased rainfall during SON and JJA may support agricultural productivity and wetland regeneration, the uncertainty in dry-season rainfall poses risks to dry-season livelihoods, pastoral resilience, and water storage systems. Therefore, adaptive strategies must prioritize flood management, dry-season water conservation, and early warning systems especially under high-emissions scenarios like SSP3-7.0, which is characterized by regional rivalry, weak climate governance, and limited mitigation efforts (IPCC, 2021).

In addition, the cumulative impacts of historical and projected climate change pose serious threats to water security in the Sudd Wetland. Rising temperatures, particularly during the dry season, are likely to intensify evaporation, reduce surface water levels, and disrupt both human livelihoods and ecological integrity. These findings are consistent with earlier research by Howell et al. (1988), Junk et al. (2013), and UNEP (2018), which highlight the vulnerability of wetlands to climate-induced hydrological stress. The challenges are further compounded by erratic rainfall patterns. While increases in wet-season precipitation may temporarily replenish water levels, their unpredictability heightens the risk of floods and droughts both of which have devastating effects on agriculture, infrastructure, and biodiversity. As noted by IPCC (2014b) and Taye et al. (2016), this dual threat of water excess and scarcity underscores the need for adaptive water governance systems that are robust, inclusive, and responsive to climate variability. Moreover, the socioeconomic implications are profound. With over 80% of households in the Sudd region dependent on rain-fed agriculture, the projected 50% reduction in crop yields under climate stress threatens not only food availability but also economic stability, public health, and gender equity. As emphasized by Mai (2018) and UNEP (2018), women are particularly vulnerable, given their limited access to land, credit, and decision-making processes. Enhancing women's participation and leadership in climate adaptation is therefore critical to building resilient livelihoods and equitable development pathways.

2.0.Conclusion

The analysis of the impacts of climate change on water security in the agroecological zone of the Sudd Wetland revealed a clear and concerning trend of rising temperatures and increasingly erratic rainfall patterns, factors that pose significant threats to water availability, agricultural productivity, and rural livelihoods. Historical data show an increase in average temperatures of over 1.5°C, alongside a 15-20% decline in summer rainfall, exacerbating water stress in a region where 86% of households depend on rain-fed agriculture. Projected climate scenarios under SSP3-7.0 indicate further warming and potential agricultural yield reductions of up to 50%, underscoring the acute vulnerability of local communities especially women, who are disproportionately affected due to existing socioeconomic inequalities.

Comparatively, the SSP1-1.9 scenario offers a more favorable outlook with moderate warming and less climatic variability, providing a pathway for enhanced predictability, adaptation, and resilience. However, the high-emission SSP3-7.0 scenario portends severe consequences, including ecosystem degradation and heightened livelihood insecurity. These findings highlight the urgent need for evidence-based and climate-informed strategies to strengthen both ecological and socioeconomic resilience.

The findings underscore the imperative for localized, inclusive, and forward-looking interventions to ensure the long-term resilience of the Sudd region amid intensifying climate challenges, this study strongly recommends the implementation of Integrated Water Resource Management (IWRM) as a central framework for climate adaptation in the Sudd region. Key components should include water conservation initiatives, the establishment of climate monitoring systems, promotion of sustainable agriculture, and the strengthening of institutional and community capacities. The integration of local knowledge and inclusive stakeholder engagement, particularly the empowerment of women.

Technological tools such as Remote Sensing (RS) and Geographic Information Systems (GIS) must be leveraged to enhance climate monitoring, data accuracy, and proactive planning. Climate-resilient agricultural practices such as drought-tolerant crops and efficient irrigation techniques are critical for sustaining food production under changing environmental conditions. Furthermore, targeted training programs and gender-equitable policies are essential to build local adaptive capacity and ensure equitable participation in decision-making processes.

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Conflict of interest

The authors declare that there are no conflicts of interest.

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