UNIVERSITY OF NAIROBI

ASSESSMENT OF THE SPATIAL AND TEMPORAL CHARACTERISTICS OF RAINFALL AND TEMPERATURE OVER SUDD WETLAND IN SOUTH SUDAN IN A CHANGING CLIMATE

By

EMMANUEL QURINO NIJAK GORBE

I56/41087/2021

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF MASTER (MSc) METEOROLOGY OF THE UNIVERSITY OF NAIROBI

November 2023

DECLARATION

I certify that this dissertation is my original work and has not been submitted elsewhere for research. Where other people's work or my work has been used, this has been appropriately acknowledged and indicated by the requirements of the University of Nairobi.

Signature…..…. ……....... Date…**27/11/2023**……………

Emmanuel Qurino Nijak Gorbe

I56/41087/2021

This dissertation has been submitted for examination with our approval as University Supervisors:

Signature……………………………………… Date ………***27/11/2023***……………

Prof. Christopher Oludhe

Department of Meteorology

University of Nairobi

P.O box 30197-00100

Nairobi Kenya

Signature… Date. **November 27, 2023**

Prof. Alfred Owuor Opere

Department of Meteorology

University of Nairobi

P.O box 30197-00100

Nairobi Kenya

DEDICATION

This dissertation is dedicated to the Almighty God, family, friends and IGAD Climate Prediction and Application Centre (ICPAC)

ACKNOWLEDGEMENT

I am thankful to the Almighty God for his protection and for keeping me healthy during the entire period of this study, I also like to express my deepest appreciation to my two Supervisors, Prof. Christopher Oludhe and Prof. Alfred Owuor Opere for their guidance and suggestions throughout this research, many thanks to all lectures, support staffs of Department of Meteorology and friends for their support during my study,

I am indebted to my sponsor IGAD Climate Prediction and Application Centre (ICPAC) for awarding me a scholarship to pursue my Master in Meteorology at the University of Nairobi under project Intra-ACP Climate Services and Related Applications (ClimSA), I am also grateful to the Government of South Sudan especially the South Sudan Civil Aviation Authority, Department of Meteorology who granted me study leave to pursue this noble course.

I could not have undertaken this Journey without the Intra-ACP Climate Services and Related Applications (ClimSA) team especially Mr. Paulino Omoj Omay for their ending guidance, encouragement and support during the whole study period.

Last but not least, sincere gratitude goes to my family, especially my parents, my wife and my children. Their belief in me has kept my spirits and motivation high during this study, to all those who made this study a success may the Almighty God bless them abundantly.

ABSTRACT

The Sudd wetland is the world's largest floodplain area and is essential for livelihoods, economic income, and water resources for communities living in the surrounding area. The communities in this area have been using traditional knowledge to forecast or predict rainfall seasons as well as when to start fishing. Each year during the rainfall season, there is heavy flooding and displacement of humans and livestock among the communities in the Sudd wetland. Thus, this study provides better knowledge regarding the variability of past and future changes in climate extremes over Wetland. This dissertation aimed to determine the temporal-spatial characteristics of past, present and projected rainfall and temperature, to examine the anomalous rainfall-related floods over the Sudd wetland area. The data used is monthly CHIRPS V2.0 data for precipitation and ERA5 for temperature. The data was obtained from the University of California, Santa Barbara, and ECMWF. ERA5 and version two of CHIRPS data for 41 years cover the period from 1981 to 2022 by using Statistical methods (Mean, Coefficient of Variation and time series analysis). For the projection of precipitation and temperature used in CMIP6 model analysis for exploring future precipitation and temperature under three scenarios SSP1-2.6, SSP2-4.5, and SSP5-5.8 for near (2030-2059), and far future (2070-2099) relative to historical (1981-2010). The findings of this study show the annual rainfall in The Sudd wetland is above 650mm, and the June to September season is the wettest. the Sudd wetland region experienced a significantly increasing rainfall in August of more than 500mm. while December to February is the driest season recording less than 10 mm. The annual mean temperature was between 27.5 to 29 ^{0}C, March, April, and May (MAM) seasons were the warmer seasons, while the colder seasons were June to September (JJAS). The results of data analysis showed that all seasonal rainfall has lower variability except for the March to May (MAM) rainfall season is moderate 20 to 30 %. The Statistical trend analysis indicates slightly increasing trends of mean annual and seasonal rainfall over The Sudd wetland region. The temperature variability was lower variability and the trend analysis indicates increasing trends of mean annual and seasonal temperature over The Sudd region. The result of rainfall anomalies showed that from 1981 to 2020 the Sudd wetland had an above-normal precipitation associated with flood recorded over this region and experienced a significantly increasing trend. The result of the CMIP6 model, June to September has shown a significant increase in seasonal rainfall over the Sudd wetland under three scenarios. quantitively, SSP1-2.6

is projected to be 0.50(0.50), SSP2-45 is projected to be 0.70(1.25) and SSP5-85 is projected to be 1.10(3.33), while the annual and all seasonal mean temperatures for the future term 2030-2059 and 2070-2099 projected to increase under three scenarios over the Sudd wetland. Future studies on The Sudd Wetland, request additional research utilizing the ensemble means of several models' best performance over The Sudd Wetland.

Keywords Projection- Precipitation- Temperature- CHIRP- ERA5- CMIP6- The Sudd wetland.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

CC:	The Correlation Coefficient
CHIRPS:	Climate Hazards Group Infrared Precipitation with Station
CMIP6:	Coupled Model Intercomparison Project Phase 6
CV:	The Coefficient of Variation
E:	East
ECMWF:	European Centre for Medium-Range Weather Forecasts
ENSO:	El Nino Southern Oscillation
ERA5:	Fifth-generation ECMWF reanalysis
H0:	Null Hypothesis
H1:	Alternative Hypothesis
IOD:	Indian Ocean Dipole
ITCZ:	Intertropical Convergence Zone
JJA:	June, July and August
LARSWG:	The Long Ashton Research Station Weather Generator mode
NDVI:	Normalized Difference Vegetation Index
MAM:	March, April and May
MC:	Mid-century
N:	North
OND:	October, November and December
RAI:	Rainfall Anomaly Index
RMSE:	Root Mean Squared Error
SPOB:	Specific Objective
SSP:	Shared Socioeconomic Pathways Scenario
SST:	Sea Surface Temperatures

CHAPTER ONE: INTRODUCTION

1.0 Introduction

The chapter provides information on the background, including the problem statement, objectives, research questions, justification, research hypothesis, and study area.

1.1 Background Information

Africa's climate varies, from the desert with almost no vegetation cover to semi-dry savannas on the coast and south, and tropical forests in the Centre and west of the continent. (Dunning et al., 1955) Precipitation is the most important part of all life on the continent. it is used in drinking and farming activities in many countries on the continent. Climate projections for the twenty-first century indicate a significant spatial change over the central areas of the continent an increase in precipitation with a decrease in the Southern and northern parts of Africa, Sahara projected the most significant rise in mean annual temperature with a bit of rise in the central and east of the continent.(Almazroui, Saeed, Saeed, Nazrul Islam, *et al.,* 2020a)

Rainfall in eastern Africa shows huge spatial and temporal variability, caused by various features operating on a regional and global scale. The main rainfall season for Sudan, Eritrea, Ethiopia, and South Sudan it's June, July, August, and September. While equatorial Eastern Africa has two rainfall seasons. The first one is March to May and the second is October to December (Endris *et al.*, 2019), (Collins, 2011). Reported that from 1979 to 2010, northern and eastern Africa was proficient in increasing temperature trends specifically the season from June to August.

The climate of South Sudan is tropical with a high amount of rainfall and relative humidity, then a drier season. Across both sides of the White Nile is a huge grassland, wetlands and tropical rainforest. Precipitation is light in the northern areas and increases in the south. The maximum precipitation is from May to October. In the mean, May is the wettest month of the year. July is the coolest month of the year with an average temperature of 16^{0}C to 30^{0}C, March is a warmer month with an average temperature between 22^{0}C to 37^{0}C (Mukhtar *et al.,* 2019).

The Sudd wetland has tropical climatology, with a wet season from the month of April to October and drier from the end of the year (November) to March (Mohamed et al., 2005). The Sudd wetland is situated along the White Nile influx from Lake Victoria in Uganda with local rainfall and surface runoff from its surrounding areas.

The temperature has a mean of between 30^0 C to 33^0 C in the drier season, dropping to a mean of 26^0 to 28^0C in the rainfall Season (Ahmed & Ismail, 2008). The daily Wetland temperature statistically in the past 100 years indicated an increase in trends by 0.6^0C for maximum daily temperature and 1.5^0C for minimum daily temperature. (Mohamed & Savenije, 2014)

1.2 Problem Statement

The Sudd Wetland area is one of the world's largest floodplains and is essential for livelihoods, ecosystem service and water resources for the communities living in the surrounding area. The communities in this area depend on the fisheries for food and livelihoods and use only their traditional knowledge and skills to forecast the weather to decide when to go fishing. (Benansio *et al.*, 2021). Recently, the Sudd wetlands brought attention to users nationally and regionally. In 2015, the estimated total economic value of the Sudd was more than US $3 billion (Lund & Services, 2022)**.** The Sudd wetland Lacks observed data and information with no scientific evidence on the effect of future rainfall change and variability of temperature and its relation to the recurrent floods over this study area. Every year, especially during the rainfall Season, there is much flooding as well as displacement of humans and livestock, disease outbreaks among the communities and livestock in the Sudd Wetland. Additionally, the flood impacts on loss of property, infrastructure and agriculture.

1.3 Research Questions

i. How do the observed rainfall and temperature vary in time and space over the Sudd wetland?
ii. Why is there an increase in the frequencies and intensities of floods over the Sudd wetland?
iii. What will the future rainfall and temperature patterns look like over the Sudd wetland?

1.4 Objectives of Research

The general objective of the study is to assess the spatial and temporal characteristics and projected changes in rainfall and temperature over The Sudd Wetland area. The specific objectives are:

i. To determine the spatial-temporal characteristics of precipitation and temperature on Sudd Wetland
ii. To examine the anomalous rainfall-related floods over the area of the Sudd Wetland
iii. To determine the projected changes in temperature and precipitation over the Sudd Wetland

1.5 Justification and Significance of the Study's

The Sudd Wetland is important for livelihoods, ecosystem service, and water resources for the communities surrounding. The Communities in the Sudd Wetland rely on livestock and fisheries for food and livelihoods.(Benansio *et al.,* 2021). During the rainy season, flood displacement increases in Sudd wetlands with an increase in outbreaks of livestock disease and mortality in Sudd wetlands is attributed to Starvation and fatigue around the region. The Sudd Wetland provides habitat, food, and shelter for many animals, especially birds and amphibians. However, the detailed temperature and rainfall characteristics over the Sudd wetland are not well known yet due to the absence of information about the area and the lack of distributed meteorological observation stations, The study therefore provides better information on the variability of historical and present climate extremes over Wetland area. Understanding the rainfall and temperature of the Sudd wetland. can aid in developing strategies for the socio-economic to fishermen and pastoral livestock to adapt to the changing climate

1.6 Research Hypothesis

In this study, statistical analyses will be done for two variables, namely, temperature and rainfall, H0 is the null hypothesis that assumes the responsibility that there are no changes in Temperature and Rainfall. H1 is the alternative hypothesis that assumes the responsibility that there is a change in Precipitation and Temperature.

1.7 Study Area

1.7.1 Sudd wetland

The Sudd wetland lies between Latitudes 5^0N to 10^0N, And Longitudes 29.5^0E to 32^0 E (Figure 1), the wetland area appreciated is almost more than one million km^2 (Mohamed *et al.,* 2005). The wetland expansion touches four South Sudan states mainly Central Equatorial, Jonglei, Lake, and Unity states.

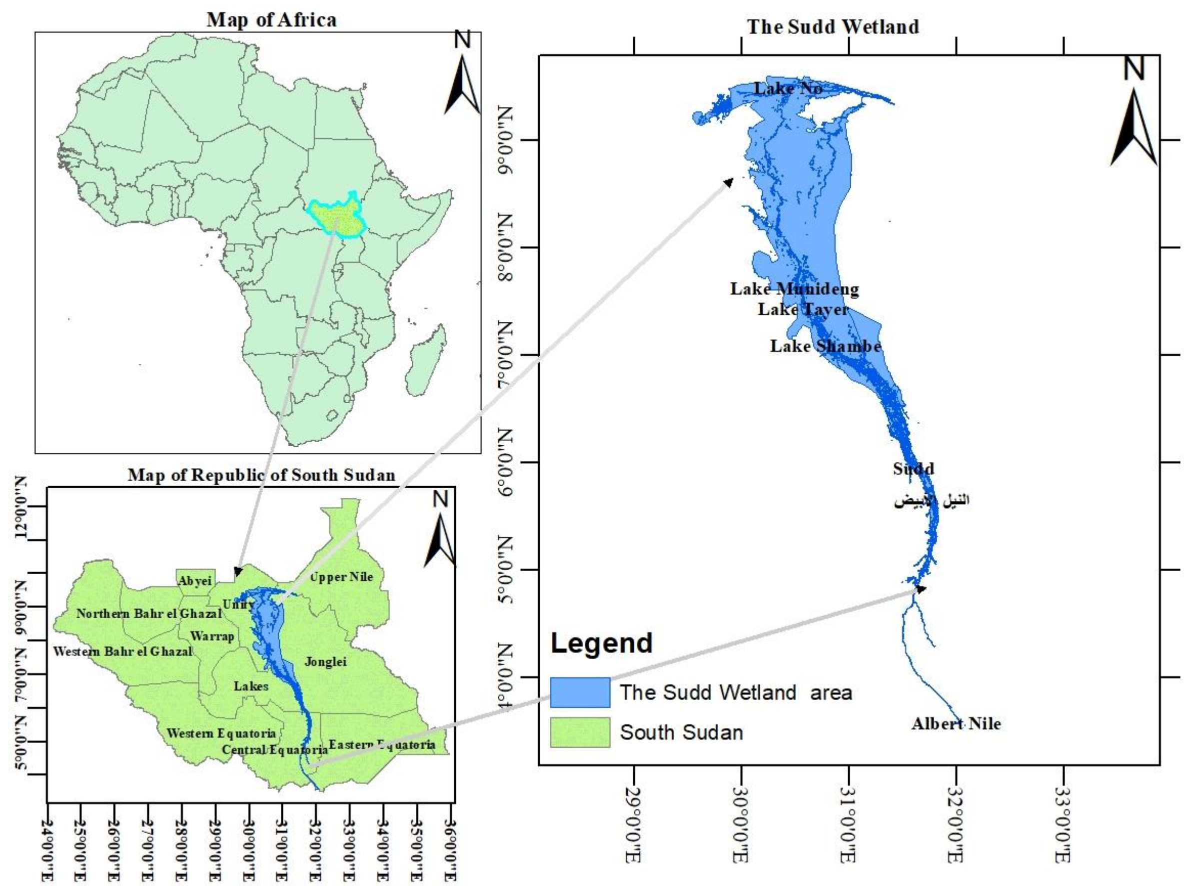


Figure 1: Maps showing the Study Area Sudd Wetland in South Sudan, Africa. The Maps were created using ArcGIS software

1.7.2 Climate of The Sudd Area

The region is located in tropical climatology and a semi-dry savanna north of the equator in latitude 5^0N to 10^0N in South Sudan, East Africa with a rainy period from April to October and drier from November to March (Mohamed *et al.,* 2005). The mean temperature is 30^0C to 33^0C in the drier season, dropping to a mean of 26^0 to 28^0C in the rainfall Season (Ahmed & Ismail, 2008).

1.7.2.1 Climate Drivers

The effect of Temperature was likely offset by the decrease in solar radiation and relative humidity over the Sudd Wetland. The Statistical testing shows a decreased significant change of 10% over the last 50 years.

The precipitation over Sudd has not shown any significant change in the last hundred years. (Mohamed & Savenije, 2014), Space and time of seasonal rainfall in The Sudd Wetland, South Sudan, and East Africa in general are driven by the Intertropical Convergence Zone (ITCZ) movement, IOD and ENSO.

1.7.2.2 Intertropical Convergence Zone (ITCZ)

The ITCZ is considered the main component of the Hadley cell, The position of the ITCZ and the landforms around The Wetland are the main characteristics of rainfall over the White Nile. The ITCZ movement seasonally, tracking the region of warmer surface temperatures. Normally the position of ITCZ Southern of The Sudd wetlands area by the end of February and moving northward crossing The Sudd wetland reaches the northern parts of Sudd wetland in May. Rainfall occurs south of the ITCZ's position approximately 300 to 600 kg. (Mohamed *et al.,* 2005b).

1.7.2.3 El Nino Southern Oscillation (ENSO)

ENSO is a global atmospheric-oceanic process resulting from the heat distribution around the Pacific Ocean and is most importantly a coupled (atmospheric-oceanic) climate phenomenon. El Nino with warmer Sea Surface Temperature in the Pacific causes a wetter OND season or short rain over Eastern Africa (Palmer *et al*., 2023)

1.7.2.4 Indian Ocean Dipole (IOD)

IOD is like ENSO-connected atmospheric-oceanic phenomena but in the equatorial Indian Ocean, IOD characterizes the differences in Sea Surface Temperatures (SST) in the western and eastern Indian Ocean, IOD impact on interannual rainfall season over the Sudd wetland it is characterized by warm and cold SST anomaly over the Indian Ocean. Positive (+ IOD) is linked with wetter OND rainy Seasons in Eastern Africa, South Sudan and particularly the Sudd wetland and results in total rainfall being two or more than two times the long-term mean. Negative Indian Ocean Dipole (- IOD) is linked with light OND rainfall season over Eastern Africa (Wainwright *et al.*, 2020).

CHAPTER TWO: LITERATURE REVIEW

2.0 Introduction

The literature review highlights different published research on the spatial-temporal characteristics of Rainfall and Temperature information.

2.1 Spatial-Temporal Characteristics of Rainfall and Temperature

Many studies showed a significant trend in spatial-temporal characteristics of Temperature and rainfall in different areas of the region and globally ((Vijith & Dodge-Wan, 2020; Xiao *et al.,* 2016), (Deng *et al.,* 2018)).

(Omoj *et al.,* 2016) studied the spatial-temporal variation of rainfall and temperature over South Sudan using monthly data from the South Sudan Meteorological Department period from 1954 to 2013. Using two methods Graphical methods and statistical techniques to examine the last and present variation of precipitation and temperature. they obtained monocular South Sudan rainfall in the primary season (JJA) contributed more than 50% of annual precipitation. Results from trends analysis indicated a drop in the June July August (JJA) seasonal trends

(Mohamed *et al.,* 2005b) Studied the long-range impact of rainfall and temperature on the Sudd area from (1900- 2000) using Mann- Kendall test and found that the water coming to and out of wetland had an increasing trend over one hundred years ago, due to the increasing rainfall over the region and in Lake Victoria in Tanzania and Uganda in the early 1960s, Also, this study analyzed daily maximum and minimum temperature and found that a significant increase trend indicates 0.6 and 1.5 ^{0}C, the rising temperature due to reducing relative humidity and solar radiation on the Sudd wetland area by 10% over the last 50 years.

(Ruuskanen, 2021) Used Remote Sensing Technology data (the historical Normalized Difference Vegetation Index (NDVI) image data) for monitoring vegetation cover over The Sudd Wetland region from March 2000 to 2020 to determine the level changing over lakes of Kyoga, Albert and

Victoria in East Africa and related this with the vegetation cover over The Sudd Wetland. The result pointed out that the spatial-temporal variability over the Sudd was affected by the rise and fall of water levels over the alert lake, expanded vegetation cover over The Sudd wetland depended on the water level of the Lake of Alert, While insignificant relation between Lake Victoria and Kyoga with vegetation cover over The Sudd Wetland in South Sudan.
in most areas of South Sudan. The temperatures showed trends in an increase in all parts deemed in a 0.05 with some slight seasonal variation in rising trends patterns.

2.2 Extremes in rainfall and temperature

(Omondi *et al.,* 2014) investigated variations in precipitation and temperature extremes over East Africa from 1961 to 2010, using station data (daily data) precipitation and temperature extremes for ten (10) East African countries to obtain observed and projected patterns of climate extremes for these ten (East African) countries. As a result, accumulated rainfall on wetter days of more than 1 mm has decreased significantly, and frequencies of warm extremes at night are increasing. but dry days in cold extremes are decreasing.

(Kilavi *et al.,* 2018) examined the effects of flooding and rainfall in central Kenya from March to May 2018 in a study published in 2018. They did this by using several databases, including five weather stations in Nairobi County for the Kenya Meteorology Department's 1981–2018 data, GPCP v1.3 analyses from 1988 to 2018, GPCC V8.S for the 1891–2018 period, and CHIRPS for the period 1981–2018. According to all of these studies, March and April were the wettest months due to days of intense rain, which resulted in flooding, fatalities, population displacement, and infrastructure damage. According to this study, tropical cyclones over Kenya and East Africa MJO events phases 2 to 4 are responsible for rainfall events and tropical cyclone activities in the Indian Ocean.

(Zakaria Lukwasa *et al.,* 2022) investigated the time and space variability of Rainfall in South Sudan using long-term CHIRPS data from 1981 to 2019 to come up with results that South Sudan Rainfall varied depending on regions and seasonality, summer decreases from North-west to the southeast of South Sudan while in the Autumn season, rainfall increases toward the Southern-west and South of country. He also investigated the relationship between easterly tropical jet, easterly African jet, and South Sudan Seasons by momentum convection, The spatial and temporal characteristics of precipitation could instead reason for floods and droughts in Southern Sudan. The precipitation amounts and period from the Northeast to the Southwest of South Sudan. It affected development with livelihood when the mitigation strategies were absent.

Sudd Wetlands are important environmental resources for rural livelihoods in the country, the Wetlands are important for the ecosystem services they provide. (Benansio *et al.,* 2021) studied the White Nile area of Sudd swamps located between the areas namely Mangalla County, Terekaka County, and Gemeza County using face-to-face interviews among the communities of these counties, The study showed that the best fishing months were May, August and September. as well, road destruction, loss and damage to fishing equipment and fishing time change due to the high frequency of floods over The Sudd wetland have affected fishing and marketing.

2.3 Evaluation of the Performance of CMIP6 Models

Thirteen of the CMIP6 were used by Shiru & Chung, (2021) to simulate rainfall and maximum and minimum temperatures between 1984 and 2014 in order to determine which CMIP6 was optimal for a multi-model ensemble that could be used to project the climate. The CRU Version Tsv.3.23 rainfall, minimum, and maximum temperature datasets are analyzed in this study using statistical measures such as RMSE, Pbias, NSE, and volumetric efficiency. The four GCM models with the highest-ranking results for precipitation were ACCESS-ESM1-5, NESM3, CMCC-CM2-SR5, IPSL-CM6A-LR, and NESM3. The best-performing modes for maximum temperature were INM-CM4-8, BCC-CSM2-MR, MRI-ESM2-0, and ACCESS-ESM1-5; for lowest temperature, the best-performing GCMs were AWI-CM-1—1-MR, IPSL-CM6A-LR, INM-CM5-0, and CanESM5.

(Ngoma *et al.,* 2021) Studies examined the evaluation of fifteen (15) CMIP6 models to simulate rainfall data over Uganda of the periods 1981-2014, using statistical metrics (bias error, normalized root means square error, and pattern correlation coefficient). The models' performance difference from the MAM and SON seasons. Additionally, some models underestimated and others overestimated during the MAM rainfall season, while most of the fifteen CMIP6 models overestimated during the September to November (SON) season.

2.4 Projected Changes in Temperature and Precipitation

(Almazroui *et al.,* 2021) Determined future rainfall and temperature changes over the United States of America (USA), the Caribbean and Central America. this study used the ensemble of thirty-one CMIP6 models for three terms (2021-2040, 2041-2060, and 2080-2099) relative to historical (1995-2014) under three Scenarios. this study comes which resulted in the largest increase in rainfall over the western United States of America in the winter and spring seasons while the northern America region in the summer season. The projected a significant increase in temperature in all of America in all three scenarios the higher increase showed under strong forcing SSP5-8.5 was 6 ^{0}C.

(Almazroui, Saeed, Saeed, Islam, *et al.,* 2020) Studies investigated changes in precipitation and temperature over six countries in southern Asia for three terms, range 2030-2049, 2060-2079, and 2080-2099. Temperature and Rainfall were projected for two seasons, the June to September season (summer) and the December to February season (winter) using the ensemble from 27 CMIP6 models under three as Shared Socioeconomic Pathways (SSPs) relative to historical (1995-2014). those are weak scenario (SSP1-2.6), mid-forcing (SSP2-4.5) and strong forcing scenario (SSP5-8.5), the results of the CMIP6 model's ensemble underestimates the annual mean temperature for all six (6) Countries. the CMIP6 models show higher sensibility to GHG emissions over these 6 countries compared with CMIP5 models. The projected temperature shows the largest increase of 6 ^{0}C under strong forcing scenario SSP5-8.5 over the Northern western part (Karakorum and Himalayan ranges). The CMIP6 model's ensemble mean projected the highest warming in the winter than other seasons over six (6) South Asian Countries. On the other hand, projected an increase in the annual average precipitation in all six countries during the three future periods (2030-2049, 2080-2079 and 2080-2099) under all three future scenarios.

(Supharatid *et al.*, 2022) Examined the future changes in temperature and precipitation over Cambodia, Myanmar, Laos, Vietnam and Thailand (5 Mainland Sea Countries) using a Multi-Model Ensemble for eighteen (18) CMIP6 models under two scenarios was mid-forcing scenario (SSP2-4.5) and strong-forcing scenario (SSP5-8.5). this multi-model ensemble (MME) projected warming over all five Mainland Sea Countries with the largest values under the SSP5-8.5 scenario than the SSP2-4.5 scenario. Additionally, the MME analysis increases precipitation during the Southwest monsoon and the northeast monsoon, while projected after 2050 decrease in precipitation trends.

(Almazroui, Saeed, Saeed, Nazrul Islam, *et al.*, 2020b) Studies the future change in rainfall and Temperature over eight (8) subregions in Africa during two projected times 2030-2059 and 2070-2099 relative to historical (1981-2010) used twenty-seven CMIP6 Models to determine the change in temperature and rainfall in future. The results show that in all eight subregions over Africa, the annual mean temperature is projected to increase and the increasing difference varies regionally. Its largest rise over the Sahara region (northern Africa) is projected at 5.6 ^{0}C while the smaller rise over central East Africa is projected at 3.5 ^{0}C. Also, the rainfall projected result, during the two future terms southern and northern regions of Africa decreasing in rainfall, with an increase in precipitation over the central of Africa.

(Chen *et al.*, 2013) Examined temperature and precipitation changes over South Sudan and Sudan by using downscaling the Long Ashton Research Station Weather Generator model (LARSWG) for (maximum and minimum) temperature and precipitation to investigate the projection of temperature and rainfall over South Sudan and Sudan based on the SRAS Scenarios of 7 General Circulation Models (GSMs) from 2011- 2030, mid-century (MC) 2046-2065, and a long team from 2080-2099. The model's result pointed out a decreasing trend in rainfall in Sudan's main Season

June to August (JJA) for all three periods while South Sudan's increasing trend in all three periods and Seasons except for periods 2011 to 2030 in seasons March, April and May (MAM).

From the literature reviewed in this study, there are significant studies have been conducted in East Africa with regard to the temporal-spatial characteristics of observed and projected temperature, rainfall, extreme rainfall, and temperature events. There is also a substantial body of research that focuses on evaluating the performance of the CMIP6 model, as well as future patterns of rainfall and temperature using climate model simulations and projections. However, there are knowledge gaps about projected future temperature and precipitation trends across South Sudan, particularly the Sudd wetland. Furthermore, the studies conducted in the past, present, and future refer to Sudd wetland; but do not use gridded data or CMIP6 Model simulations and forecasts. There is also no body of knowledge on changes in future patterns of temperature and rainfall over the Sudd wetland.

Therefore, the aim of this study is to fill the knowledge gaps and provide a better understanding of the historical, present, and future patterns of change and variability in rainfall and temperature over the Sudd wetland.

2.5 Conceptual Framework

Monthly Data (CHIRPS V2.0 and ERA5) used these two data with Statistical Methods to produce the Observed Rainfall and Temperature pattern's spatial objective one (SPOB1). CHIRPS V2.0 was used with Rainfall Anomaly Index analysis to obtain objective two (Examine the anomalous rainfall related to flood)

The CMIP6 High-resolution simulations (Monthly) were validated using Statistical Metrics (Correlation Coefficients, Bias, and Roof Mean Squared Error) to obtain objective three to produce a projection of future rainfall and temperature patterns. See Figure 2 below for details

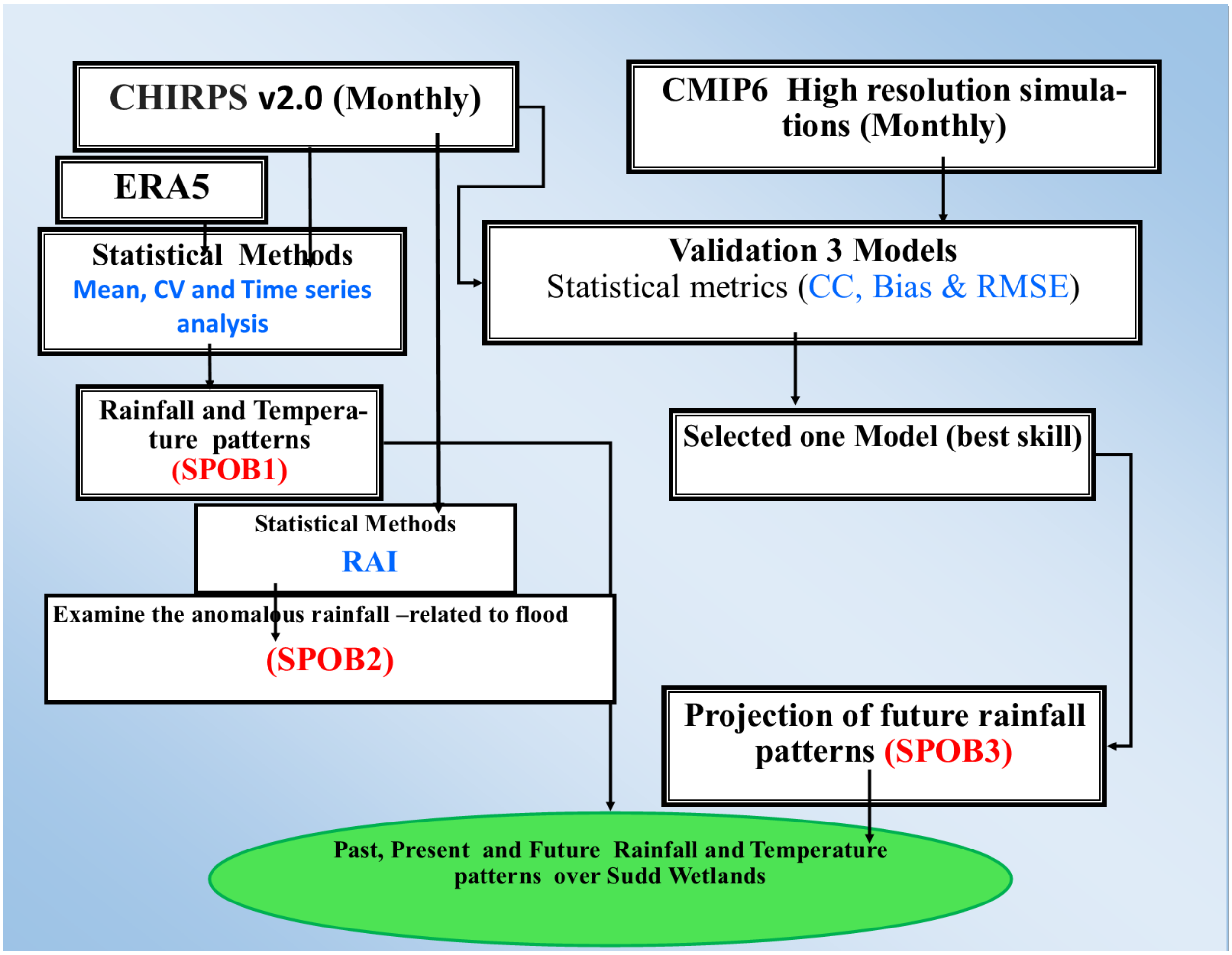


Figure 2: Demonstrate the framework of the concept for this research, The map was created using Microsoft Office (Publisher)

CHAPTER THREE: DATA AND METHODOLOGY

3.0 Introduction

Chapter three provides in detail the different data and methods used to achieve the specific objectives outlined in section 1.4.

3.1 Data

South Sudan was 619,745 sq km and has only five synoptic stations namely Juba, Wau, Raja, El Renk, and Malakal (Omoj et al., 2016), The civil war in South Sudan that dominated for over fifty years led to brittle security, economic and social situations. Therefore, there is no meteorological station and observation information over the Sudd Wetlands areas. This study will therefore utilize CHIRPS V2.0 and ERA5 data and CMIP6 model data. The study used (CHIRPS) V2.0 Monthly data for rainfall; and ERA5 for the Temperature. The CHIRPS and ERA5 data obtained from the University of California at Santa Barbara (UCSB) (Funk *et al.,* 2015) and ECMWF, CHIRPS V2.0 and ERA5 data for 41 years cover the period from 1981 to 2022. For the projection of rainfall and temperature, the study will use CMIP6 model analysis to explore future rainfall and temperature.

3.1.1 CHIRPS V2.0 Database

Climate Hazards Group Infrared Precipitation with in-situ station version two (CHIRPS V2.0) is a more than 41-year rainfall data set ranging from 1981 to near date. CHIRPS V2.0 data is a multiple-source product dataset the U.S. Geological Survey and the University of California developed. CHIRPS 0.05 resolution Satellite data and station data to gridded rainfall time series. (Funk *et al.,* 2015) the CHIRPS datasets website Index of /products/CHIRPS-2.0 (ucsb.edu).

3.1.2 ERA5 Re-analysis data

The latest high-resolution reanalysis was developed by ECMWF, the data was available and running from 1940 to the near present and has had an aspatial resolution of 31 km with 137 levels for weather and climate globally for the past four to seven decades (Jiao *et al.*, 2021) (Quagraine *et al.*, 2020)

3.1.3 Projection/Model Data

This study used three (3) of CMIP6 Models analysis For exploring future precipitation and temperature, the CMIP6 data is available at the website (https://esgf-node.llnl.gov/search/cmip6) is obtained for monthly rainfall and temperature at the multi-model ensemble, The model considered in this is high resolution 1.1^0 x 1.1^0 (Almazroui, Saeed, Saeed, Nazrul Islam, *et al.*, 2020a), The Models they CAMS-CSM1-0, BCC-CSM2-MR, and MR-ESM2-0 global climate model from CMIP6, under three projection scenario they SSP1-26, SSP2-45 and SSP5-58 for two projection time (2030-2059) and (2070-2099) relative to historical (1981-2010).

3.2 Methods

This study aims to determine the spatial-temporal characteristics of observed and projected temperature and rainfall in The Sudd Wetland by different methods used firstly climatology of spatial-temporal characteristics of rainfall and temperature, (Vijith & Dodge-Wan, 2020) assessing the spatial-temporal variability in the rainfall and temperature over the Sudd wetland, (Mohamed *et al.*, 2005b).To examine the anomalous rainfall-related floods over Sudd Wetland in South Sudan and lastly use Model data in this study to evaluate future change under the CMIP6 data for 30 years of historical data period 1981 to 2010.

3.2.1. Spatial-Temporal characteristics of precipitation and temperature on Sudd

3.2.1.1 Climatology of Spatial-Temporal Characteristics of Rainfall and Temperature

The climatology of annual and seasonal mean characteristics of rainfall and temperature over Sudd area was computed using Equation 1. The period used for the climate is an average of 30 years (1981-2010)

$$\bar{X} = \frac{\mathbf{1}}{\boldsymbol{N}} \sum_{\boldsymbol{i}=\mathbf{1}}^{\boldsymbol{n}} \boldsymbol{X}_{\boldsymbol{i}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{1})$$

Where $\bar{X}$ = average number of total rainfalls, N = number of years sample, which are 30 years.

X_i = the value of each season and yearly number of rainfalls being averaged.

3.2.1.2 To examine the spatial variability of Rainfall and Temperature over the Sudd Wetland

The study used the Coefficient of Variation (CV), which is known as the ratio of the standard deviation to an average or a mean. The database is uniform by the difference between all databases from the average of 41 years (1981 to 2022) for a given temporal sept and dividing it by the Standard deviation as shown below:

The Standard deviation is calculated using the square root of the average of the series:

$$SD = \sqrt{\frac{1}{n}\sum_{1}^{n}(X_j - \bar{X})^2} \quad \ldots\ldots\ldots\ldots \quad (2)$$

SD is the Standard deviation from the average of the series.

The Coefficient of Variation (CV)is given by:

$$CV = \frac{SD}{\bar{X}} \quad \ldots\ldots\ldots\ldots \quad (3)$$

The value of Coefficient of Variation close to zero was lower variability, The value of Coefficient of Variation 20% < CV< 30% was moderate variability and the value of Coefficient of Variation more than 30% was high variability (Muthoni et al., 2019)

3.2.1.3 Assess the Temporal characteristics of rainfall and Temperature records over the Sudd wetland

In this study, temporal variability is investigated by annual cycles, and inter-annual variability that will involve plotting a histogram of monthly Rainfall and temperature against time.

3.2.1.3.1 Time Series Analysis

The study used a time series of statistical significance was done using applying the Mann-Kendall (MK) and A graphical method to portray changes in Temperature and rainfall characteristics over the Sudd wetland area. (Panda & Sahu, 2019a)

Mann-Kendall test: In 1945 Mann proposed this Mann-Kendall test and it has been widely used with environment series. According to Mann-Kendall, H0 the null hypothesis assumes that it doesn't have a trend. Against H1 the alternative hypothesis assumes that there is a trend. (Panda & Sahu, 2019b). S- statistics are used when the number of data values is less than 10 while Z- statistics are for data when more or equal to 10.

This statistic S is complete as:

$$S = \sum_{j=1}^{n-1} \sum_{k=j+1}^{n} Sgn\left(X_k - X_j\right) \quad \dots\dots\dots\dots\dots \quad (4)$$

Where X_k and X_j were annual values in years k and j by respectively k> j, n is the number of data points, and sgn $(X_k - X_j)$ calculated as:

$$Sgn\left(X_k - X_j\right) = \begin{cases} 1, \; if \quad \left(X_k - X_j\right) > 0 \\ 0, \quad if\left(X_k - X_j\right) \; = 0 \\ -1, \; if\left(X_k - X_j\right) \; < 0 \end{cases} \quad \dots\dots\dots\dots \quad (5)$$

When several values are 10 or greater, S- statistics run roughly as normally distributed and the test is a Procedure with normal distribution with an average and variation as shown in equation (7):

$$E(S) = 0 \;\dots\dots\dots\dots \;(6)$$

$$VAR(s) = n(n-1)(2n+5) - \sum_{p=1}^{g} t_p\left(t_p - 1\right)\left(2t_p + 5\right) \;\dots\dots\dots.. \;(7)$$

g is the number of groups and t_p is the amount of values data in p^{th} a group. and VAR(s) and used to calculate the test statistic Z, and the standard distribution (Z -statistics) is calculated using the equation (7) below:

$$Z = \begin{cases} \frac{S-1}{\sqrt{var(s)}}, & if \quad S > 0 \\ 0, & if \quad S = 0 \\ \frac{S+1}{\sqrt{var(s)}}, & if \quad S < 0 \end{cases} \quad \dots \dots \dots . (7)$$

3.2.3 To examine the anomalous rainfall-related floods over the area

The study used the Rainfall Anomaly Index Analysis of precipitation and long-term mean for the baseline period from 1981 to 2022.

3.2.3.1 Rainfall Anomaly Index Analysis (RAI)

RAI is a widely used anomaly to indicate trends and variability in seasonal and annual mean rainfall time series. RAI is calculated by taking the difference between rainfall and the long-term average for the baseline, and then dividing it using the standard deviation shown in equation (8) (Aryal *et al.*, 2022) (Omoj *et al.*, 2016).

$$RAI = \frac{X_i - \bar{X}}{S_x} \dots \dots \dots \dots \dots \dots . . (8)$$

Where X_i is average precipitation, $\bar{X}$ is the average of the series (season/annual), and the standard deviation from the average of the series represented by S_x. The RAI is a dimensionless pointer where negative values are they indicate dry conditions, while positive values wet conditions. The result from the rainfall anomaly index analysis will be compared with the previous floods recorded over the Sudd wetland. (https://floodlist.com/africa/)

3.3.1 Validation

Before the projection of the rainfall and temperature we validated three CMIP6 high-resolution was (CAMS-CSM1-0, BCC-CSM2-MR and MRI-ESM2-0) by CHIPRS V2.0 data from 1981 to 2014, The individual CMIP6 high-resolution was re-gridded to CHIPRS V2.0 0.05 resolution of latitude and longitude to uniform resolution of all CMIP6 models with CHIRPS V2.0 data. then used statistical metrics (CC, Bias, and RMSE) and selected the model simulated with CHIRPS data from three CMIP6 high resolution (1.1^0 X 1.1^0) and used for the project of the rainfall and temperature over the Sudd wetland in South Sudan, under three scenarios relative to the present period from 1981 to 2014.

The Bias mensuration of the CMIP6 values if it greater or smaller than CHRIPS V2.0 the best-performing is zero (0), and the positive value means the CMIP6 Model overestimation, while negative values mean the CMIP6 Model underestimation.

The Bias is computed using the equation 9 below:

$$B = \frac{1}{N}\sum_{K=1}^{N}(M_i - O_i) \quad \ldots\ldots\ldots\ldots\ldots (9)$$

Where: M is the model simulated and O_i is CHIPRS V2.0 data and N is the total number of CHIRPS V2.0 and the Model simulated evaluated

The Correlation Coefficient (CC) is used to describe both temporal similarities between the CHIRPS and model simulation and is given by equation (10)

$$CC = \frac{\sum_{k=1}^{n}(O_i - \bar{O}_I)(M_i - \bar{M}_I)}{\sqrt{\sum_{k=1}^{n}(O_i - \bar{O}_I)^2 \sum_{k=1}^{n}(M_i - \bar{M}_I)^2}} \ldots\ldots\ldots (10)$$

Where: n is the number of CHIRPS data for the rainfall.

The Correlation Coefficient defines a linear Correlation Coefficient relationship between CHIRPS and model simulation, a positive correlation is a value of +1, meaning the CHIRPS and model simulation moving in the same direction while a negative correlation is a value of -1, meaning the CHIRPS are and model simulation moving in a difference direction.

Root Mean Squared Error (RMSE) given by equation (11) is the difference between model output and CHIPRS output

$$RMSE = \sqrt{\frac{1}{N}\sum_{k=1}^{n}(M_i - \bar{O}_I)^2} \quad \ldots\ldots\ldots\ldots (11)$$

The RMSE was different between the CMIP6 Model's simulation and CHIRPS V2.0 the best value of RMSE was close to or equal to zero (0).

3.3.2 Projected Changes in Rainfall and Temperature over the Sudd Wetland

The study used the three high-resolution 1.1^0 x 1.1^0 global climate models (GCM) from CMIP6 data to have more simulations over longer periods. the annual mean and seasonal data of rainfall and temperature are used in this study to determine future change under three varied scenarios. The CMIP6 data for 30 years of historical data period 1981 to 2010, historical evaluations and future projections analyzed from the mid-century (MC) or near team i.e., from 2030 – 2059 And long team from 2070- 099 To characterize annual and seasonal variations in rainfall and temperature over The Sudd wetland in South Sudan. The future change in precipitation (mean Temperature) was calculated as the difference between historical precipitation (mean Temperature) from 1981 to 2010 and the near (long) term period 2030-2059 (2070-2099) in The Sudd wetland region.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.0 Introduction

The chapter provides in detail the results obtained in this study based on the methodologies to achieve the objectives outlined in section 1.4

4.1 Temporal and Spatial characteristics of precipitation and temperature on the Sudd Wetland

4.1.1 Climatology

The spatial-temporal variability in total annual precipitation and seasonal of 30 years (1981-2010) in The Sudd wetland area, long-term mean (climatology) between 500 to 700mm and Seasonal rainfall between 50 to 700 (figures 3,4,5 and 6). The highest annual rainfall value in the Northern of The Sudd wetland, was above 650mm, for long-term seasonal rainfall the highest value was from June to September (1981-2010) season north of The Sudd wetland, while the December to February season winter season (driest season) with light rains and has received less than 10 mm because the ITCZ lies outside South Sudan in northern Uganda. See Figure 3.

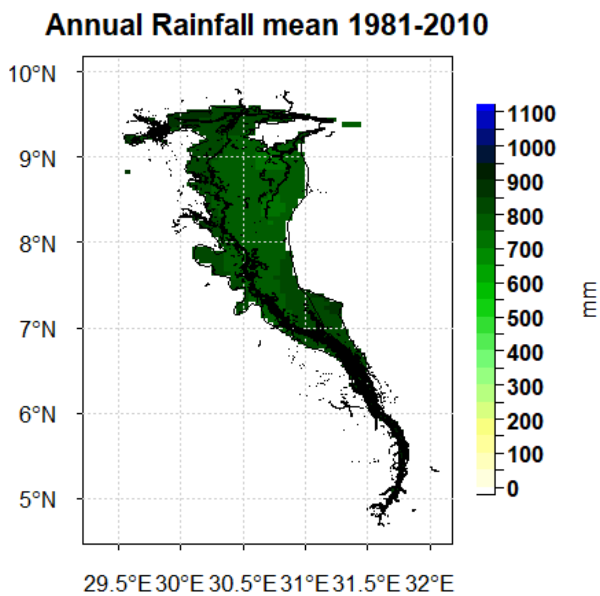


Figure 3: Spatial Mean Annual and Rainfall (1981-2010) CHIRPS-v2 rainfall (mm) for The Sudd wetland region

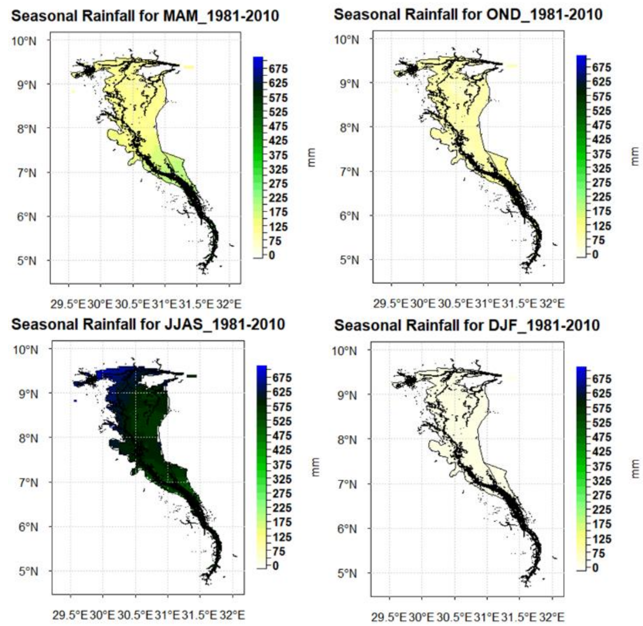


Figure 4:Spatial total Seasonal Rainfall (1981-2010) CHIRPS-v2 rainfall (mm) for The Sudd wetland region

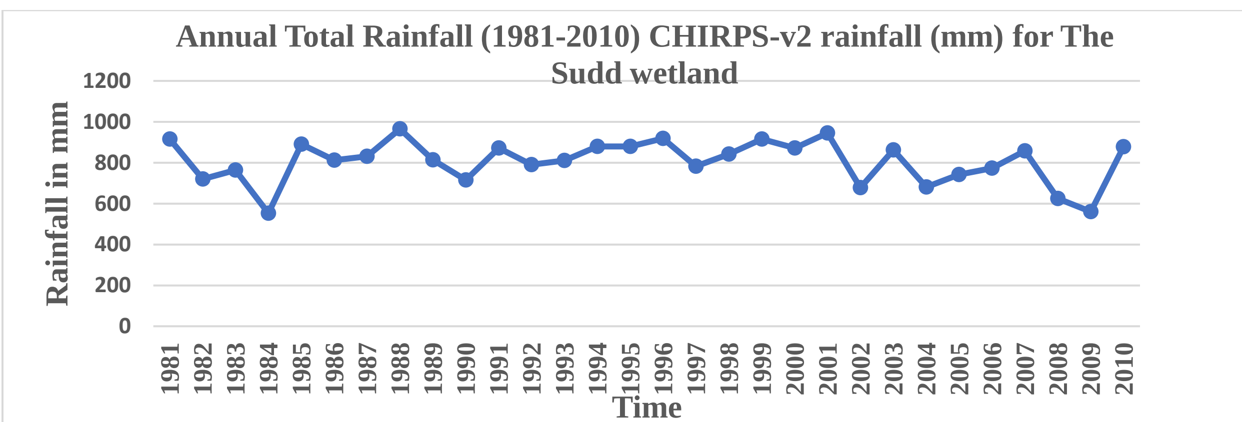


Figure 5: Annual total Rainfall (1981-2010)

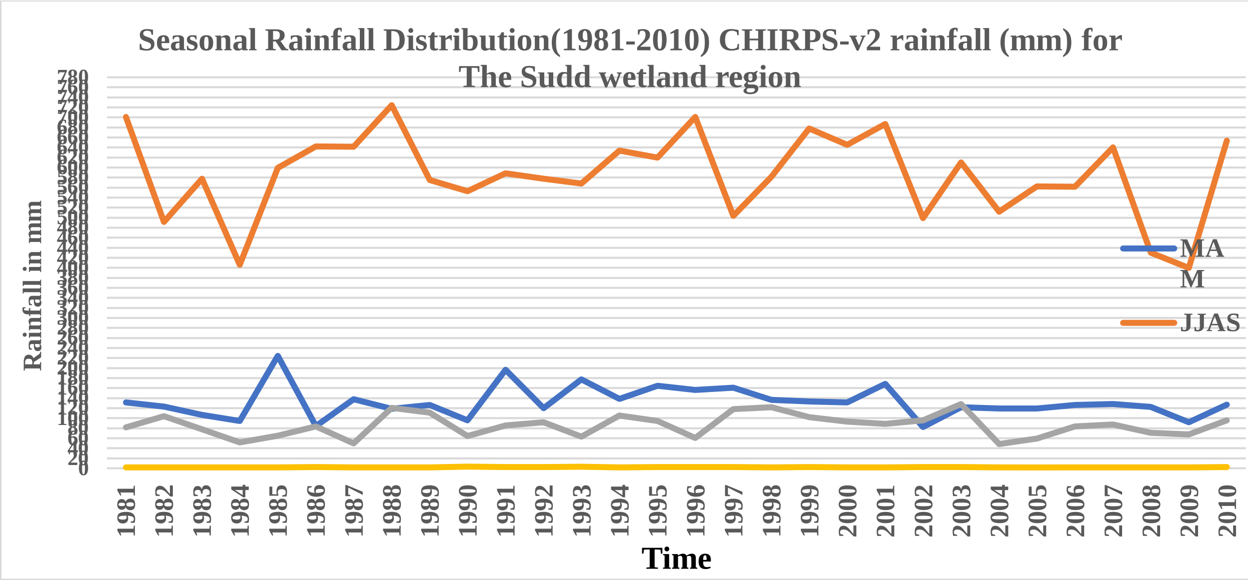


Figure 6: Seasonal Total Rainfall Distribution over The Sudd Wetland

The total annual monthly rainfall distribution for 30 years (1981-2010) over The Sudd Wetland showed varied spatial-temporal The Sudd Wetland region experienced a significantly increasing Rainfall in the month of August more than 150 mm followed by the months of July, September, June, May, October, April, March and November. See Figures 7 & 8.

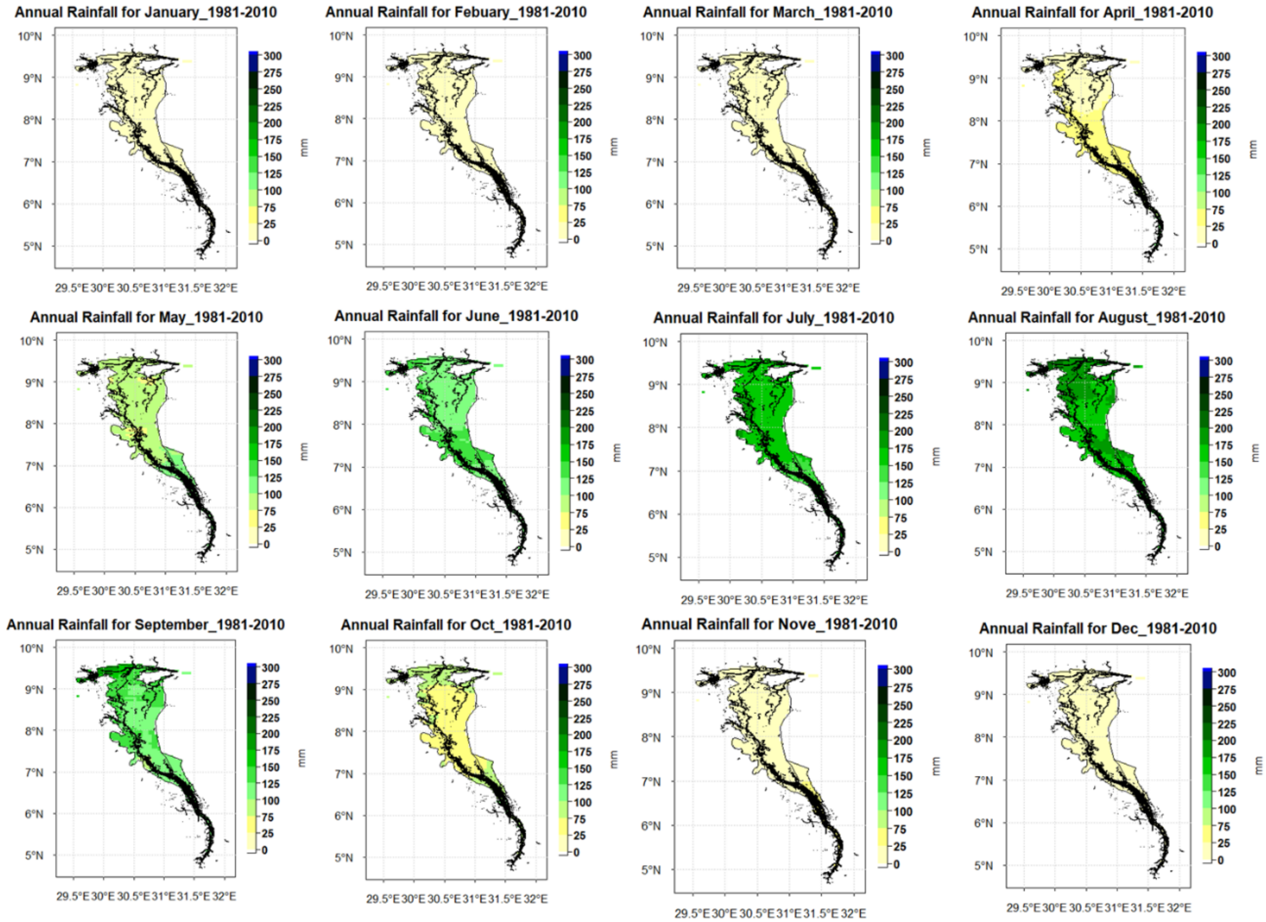


Figure 7: Spatial mean annual Monthly Rainfall (mm)over The Sudd wetland

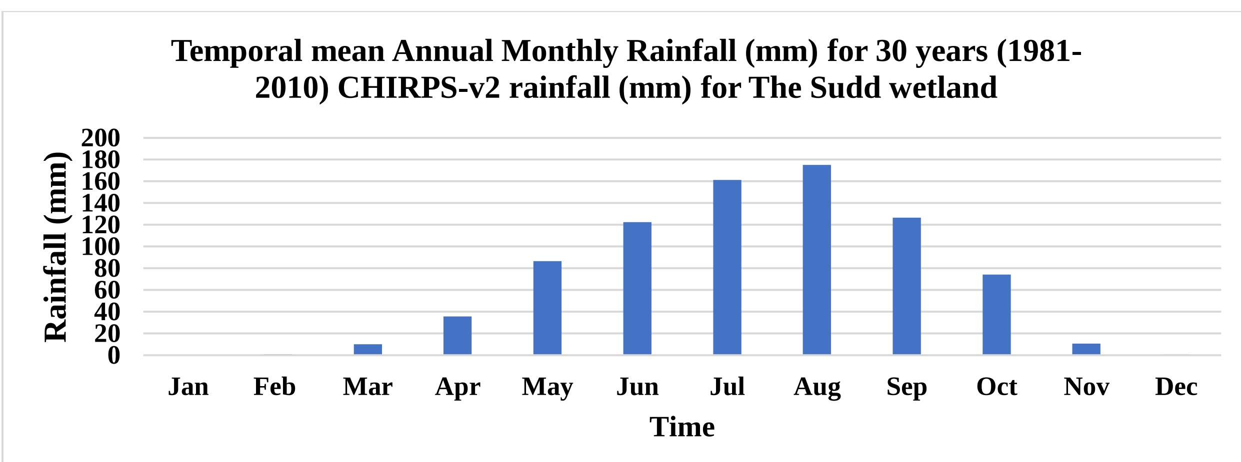


Figure 8: Temporal Total Annual Monthly Rainfall (mm) for 30 years (1981-2010)

The spatial-temporal variability in annual and seasonal mean Temperature of the last 30 years 1981-2010 in The Sudd wetland area, the Annual mean temperature between 27.5 to 29 shown in Figures 9 and 11, the March to May was the wormer Season followed by December to February season, October to December and the colder season was June to September. See Figures 10 and 12.

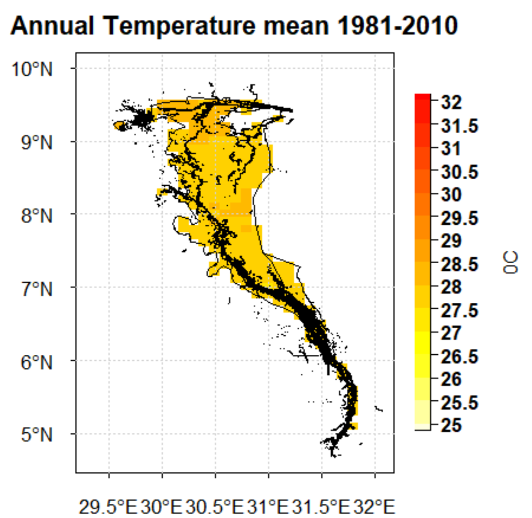


Figure 9: Annual Temperature Mean over The Sudd Wetland

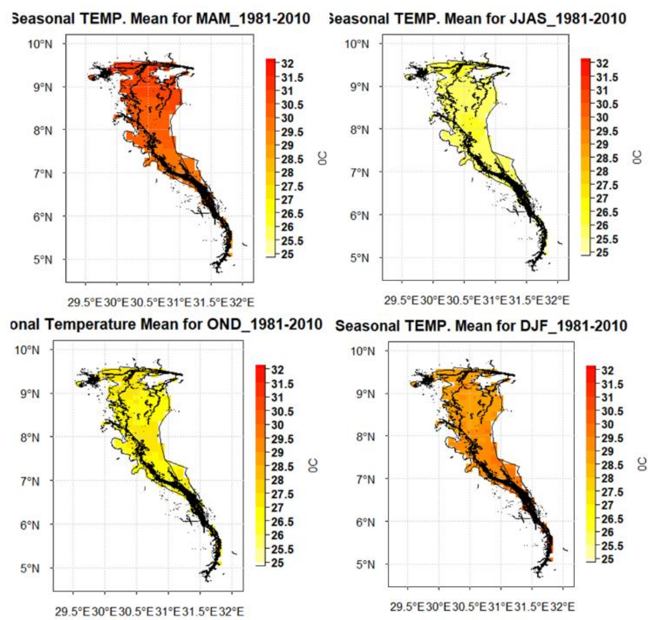


Figure 10: Seasonal Temperature Mean over The Sudd Wetland

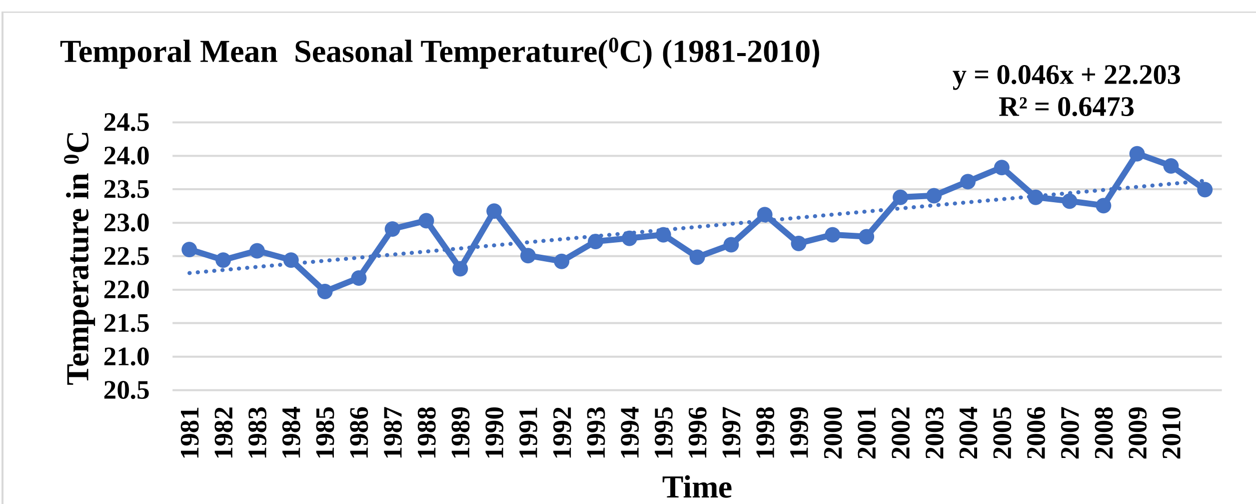


Figure 11: Annual Mean Temperature over The Sudd Wetland

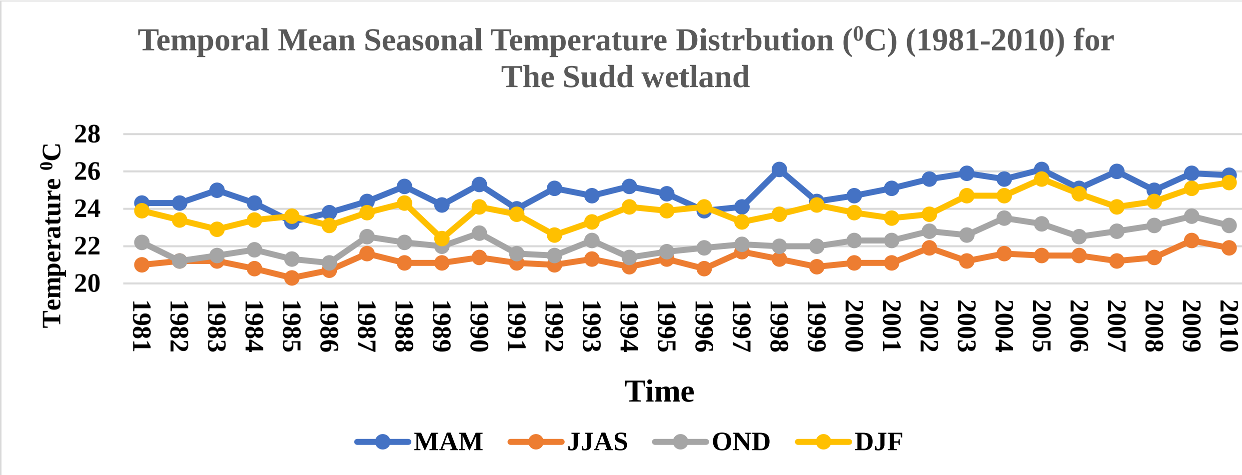


Figure 12: Seasonal Temperature Distribution over The Sudd Wetland

The annual mean monthly Temperature distribution for climatology (1981-2010) showed varied spatial-temporal for The Sudd wetland region experienced significantly increasing mean Temperature in the month of March followed by a month of April, February, January, May and colder months was July and August. See Figures 13 & 14.

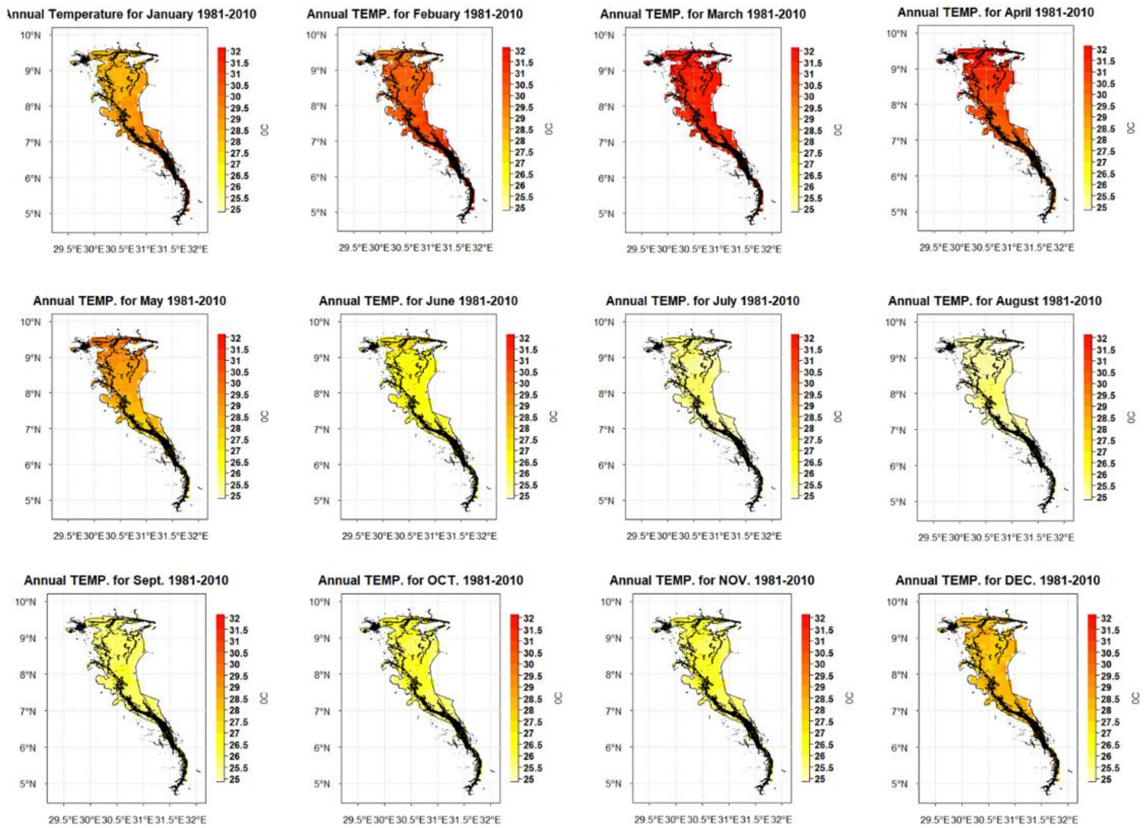


Figure 13:Spatial Mean annual monthly Temperature (0C) for 30 years (1981-2010)

Temporal Mean annual monthly Temperature (^{0}C) for 30 years (1981-2010) for The Sudd wetland

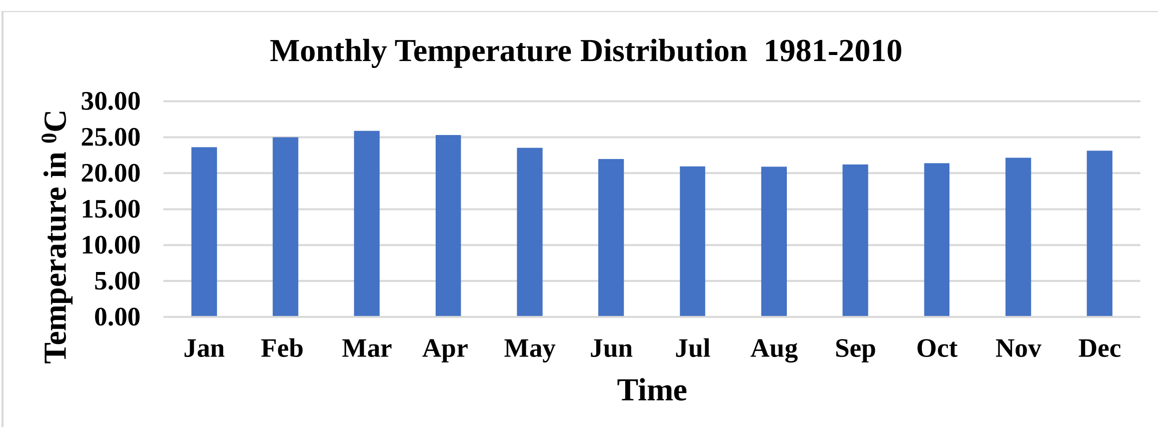


Figure 14: Temporal Temperature (0C) for 30 years (1981-2010)

4.1.2 The Coefficient of Variation (CV)

The Coefficient of Variation (%) of annual mean rainfall and Temperature (1981-2022) in The Sudd wetland region. between 8^0N and 9^0N moderate variability of 20 to 25 % was recorded in The Sudd wetland for annual Rainfall while for long-term Temperature was less than 10% for all the Sudd wetland areas. See Figure (15&16).

The Coefficient of Variation (%) of seasonal rainfall and temperature from 1981 to 2022 all had lower variability in The Sudd wetland except the Coefficient of Variation rainfall for the March to May season had moderate variability between 20% and 30%. See Figure (15&16)

The Coefficient of Variation (%) of monthly rainfall and temperature from 1981to 2022 in The Sudd wetland area, the Coefficient of Variation of April rainfall from 1981 to 2022 was the highest variability recorded in The Sudd Wetland followed by November, March and May while the Moderate variability the Coefficient of Variation (%) of monthly rainfall was June, July, August, September and October than December, January and February were do not have rainfall. See figure (17) while the coefficient of Variation (%) of monthly temperature from 1981 to 2022 all are lower variability recorded in The Sudd wetland close to zero or less than 20%. See Figure (18).

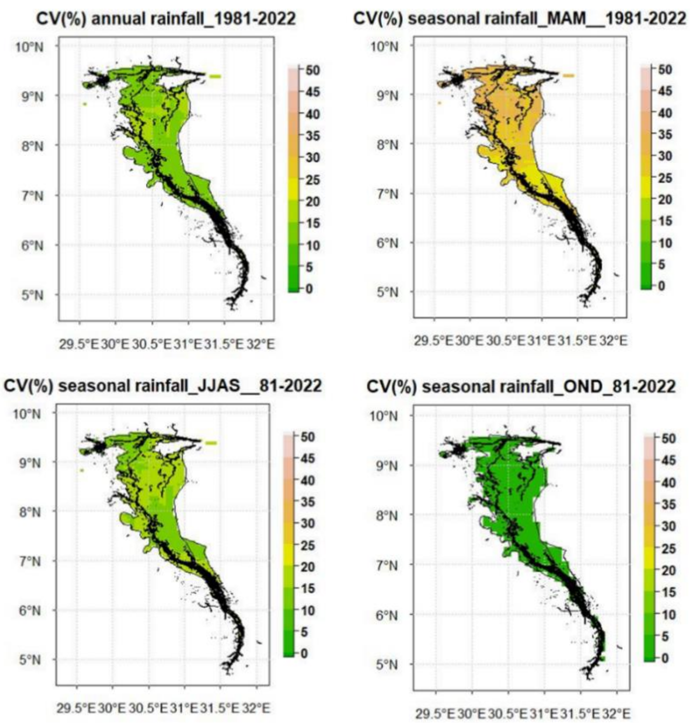


Figure 15: Coefficient of Variation (%) of annual and seasonal mean precipitation

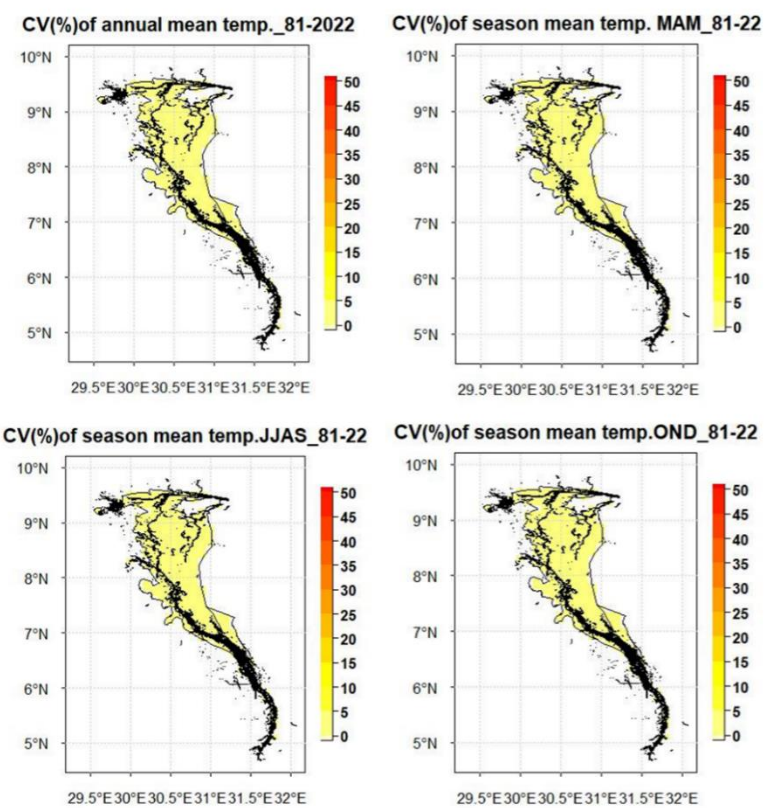


Figure 16: Coefficient of Variation (%) of annual and seasonal mean Temperature

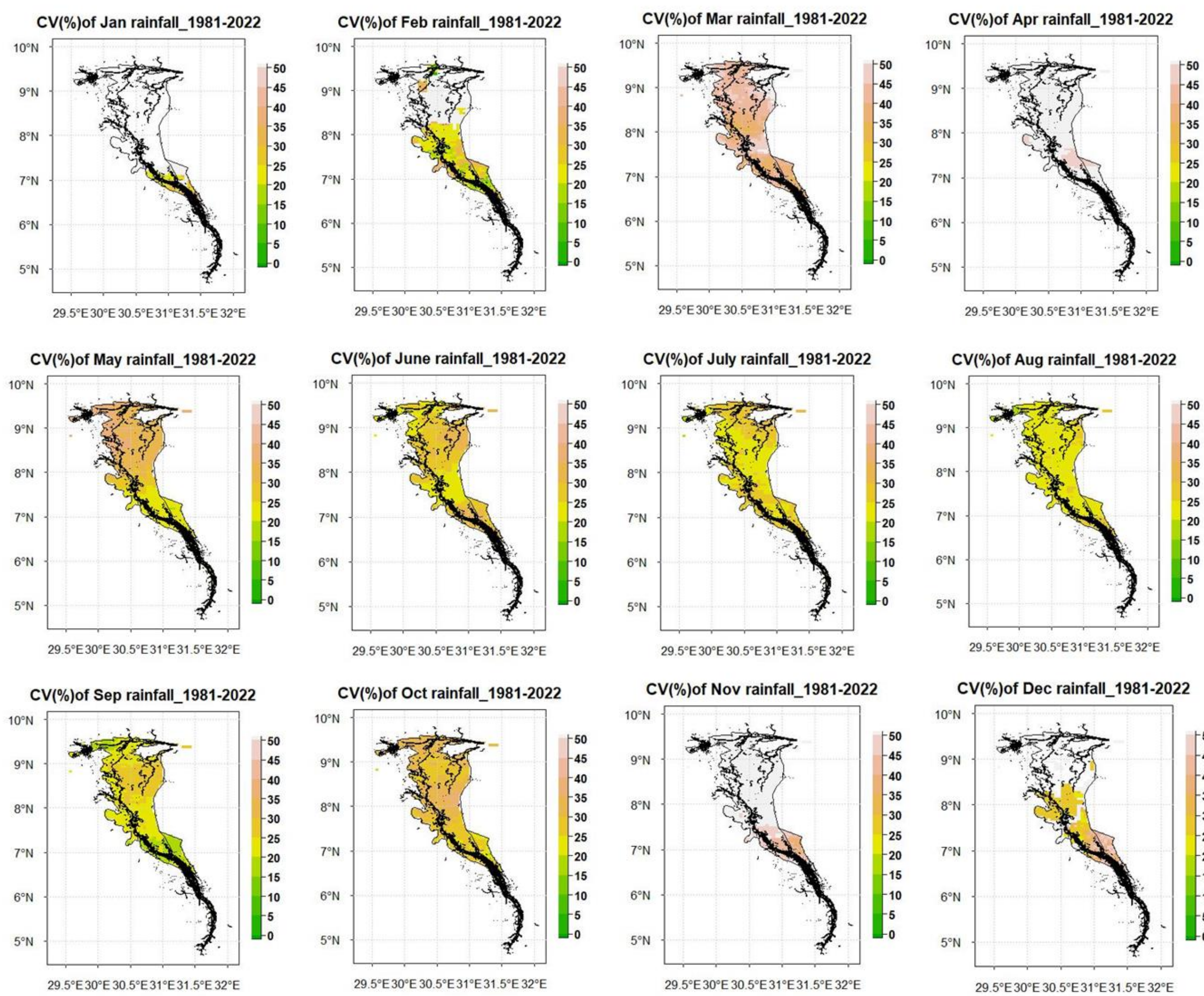


Figure 17: The Coefficient of Variation (%) of monthly mean Rainfall (1981-2022)

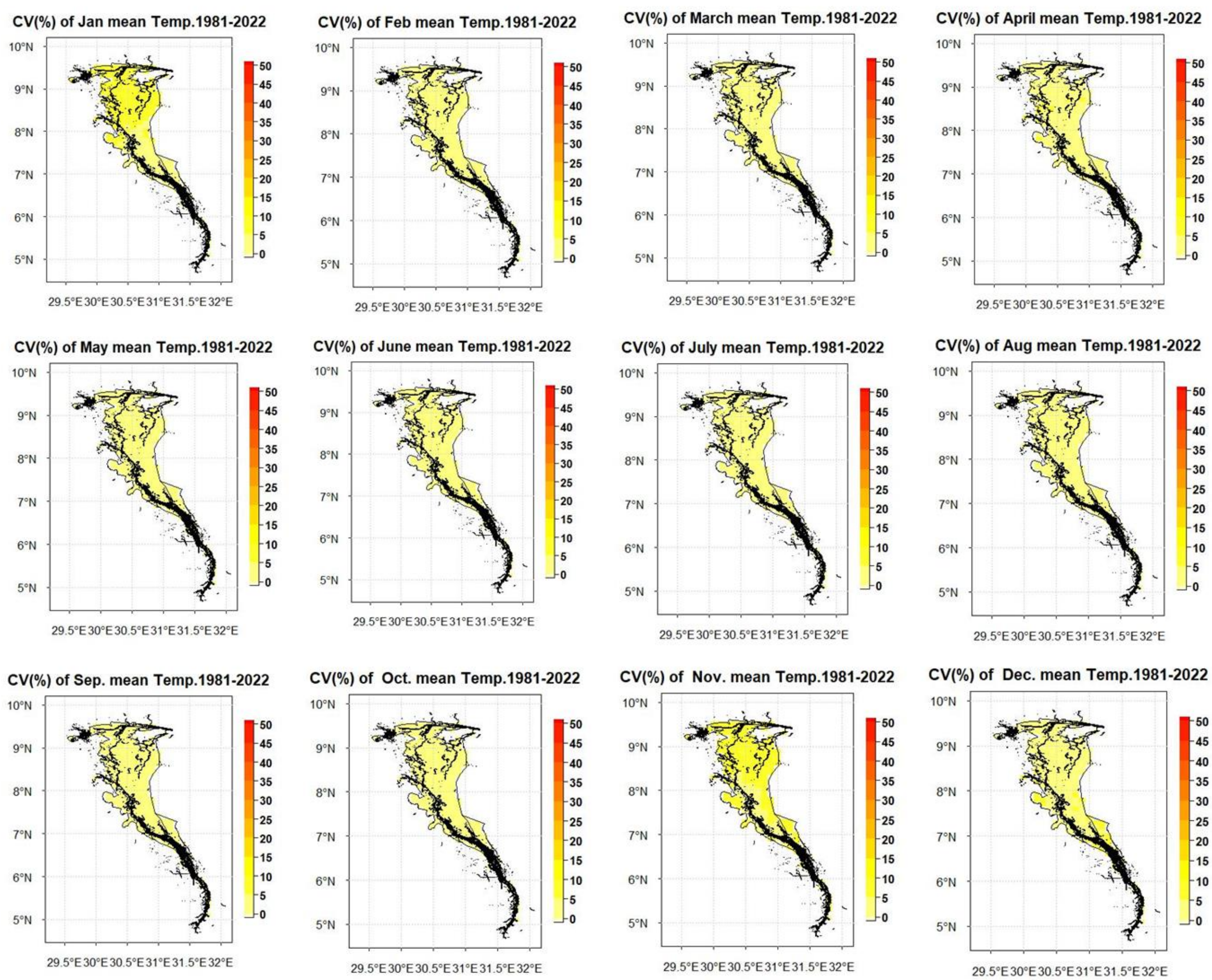


Figure 18: The Coefficient of Variation (%) of monthly mean Temperature (1981-2022)

4.1.3 Times Series Analysis

The slightly increasing trends of average rainfall (annual and seasonal) in the Sudd wetland except the December, January and February seasons show decreasing trends See figures (19, 20, 21,22 and 23), while the increasing trends analyzed in all annual and seasonal Temperature over The Sudd wetland region. See figures (24, 25, 26, 27 and 28).

The Mann-Kendall Times series analysis Showed annual and Seasonal total precipitation over The Sudd wetland region. when the p-value was smaller than 0.05 ($p<0.05$) the Times series is significant while the p-value was greater than 0.05 ($p>0.05$) the Trend is considered insignificant. All the Annual and Seasonal total Rainfall and mean temperature have positive values.

All p-values for annual and seasonal total rainfall showed a p-value greater than 0.05 ($p> 0.05$) the Times series is considered insignificant, See Table 1. While all annual and seasonal mean temperatures showed a significant p-value the time series analysis had a positive value and less than 0.05($p<0.05$). See Table 2.

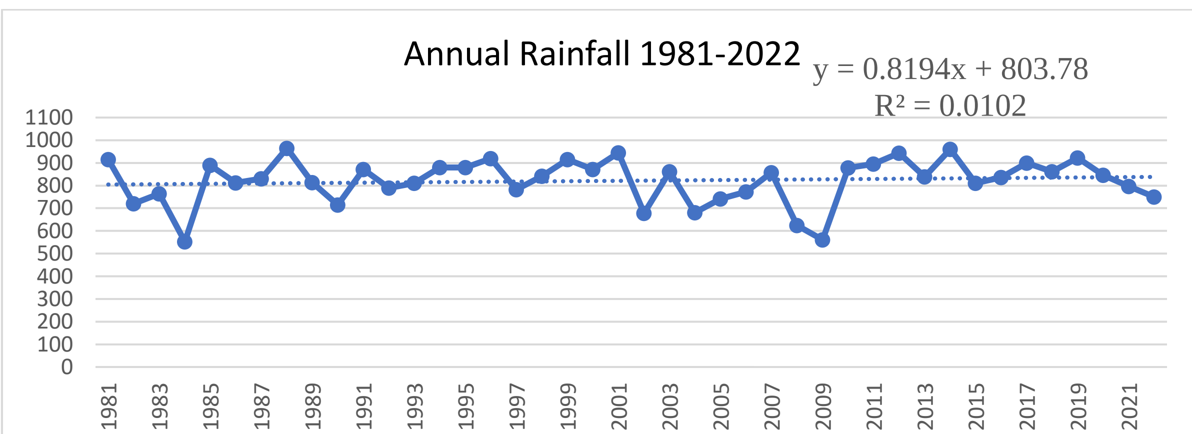


Figure 19: Annual Rainfall 1981-2022

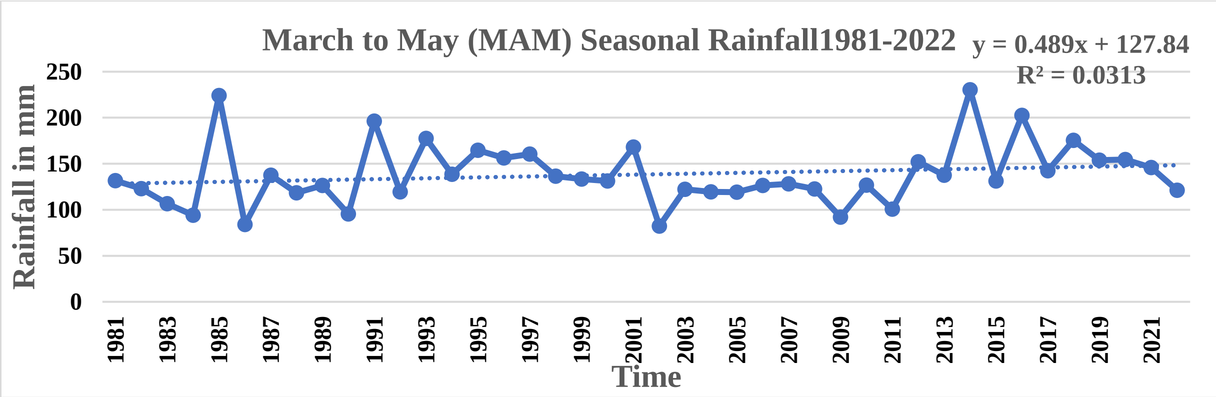


Figure 20: March to May (MAM) Seasonal Rainfall 1981-2022

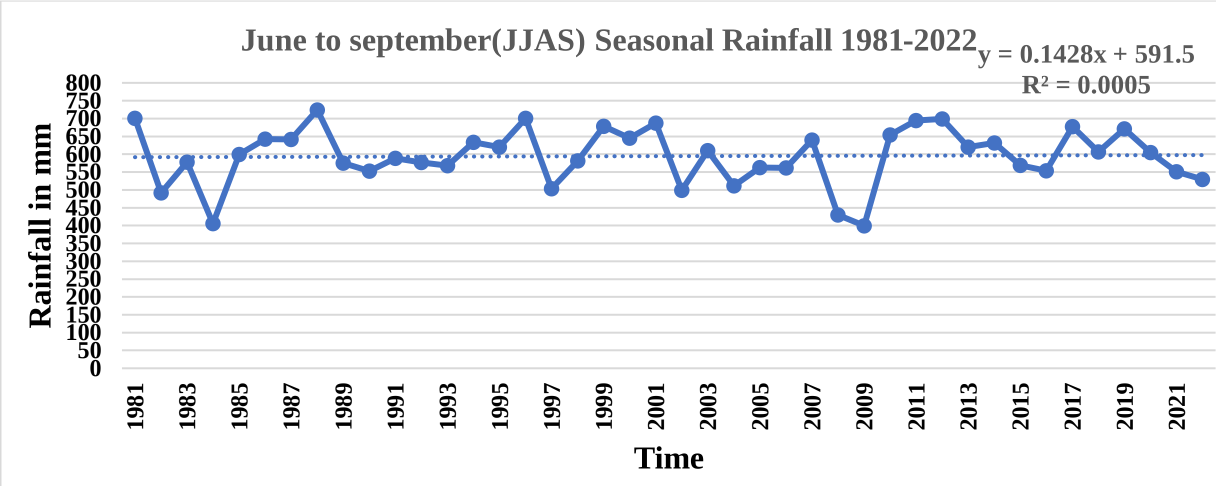


Figure 21: June to September (JJAS) Seasonal Rainfall 1981-2022

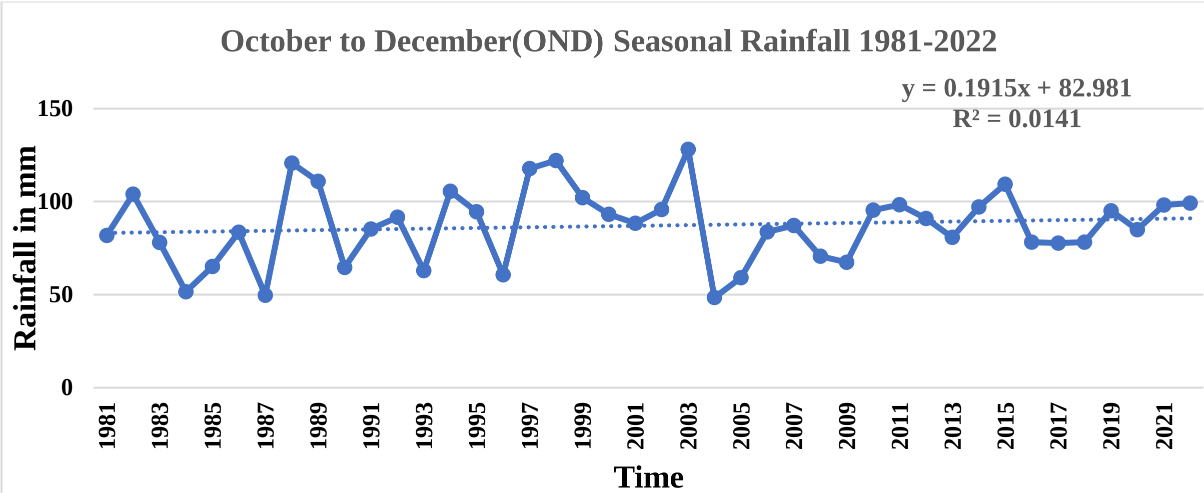


Figure 22: October to December (OND) Seasonal Rainfall 1981-2022

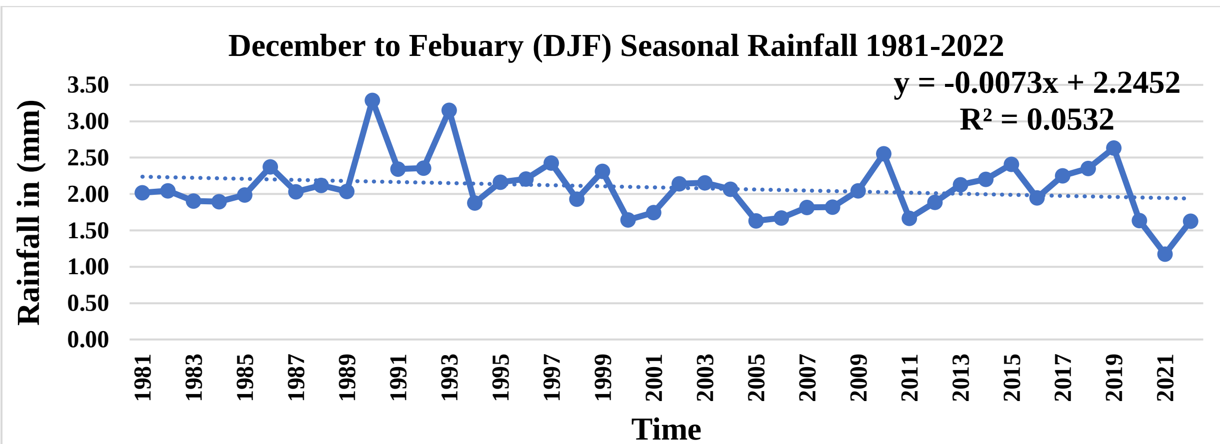


Figure 23: December to February (DJF) Seasonal Rainfall 1981-2022

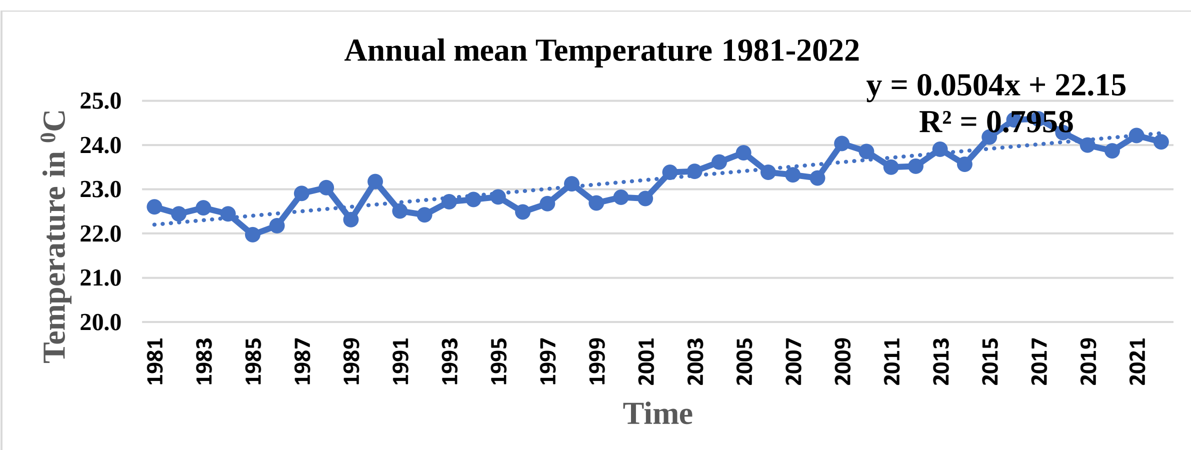


Figure 24: Annual mean Temperature 1981-2022

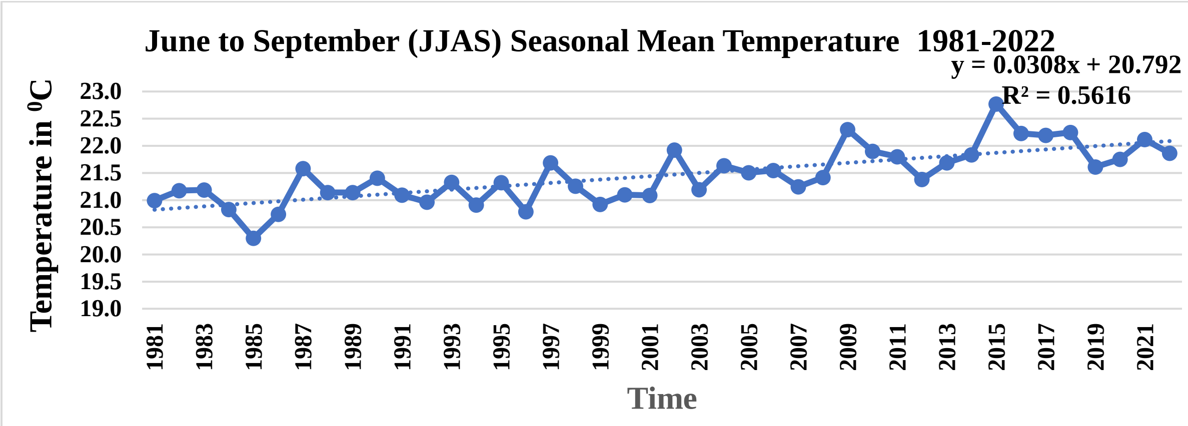


Figure 25: June to September (JJAS) Seasonal mean Temperature 1981-2022

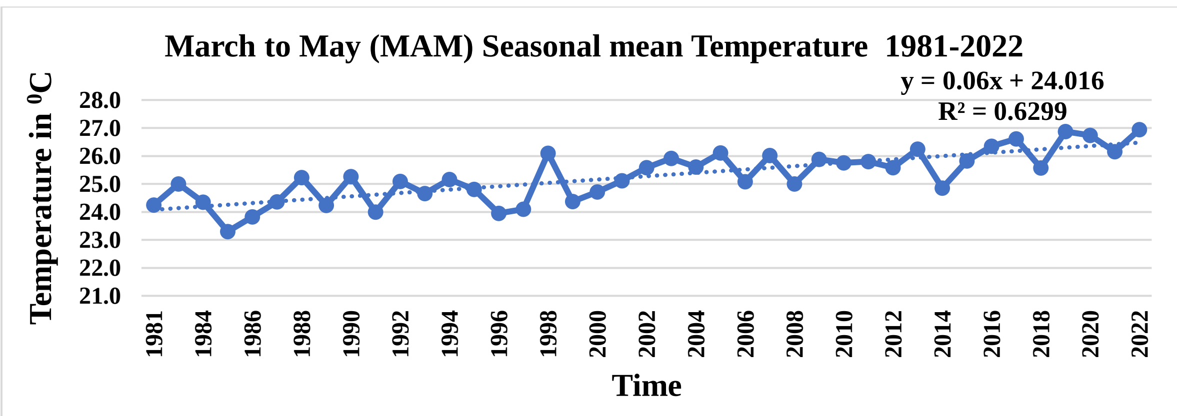


Figure 26: March to May (MAM) Seasonal mean Temperature 1981-2022

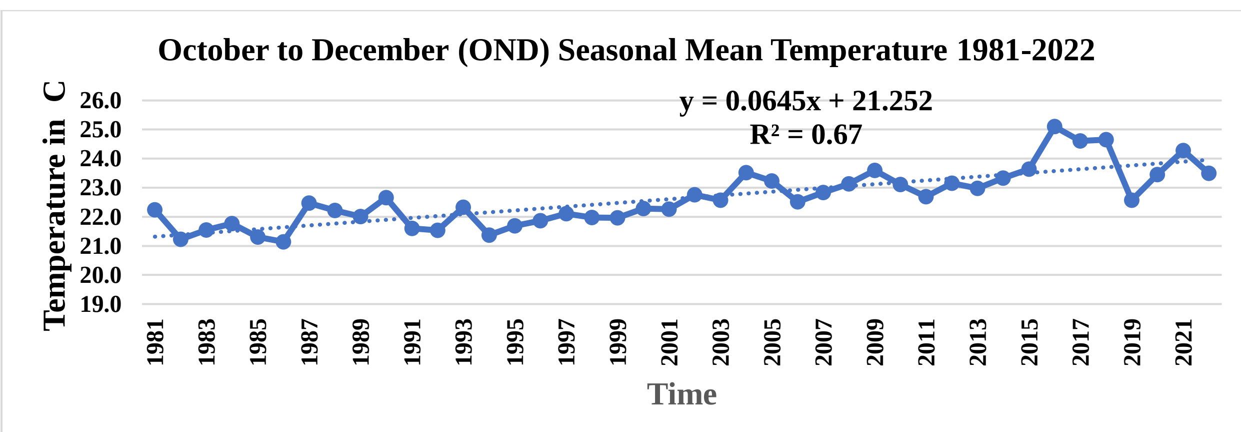


Figure 27: October to December (OND) Seasonal mean Temperature 1981-2022

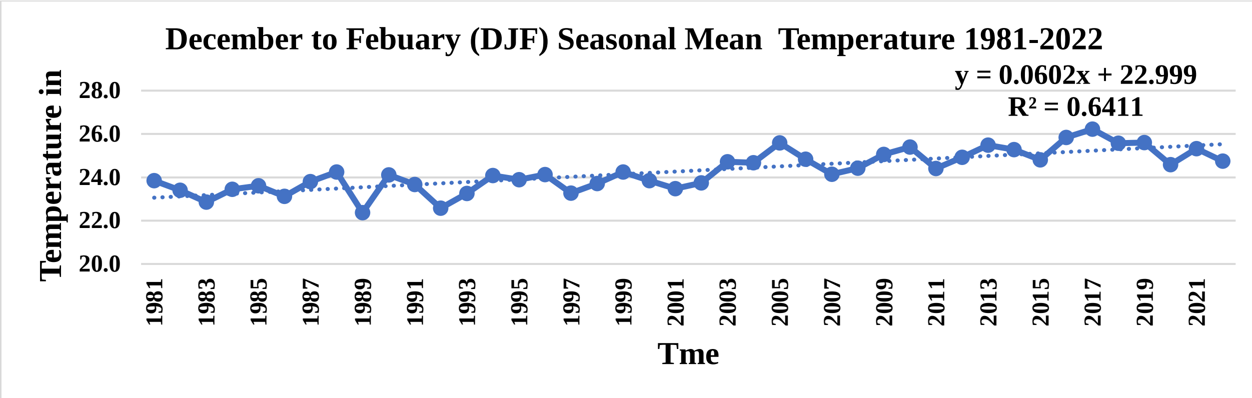


Figure 28: December to February (DJF) Seasonal mean Temperature 1981-2022

Table 1: Mann-Kendall analysis of minor Annual and Seasonal mean precipitation over The Sudd wetland region

	Trend	**P**	**Kendall's Tau**	**S**	**V(s)**	**S slope(mm/annual)**
Annual	Insignificant	0.40	0.093	76	7926	1.049
MAM	Insignificant	0.189	0.144	118	7926	0.513
JJAS	Insignificant	0.623	0.067	12	500	1.285
OND	Insignificant	0.459	0.094	22	806	-0.227
DJF	Insignificant	0.972	- 0.009	-2		0.008

Table 2: Mann-Kendall analysis of minor Annual and Seasonal mean temperature over The Sudd wetland region

	Trend	**P**	**Kendall's Tau**	**S**	**V(s)**	**S slope(mm/annual)**
Annual	Significant	<0.0001	0.723	589	7896	0.053
MAM	Significant	<0.0001	0.607	142	806	0.174
JJAS	Significant	<0.0001	0.567	102	500	0.128
OND	Significant	<0.0001	0.718	168	806	0.208
DJF	Significant	<0.0001	0.692	162	806	0.172

4.2. Examining the anomalous rainfall-related floods on the Sudd Wetland

4.2.1 Anomalies

Standardized anomalies Spatial-Temporal for annual precipitation in The Sudd wetland refers to the magnitude of deviation from long-term annual precipitation (1981-2022). The red colour (Negative values(-ve)) represents below-normal precipitation associated with drought conditions while the blue colour (positive values (+ve)) represents above-normal precipitation associated with flood conditions. The flood years were 1981, 1985, 1986, 1987, 1988, 1991, 1993, 1994, 1995, 1996, 1998, 1999, 2000, 2001, 2003, 2007, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019 and 2020 almost every year we have a flood on The Sudd wetland area with an increasing in the frequencies and intensities of flood over the Sudd wetland experienced a significantly increasing trend indicated on figure 27 & 28. South Sudan has witnessed floods in these years and loss of lives, especially the States of Jonglei and Unite and these states are the place of the Sudd Wetland.

See Figures 29& 30. In a 2014 report by United nation people passed away and lost property because of floods in those areas along The Sudd wetland in Jonglei State more than three thousand homes were destroyed in the northern part of the area called Twic East County reported by Sudan Tribune, (https://floodlist.com/africa/10-killed-south-sudan-floods-october-2014)

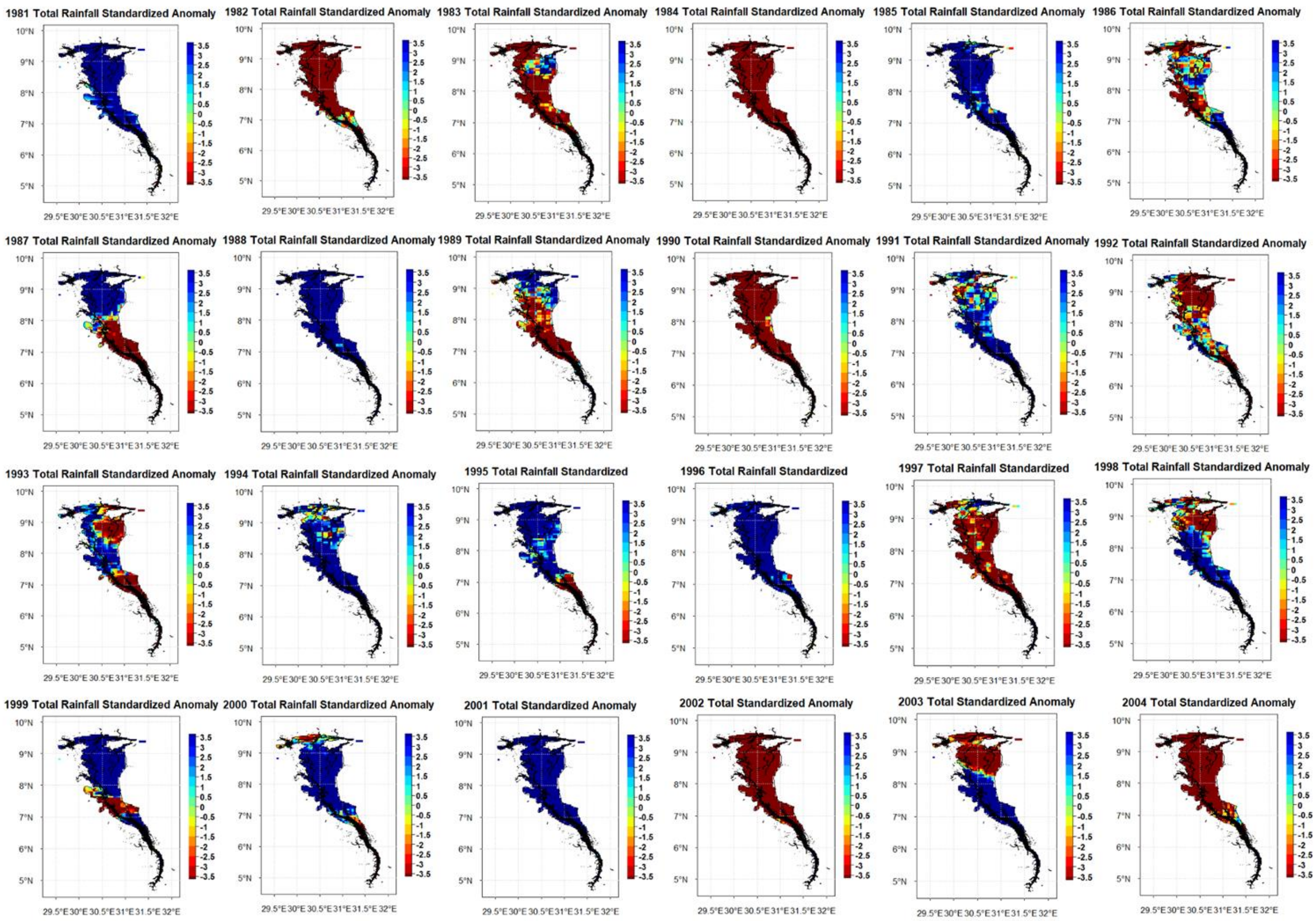


Figure 29: Standardized anomalies Spatial for annual rainfall in The Sudd wetland area (1981-2004)

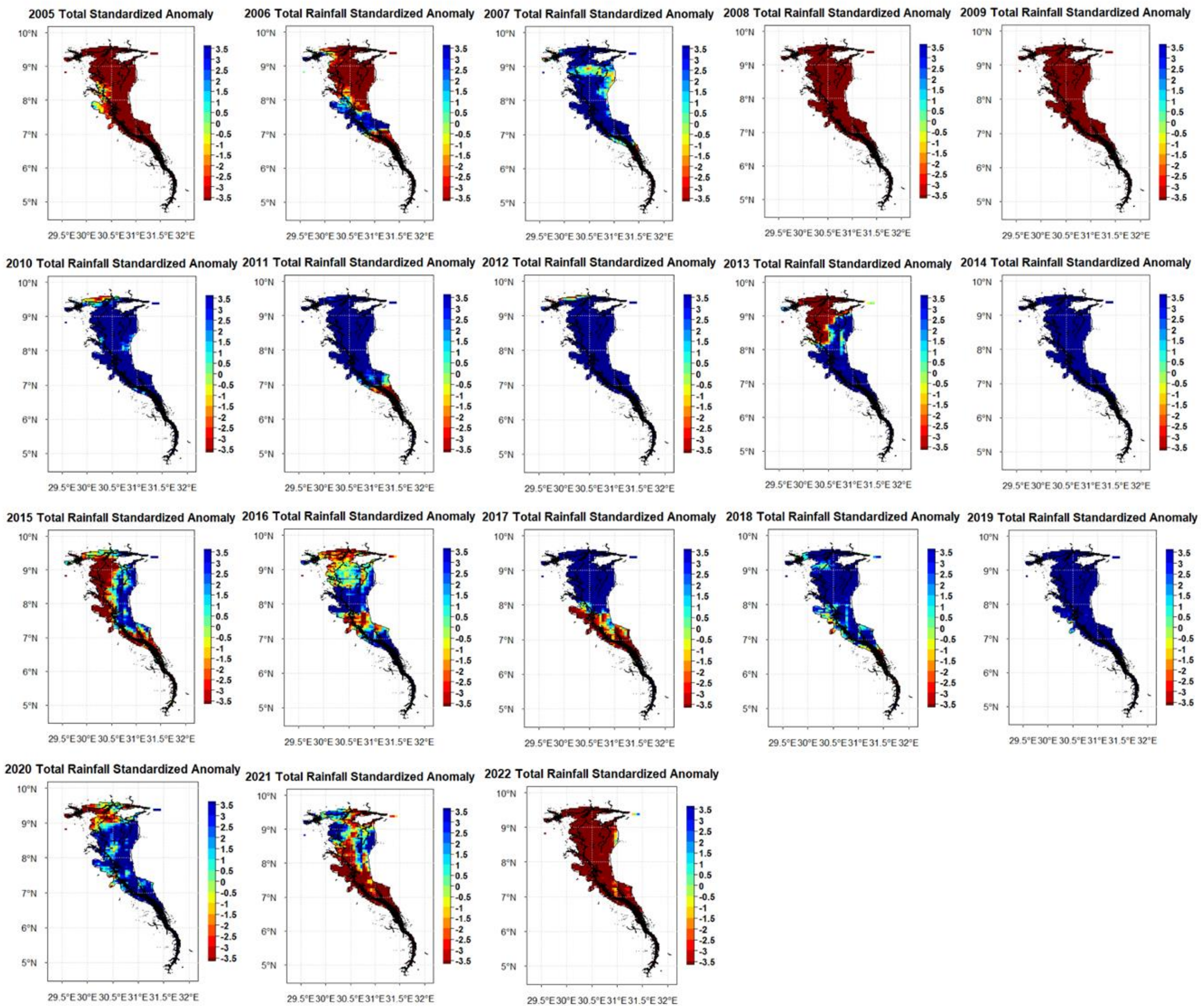


Figure 30: Standardized anomalies Spatial for annual rainfall in The Sudd wetland area (2005-2022)

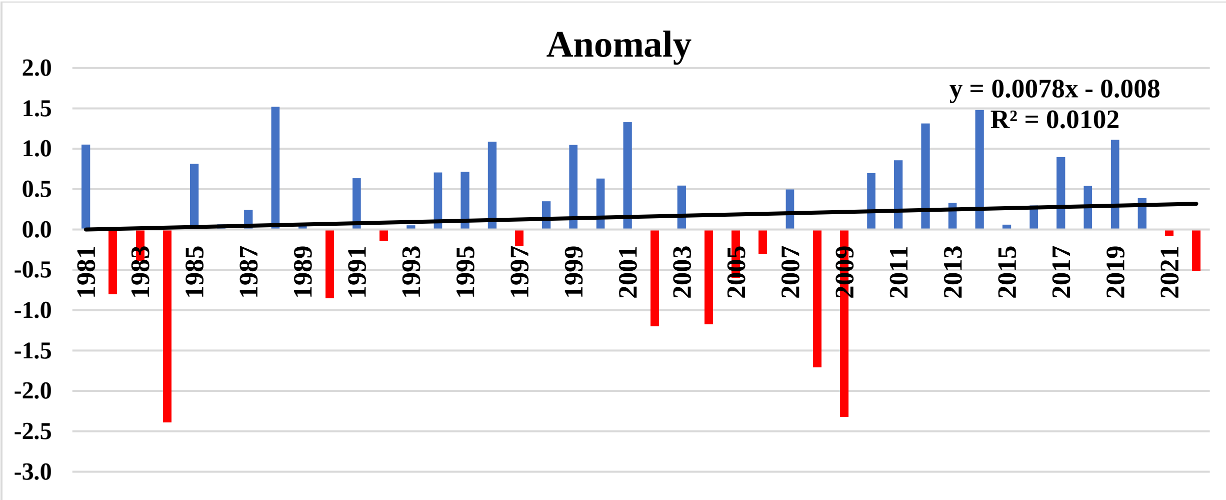


Figure 31: Standardized anomalies Temporal for annual rainfall over The Sudd wetland (1981-2022)

Floods in Northern of The Sudd wetland, in Upper Nile State on 2011

Figure 32: Floods in Upper Nile 2011, photo: UN photo Flickr Source (https://floodlist.com/africa/south-sudan-floods)

Floods in The Sudd wetland area, in Jonglei State, South Sudan on 2021

Figure 33: Floods in Fangak, Jonglei State, South Sudan on October 2021 photo: WFO South Sudan, Source (https://floodlist.com/africa/south-sudan-floods)

4.3. Validation performance of The CMIP6 model and projected Temperature and Rainfall over The Sudd wetland

The section below presents the performance and validation of the CMIP6 model and projected of Temperature and Rainfall over The Sudd wetland region.

4.3.1 Validation of the performance of CMIP6 Models over The Sudd wetland

Three methods were used to validate the CMIP6 models in high simulation 1.1^0 x 1.1^0 in simulating the CHIRPS v2.0 reference data periods from 1981 to 2014. The methods included the Correlation Coefficient, Bias and RMSE. The results of each metric are shown in Figures 34, 35 and 36, Tables 3, 4, and 5.

.

Figure 34 shows the correlation coefficient for three models during the MAM, JJAS, and OND seasons. According to Figure 34 and Table 3, the result revealed that all three models had strong correlation coefficients (0.5 - 0.8) and the best model was MRI-ESM2-0, for the June to September season the strong relation to CHIRPS was model BCC-CSM2-MR, the lest last season October to September the CAMS-CSM1-0.
The BCC-CSM2-MR model was more simulating the CHIRPS v2.0 relative to the other two models. It had a high positive correlation during the main seasons June, July, August and September (JJAS). It's the second model simulating CHIRPS v2.0 in the March to May (MAM) season over the Sudd Wetland.

Figure 35 shows The Bias for three models during the MAM, JJAS. and OND season. The result is that all three models overestimated, the best performance was BCC-CSM2-MR because closer to zero according to Figure 35 and Table 4.

Figure 36 shows The RMSE for three models during the MAM, JJAS and OND seasons. The result is that all three models closely simulated CHIRPS v2.0, the best skill was BCC-CSM2-MR because closer to CHIRPS v2.0 data according to Figure 36 and Table 5

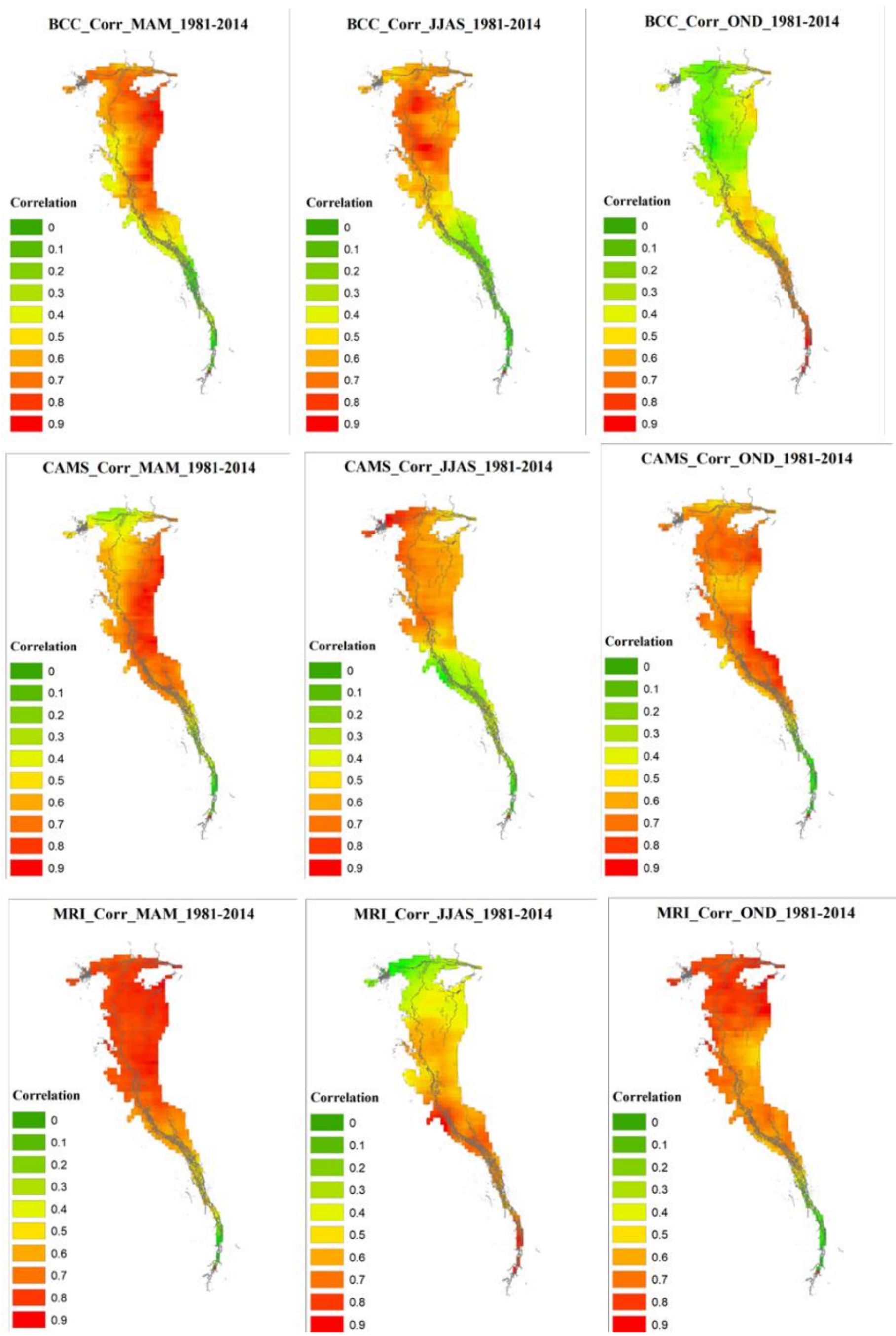


Figure 34: Correlation of three models

Table 3: Correlation of three models

	MAM	**JJAS**	**OND**
BCC-CSM2-MR	0.56	0.15	0.57
CAMS-CSM1-0	0.56	0.13	0.80
MRI-ESM2-0	0.71	0.07	0.61

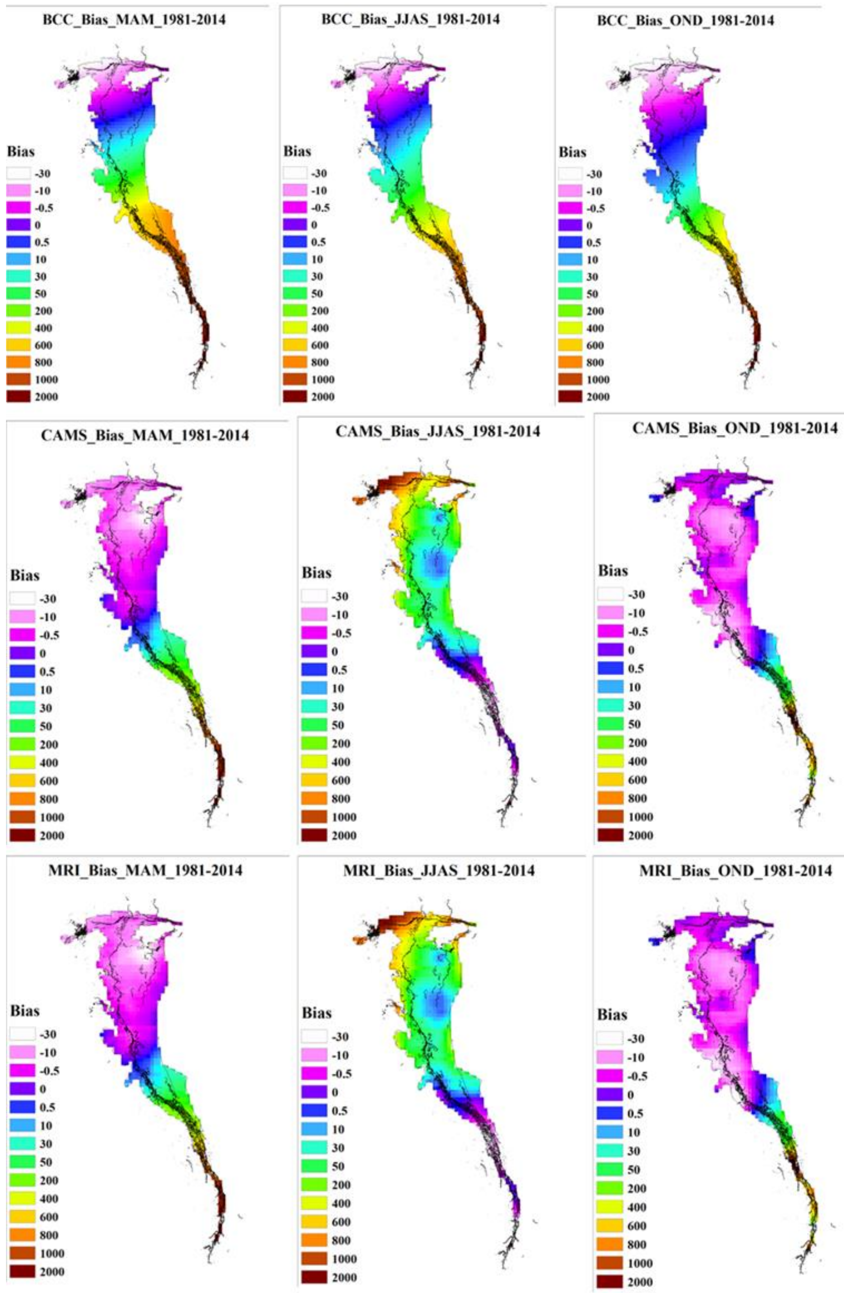


Figure 35: Bias of the three models

Table 4: Bias of the three models

	MAM	JJAS	OND
BCC-CSM2-MR	-5.5	-14.4	-3.4
CAMS-CSM1-0	-5.9	-14.7	-3.5
MRI-ESM2-0	-5.7	-14.6	-3.5

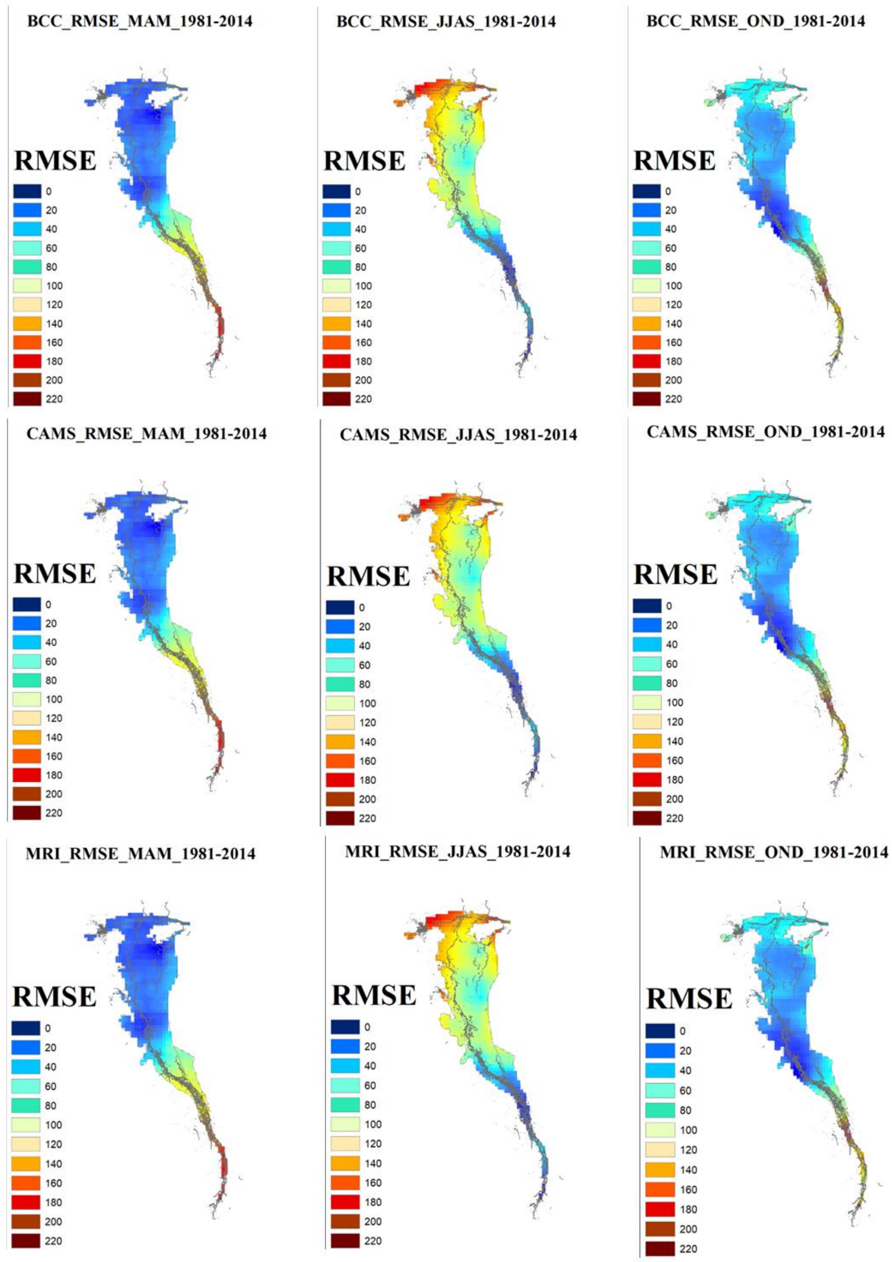


Figure 36: Root Mean Square Error of the three models

Table 5: Roots Mean Square Error means for three models

	MAM	JJAS	OND
BCC-CSM2-MR	07.2	15.1	5.4
CAMS-CSM1-0	07.4	15.4	5.5
MRI-ESM2-0	07.2	15.3	5.5

4.3.2 Determine the projected changes in temperature and rainfall on Sudd Wetland

The CMIP6 (BCC-CSM2-MR) projected a large and sustained increase in precipitation in the Annual and June to September Season for two terms 2030-2059 and 2070-2099 over The Sudd wetland (See figure 37) is projected to increase by 83(143),145(204) and 177(516) and the same time June to September season projected to increase by 75(0), 114(192) and 162(457) under all three scenarios SSP1-2.6, SSP2-4.5, and SSP5-8.5. respectively (See Figures 37, 39 and Table 6).

The spatial-temporal of the future changes in annual mean temperature and seasons mean temperature MAM, JJAS and OND seasons under three SSPs scenarios during two terms 2030-2059 and far future 2070-2099 shown in Figure 40.

For near-term projection (2030-2059) the annual average temperature over the Sudd Wetland is projected by 1.24 ^{0}C, 1.16 ^{0}C and 1.20 ^{0}C under all three scenarios SSP1-2.6, SSP2-4.5 and SSP5-8.5. Seasonal mean temperature MAM, JJAS and OND are projected by 0.80 ^{0}C, 1.20 ^{0}C, and 1.50 ^{0}C under the same scenarios in the MAM season. 0.90 ^{0}C, 1.05 ^{0}C and 1.50 ^{0}C under three scenarios in JJAS season. For last season OND is projected 1.26 ^{0}C, 1.28 ^{0}C, and 1.54 ^{0}C. For the far future (2070-2099) the annual average temperature over the Sudd Wetland was 1.24 ^{0}C, 2.34 ^{0}C, and 3.20 ^{0}C under SSP1-2.6, SSP2-4.5, and SSP5-8.5respectively.

The distribution projected changes in the annual mean temperature in SSP5-85 shows the largest spatial variability. The seasonal mean temperature average (MAM, JJAS and OND) for the far future is projected by 0.892 ^{0}C, 2.00 ^{0}C, and 3.43 ^{0}C under three scenarios in MAM season. 0.93 ^{0}C, 1.80 ^{0}C and 3.24 ^{0}C under three scenarios in JJAS season. For last season OND is projected at 1.34 ^{0}C,2.23 ^{0}C, and 3.20 ^{0}C under the Shared Socioeconomic Pathways (SSP) three scenarios.

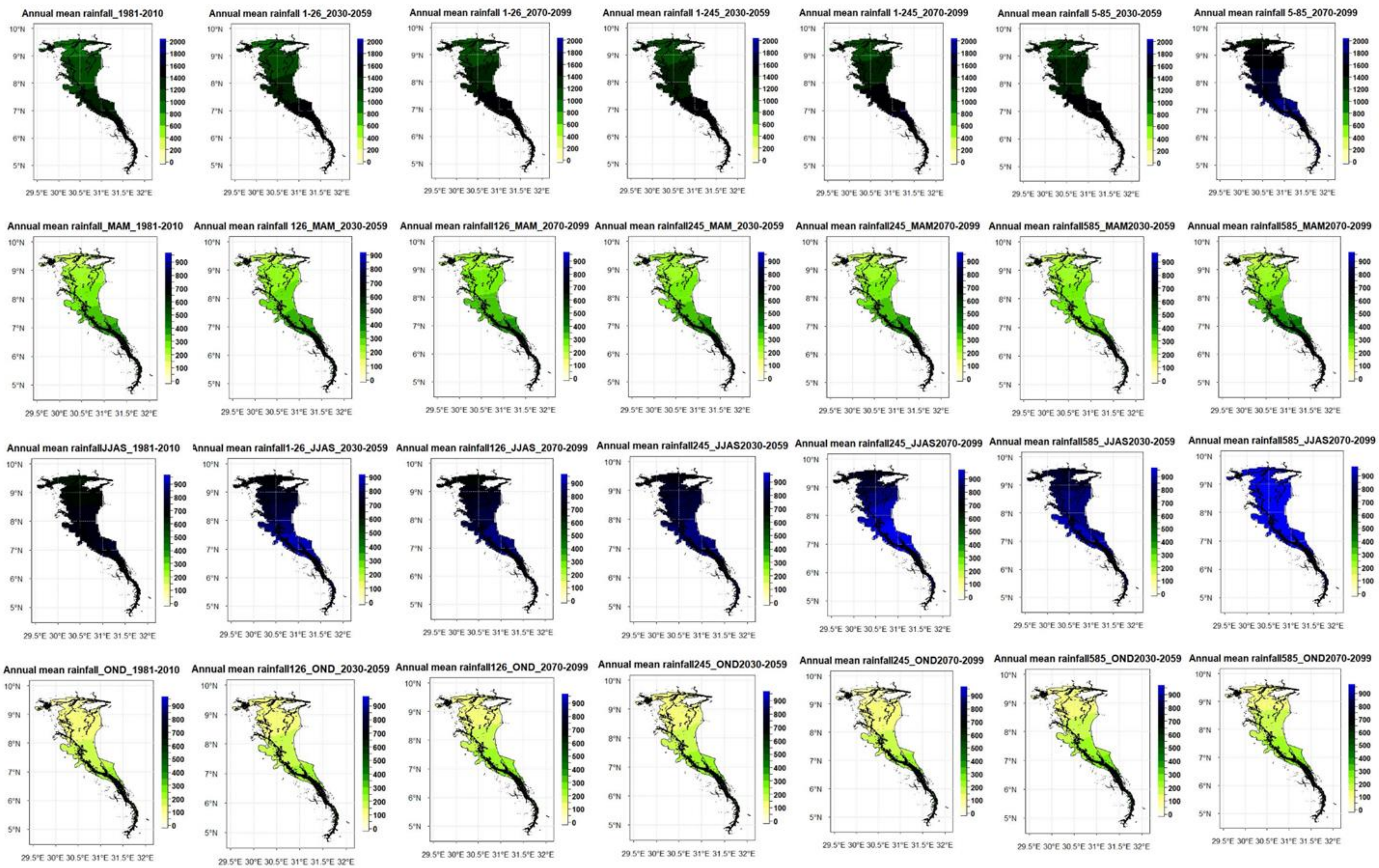


Figure 37: Annual and Seasonal mean Rainfall for the period 1981-2010 and two future times (2030-2059 and 20 070-2099)

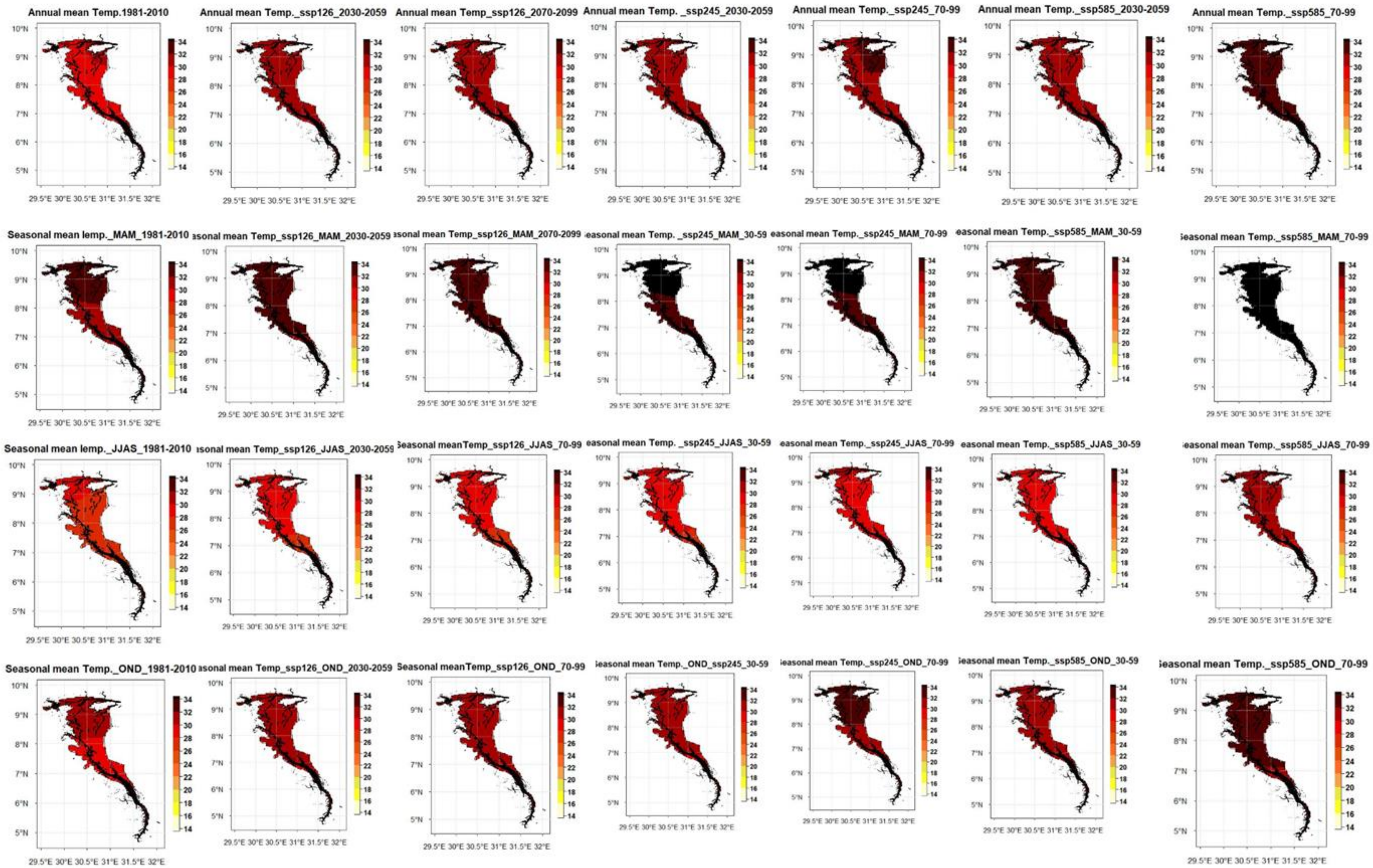
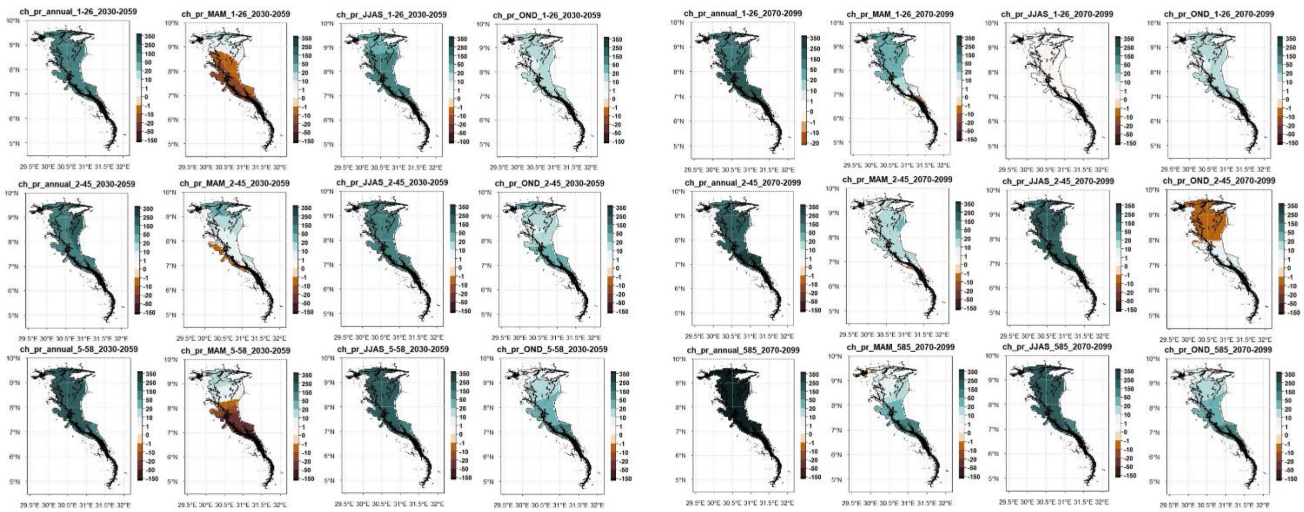


Figure 38: Annual and Seasonal mean Temperature for the period 1981-2010 and two future times (2030-2059 and 20 070-2099)



(a) Future change in precipitation (2030-2059) (b) Future change in precipitation (2070-2099)

Figure 39: Future change in Precipitation(mm) for two future times 2030-2059 and 2070-2099

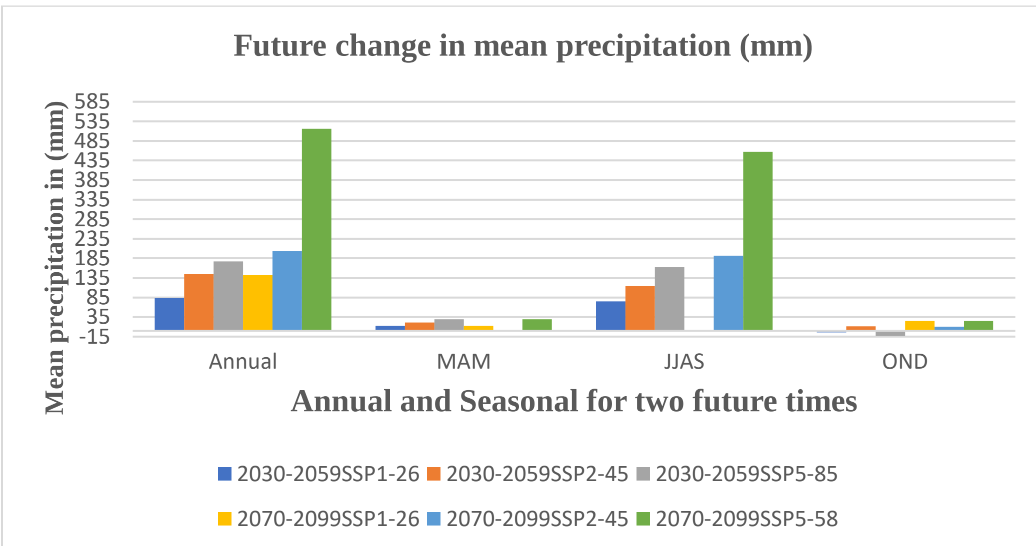
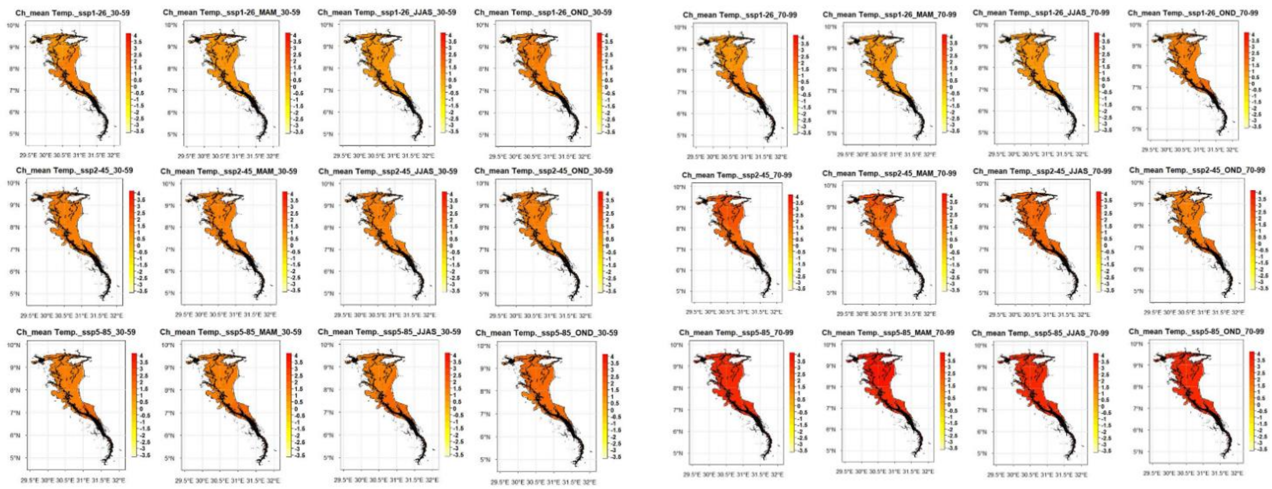


Table 6: Future change in mean precipitation (mm) over The Sudd wetland for two projected times (2030-2059 and 2070-2099) concerning the historical (1981-2010)

Scenario	2030-2059				2070-2099			
	Annual	OND	JJAS	MAM	Annual	OND	JJAS	MAM
SSP1-26	83	13	75	-4	143	13	0	25
SSP2-45	145	21	114	11	204	-0.5	192	10
SSP5-58	177	29	162	-13	516	29	457	25



(a) Future change in mean Temp. 2030-2059 (b) Future change in precipitation (2070-2099)

Figure 40: Future change in mean Temperature (0C) for two future times (2030-2059 and 2070-2099) under three scenarios

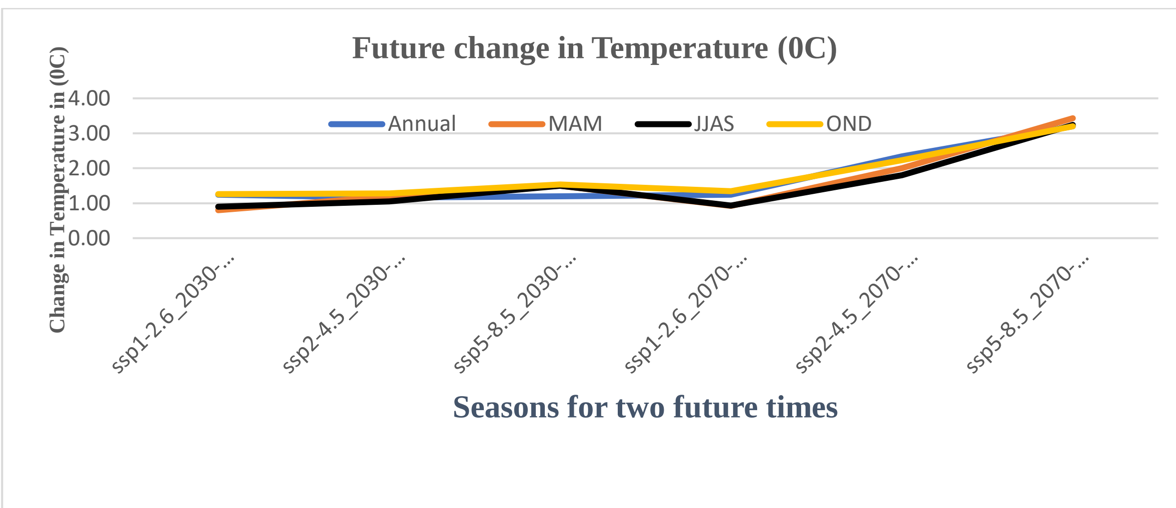


Table 7: Future change in Mean Temperature (^{0}C) over The Sudd wetland for two projected times (2030-2059 and 2070-2099) concerning the historical period (1981-2010)

Scenario	2030-2059				2070-2099			
	Annual	**OND**	**JJAS**	**MAM**	**Annual**	**OND**	**JJAS**	**MAM**
SSP1-26	1.24	1.26	0.90	0.80	1.24	1.34	0.93	0.92
SSP2-45	1.16	1.28	1.05	1.20	2.34	2.23	1.80	2.00
SSP5-58	1.20	1.54	1.50	1.50	3.20	3.20	3.24	3.43

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.0 Conclusion and Recommendations

5.1 Conclusion

Spatial-Temporal Characteristics of Rainfall and Temperature in The Sudd Wetland, the climatology (1981-2010) of the region shows that the highest annual average precipitation value in The Sudd Wetland was above 650 mm. JJAS had the highest rainfall season value. at the same time, the December to February season was the driest season recording less than 10 mm. In August, the Sudd wetland region experienced a significantly increasing rainfall of more than 175mm. The annual mean temperature was between 27.5 to 29 ^{0}C, the MAM seasons were the warmer seasons, while the colder seasons were JJAS. The Sudd wetland region experienced a significantly increasing mean temperature in March followed a month's April, February and May, the colder months were July and August.

The Coefficient of Variation (%) of annual rainfall and temperature 1981-2022 in The Sudd wetland. The highest variability of 20 to 25% was recorded over The Sudd wetland while the mean temperature was lost at 10%. February rainfall from 1981 to 2022 was the highest variability recorded in The Sudd wetland and the lower Coefficient of Variation (%) of months rainfall was June, July, August and September respectively.

The coefficient of Variation (%) of seasonal rainfall and temperature all had lower variability except the March to May rainfall season which had moderate variability between 20% and 30%. The Coefficient of Variation (%) of monthly temperature from 1981 to 2022 all are lower variability recorded in The Sudd wetland except April mean temperature from 1981 to 2022 had the highest variability of more the 30% recorded in The Sudd wetland. The slightly increasing trends on time series analysis of annual and Seasonal mean rainfall over the Sudd wetland region except the December, January and February seasons showed a decrease, while the increasing trends of all annual and seasonal mean Temperatures, a significantly increasing trend over The Sudd wetland region.

South Sudan has witnessed floods in these years and loss of lives, especially in the States of Jonglei and the United these states area the place of Sudd Wetland, almost every year from 1981 to 2020 we have a flood in The Sudd Wetland area with increasing frequencies and intensifies of flood over the Sudd wetland experienced a significantly increasing trend. The best model was BCC-CSM2-MR from the three high resolutions (CAMS-CSM1-0, BCC-CSM2-MR and MRI-ESM2-0) global climate model from the CMIP6, projected Temperature and rainfall changes were determined near term (2030-2059) and long term (2070-2099) relative to the historical climate (1981-2010) under the low (SSP1-2.6), moderate (SSP2-4.5) and strong forcing (SSP5-8.5).

The CMIP6 projected a significant increase in the annual mean temperature over The Sudd wetland for the mid-century or near term and long-term periods are projected to increase by 1.24(1.24), 1.16(2.34) and 1.20(3.20). The CMIP6 (BCC-CSM2-MR) model projected a significant increase in rainfall in JJAS season for two terms 2030-2059 and 2070-2099 over The Sudd wetland is projected to increase by 75(0), 114(192) and 162(457) under the weak forcing (SSP1-2.6), moderate forcing (SSP2-4.5) and strong forcing (SSP5-8.5).

5.2. Recommendation

Based on this study. the following are the recommendations:

Recommendation for policymakers

- Recently The Sudd wetland brought attention to users nationally and regionally for the government of South Sudan should establish a separate institution to develop and advance the management of The Sudd wetland resources.
- The government of South Sudan should establish a model village to avoid loss of life every year.
- The Sudd wetland area is without any hydrometeorological station, the Government of South Sudan through the meteorological department should be:
    - installing hydrometeorological observation stations
    - provide capacity building for local communities and

- provide climate and weather information such as daily, monthly and Seasonal forecasting to the users.

Recommendation for Researchers

Historical and projected precipitation and temperature call for further studies and research in The Sudd Wetland to explain and interpret the negative impact of climate change that may happen. Therefore,

- future studies and research in the same region (The Sudd Wetland) should involve other meteorological variables such as wind direction and speed, evaporation, and relative humidity to verify further confidence.
- Future studies and research should project future changes in climate variabilities based on the multiple model's ensemble mean forecasts on general circulation models and regional models (GCMs)output.

Recommendation for Local community

Every year during the rainfall season there is flooding and displacement of humans and livestock among the communities in the Sudd wetland, for the local community should move to higher places before the rainy season.

References

Ahmed, A. A., & Ismail, U. H. A. E. (2008). Sediment in the Nile River System. *Consultancy Study Requested by UNESCO, January*, 93 pp.

Almazroui, M., Islam, M. N., Saeed, F., Saeed, S., Ismail, M., Ehsan, M. A., Diallo, I., O'Brien, E., Ashfaq, M., Martínez-Castro, D., Cavazos, T., Cerezo-Mota, R., Tippett, M. K., Gutowski, W. J., Alfaro, E. J., Hidalgo, H. G., Vichot-Llano, A., Campbell, J. D., Kamil, S., … Barlow, M. (2021). Projected Changes in Temperature and Precipitation Over the United States, Central America, and the Caribbean in CMIP6 GCMs. *Earth Systems and Environment*, *5*(1), 1–24. https://doi.org/10.1007/s41748-021-00199-5

Almazroui, M., Saeed, F., Saeed, S., Nazrul Islam, M., Ismail, M., Klutse, N. A. B., & Siddiqui, M. H. (2020a). Projected Change in Temperature and Precipitation Over Africa from CMIP6. *Earth Systems and Environment*, *4*(3), 455–475. https://doi.org/10.1007/s41748-020-00161-x

Almazroui, M., Saeed, F., Saeed, S., Nazrul Islam, M., Ismail, M., Klutse, N. A. B., & Siddiqui, M. H. (2020b). Projected Change in Temperature and Precipitation Over Africa from CMIP6. *Earth Systems and Environment, 4*(3), 455–475. https://doi.org/10.1007/s41748-020-00161-x

Almazroui, M., Saeed, S., Saeed, F., Islam, M. N., & Ismail, M. (2020). Projections of Precipitation and Temperature over the South Asian Countries in CMIP6. *Earth Systems and Environment*, *4*(2), 297–320. https://doi.org/10.1007/s41748-020-00157-7

Aryal, A., Maharjan, M., Talchabhadel, R., & Thapa, B. R. (2022). Characterizing Meteorological Droughts in Nepal: A Comparative Analysis of Standardized Precipitation Index and Rainfall Anomaly Index. *Earth*, *3*(1), 409–432. https://doi.org/10.3390/earth3010025

Benansio, J. S., Balli, J. J., Dendi, D., Ajong, S. N., Pacini, N., & Luiselli, L. (2021). Fish community composition indicates a low impact of capture efforts in the Sudd wetlands of South Sudan. *European Journal of Ecology*, *7*(2), 40–53. https://doi.org/10.17161/EUROJECOL.V7I2.14993

Chen, H., Guo, J., Zhang, Z., & Xu, C. Y. (2013). Prediction of temperature and precipitation in Sudan and South Sudan by using LARS-WG in future. *Theoretical and Applied Climatology*, *113*(3–4), 363–375. https://doi.org/10.1007/s00704-012-0793-9

Collins, J. M. (2011). Temperature variability over Africa. *Journal of Climate*, *24*(14), 3649–3666. https://doi.org/10.1175/2011JCLI3753.1

Deng, S., Chen, T., Yang, N., Qu, L., Li, M., & Chen, D. (2018). Spatial and temporal distribution of rainfall and drought characteristics across the Pearl River basin. *Science of the Total Environment*, *619–620*, 28–41. https://doi.org/10.1016/j.scitotenv.2017.10.339

Dunning, C. M., Black, E. C. L., & Allan, R. P. (1955). Journal of geophysical research. *Nature*, *175*(4449), 238. https://doi.org/10.1038/175238c0

Endris, H. S., Lennard, C., Hewitson, B., Dosio, A., Nikulin, G., & Artan, G. A. (2019). Future changes in rainfall associated with ENSO, IOD and changes in the mean state over Eastern Africa. *Climate Dynamics*, *52*(3–4), 2029–2053. https://doi.org/10.1007/s00382-018-4239-7

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., & Michaelsen, J. (2015). The climate hazards infrared precipitation with stations - A new environmental record for monitoring extremes. *Scientific Data*, *2*, 1–21. https://doi.org/10.1038/sdata.2015.66

Jiao, D., Xu, N., Yang, F., & Xu, K. (2021). Evaluation of spatial-temporal variation performance of ERA5 precipitation data in China. *Scientific Reports*, *11*(1), 1–13. https://doi.org/10.1038/s41598-021-97432-y

Kilavi, M., MacLeod, D., Ambani, M., Robbins, J., Dankers, R., Graham, R., Helen, T., Salih, A. A. M., & Todd, M. C. (2018). Extreme rainfall and flooding over Central Kenya Including Nairobi City during the long-rains season 2018: Causes, predictability, and potential for early warning and actions. *Atmosphere*, *9*(12). https://doi.org/10.3390/atmos9120472

Mohamed, Y. A., Van Den Hurk, B. J. J. M., Savenije, H. H. G., & Bastiaanssen, W. G. M. (2005a). Impact of the Sudd wetland on the Nile hydroclimatology. *Water Resources Research*, *41*(8), 1–14. https://doi.org/10.1029/2004WR003792

Mohamed, Y. A., Van Den Hurk, B. J. J. M., Savenije, H. H. G., & Bastiaanssen, W. G. M. (2005b). Impact of the Sudd wetland on the Nile hydroclimatology. *Water Resources Research*, *41*(8), 1–14. https://doi.org/10.1029/2004WR003792

Mohamed, Y., & Savenije, H. H. G. (2014). Impact of climate variability on the hydrology of the Sudd wetland: Signals derived from long term (1900-2000) water balance computations. *Wetlands Ecology and Management*, *22*(2), 191–198. https://doi.org/10.1007/s11273-014-9337-7

Mondal, A., Khare, D., & Kundu, S. (2015). Spatial and temporal analysis of rainfall and temperature trend of India. *Theoretical and Applied Climatology*, *122*(1–2), 143–158. https://doi.org/10.1007/s00704-014-1283-z

Mukhtar, A. Y. A., Munyakazi, J. B., & Ouifki, R. (2019). Assessing the role of climate factors on malaria transmission dynamics in South Sudan. *Mathematical Biosciences*, *310*, 13–23. https://doi.org/10.1016/j.mbs.2019.01.002

Muthoni, F. K., Odongo, V. O., Ochieng, J., Mugalavai, E. M., Mourice, S. K., Hoesche-Zeledon, I., Mwila, M., & Bekunda, M. (2019). Long-term spatial-temporal trends and variability of rainfall over Eastern and Southern Africa. *Theoretical and Applied Climatology*, *137*(3–4), 1869–1882. https://doi.org/10.1007/s00704-018-2712-1

Ngoma, H., Wen, W., Ayugi, B., Babaousmail, H., Karim, R., & Ongoma, V. (2021). Evaluation of precipitation simulations in CMIP6 models over Uganda. *International Journal of Climatology*, *41*(9), 4743–4768. https://doi.org/10.1002/joc.7098

Omoj, P., Ogallo, L., Oludhe, C., & Gitau, W. (2016). Temporal and Spatial Characteristics of the June-August Seasonal Rainfall and Temperature over South Sudan. *Journal of Meteorology and Related Sciences*, *9*(2). https://doi.org/10.20987/jmrs.5.08.2016

Omondi, P. A. o., Awange, J. L., Forootan, E., Ogallo, L. A., Barakiza, R., Girmaw, G. B., Fesseha, I., Kululetera, V., Kilembe, C., Mbati, M. M., Kilavi, M., King'uyu, S. M., Omeny, P. A., Njogu, A., Badr, E. M., Musa, T. A., Muchiri, P., Bamanya, D., & Komutunga, E. (2014). Changes in temperature and precipitation extremes over the Greater Horn of Africa region from 1961 to 2010. *International Journal of Climatology*, *34*(4), 1262–1277. https://doi.org/10.1002/joc.3763

Palmer, P. I., Wainwright, C. M., Dong, B., Maidment, R. I., Wheeler, K. G., Gedney, N., Hickman, J. E., Madani, N., Folwell, S. S., Abdo, G., Allan, R. P., Black, E. C. L., Feng, L., Gudoshava, M., Haines, K., Huntingford, C., Kilavi, M., Lunt, M. F., Shaaban, A., & Turner, A. G. (2023). Drivers and impacts of Eastern African rainfall variability. *Nature Reviews Earth and Environment*, *4*(April). https://doi.org/10.1038/s43017-023-00397-x

Panda, A., & Sahu, N. (2019a). Trend analysis of seasonal rainfall and temperature pattern in Kalahandi, Bolangir and Koraput districts of Odisha, India. *Atmospheric Science Letters*, *20*(10), 1–10. https://doi.org/10.1002/asl.932

Panda, A., & Sahu, N. (2019b). Trend analysis of seasonal rainfall and temperature pattern in Kalahandi, Bolangir and Koraput districts of Odisha, India. *Atmospheric Science Letters*, *20*(10), 1–10. https://doi.org/10.1002/asl.932

Quagraine, K. A., Nkrumah, F., Klein, C., Klutse, N. A. B., & Quagraine, K. T. (2020). West African summer monsoon precipitation variability as represented by reanalysis datasets. *Climate*, *8*(10), 1–18. https://doi.org/10.3390/cli8100111

Ruuskanen, C. (2021). *Monitoring wetland cover changes during the past two decades within the protected areas of the Sudd wetland in South Sudan using MODIS data*. *548*.

Shiru, M. S., & Chung, E. S. (2021). Performance evaluation of CMIP6 global climate models for selecting models for climate projection over Nigeria. *Theoretical and Applied Climatology*, *146*(1–2), 599–615. https://doi.org/10.1007/s00704-021-03746-2

Supharatid, S., Nafung, J., & Aribarg, T. (2022). Projected changes in temperature and precipitation over mainland Southeast Asia by CMIP6 models. *Journal of Water and Climate Change*, *13*(1), 337–356. https://doi.org/10.2166/wcc.2021.015

Vijith, H., & Dodge-Wan, D. (2020). Spatial and temporal characteristics of rainfall over a forested river basin in NW Borneo. *Meteorology and Atmospheric Physics*, *132*(5), 683–702. https://doi.org/10.1007/s00703-019-00714-4

Wainwright, C. M., Finney, D. L., Kilavi, M., Black, E., & Marsham, J. H. (2020). Extreme rainfall in East Africa, October 2019–January 2020 and context under future climate change. *Weather*, *3*(January), 1–6. https://doi.org/10.1002/wea.3824

Xiao, Y., Zhang, X., Wan, H., Wang, Y., Liu, C., & Xia, J. (2016). Spatial and temporal characteristics of rainfall across Ganjiang River Basin in China. *Meteorology and Atmospheric Physics*, *128*(2), 167–179. https://doi.org/10.1007/s00703-015-0411-3

Zakaria Lukwasa, A., Ayal, D. Y., Zeleke, T. T., & Beketie, K. T. (2022). Spatio-temporal rainfall variability and its linkage with large scale climate oscillations over the Republic of South Sudan. *Climate Services*, *28*(July), 100322. https://doi.org/10.1016/j.cliser.2022.100322