TRENDS IN EXTREME TEMPERATURE AND PRECIPITATION EVENTS OVER ZAMBIA FOR THE PERIOD 1981-2021

By

Memory Zulu

A dissertation submitted to the University of Zambia in partial fulfillment of the requirements for the degree of Master of Science in Statistics.

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DECLARATION

The work described in this Master of Science (MSc) dissertation was carried out under the supervision of **Mrs. S Jain**, Department of Mathematics and statistics, University of Zambia, Lusaka.

The MSc dissertation represents original work by the author and has not otherwise been submitted in any form for any degree or diploma to any other University. Where use has been made of the work of others it is duly acknowledged in the text.

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CERTIFICATE OF APPROVAL

This dissertation of Memory Zulu has been approved as fulfilling the requirements or partial fulfillment of the requirements for the award of Master of Science in Statistics by the University of Zambia.

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ABSTRACT

Human activities such as burning fossil fuels, cutting down forests and livestock farming have caused an increase in the earth's surface temperature by 1.0°C since the preindustrial levels. Warmer temperatures over time are altering global weather patterns. These alterations have been resulting in more frequent and intense extreme weather events that were previously unheard of in many regions, including Zambia. Extreme weather events such as hot spells, dry spells, flash floods, etc. pose many risks to water availability and food security. Agriculture in Zambia heavily relies on rainfall. The shifting patterns of temperature and precipitation in Zambia have led to reduced crop yields, failed harvests, and challenges in animal farming. Consequently, food security is now at risk. The frequent occurrences of extremely hot days, floods, and droughts have severe implications on the livelihoods of many individuals and pose serious harm to the infrastructure such as roads, dams, and schools in the country. The districts are affected differently by the extreme weather events. Therefore, it is crucial to understand the annual trends in extreme temperature and precipitation events based on daily historical and current meteorological observations at a finer resolution for assessing climate change vulnerability at the local (district) scale and consequently designing local adaptation strategies. This study conducted a comprehensive evaluation of annual/seasonal trends in some selected extreme weather events by utilizing the ERA5 data set of resolution 0.5 x 0.5 degrees for the period 1981-2021. The research investigated the annual trend in the frequency of days with maximum temperature exceeding 35°C (very hot day) as well as the maximum daily temperature across regions in Zambia. The study partitioned the regional domain of Zambia into three climate zones based on mean total seasonal rainfall. Findings reveal significant increases in both the frequency of days with maximum temperature exceeding 35°C and annual maximum daily temperature most especially in climatic zone 1 indicating urgent implications for agriculture and ecosystems. In terms of precipitation, the study examined seasonal total rainfall and the seasonal frequency of days when daily rainfall exceeds 20mm and 30mm thresholds. Results indicated a general decrease in seasonal total rainfall during the October, November and December (OND) season, and increasing trends regardless of some fluctuating patterns observed in the January, February and March (JFM) season. The analysis identified districts that are hotspots of the considered extreme weather events emphasizing the need for region-specific adaption strategies to address the negative impacts of weather events. These findings contribute to a broader understanding of Zambia's climate dynamics and underscore the necessity for informed decision-making to enhance resilience against changing climatic conditions.

Keywords: Trends, Temperature, Precipitation, Extreme Events, ETCCDI Climate Indices.

DEDICATION

This thesis is without reservation dedicated to God Almighty, the first and last, who created me and is responsible for my existence.

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First, I want to give thanks, praise, and glory to God, the Almighty, for His unfailing compassion, which sustained me to complete my studies successfully. I give God even more glory for the wonderful gift of Prophet TB Joshua, through which the SCOAN was founded. His teachings, through sermons and prayers, kept me going during difficult times.

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ACRONYMS AND ABBREVIATIONS

^{O}C	Degrees Celsius
CDO	Climate Data Operators
C3S	Copernicus Climate Change Service
CRU	Climate Research Unit
ETCCDI	Expert Team on Climate Change Detection and Indices
GHG	Greenhouse Gas
GCM	Global Climate Model
GMT	Global Mean Temperature
GPCC	Global Precipitation Climatology Centre
GPCP	Global Precipitation Climatology Project
GRZ	Government of the Republic of Zambia
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-Tropical Convergence Zone
RCM	Regional Climate Model
PRCPTOT	Seasonal Total Rainfall
USAID	United States Agency for International Development
TXx	Monthly maximum value of daily maximum temperature
TX35	Number of days when the monthly maximum value of daily temperature exceeds 35^{0}
UNFCCC	United Nations Framework Convention on Climate Change
WMO	World Meteorological Organization

CHAPTER 1: INTRODUCTION

1.1. Background

The global mean surface temperature of the earth has risen more than 1.0°C since the pre-industrial period (between 1850 and 1900) due to human activities primarily fossil fuel burning, cutting down forests, and changes in land use. These activities emit Greenhouse Gases (GHG) such as Carbon dioxide, Carbon monoxide, Nitrogen, Methane, etc. Currently, the concentration of GHGs in the earth's atmosphere has been increasing resulting in the increasing global mean surface temperature. The rise in the global mean surface temperature has led to the frequent occurrence of extreme weather events of varied severity and duration at regional and local levels. These weather events have claimed the lives of humans and devastated ecosystems across the globe (Handmer, 2012). This is evidenced by natural disasters induced by heatwaves, floods, droughts, and tropical cyclones observed in different regions of the earth in recent years.

Extreme weather events associated with surface temperature and precipitation variables affect the hydrological cycle and negatively impact many economic sectors such as Agriculture, Water, Energy, Health, Forest, Infrastructure, Mining, Wildlife, and Tourism of an economy. Most existing systems in various aforementioned sectors have been designed under the assumption that climate is stationary.

Temperature and Precipitation extremes have negatively impacted various aspects of Zambian society as well. Zambia experienced severe droughts in 1916-17, 1924-25, 1949-50, 1983-84, 1987-88, 1991-92, 1994-95, and 1997-98 (Sichingabula, 1998). The country has also recently experienced extremely intense floods in 2007-08 and 2009-2010 with 2006-2007 having the worst occurrence. These Extreme events resulted in the loss of livelihoods, loss of human and animal life, and reduced crop output (GRZ, 2007).

The Expert Team on Climate Change Detection and Indices (ETCCDI) was a UN-backed working group formed about two decades ago to assess the best practices for the characterization of climate variability and climate change at the regional level. The group recommended 27 extreme temperature and precipitation-related indices known as ETCCDI indices (Zhang et al., 2011) which are based on daily observations of temperature and precipitation. All 27 indices are calculated for annual values but a subset of these indices are also calculated on seasonal and monthly time scales.

The World Meteorological Organization (WMO) advises national meteorological and hydrological services to utilize the same indices when assessing the occurrence of climate extremes (WMO, 2009) relevant to their respective countries. Several studies have been carried out to detect trends in relevant

ETCCDI temperature and precipitation indices for various regions of the earth using historical and present daily weather data.

Though several techniques can be applied to detect seasonal/annual trends in the extreme weather indices, the Mann-Kendall nonparametric test is preferred in hydrological and climatological sciences (Pohlert 2016). The magnitude of the trend is computed using Theil-Sen's slope method.

Several studies on the detection of annual trends in extreme weather events in Zambia have been done. Chisanga et al (2017) investigated trends of extreme events in Precipitation and Temperature using daily weather data for the period 1963 - 2012 for Mt Makulu. The findings of the study showed increasing trends of warm (daily temperature >30°C) and extremely warm (daily temperature >35°C) days, a decreasing trend in the frequency of extreme precipitation events (one-day rainfall and five consecutive days' rainfall), a significant decrease in annual total precipitation, and a significant increase in the maximum number of consecutive dry days. The study was limited to only one station and thus does not represent the trends scenarios nationwide.

A study by Nyirenda and Sachikumba (2019) on the trends of extreme weather events based on data for the period 1979 to 2017 covered three districts Livingstone, Lusaka, and Kasama to represent the Zambia agro-ecological regions I, II, and III respectively.

The Third National Communication of Zambia to the United Nations Framework Convention on Climate Change (UNFCCC) reported trends in extreme weather events for only those ZMD stations for which complete time series data was available for the period 1971 to 2000(http://unfccc.int/documents/254196). All these studies utilized station data from the Zambia Meteorological Department (ZMD).

Complete 40-year time series of daily temperature and precipitation data of ZMD for the period 1981 to 2021 cover not more than thirty stations countrywide. Therefore, currently, available climate change information, in particular annual trends in extreme weather events for planning adaptations for districts of Zambia is insufficient. The districts have been differently impacted by extreme weather events. These studies have indicated a need for an updated trend analysis of extreme weather events at a fine spatial resolution of about 50 km-by-50 km grid cells which will provide useful insights and knowledge to design effective climate change adaptation strategies in the impacted sectors at district level countrywide for Zambia.

Some gridded data sets at about 50 km by 50 km grid cells have been constructed internationally such as the Climate Research Unit (CRU) climate data of the university of East Anglia, UK, the fifth – generation atmospheric reanalysis of the global climate (ERA5) of the Copernicus Climate Change

Service (C3S). These data are constructed for the entire globe using in situ meteorological observations and satellite data and are downloadable from the official sites.

Some of the extreme weather events relevant to the agriculture sector in Zambia include the number of days in a season when daily rainfall exceeds 20mm and 30mm, seasonal total rainfall, maximum daily temperature, and number of days in a year with maximum temperature exceeding 35°C. Annual/seasonal trends in these extreme weather events based on historical and current observations of gridded data from 1981 to 2021 will provide understanding and useful information to adapt to the changing climate in the agricultural sector at the district level. This study aims to determine the rate of change of some extreme temperature and precipitation indices that negatively impact agriculture in Zambia.

1.2. Statement of the Problem

Human-induced climate change has caused significant and potentially irreversible changes to the Earth's climate system. These alterations have resulted in more frequent and more intense extreme weather events that were previously unheard of in many regions, including Zambia. Since agriculture in Zambia heavily relies on rainfall, the shifting patterns of temperature and precipitation have led to reduced crop yields, failed harvests, and challenges in animal farming. Consequently, food security is now at risk. Therefore, there is a need to adapt to new agricultural practices to reduce the negative impacts of extreme temperature and precipitation events. The occurrences of heat waves, floods, and droughts have severe implications on the livelihoods of individuals and the infrastructure of the country. These extreme weather events have a high spatial variability. Their impacts are different from one district to the other. Currently climate change information, particularly seasonal trends in the occurrences of extreme temperature and precipitation events in Zambia is available for ZMD stations only. This information is not available at the district level. There is a need to design district-specific adaptations that require an understanding of these severe weather events and knowledge of trends in the annual occurrences at a fine resolution of about 50 km by 50 km.

1.3. Aim of Study

This study aims to provide annual/seasonal trends in the extreme temperature and precipitation events over Zambia based on gridded observations for the period 1981-2021 at a spatial resolution of about 50 km by 50 km.

1.4. Specific Objectives

1. Assess the ability of the observatinal gridded data sets ERA5, CRU, GPCP, and GPCC to reproduce the climatology of temperature and precipitation over Zambia.
2. Determine the annual/seasonal trends in weather events namely maximum daily temperature, the frequency of days with maximum temperature exceeding 35°C, the number of days when daily rainfall exceeds 20mm and 30mm, and seasonal total rainfall over Zambia.
3. Generate spatial maps for annual/seasonal mean of extreme temperature and precipitation events described in objective 2 across the regions of Zambia to locate the districts that are hot spots of the event.

1.5. Research Questions

1. How credible are ERA5, CRU, GPCP, and GPCC data in reproducing the climatology of temperature and precipitation over Zambia?
2. Are there annual/sesonal trends of the extreme weather indices: maximum daily temperature, frequency of days with maximum temperature exceeding 35°C, number of days when daily rainfall exceeds 20mm and 30mm, and the seasonal total rainfall that remain constant from South to North.
3. Which districts are the hotspots of weather indices considered in the study.

1.6. Rationale

The agricultural sector in Zambia is highly negatively impacted by the extreme temperature and precipitation events. Extreme weather events have high spatial variability. These occur at different frequencies and severity over the districts. Consequently, comprehending the patterns and assessing annual/seasonal trends in these extreme weather events at a fine resolution of about 50 km by 50 km is of utmost importance for effective water resource management and optimal food production at the district level. Therefore, the findings from this study envisage contributing to the development of national adaptation plans, ensuring more climate-resilient and sustainable practices in Zambia.

1.7. Organization of the Dissertation

The structure of this dissertation is organized as follows:

Chapter 1 presents an overview of the trends in temperature and precipitation extremes and their impacts on agriculture. It includes a statement of the problem, the aim of the study, specific objectives, and the significance of this study. *Chapter 2* lays out a comprehensive review that informs this study.

Chapter 3 gives detailed information on the study area, presents the data utilized, and describes the methodology applied in this study. *Chapter 4* presents the findings of the study; the results are discussed through graphs, tables, and maps to enhance the understanding. *Chapter 5* summarizes the key findings of this study concerning the research objectives, and makes some recommendations for future studies.

CHAPTER 2: LITERATURE REVIEW

2.1 Global Trends in Human-Induced Climate Change

The comprehensive examination of climate variables, including surface temperature and precipitation, conducted globally, has revealed compelling evidence of the pivotal role of humans in shaping observed trends in global and regional climates since 1850. The Intergovernmental Panel on Climate Change (IPCC, 2021) has consistently reported a discernible shift towards less severe and less frequent cold extremes, and more frequent and more intense hot weather events happening now. Concurrently, many studies have stated that heavy precipitation events have become more frequent and intense in some regions globally. The Intergovernmental Panel on Climate Change emphasizes the inevitability of altered frequencies in extreme temperature and precipitation events with each incremental rise in global warming, influencing warm extremes (virtually certain), cold extremes (extremely likely), and precipitation extremes (very likely).

The implications of global warming, as explained by NASA's hydrologist, Matt Roddell, extend far beyond meteorological changes. The intensification of droughts and wet periods, as affirmed by Roddell (NASA, 2023), underscores the profound effects on populations, economies, and agriculture worldwide. This acknowledgment heightens the urgency for monitoring hydrological extremes, not merely as an academic pursuit but as an imperative for preparing, mitigating, and adapting to the foreseeable challenges posed by future climate extreme events.

While concerted global efforts are underway for climate change mitigation, the pervasive nature of climate change renders complete elimination of its impacts virtually impossible. As societies grapple with the visible repercussions of climate change, the world finds itself in a silent war against global warming (IPCC, 2021; NASA, 2023). The socioeconomic and geopolitical challenges emerging from this silent war necessitate multifaceted approaches such as generating traditional and scientific knowledge at regional and local scales.

2.2 Regional Trends in Extreme Temperature and Precipitation

2.2.1. South America

South America, a continent rich in biodiversity, experiences various extreme events affecting millions of people. The vulnerability of Latin America and the Caribbean to climate extremes is heightened by factors such as low socio-economic development and low agricultural productivity (Seneviratne et al., 2021; Marengo et al., 2014).

The complexities of current regional climate trends are evident in studies such as Dos Santos et al. (2023), which reports increased hot extremes and reduced cold extremes in the Brazilian Midwest, alongside intensified precipitation in Amazonia.

2.2.2. North America

North America, as the third-largest continent, witnesses significant trends in climate extremes such as storms, tropical cyclones, floods, droughts, and heatwaves, with far-reaching impacts on vital sectors such as agriculture, infrastructure, and water security (IPCC, 2021).

2.2.3. Middle East

The Middle East, a designated climate change hotspot (Zittis et al., 2019), grapples with consistent hot and dry conditions. Despite regional variations, this predominantly arid region faces challenges posed by extreme temperatures and precipitation.

2.2.4. Southern Africa

Southern Africa's unique challenges from climate change stem from its dependence on rain-fed agriculture. Several studies indicate a trend towards drier conditions, posing threats to agriculture and water resources. The complex negative impacts of climate change in the region highlight substantial challenges to resilience (Dosio A et al., 2019; Omondi et al., 2012).

Tadross et al (2007) explored observed changes in daily rainfall records and evaluated the agricultural implications of these changes over Southern Africa. The findings indicated increases in seasonal dry spell length and reductions in rain day frequency over Zambia, Malawi, and Zimbabwe. It was noted that there have been documented increases in annual temperature (which are expected to continually increase in the future) that will place additional water-related stresses on agriculture. An examination of heat waves and corresponding trends across Mozambique for the period 1983 to 2023 by Marghidan et al (2023) showed that Mozambique has experienced many heat waves over the past decades. Further, heatwave frequency (number of episodes/year) and duration (days) were found to be significantly increasing ($p < 0.05$) for many populated regions. Heatwaves are known to negatively impact human health, and cause economic damage through reduced crop yield and lost work hours.

2.2.5. Botswana

Botswana emerges as a highly vulnerable country to climate change, confronting increasing drought risk and alterations in precipitation patterns, especially in its northern regions (Nkemelang, 2018).

2.2.6. The Democratic Republic of Congo

The Democratic Republic of Congo (DRC) confronts social vulnerability, political instability, and food insecurity, all exacerbated by climate change. Extreme precipitation events and rising temperatures pose substantial threats to agriculture, a cornerstone of the country's economy (USAID, 2022).

2.2.7. Zambia

Zambia, reliant on agriculture, has grappled with vulnerability to extreme climate events quite often in the last fifty years. It is stated in the Third National Communication (TNC, 2020) that the country has experienced several climate hazards over the past decades, which include droughts, seasonal and flash floods, extreme temperatures, and dry spells. The frequent occurrence of these climate hazards adversely influences food and water security, infrastructure, energy, health, and sustainable livelihoods of individuals and communities (TNC, 2020). These climate hazards are influenced by remote factors such as the movement of the Inter-Tropical Convergence Zone (ITCZ) and El Niño-Southern Oscillation (ENSO) (Colin et al., 2006). Shifts in these drivers contribute to high variability in temperature and precipitation, affecting the country's water resources, agriculture, and overall climate resilience (Hachigonta and Reason, 2006). Several studies have been done to investigate the patterns of climate disasters associated with extreme temperature and precipitation events, most of which focused on particular regions of Zambia.

Chisanga et al (2017) investigated trends of extreme events in Precipitation and Temperature using daily weather data for the period 1963 - 2012 for Mt Makulu. The findings of the study showed increasing annual trends of warm (daily temperature >30°C) and extremely warm (daily temperature >35°C) days, a decreasing trend in the frequency of extreme precipitation events (one-day rainfall and five consecutive days' rainfall), a significant decrease in annual total precipitation, and a significant increase in the maximum number of consecutive dry days. The study was limited to only one station and thus does not represent the extreme weather events trends nationwide.

A study by Nyirenda and Sachikumba (2019) on the trends of extreme weather events based on daily observations for the period 1979 to 2017 covered three districts Livingstone, Lusaka, and Kasama to represent the Zambia agro-ecological regions I, II, and III respectively. Its findings revealed a statistically significant decreasing trend in seasonal total precipitation, and persistence of intense rainfall events (daily rainfall>10mm, daily rainfall>20mm, and daily rainfall>25mm) in Kasama town. Further, it stated that a statistically significant increasing trend in seasonal consecutive dry days and a decreasing trend in seasonal consecutive wet days in Lusaka were observed. Similarly, a seasonal decreasing trend in consecutive wet days and an increasing trend in consecutive dry days were observed in Livingstone though not statistically significant.

Demissie and Gebrechorkos (2024) investigated the spatial trends in precipitation and temperature extremes over Malawi and Zambia using Climate Hazards Group Infrared Precipitation (CHIRPS) and Multi-Source Weather (MSWX) gridded data sets. The findings showed a non-significant increasing trend in annual total precipitation in many parts of Zambia and a statistically significant increasing trend in the annual daily mean temperature and maximum and minimum temperatures.

Almost all these studies utilized ZMD station data, hence were insufficient to provide climate extremes information at the district or provincial level. Variability in extreme weather events differs from one district to the other, therefore, understanding historical and present change based on a gridded dataset at a fine resolution of about 50 km by 50 km is essential to provide context for a credible basis for adaptation strategies at the district level.

2.3. Challenges and Opportunities for Adaptation

Given the escalating frequency and intensity of extreme weather events globally and regionally, predicting the frequency of climate extremes becomes a vital aspect of effective decision-making for adaptations. For nations like Zambia, heavily reliant on rain-fed agriculture, adapting to weather changes presents significant challenges without credible information, hence underscoring the importance of strategic planning for both adaptation and mitigation strategies (NASA, 2023; Mahmood and Babel, 2014).

This comprehensive literature review attempted to highlight the need for global and regional information on extreme weather events emphasizing the urgency for informed decision-making about, adaptation, and mitigation strategies.

CHAPTER 3: MATERIALS AND METHODOLOGY

This chapter is divided into three sections. The first section covers the study region, its physical features, climate, and administrative attributes, the second section presents detailed information about the data used, and the last section outlines the details of the methods employed for statistical analysis.

3.1 Study Region

3.1.1 Geographical Location and Topography

Zambia, located in Central-Southern Africa, is positioned between 22 and 34 degrees east (longitudes) of the Greenwich and 8 to 18 degrees south (latitudes) of the equator (Figure 1). As a landlocked country, it shares borders with eight countries: Congo, Tanzania, Angola, Namibia, Botswana, Zimbabwe, Mozambique, and Malawi. The country's landscape spans approximately 752,614 km^2 and is predominantly characterized by a high plateau, ranging in elevation from 950 to 1500 meters above sea level (Jain, 2007; Couroche, 2010). The topography features a network of rivers, valleys, hills, and mountains that traverse the plateaus (Lemenkova, 2021). Notably, around 34% of the estimated land area is effectively utilized for agriculture (Couroche, 2010).

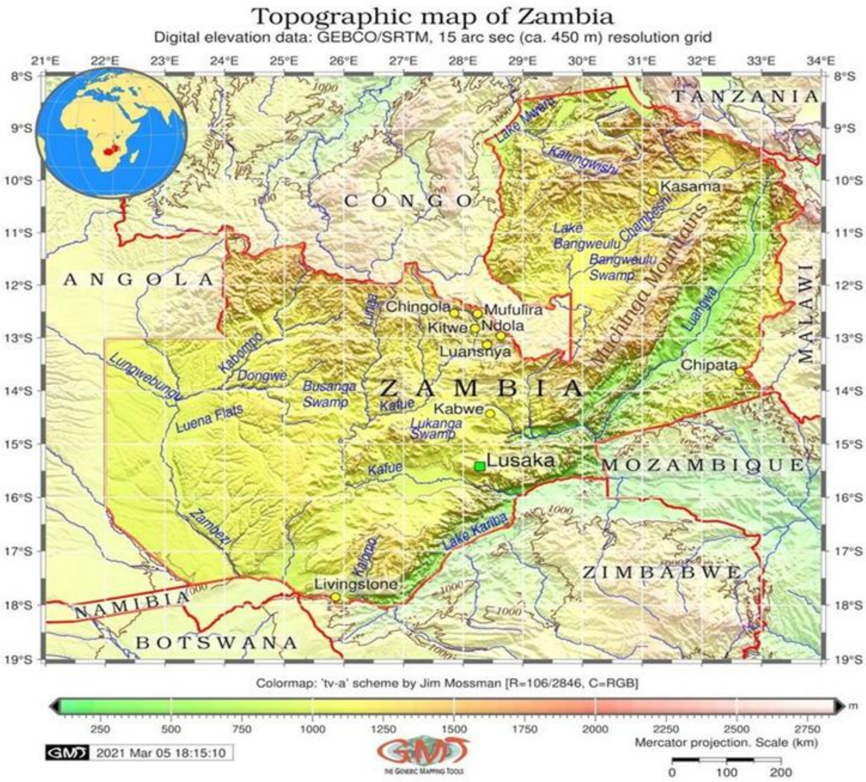


Figure 1: Topographic Map of Zambia. Source: Lemenkova 2021

3.1.2 Climate

Zambia exhibits a predominantly humid subtropical climate, as classified by the Köppen classification system (Geiger, 1954). The country undergoes distinct rainy and dry seasons, influenced by various factors including the annual migration of the Inter Tropical Convergence Zone (ITCZ) (Thurlow et al., 2009). The rainy season spans from November to April, during which the ITCZ moves southward (Thurlow et al., 2009; Jain, 2007). This southward movement brings moist air masses from the Indian Ocean. Rainfall intensity and duration vary across the country, resulting in the division of Zambia into three agroecological zones. The northern regions of the country receive higher rainfall amounts (total seasonal rainfall>1000mm) compared to the southern regions (total seasonal rainfall <800 mm). The dry season extends from May to October, with the ITCZ situated north of the country during this period (Thurlow et al., 2009). The dry season can be further subdivided into two periods: the cool dry winter season (May to July), characterized by mean temperatures ranging from 15° C to 27° C, and the hot dry season (August to October), featuring average maximum temperatures of 27° C to 37° C (Jain, 2007; Thurlow et al., 2009). In the hotter months of October and November, temperatures in the Zambezi and Luangwa valleys can exceed 35°C.

3.1.3 Climatic Zones

Due to different rainfall regimes, from South to North Zambia, the geographical domain of Zambia has been partitioned into three climatic zones. Zone 3 spans over latitudes from 8° S to 12.6° S, Zone 2 spans over latitudes from 12.6° S to 15.6° S, and Zone 1 spans over latitudes from 15.6° S to 18.6° S. The longitude range for all the three zones has remained from 21° E to 34° E. The mean seasonal rainfall for the period 1981 to 2021 in the three zones is presented in Table 1.

Table 1: *Mean seasonal rainfall for the period 1981 to 2021*

ZONE	Mean seasonal total rainfall (mm)
3	1435.4
2	1118.7
1	893.7

This study will analyze seasonal trends of extreme weather events for the three zones separately.

3.1.4 Administrative Attributes

As of the year 2011, Zambia comprised 9 provinces and 72 districts. However, due to unequal sizes of administrative units, these have been redefined. Currently, the country is divided into 10 administrative provinces and 105 districts (Figure 2). According to the latest data (2023) from Zambia Statistics Agency (ZamStats), Zambia's population stands at 19,610,769 individuals. The population is primarily concentrated in five provinces, namely Southern, Central, Lusaka, Eastern, and Copperbelt.

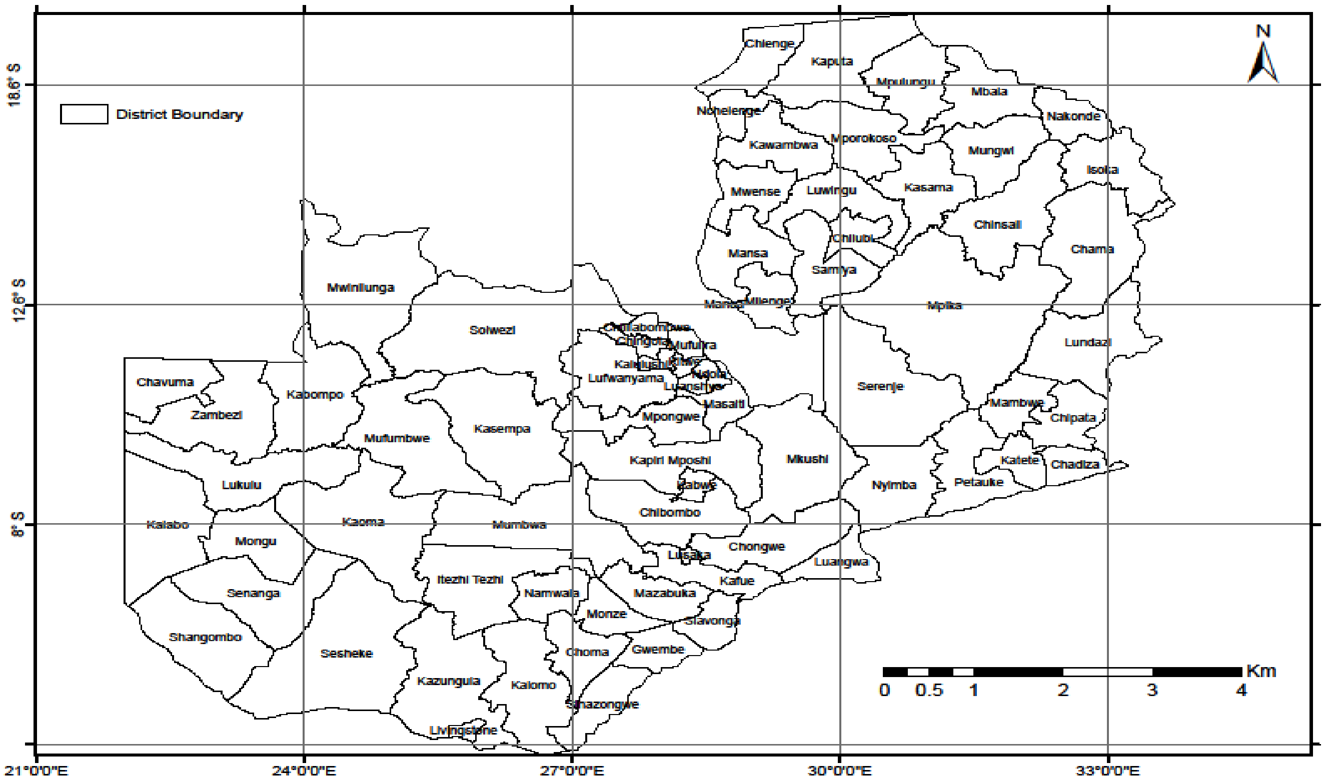


Figure 2: Climatic zones. Source: Euphrasia Chilongoshi Simutami, GIS analyst, Department of Geography and Environmental Studies, UNZA.

3.2. Description of Data

ERA5 is the fifth-generation atmospheric reanalysis of the global climate, produced by the Copernicus Climate Change Service (C3S) at the European Centre for Medium-Range Weather Forecasts (ECMWF). Reanalysis combines model data with observations from across the world into a globally complete and consistent dataset. ERA5 replaces its predecessor, the ERA-Interim reanalysis.

ERA5 daily data provides aggregated values for each day for seven ERA5 climate reanalysis parameters: 2m air temperature, 2m dew point temperature, total precipitation, mean sea level pressure, surface pressure, 10m u-component of wind, and 10m v-component of wind. Additionally, the daily minimum and maximum air temperature at 2m has been calculated based on the hourly 2m air temperature data. Daily total precipitation values are given as daily sums. All other parameters are provided as daily averages. ERA5 data is available from 1979 to three months in real-time at roughly 31 km spatial resolution. ERA5 represents a significant leap forward in providing high-quality, globally consistent estimates of atmospheric, land, and oceanic climate variables.

The integration of satellite and in-situ observations into the reanalysis process is a key strength of ERA5. This approach ensures that the dataset reflects the most up-to-date and comprehensive understanding of atmospheric conditions. The assimilation of observational data contributes to the dataset's reliability, enabling researchers, meteorologists, and climate scientists to conduct detailed analyses with confidence in the accuracy of the underlying information.

Hersbach et al. (2020) have extensively demonstrated the enhanced capabilities of ERA5 through comprehensive evaluations. Their findings underscore the dataset's superior simulation accuracy compared to earlier reanalysis generations. The rigorous integration of observational data, coupled with advancements in modelling and assimilation techniques, positions ERA5 as a reliable resource for climate research, weather forecasting, and related applications.

In addition, two monthly gauge-based gridded observational datasets and another monthly satellite-gauge combined dataset were also used in assessing the ability of ERA5 data to reproduce both precipitation and temperature climatology of Zambia. These monthly observational data sets include: Global Precipitation Climatology Centre (GPCC, version 2020, 1891-2016; Schneider et al., 2020), Climate Research Unit (CRU TS, version 4.07, 1901-2020; Harris et al., 2020) and the Global Precipitation Climatology Project (GPCP, version 2.3; 1979 - 2023; https://climatedataguide.ucar.edu/climate-data/gpcp-monthly-global-precipitation-climatology-project) data. All the data sets used in this study were available at 0.5° resolution except for GPCP was used at a coarse resolution (2.5°); the datasets were downloaded from the World Meteorological Organization website https://climexp.knmi.nl/start.cgi.

This study will perform trends analysis of extreme weather events based on gridded data ERA5 whose time scale is daily whereas the other three gridded observations data sets GPCC, CRU, and GPCP are monthly. More GPCC and GPCP data are for precipitation only. Hence, ERA5 is the only gridded observation data suitable for this study.

3.3. Methodology

3.3.1 Assessment of the ERA5 Data

Several criteria were undertaken to assess the ability of ERA5 to reproduce the rainfall and temperature climatology of Zambia. Comparisons were against observational datasets namely GPCC, CRU, and GPCP. GPCC and GPCP observational data sets are only on precipitation variables, whereas CRU includes temperature (minimum and maximum) as well. Hence, the ability of ERA5 to reproduce the surface temperature climatology of Zambia was assessed against Climate Research Unit (CRU) data only. The preference for these observational datasets is based on their sufficiently long time series and has been used in numerous studies to validate the credibility of climate simulations generated from Regional Climate Models (RCMs) and Global Climate Models (GCMs) in reproducing climatology of different parts of the globe.

In the first assessment, we examined the ability of ERA5 to capture the mean annual monthly cycles of rainfall and temperature (minimum and maximum). The second assessment of the ability of ERA5 is to capture the inter-annual rainfall and temperature variability. We assessed the ability of ERA5 to reproduce the year-to-year variability for the October to March (ONDJFM) season for rainfall, April to August (AMJJA) for minimum temperature, and September to March (SONDJFM) for maximum temperature. The third criterion examined the ability of ERA5 to capture the spatial distribution of mean rainfall and temperature. Pearson correlation coefficient between the spatially averaged seasonal value of ERA5 and each of the other observational data was computed using the formula.

$$r = \frac{\sum(x_e - \overline{x_e})(x_o - \overline{x_o})}{\sqrt{\sum(x_e - \overline{x_e})^2 \sum(x_o - \overline{x_o})^2}} \tag{1}$$

Where x_e and x_o denote the seasonal value in the ERA5 and the other observational datasets, respectively, and $\overline{x_e}$ and $\overline{x_o}$ represent the corresponding means. Test of hypothesis based on statistic

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} \tag{2}$$

This was performed to determine the significance of computed correlation coefficients.

3.3.2 Extreme Temperature and Precipitation Indices

In undertaking the analysis of climate indices for this project, a precise and comprehensive methodology has been employed, focusing on key indices established by the Expert Team on Climate

Change Detection and Indices (ETCCDI). This approach aims to investigate detailed patterns in both temperature and precipitation extremes, offering a refined understanding of climatic variations.

The four chosen climate indices play a pivotal role in capturing diverse facets of climatic behavior:

1. **Maximum Daily Temperature (TXx)**
    - *Definition:* TXx represents the highest daily maximum temperature, providing insights into the intensity of heat extremes.
2. **Frequency of Days with Maximum Temperature Exceeding 35 Degrees (TX35)**
    - *Definition:* TX35 counts the days where the maximum temperature surpasses 35 degrees Celsius, revealing trends in extremely hot days.
3. **Number of days when daily rainfall exceeds 20mm**
    - *Definitio*n: The frequency of days when daily rainfall exceeds 20mm
4. **Number of days when daily rainfall exceeds 30mm**
    - *Definition*: The frequency of days when daily rainfall exceeds 30mm
5. **Seasonal Total Rainfall (PRCPTOT)**
    - *Definition:* PRCPTOT represents the sum of precipitation during a specified season, providing a holistic view of seasonal precipitation patterns.

3.3.3 Statistical Analysis

The methodology adopted for the analysis of climate indices in this study integrates the following cutting-edge techniques and tools, ensuring a thorough exploration of selected extreme weather events.

3.3.3.1 Pre-Analysis Steps

A critical pre-analysis step involves the application of the **Trend-Free Pre-Whitening (TFPW) Method**. This method addresses potential biases arising from positive serial correlation in time series data, mitigating the risk of Type I errors. The TFPW method ensures that subsequent analyses are based on data free from serial correlation influences (Felix et al., 2021).

3.3.3.2 Trend analysis

The annual/seasonal trend analysis of the extreme weather events maximum daily temperature, the frequency of days with maximum temperature exceeding 35°C, the number of days when daily rainfall exceeds 20mm and 30mm, and seasonal total rainfall was carried out for each of the three climate zones as it was noted in Chapter Two that these three zones have different climate regimes.

Further, the period 1981 to 2021 was partitioned into two sub-periods namely 1981-2000 and 2001-2021 to allow detection of the rate of change in the trends of the extreme events. The core of the analysis involves the statistical procedures:

3.3.3.2.1 Theil-Sen's Slope Procedure

It was applied to estimate the rate of change in climatological time series. This procedure provides reliable trend estimates while being resilient to outliers (Mahdi A. Z., et al., 2015; Yang. X. L., et al., 2012; Felix, et al., 2021; Gebrechorkos, S.H., et al., 2019). The calculations are done as follows:

Compute $Q_i = \frac{x_j - x_{j\prime}}{j - j\prime}, j' < j,$ (3)

If the time series has n values, there will be $N = n\,(n-1)/2$ slopes Q_i. Then Sen's slope estimator is obtained by calculating the median of these N values:

$$Q_{med} = \begin{cases} Q_{\left[\frac{N+1}{2}\right]}, if\ N\ is\ odd \\ \frac{1}{2}\left(Q_{\left[\frac{N}{2}\right]} + Q_{\left[\frac{N+2}{2}\right]}\right), if\ N\ is\ even \end{cases} \quad (4)$$

The positive values of Sen's slope estimator indicate an increasing trend, while negative values indicate a decreasing trend in the data set.

3.3.3.2.2 Mann-Kendall Test

This test is instrumental in identifying significant annual/seasonal trends within the selected climate indices, offering statistical robustness to the findings.

The significance of trends in climate indices was analyzed using the Mann-Kendall test, with the null hypothesis (H_0) stating that there is no trend in the temperature/precipitation index and the alternative hypothesis (H_1) suggesting the presence of a trend in the temperature/precipitation Index.

The Mann-Kendall test involves the following mathematical equations for calculations:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign\,(X_i - X_{i+1}) \quad (5)$$

Where n is the length of the data, X_i and X_{i+1} are consecutive data values and $sign(X_i - X_{i+1})$ is defined as:

$$sign(X_i - X_{i+1}) = \begin{cases} 1, if X_i > X_{i+1} \\ 0, if X_i = X_{i+1} \\ -1, if X_i < X_{i+1} \end{cases} \tag{6}$$

For $n \geqslant 8$, the statistic S is approximately normally distributed with mean

$$E(S) = 0 \tag{7}$$

And variance

$$Var(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum t_p\left(t_p - 1\right)\left(2t_p + 5\right)\right] \tag{8}$$

Where t_p is the number of data in a tied group, and p indicates the number of groups of tied ranks. Tied ranks occur in statistics when two or more items in a dataset have the same value. The standardized test statistic Z is calculated using the values of S and $Var(S)$ and is given by:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}}, if\ S > 0 \\ 0, \quad if\ S = 0 \\ \frac{S+1}{\sqrt{Var(S)}}, if\ S < 0. \end{cases} \tag{9}$$

3.3.3.3 Spatial Analysis to Detect Hotspots

Spatial analysis of mean climate serves as a powerful tool to unveil the systematic distribution of temperature and precipitation events across a study region, shedding light on the geographical nuances of climatic variations (Şen, 2017). This analytical approach provides valuable insights into the spatial variability in climate, facilitating informed decision-making by policymakers and researchers alike.

In this study, the total analysis period from 1981-2021 has been divided into two equal periods namely 1981-2000 and 2001-2021. The annual/seasonal trend value of the five indices was computed for each of the two periods and each of the grid cells of the study domain. A map for differences in the annual trends from 2001-2020 to 1981-2000 was created. The grid cells with the largest trend difference were spotted as hotspots of extreme weather events. Districts falling in the hotspots were identified to represent regions of priority for adaptations to climate change.

Incorporating spatial analysis into our research not only enhances our understanding of local /regional climate change patterns but also may provide critical information for devising climate adaptation and mitigation strategies. By scrutinizing the spatial distribution of temperature and precipitation means, we will be able to identify hotspots, assess the vulnerability of specific regions, and may contribute to the development of targeted climate policies. This approach will ensure that decision-makers are equipped with accurate and context-specific information, fostering more effective responses to the challenges posed by changing climatic conditions.

3.3.3.4 Computational Tools

- **Climate Data Operators (CDO):** Utilized for adept manipulation and analysis of climate data.
- **Python:** Employed for data processing, allowing for a flexible and tailored approach to the analysis.

3.4. Limitations and Challenges of the Study

A significant limitation of this study was the inability to utilize station data obtained from the Meteorological Department of Zambia. This was primarily attributed to the lack of information regarding how the data was gridded, inabling the making of definitive assertions about its reliability and suitability for analysis.

CHAPTER 4: RESULTS AND DISCUSSION

In this chapter, we present the statistical analysis and visualizations of ERA5 data and other observational data sets and provide a comparative discussion of the results obtained. The first part of this chapter presents results on the assessment of ERA5 against observations data GPCC, CRU, and GPCC. The assessment metrics consist of the monthly cycles, the inter-annual variability, and the spatial patterns of mean total precipitation and mean temperature of Zambia for the period 1981-2010. The second part of the chapter presents results on the annual/seasonal means of extreme precipitation and temperature events over Zambia for the periods 1981-2000 and 2001- 2021 and compares these means for assessing the rate of change of the extreme event.

4.1. Assessing the Performance of ERA5 in Reproducing the Climate of Zambia

4.1.1. Precipitation

4.1.1.1 Monthly Cycle

The annual mean monthly cycle of total rainfall from ERA5, GPCC, CRU, and GPCP datasets is illustrated in Figure 3, and their data values are indicated in Appendix 1. There is a good agreement between ERA5 and the other three observed datasets in capturing the monthly cycle. However, ERA5 indicates a slight wet bias for the NDJFM season. Nonetheless, all the datasets capture January as the month of peak rainfall. Furthermore, all the datasets are in agreement over the dry season MAMJJAS.

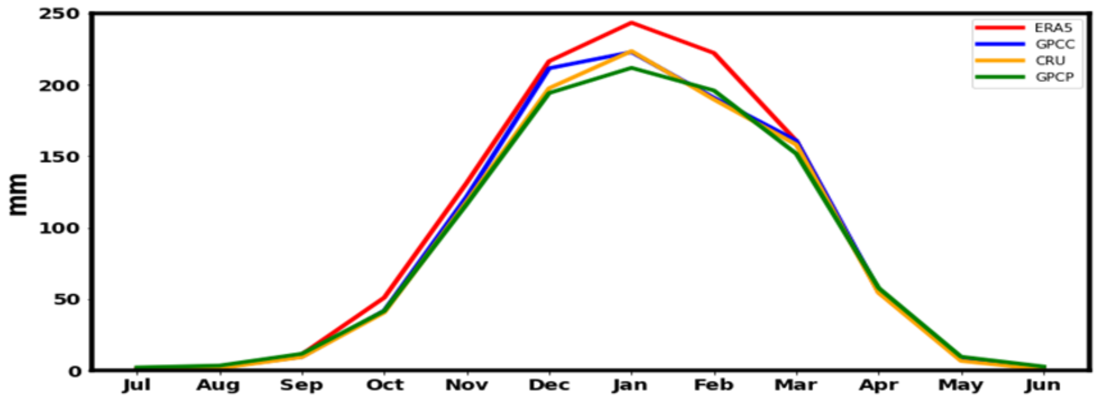


Figure 3: Mean monthly cycle of rainfall over Zambia for the period 1981-2010 from ERA5, GPCC, CRU and GPCP Observational data sets

4.1.1.2 Inter-annual Variability

Figure 4 shows a time series analysis of annual total rainfall over the ONDJFM season for the period 1981-2010. Data is presented in Appendix 2. All four data show strong agreement in inter-annual variability. However, ERA5 consistently mildly overestimates the total amount of rainfall, nonetheless, realistically reproduces inter-annual rainfall variability well. Generally, all data capture the extreme total annual rainfall influenced by El Nino events and La Nina events (e.g. El Nino 1986/1987 season).

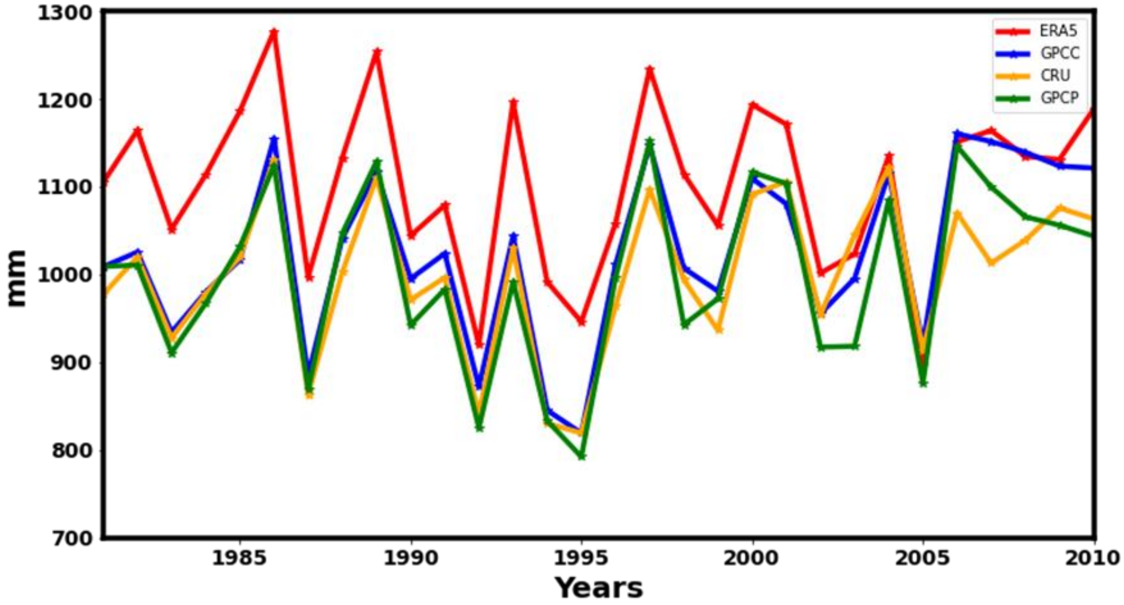


Figure 4: Time plots of annual total rainfall from ERA5 and other observational datasets observed rainfall for the period 1981 to 2010 over Zambia.

4.1.1.3 Spatial Variability

The spatial distribution of mean rainfall depicted in *Figure 5* for the ONDJFM season, for GPCC, CRU, and GPCP indicates that a significant amount of rainfall is received in the northern part, followed by the central part, and the least amounts are received in the southern parts of Zambia. This gradient distribution of rainfall across the country is captured by ERA5 as well. Still, ERA5 shows parches of wet and dry biases in certain parts of the country.

However, it is difficult to conclude these biases in different parts of the country. Therefore, the coefficient of correlation is determined between the spatially averaged annual total rainfall of ERA5 and each of the other three datasets, and its significance is tested at the 0.05 level of significance. The null hypothesis is that the correlation coefficient is zero, against the alternative hypothesis that the correlation coefficient is not zero. The Pearson coefficient of correlation was calculated between spatially averaged annual total rainfall for ERA5 and the other three datasets one at a time. Table 2 summarizes the correlations and their significance.

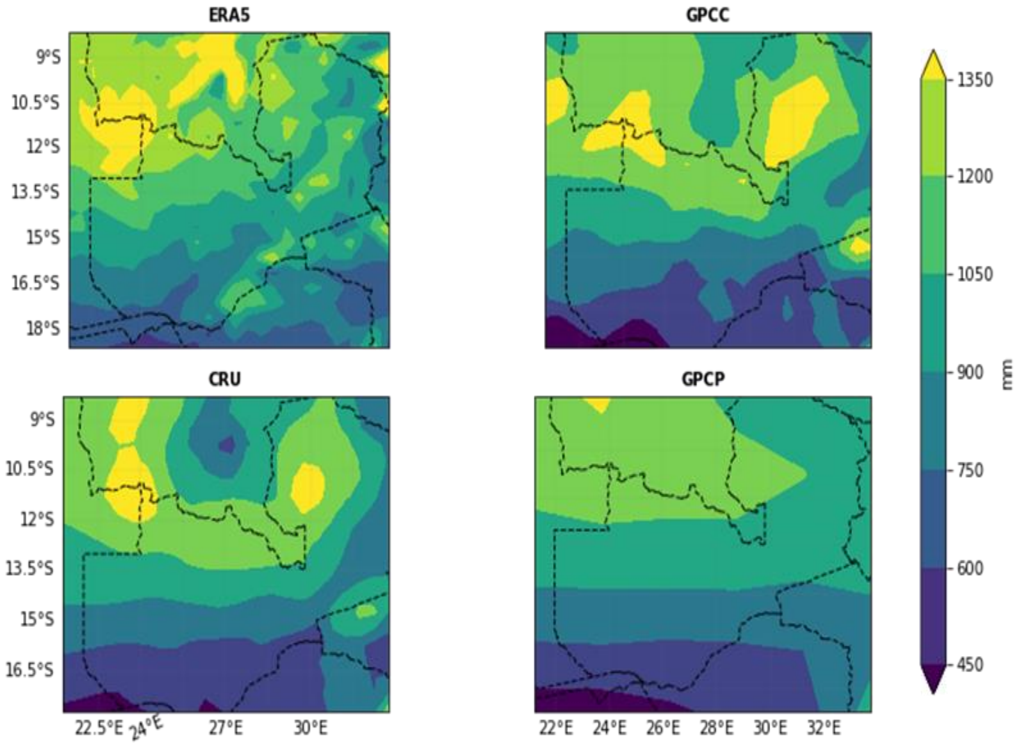


Figure 5: Spatial distribution of mean annual total precipitation (mm) over Zambia for the period 1981-2010 based on ERA5, GPCC, CRU and GPCP data sets.

There is a strong positive correlation (>.85) between ERA5 and the observed datasets as presented in Table 2.

Table 2: Coefficients of Correlation between annual total rainfall of ERA5 and each of GPCC, CRU, and GPCP. Bold values are significant at the 0.05 level.

Comparison	**Correlation**	**t-value**	***P*-Value (two-sided)**
GPCC - ERA5	0.850	8.384	< 0.001
CRU - ERA5	0.857	8.641	< 0.001
GPCP - ERA5	0.89	10.142	< 0.001

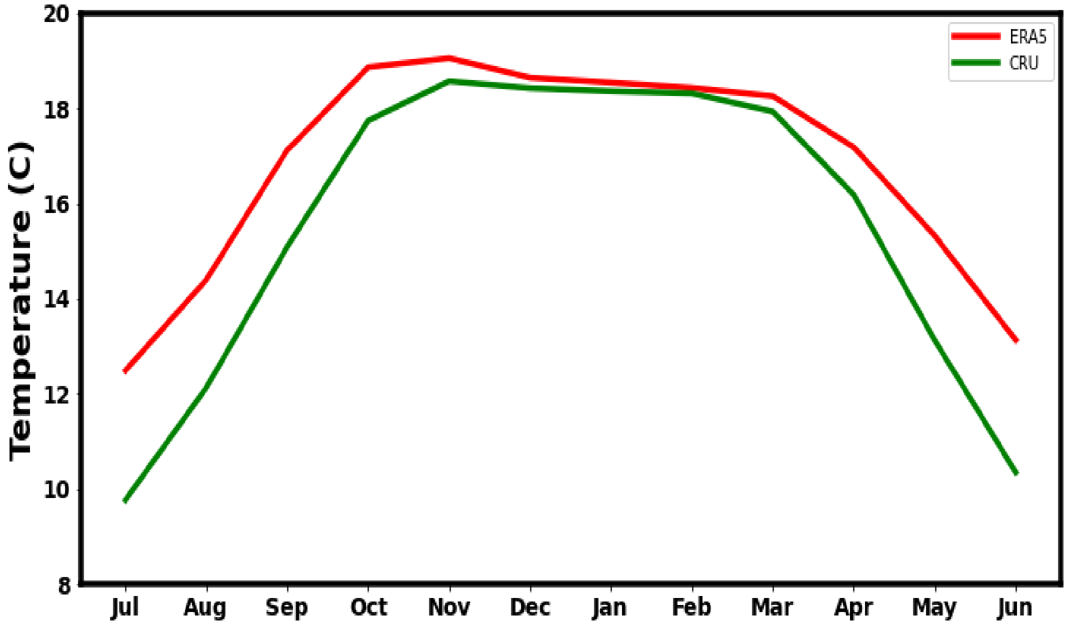
In general, ERA5 shows good agreement with the other three observed data sets in representing the annual mean monthly rainfall cycle, inter-annual variability, and spatial distribution of mean rainfall of Zambia despite mild wet biases.

4.1.2 Surface Temperature

4.1.2.1 Mean Monthly Cycle

Figures 6a and 6b illustrate the comparison between ERA5 and CRU in representing the annual mean monthly cycles of minimum temperature (6a) and maximum temperature (6b) for the period 1981-2010 and their data values are presented under Appendix 1. Results show that ERA5 replicates the monthly patterns relatively well, albeit with a hot bias for minimum temperature and a colder bias for maximum temperature. The biases in minimum temperature are smaller in magnitude than in maximum temperature. For minimum temperature, there are no biases for NDJFM which is the summer season, while for maximum temperature consistently under-represented for all seasons.

Figure 6a: Annual cycle of the monthly mean minimum temperature over the period 1981-2010



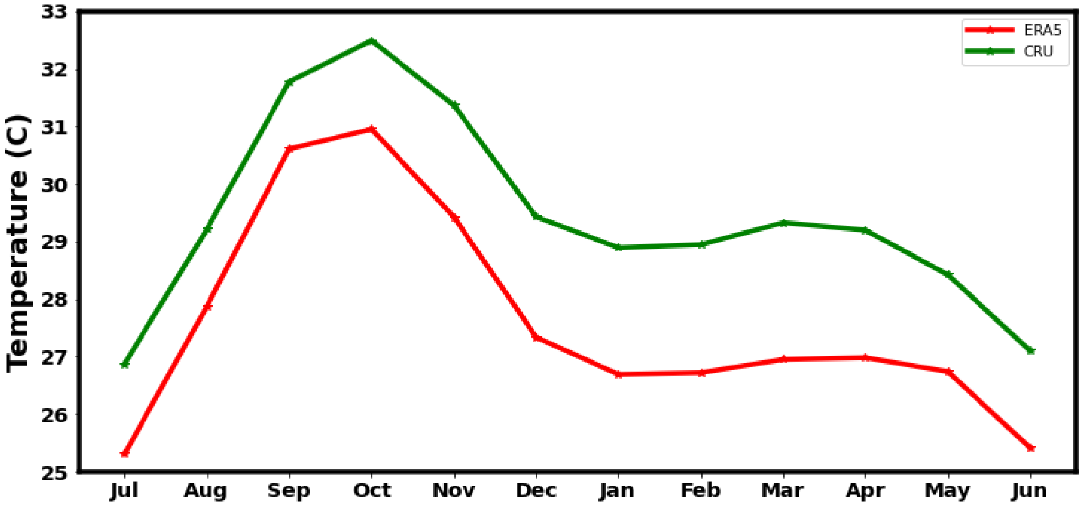
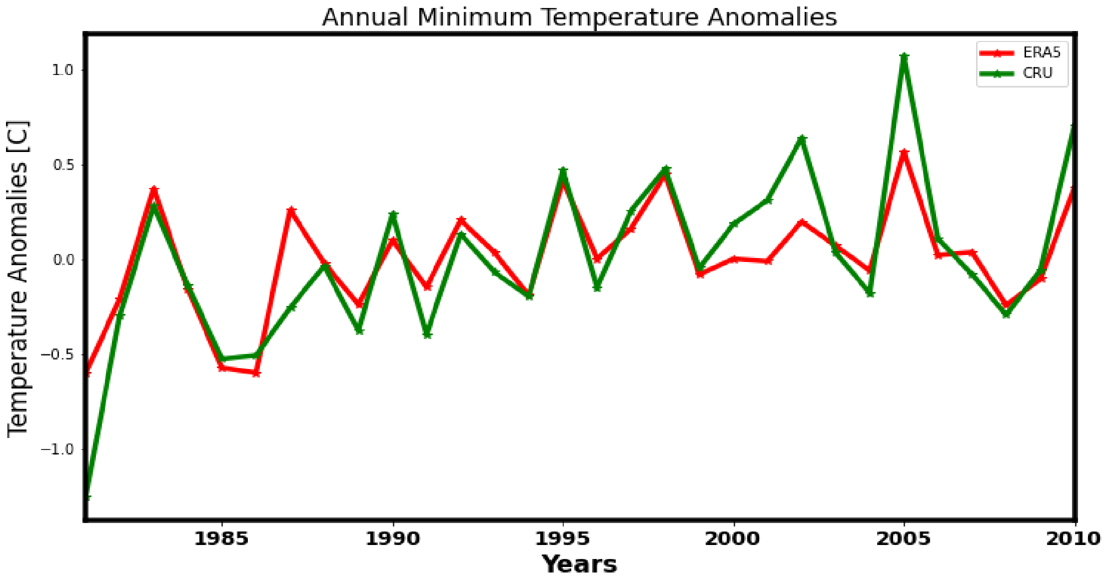


Figure 6b: Annual cycle of the monthly mean maximum temperature over the period 1981-2010.

4.1.2.2 Inter-annual Variability

The year-to-year variability of ERA5 minimum temperature and maximum temperature are depicted in *Figures 7a and 7b* respectively and their data values are presented in Appendix *3*. The analysis of minimum temperature was over the winter AMJJA season, while the maximum temperature was over the summer ONDJFM. ERA5 reproduces the pattern of year-to-year variability of CRU more closely for maximum temperature than for minimum temperature (*Fig. 7a &7b*). There are fewer biases and of lower magnitude in maximum temperature compared to minimum temperature. Overall, there is good agreement in inter-annual minimum and maximum surface temperature in EREA5 and CRU.

Figure 7a: Time series of ERA5 and CRU seasonal minimum temperature anomalies (C) concerning mean minimum temperature for the period 1981-2010 and the season AMJJA.



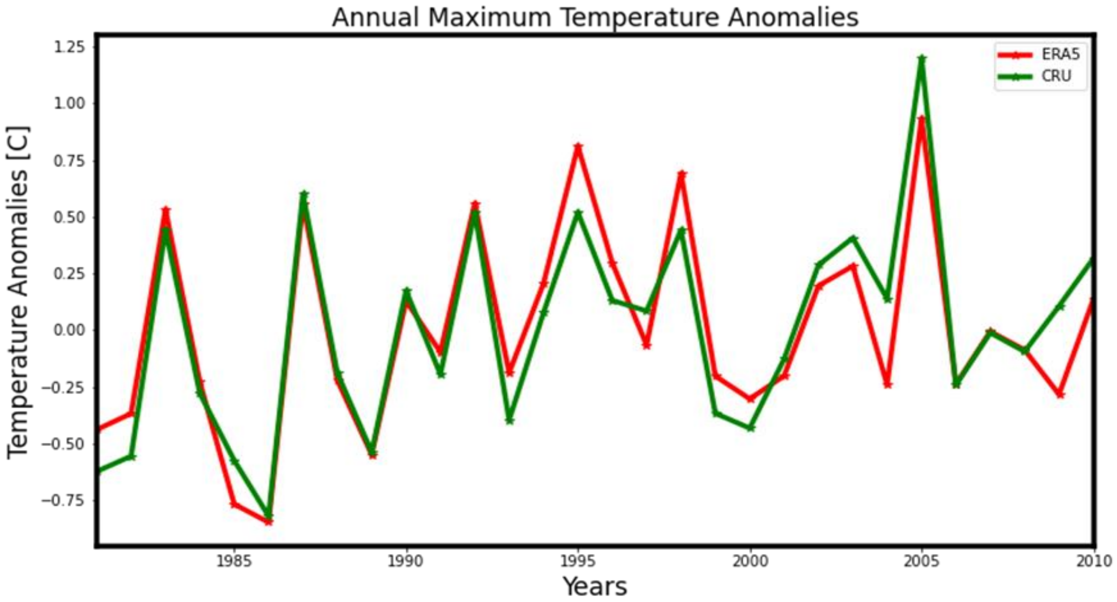


Figure 7b: Time series of ERA5 and CRU maximum temperature anomalies (C) with respect to the mean maximum temperature for the period 1981-2010 and the season ONDJFM

4.1.2.3 Spatial Variability

Further assessment was done on the ability of ERA5 to represent the spatial distribution of temperature over Zambia. *Figure 8* shows the spatial distribution of the mean minimum temperature for the seasons AMJJA.

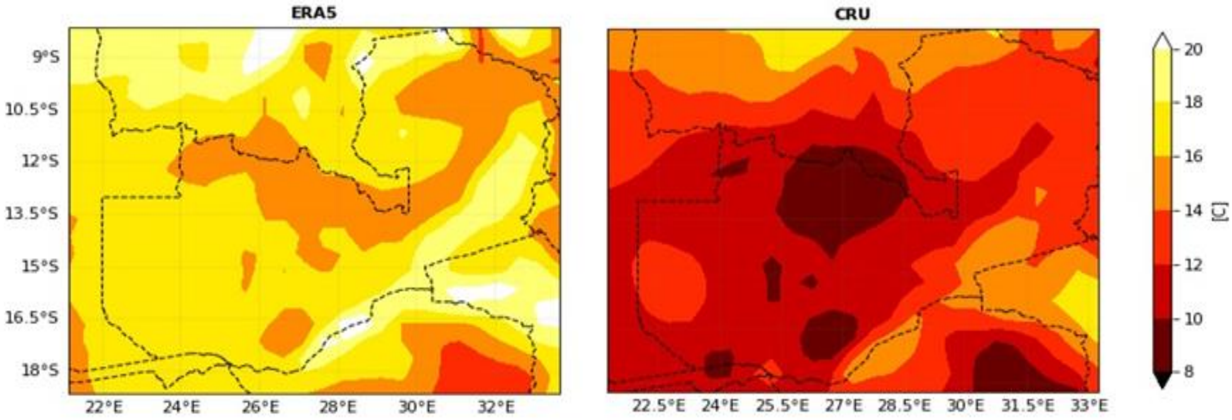


Figure 8: Spatial distribution of minimum temperature of ERA5 and CRU over the AMJJA season for the period 1981 - 2010

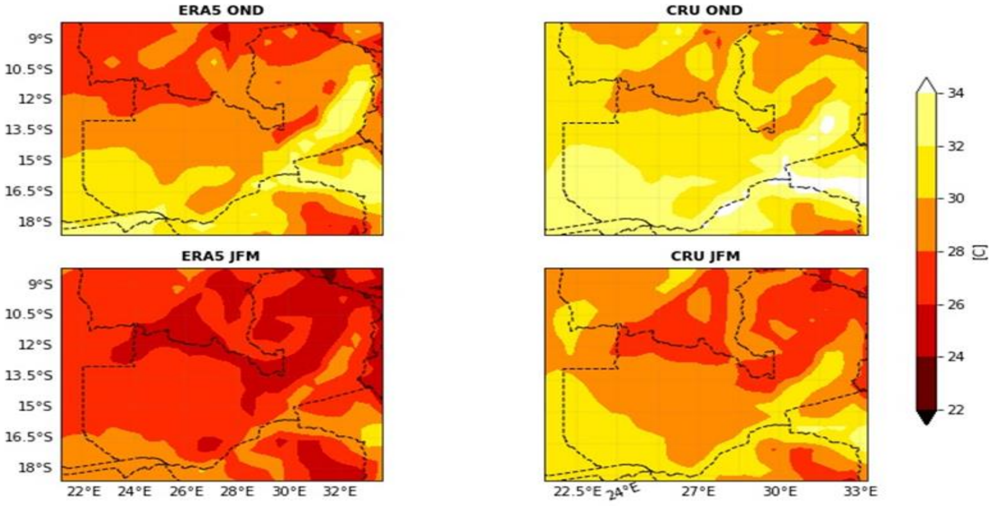


Figure 9: Spatial distribution of maximum temperature of ERA5 and CRU over ONDJFM season for the period 1981 - 2010.

Maximum temperature is the mean of summer months ONDJFM. The first half of this period is usually mild wet whereas the second half is very wet. Hence the ONDJFM is split into two subseasons and the maximum temperature is analyzed for the mean of OND and JFM.

ERA5 and CRU capture well the spatial distribution of minimum temperature and maximum temperature of Zambia (*Figure 8 & Figure 9*). The spatial patterns of ERA5 are similar to that of

CRU, however, ERA5 overestimates the mean minimum temperature across the country in comparison to CRU (*Figure 8*). While, for maximum temperature, ERA5 is in agreement with CRU over certain regions of Zambia especially in OND season in the southern parts of the country (*Figure 9*). Similarly, during JFM spatial distribution of maximum temperature of ERA5 agrees with CRU with little positive bias.

The correlations of seasonal minimum temperatures of Zambia between ERA5 and CRU data are very high (r > **0.8**) and the maximum temperature of Zambia between ERA5 and CRU data is equally very high (**r>0.9**) (Table *3)* indicating the capability of ERA5 in reproducing the temperature (minimum and maximum) climatology of Zambia.

Table 3: Coefficient of correlation between seasonal maximum and minimum temperature of ERA5 and CRU. Bold values are significant at the 0.05 level.

CRU-ERA5	**Minimum Temperature**	**Maximum Temperature**
Correlation	**0.871**	**0.925**
t-value	9.212	12.650
P-Value	< 0.001	< 0.001

In summary, ERA5 has shown good agreement with CRU in all three metrics of assessment for surface temperature: annual monthly cycles, the inter-annual variability, and spatial distributions while showing hot and cold biases for minimum and maximum temperature respectively. These findings are consistent with results found by other researchers e.g. Choudhury et al (2023) and Zhao et al (2023) for Australia and the Qilian mountains of China respectively.

4.2. Annual Trends in the Extreme Weather Events for the Three Climate Zones

4.2.1 Frequency of days with maximum temperature exceeding 35°C

Annual trends in the number of days in a year (1 July to 30 June) exceeding temperature 35° C for periods 1981-2000 and 2001-2021 for three climatic zones are presented in Figure 10. Concurrently, Table 4 provides Sen's slopes, Mann-Kendall statistical test result (s), and other appropriate statistical values for the studied index across the three climatic zones of Zambia. Additionally, the frequencies of days with maximum temperatures exceeding 35°C for periods 1981 to 2000 and 2001 to 2021are detailed in APPENDIX 5.

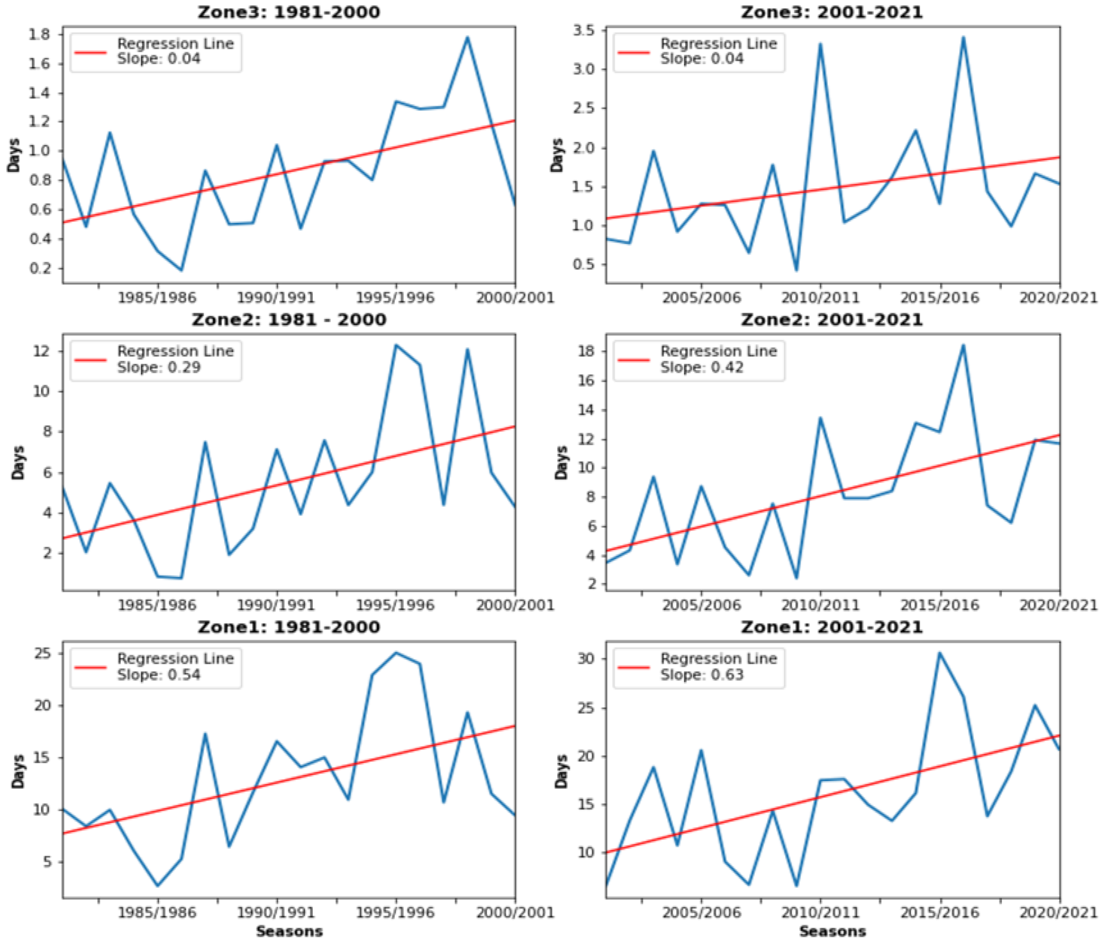


Figure 10: Trend lines for the annual frequency of days with maximum temperature exceeding **35**°*C*

The examination of the annual frequency of days with maximum temperatures exceeding 35°C across Zambia's climatic zones reveals a pronounced increasing trend over time. The annual number of days with maximum temperature exceeding 35°C is increasing at a constant rate (0.04) in zone 3 for both periods (1981-2000 and 2001-2021). Climatic zone 2 shows increasing trends for both periods (1981-2000 and 2001-2021) with the later period (2001-2021) warming at a faster rate (0.42). Zone 1 equally indicates increasing trends for both periods (1981-2000) and 2001-2021 with the later period warming at a much faster rate (0.63). In general, Climatic zone 1 is warming at a faster rate followed by zone 2 while zone 3 is warming at a constant rate for the two periods. Statistical analysis indicates the significance of this upward trend in all three Zones for the period 1981-2000 and in Zone 1 for the period 2001-2021 each at a 5% level of significance. Trends significant at 5% are shown in bold numbers (Table 4).

Table 4: Mann-Kendall trend analysis for frequency of days with maximum temperature exceeding 35°C

Period	**1981-2000**			**2001-2021**		
	Slope	**Z**	**P-value**	**Slope**	**Z**	**P-value**
Zone 3	**0.04**	2.174	0.030	0.04	1.623	0.105
Zone 2	**0.29**	2.044	0.041	0.42	1.948	0.051
Zone 1	**0.54**	1.979	0.048	**0.63**	2.304	0.021

The vulnerability of agriculture-dependent regions to temperature extremes is a shared concern, emphasizing the need for adaptive strategies tailored to specific regional impacts. The interconnectedness of temperature trends with agriculture, water resources, and socio-economic aspects underscores the multifaceted impact of climate change on Zambia's climatic zones.

4.2.2 Annual mean maximum daily temperature

Annual trends in the mean maximum daily temperature for periods 1981-2000 and 2001-2021 for three climatic zones are presented in Figure 11. Correspondingly, Table 4 presents Sen’s slopes, Mann-Kendall statistical test results, and other relevant statistical parameters for the annual maximum daily temperature across the three climatic zones of Zambia for the periods 1981-2000 and 2001-2021.

Furthermore, annual mean maximum daily temperature values obtained from ERA5 data are provided in APPENDIX 6.

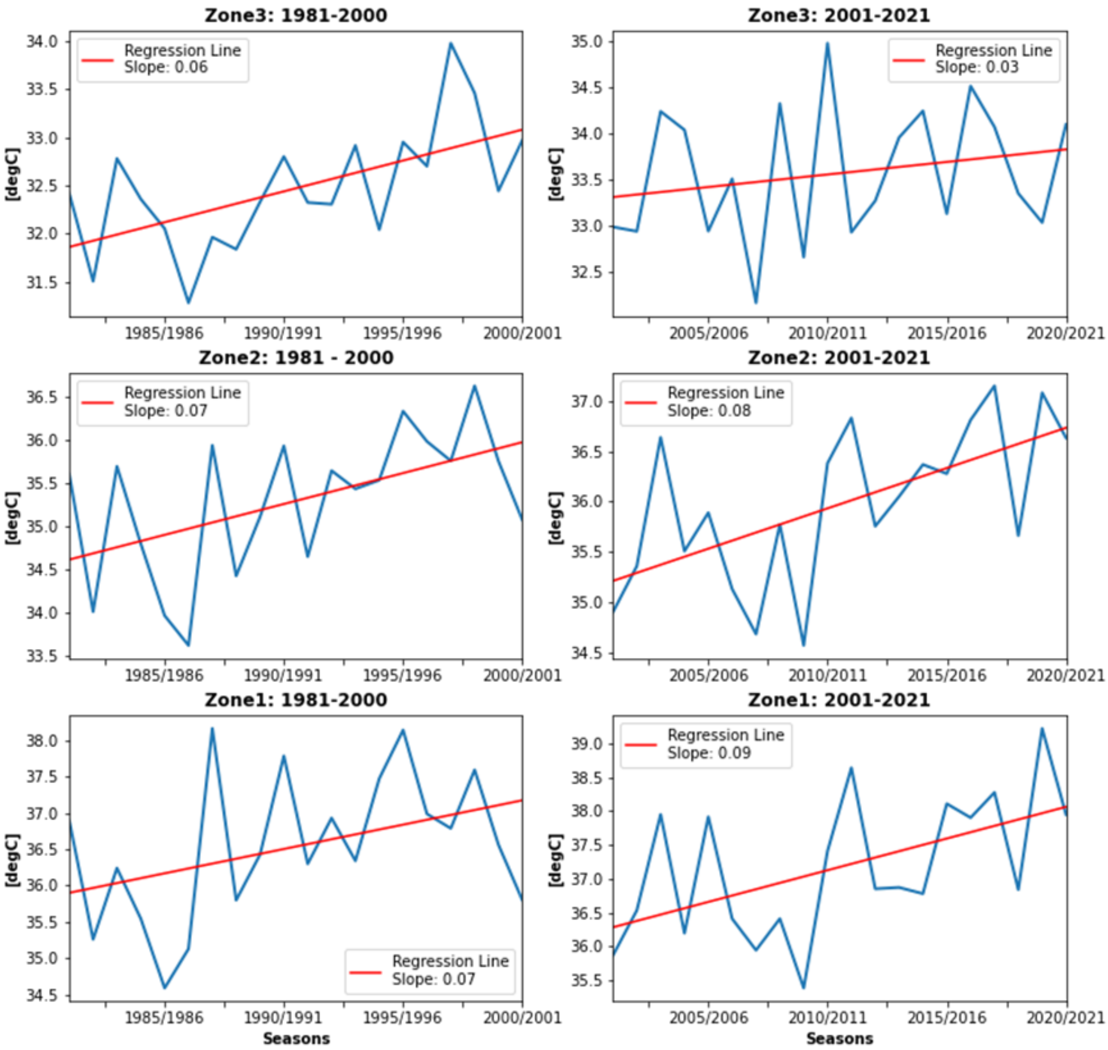


*Figure 11: Trends in annual mean maximum daily temperature for the period 1981-2000 and 2001-2021***.**

The analysis of annual mean maximum daily temperatures across Zambia's three climatic zones reveals a measurable upward trend during both the former period (1981-2000) and the more recent period (2001-2021). Climatic zone 3 shows increasing trends for both periods (1981-2000 and 2001-2021) with the former period indicating to have been warming at a faster rate of 0.06° C per year and the later period with warming at the rate of 0.03° C per year. Zone 2 indicates that the later period (2001-2021) is warming at a faster rate (0.08° C) than the former period with a warming rate of 0.07° C per year. Climatic zone 1 shows that the later period is warming at a faster rate of 0.09° C per year than the warming of 0.07° C per year in the former period. Generally, warming is happening at the fastest rate in Zone 1 followed by Zone 2. Statistical analysis indicates the significance of this upward trend, notably in Zone 2 and Zone 3 for the period 1981-2000 and in Zone 1 and Zone 2 for the period 2001-2021, each at a 5% level of significance. Trends significant at 5% are shown in bold numbers (Table 5).

Table 5: Mann-Kendall trend analysis for annual maximum daily temperature.

Period	**1981-2000**			**2001-2021**		
	Slope	**Z**	**P-value**	**Slope**	**Z**	**P-value**
Zone 3	**0.06**	2.433	0.015	0.03	1.006	0.315
Zone 2	**0.07**	2.044	0.041	**0.08**	2.498	0.012
Zone 1	0.07	1.655	0.098	**0.09**	2.368	0.018

Notably, the rate of annual mean maximum daily temperature increase exhibits a gradient from South to North, with Zone 1 displaying the highest estimates of 0.07°C and 0.09°C of annual trends in the two sub-periods. This suggests a magnification of temperature trends as one moves from Zone 3 to Zone 1. In terms of absolute values, Zone 1 consistently records the highest annual mean maximum daily temperature values, followed by Zone 2 and, lastly, Zone 3 across all periods.

The consistently increasing trends in annual mean maximum daily temperatures in Zambia's climatic zones highlight the need for comprehensive climate adaptation strategies. The vulnerability of key sectors such as agriculture, water resources, and socio-economic stability underscores the urgency of proactive measures.

4.2.3 Seasonal total rainfall

The analysis of trends in seasonal total rainfall also spans two distinctive periods, the baseline period (1981-2000) and the recent period (2001-2021). Figures 12a and 12b show the observed seasonal trends of total seasonal rainfall for the seasons OND and JFM respectively. Simultaneously, Tables 6a and 6b compile and compare relevant statistical information, including Sen's slopes, Mann-Kendall statistical test results, and other relevant parameters across the three climatic zones of Zambia for the baseline period 1981-2000 and the later period 2001-2021. Additionally, a comprehensive breakdown of the seasonal total rainfall for the seasons OND and JFM is provided in APPENDIX 7.

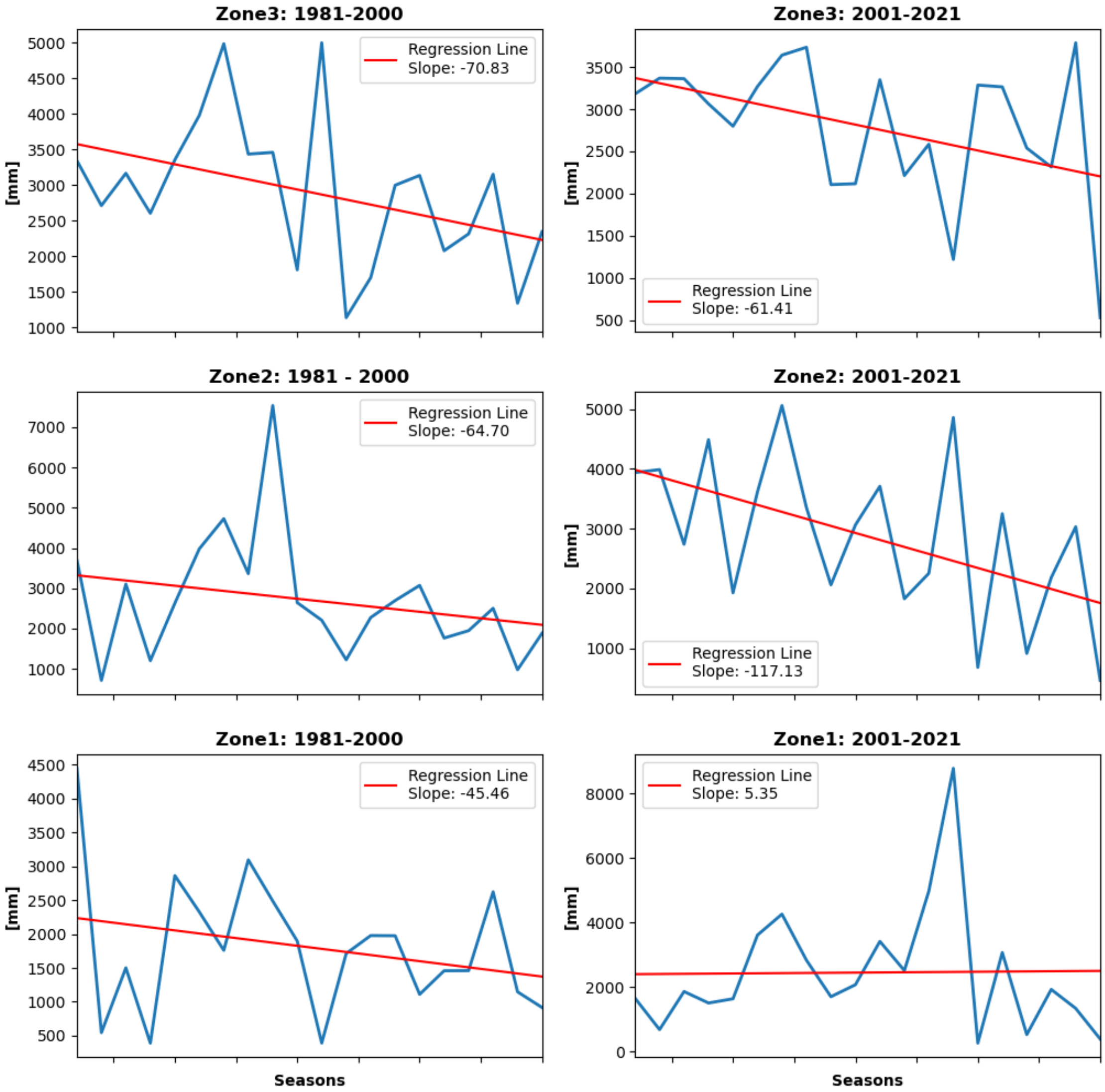


Figure 12a: Annual trends in seasonal total rainfall for the period 1981-2000 and 2001-2021 over the OND season.

An examination of the seasonal total rainfall across Zambia's climatic zones three and two over the season OND reveals a pronounced decreasing trend with time for both the baseline period (1981-2000) and the later period (2001-2021). However rate of decrease for zone three is indicating less drier conditions in the latter half of the period. Zone two shows that the seasonal trend for both periods is negative. However drying increases from the former period to the later period. Zone 1 shows a decreasing trend in seasonal total rainfall in the former period but the direction of trend changes in the later period indicating wetter conditions as time increases. Generally, Zone 2 is getting drier whereas Zone 1 and 3 are showing better performance of the season in the later half. Trends significant at 5% are shown in bold numbers (table 6a).

Table 6a: Mann-Kendall trend analysis for seasonal total rainfall over OND

Period	**1981-2000**			**2001-2021**		
	Slope	**Z**	**P-value**	**Slope**	**Z**	**P-value**
Zone 3	-70.83	-1.460	0.1442	-61.41	-1.395	0.1630
Zone 2	-64.70	-1.395	0.1630	**-117.13**	-2.2387	0.0252
Zone 1	-45.46	-1.136	0.2561	5.35	-0.0324	0.9741

The later half of rain season in Zambia is JFM which is experiencing a decreasing seasonal rainfall trend across all the three climatic zones (figure 12b). Zone 3 has a positive trend of 44 mm/ season of total rainfall in the period 1981-2000 but the trend changes to decreasing seasonal rainfall at the rate of 29 mm per season in the period from 2001 to 2021. Zone 2 presents the same scenario. Here JFM's total rainfall trend is decreasing from a gain of 27/season from 1981 to 2000 to decreasing at the rate of 19 mm/season during the period 2001 to 2021. Total JFM rainfall in Zone 1 is increasing at the rate of 14 mm per season. However, the increasing trend reduces to .98 mm/season indicating drier conditions in the later period.

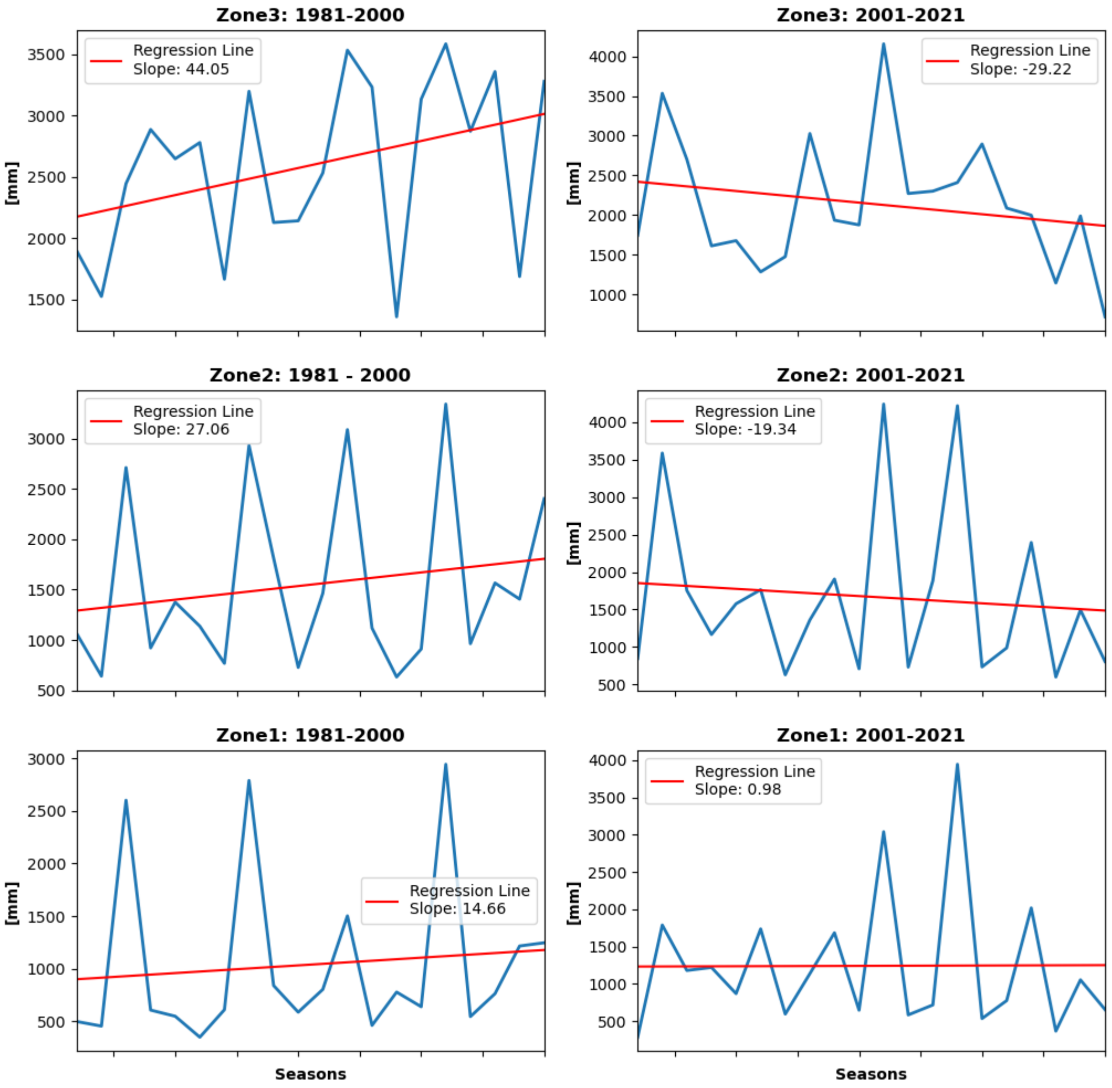


Figure 12b: Annual trends in seasonal total rainfall for the period 1981-2000 and 2001-2021 over the JFM season

Notably, the OND season is getting drier faster than JFM. An examination of seasonal total rainfall trends within Zambia's climatic zones offers a refined perspective, revealing a complex interplay of temporal dynamics. Statistical analysis through the Mann-Kendall test indicates that the general rise and fall observed across all three zones and study periods do not attain significance at the conventional 5% threshold (Table 6b).

Table 6b: Mann-Kendall trend analysis for seasonal total rainfall over JFM

Period	**1981-2000**			**2001-2021**		
	Slope	**Z**	**P-value**	**Slope**	**Z**	**P-value**
Zone 3	44.05	1.914	0.0556	-29.22	-0.487	0.6265
Zone 2	27.06	0.9409	0.3468	-19.34	-0.423	0.6732
Zone 1	14.66	1.5898	0.1119	0.98	-0.552	0.5813

4.2.4 Number of days in a season when daily rainfall exceeds 20mm

World Meteorological Organization (WMO) recommends that daily rainfall exceeding 20mm is an extreme rainfall event. Therefore in this study, thresholds of 20mm and 30 mm on daily rainfall are utilized.

For the trend analysis of the number of days in a rainfall season with daily rainfall exceeding 20mm, Figure 13 outlines the observed seasonal trends associated with this daily rainfall threshold spanning the periods 1981-2000 and 2001-2021. Table 7 consolidates crucial statistical information, including Sen slopes and Mann-Kendall statistical test results across the three climatic zones of Zambia for the periods 1981-2000 and 2001-2021. Detailed information on the seasonal frequencies of days with daily rainfall exceeding 20mm is presented in APPENDIX 8.

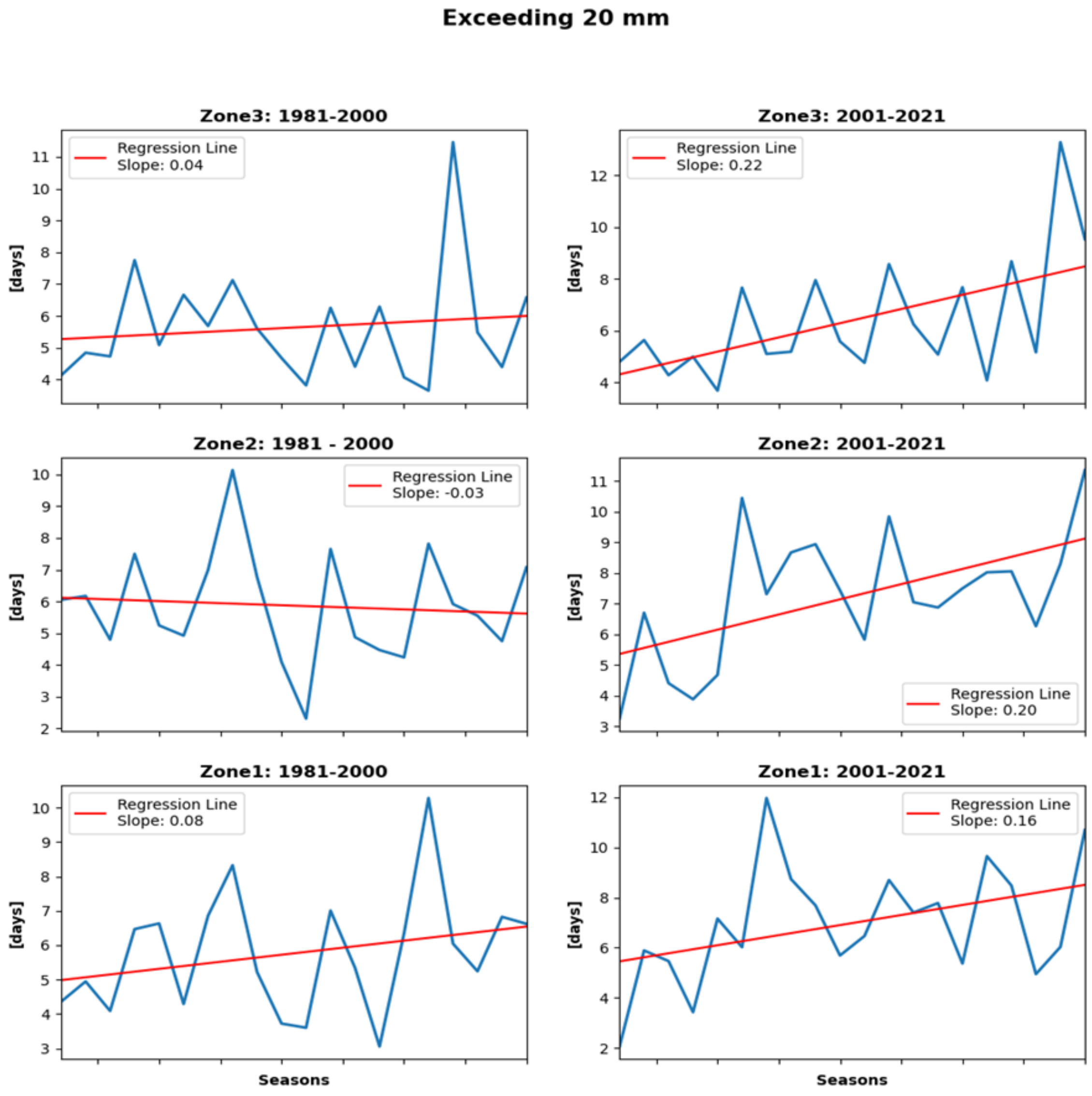


Figure 13: Seasonal trends in the number of days when daily rainfall is exceeding 20mm over ONDJFMA season. 1981-2000 and current period2001-2021 over ONDJFMA season.

There are generally increasing trends in the number of days with rainfall exceeding the 20 mm threshold across all three climatic zones for both periods (1981-2000 and 2001-2021) except zone 2 exhibiting a decreasing trend during the former period (1981-2000). The observed trends also demonstrate an increase in the frequency of daily rain of more than 20 mm as one moves from zone 1 to zone 3, indicating that these extreme rainfall events are increasing faster as there is movement from south towards north in Zambia. In the later period (2001-2021), a discernible increasing trend points to a higher frequency of heavy rainfall events, aligning with the broader context of climate change. This provides valuable insights into precipitation patterns across the three climatic zones of Zambia.

Statistical analysis through the Mann-Kendall test indicates that the increasing trends observed across zones 2 and 3 of the later period (2001-2021) attain significance at the 5% threshold. Trends significant at 5% are shown in bold numbers (Table 7).

Table 7: Mann-Kendall trend analysis for number of days when daily rainfall exceeds 20mm

Period	**1981-2000**			**2001-2021**		
	Slope	**Z**	**P-value**	**Slope**	**Z**	**P-value**
Zone 3	0.04	-0.162	0.871	**0.22**	2.304	0.0212
Zone 2	-0.03	-0.357	0.721	**0.20**	2.368	0.018
Zone 1	0.08	1.006	0.315	0.16	1.655	0.098

4.2.5 Number of days in a season when daily rainfall exceeds 30mm

The observed trends associated with the number of days of the event when daily rainfall exceeds the 30mm threshold for the periods 1981–2000 and 2001–2021 are shown in Figure 14. On the other hand, Table 8 consolidates crucial statistical information, including Sen’s slopes and Mann-Kendall statistical test results (s), Data on the frequency of this event in seasons from 1981 to 2021 is provided in APPENDIX 9.

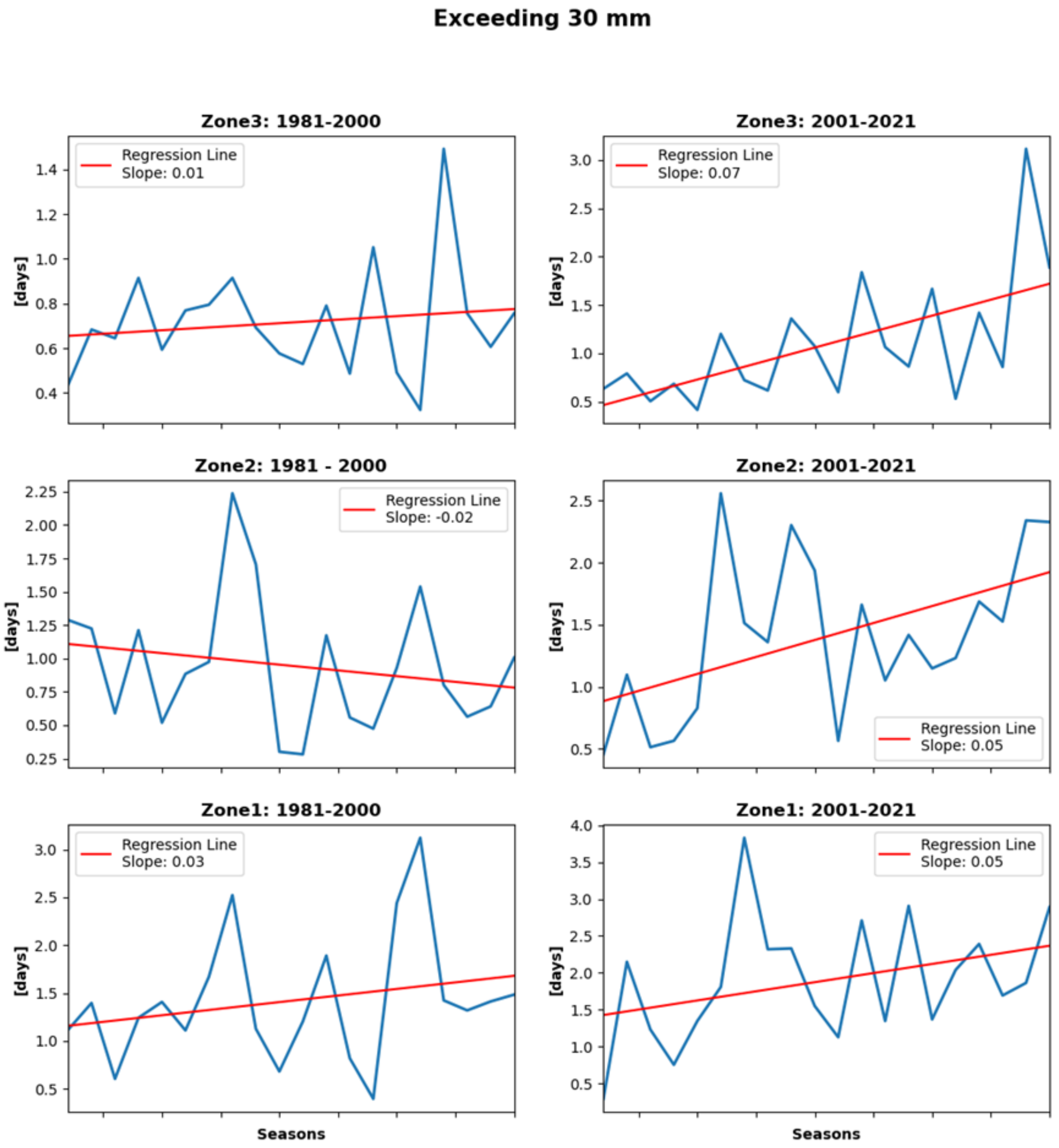


Figure 14: Trends in the number of days when daily rainfall is exceeding 30mm for the baseline period 1981-2000 and 2001-2021 over ONDJFMA season.

All three climatic zones show generally rising seasonal trends in the number of days with rainfall above the 30mm threshold for both the 1981-2000 and 2001-2021 periods except zone 2 indicating a decreasing trend for the 1981-2000 period (Figure 14). The seasonal trend from the former period to the latter across all three zones is also increasing hinting that these extreme events are becoming more frequent as time moves ahead. Another noticeable feature of this event is that the seasonal trend of the event is increasing from south to north indicating more flash flooding occurring in the north as compared to the south.

Table 8 presents the seasonal trends of the number of extreme rainfall events when daily rainfall exceeds 30 mm for the three climatic zones and two sub-periods. Trends significant at 5% are shown in bold numbers.

Table 8: Mann-Kendall trend analysis for number of days when daily rainfall exceeds 30mm

Period	**1981-2000**			**2001-2021**		
	Slope	**Z**	**P-value**	**Slope**	**Z**	**P-value**
Zone 3	0.01	0.032	0.974	**0.07**	2.368	0.018
Zone 2	-0.02	-0.876	0.381	**0.05**	2.467	0.014
Zone 1	0.03	1.330	0.183	0.05	1.883	0.060

Additionally, our thorough examination of precipitation extremes at the 30mm threshold provides insightful information on how rainfall patterns are changing over the three climatic zones of Zambia.

Summing up together the annual/ seasonal trends in extreme temperature and rainfall events, it is seen that all three climatic zones are getting warmer with time. However, the rate of warming is higher in the south as compared to the north that is south is getting warmer faster than the north of the country. Rainfall analysis shows that total seasonal rainfall is decreasing in all three climatic zones during the period 1981 to 2000. Further total seasonal rainfall in Zone 2 continues to reduce in the later period where whereas total seasonal rainfall in Zone 1 and Zone 3 shows better performance in the later period. The extreme rainfall events of daily rainfall of more than 20 mm and 30 mm are also increasing with time in all three climatic zones and the rate of increase also rises from south to north.

4.3. Spatial analysis of extreme weather events

It is seen in Section 4.2 that the five extreme weather events considered in this study have been getting more frequent and more severe over Zambia in recent years but with varied rates over the three climatic zones. Economies design and implement adaptation strategies to reduce the negative impacts of extreme weather events and gain resilience. Due to limited resources, the government usually focuses on administrative units which are most hit by the occurrence of extreme weather events. In Zambia, level 1 administrative units are provinces and level 2 administrative units are districts. This section highlights the districts that are most impacted by the occurrence of the extreme weather events under consideration.

4.3.1 Frequency of days with maximum temperature exceeding 35°C

The difference in the annual trend of the number of days with a maximum temperature of more than 35° C for the period 2001-2021 from the corresponding trend for the period 1981-2000 is presented in Figure 15. Districts with red color are experiencing an increasing number of days annually when the daily maximum temperature exceeds 35° C.

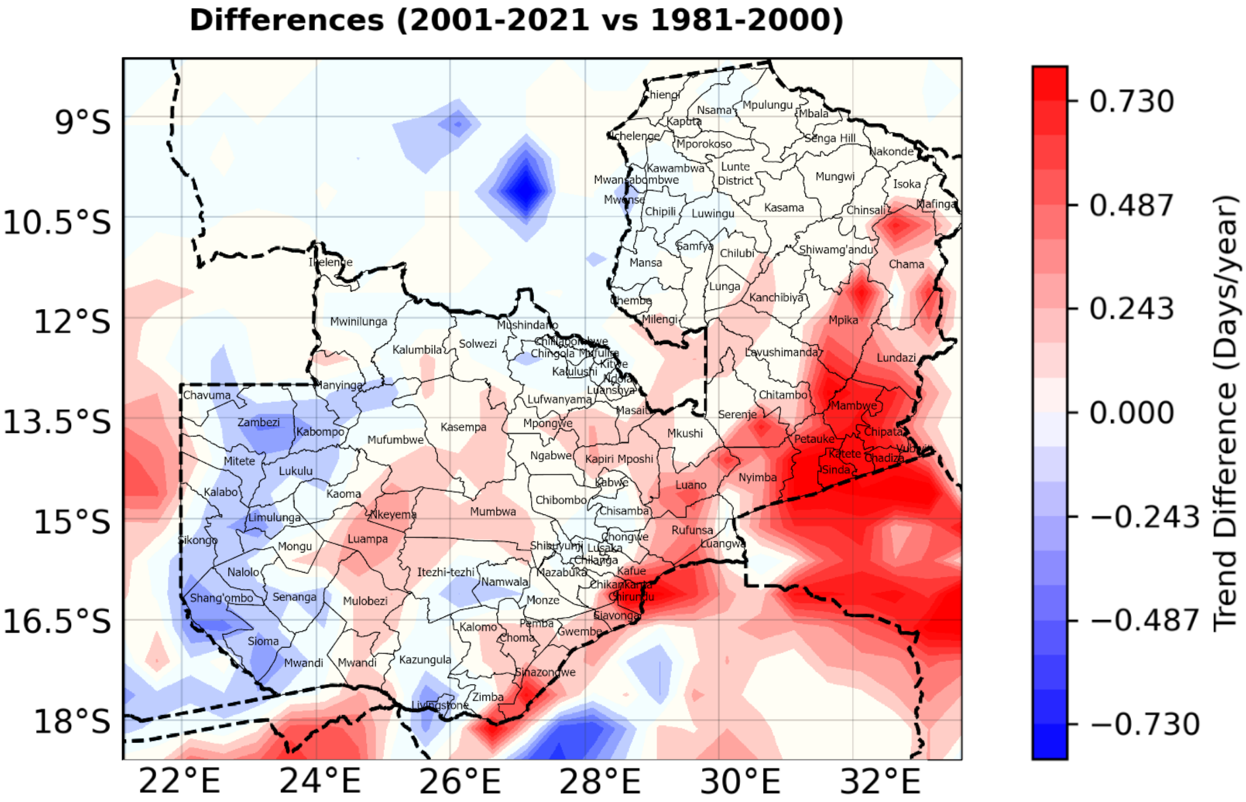


Figure 15: Difference of annual trend in the number of days when maximum temperature exceeds 35°C for the period 2001-2021 from the corresponding trend for 1981-2000

Extreme hot days (daily maximum temperature more than 35°C) are increasing per year in the periods 1981-2000 and 2001-2021 over almost the entire Zambia. However, the trends (rate of increase per year) are different for the two periods over different regions of Zambia. The difference in the trend from the later period to the earlier period is lowest (between -0.487 and -0.243 days per year) in the districts Zambezi, Limulunga (partly), Shang'ombo, and partly Sioma (Figure 15) which indicates that hot days per year are increasing annually in both periods but at slower rate in the later period as compared to the former period. This is followed by trends difference between -0.243 to 0.000 and 0.000 to 0.243 for the number of days per year when maximum temperature exceeds 35°C These differences indicate that the annual trends remain closely the same for the former period and the current period. Meanwhile, the trend difference between 0.243 and 0.730 holds for districts

Sinazongwe, Chirundu, Kafue, Rufunsa, Luano, Nyimba, Serenje(partly), Petauke, Sinda, Katete, Chipata, Chadiza, Vubwi, Mambwe, Lundazi, Mpika, and Chama indicates that these districts are the hottest spots for increasing rate of trend for the event under consideration.

These findings are in agreement with Chisanga et al (2017) who investigated trends of extreme weather events in precipitation and temperature at Mt Makulu. , The findings of their study showed a significant increasing trend of extremely warm (daily temperature >35°C) days despite being limited to only one station.

4.3.2 Annual maximum daily temperature

The difference in the annual trend in maximum daily temperature for the period 2001-2021 from the corresponding annual trend for the period 1981-2000 is presented in Figure 16.

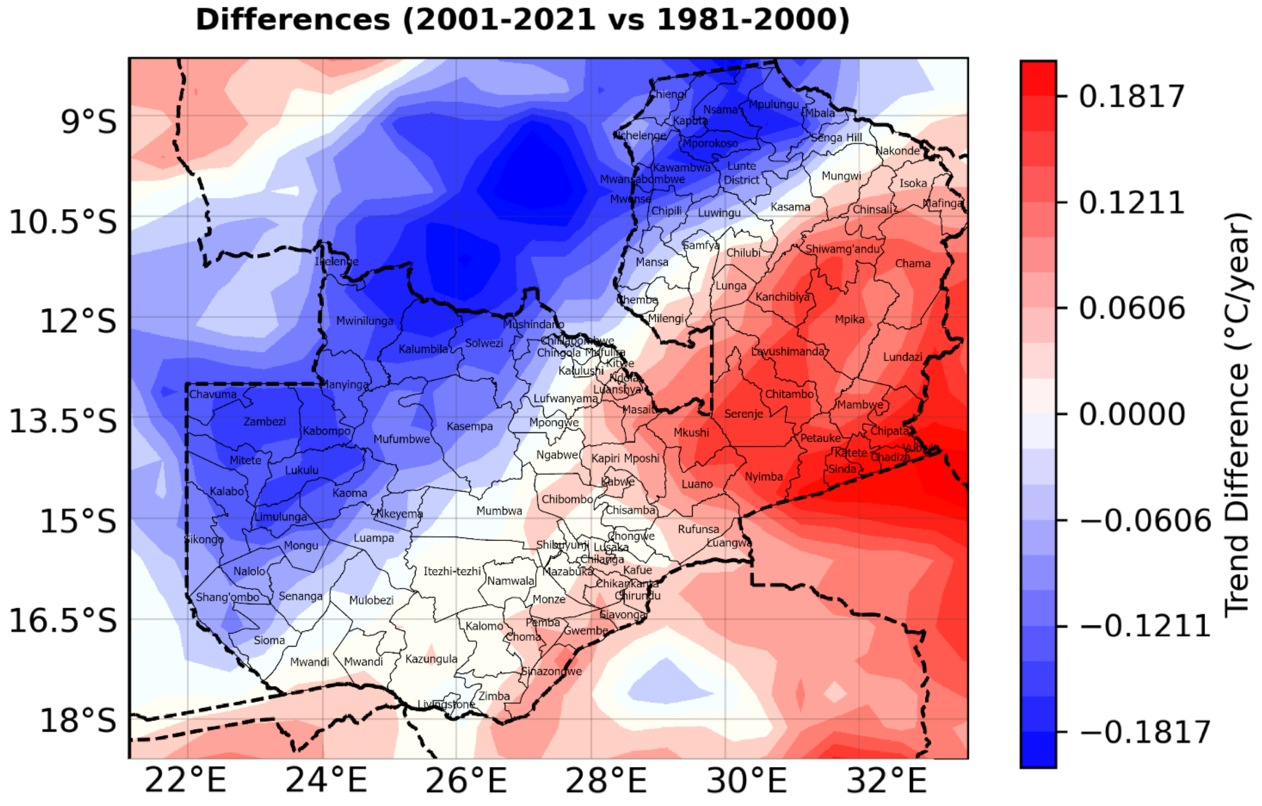


Figure 16: Difference of annual trend of the daily maximum temperature for the period 2001-2021 from 1981-2000.

The daily maximum temperature is increasing over all the regions of Zambia during the period 1981-2000 and 2001-2021but at different rates. Daily maximum temperatures in most districts in the North and North West regions of the country are also increasing but at a decreasing rate (increasing in the former period and decreasing in the later period) from the period 1981-2000 to 2001-2021. The difference in the annual rate of decrease from the former period to the latter ranged between -0.1817 and -0.0606 degrees Celsius. This implies that warming is happening in the districts mentioned above at a lower rate with time. Across the central region of Zambia, the difference in the rate of change of warming from the former period to the latter ranges from -0.0606 to 0.0606 degrees Celsius per year indicating the rate of warming is nearly the same in the two periods. The eastern region predominantly consists of districts which are hot spots for the increase in the annual maximum daily temperature where warming is happening at a faster rate (0.1211 to 0.1817 degrees Celsius per year more in the period 2001-2021 from the period 1981-2000). These districts include Mkushi, Serenje, Chitambo, Lavushimanda, Kanchibiya, Shiwang'andu, Mpika, Nyimba, Petauke, Sinda, Katete, Mambwe, Chipata, Chadiza, Vubwi, Lundazi and Chama.

Chabala et al (2013) investigated the characterization of temporal changes in rainfall, temperature, flooding hazard, and dry spells over Zambia. The study considered five stations (Choma, Petauke, Mpika, Serenje, and Chipepo) and its findings generally showed that mean temperature had an increasing trend. This is in agreement with the IPCC publications which repeatedly emphasize rising average temperatures and extreme weather events as indications of climate change.

4.3.3 Seasonal total rainfall

The difference in the seasonal trend of the ONDJFMA total rainfall for the period 2001-2021 from the corresponding trend for the period 1981-2000 is presented in Figure 17.

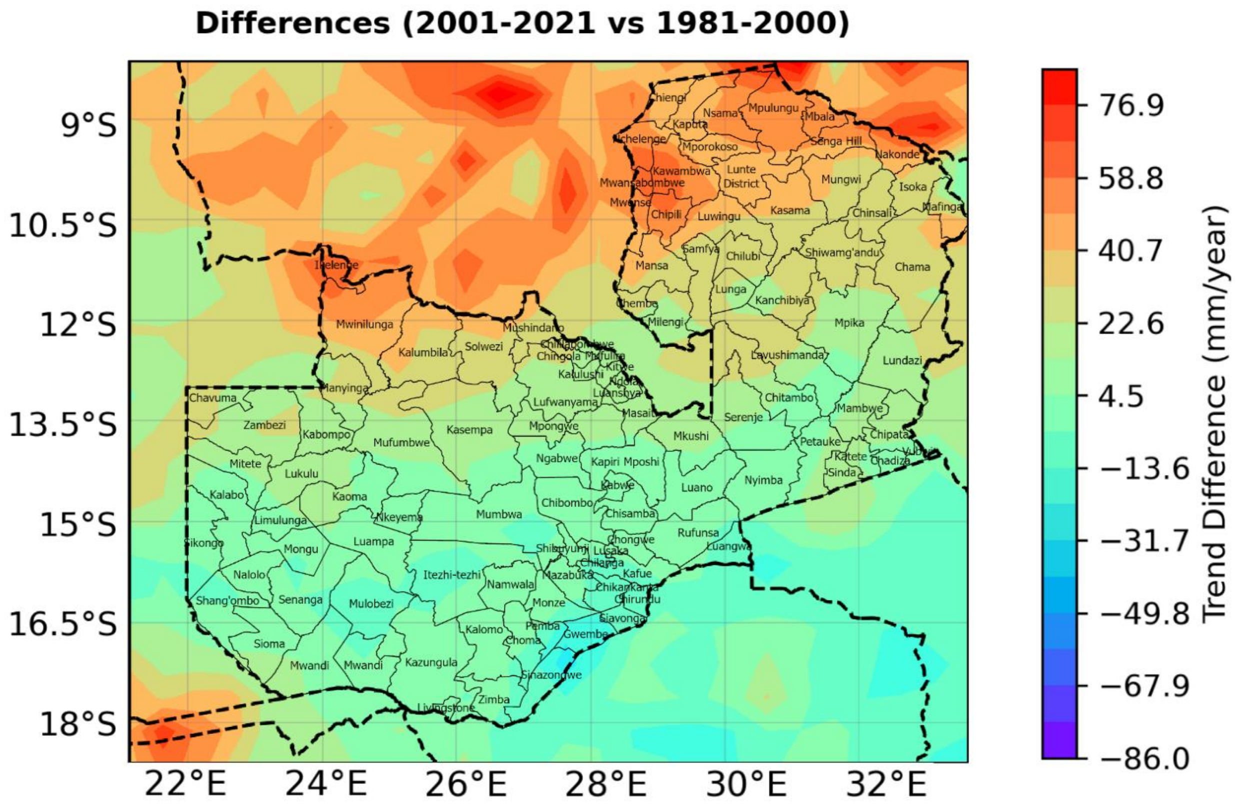


Figure 17: Difference of seasonal trend of total rainfall for the period 2001-2021 from 1981-2000 over ONDJFMA Season

The total seasonal rainfall decreased at the slowest rate from the period 1981-2000 to the period 2001-2021 in most districts of the north and north-west regions of the country namely Ikelenge, Mwinilunga, Mwense, Chipili, Mwansabombwe, Kawambwa, Nchelenge, Nsama, Mpulungu, Mbala, Senga Hill, and Nakonde. In the remaining districts, the seasonal total rainfall is also decreasing but at a faster rate during 2001-2021 as compared to the seasonal decreasing rate for the period 1981-2000. Therefore districts represented in shades of green are the hot spots for reducing total season rainfall.

4.3.4 Number of days when daily rainfall exceeds 20mm

The difference in the trend of the number of days in a year (1 July to 30th June) when daily rainfall exceeds 20mm for the period 2001-2021 from the corresponding trend for the period 1981-2000 is presented in Figure 18.

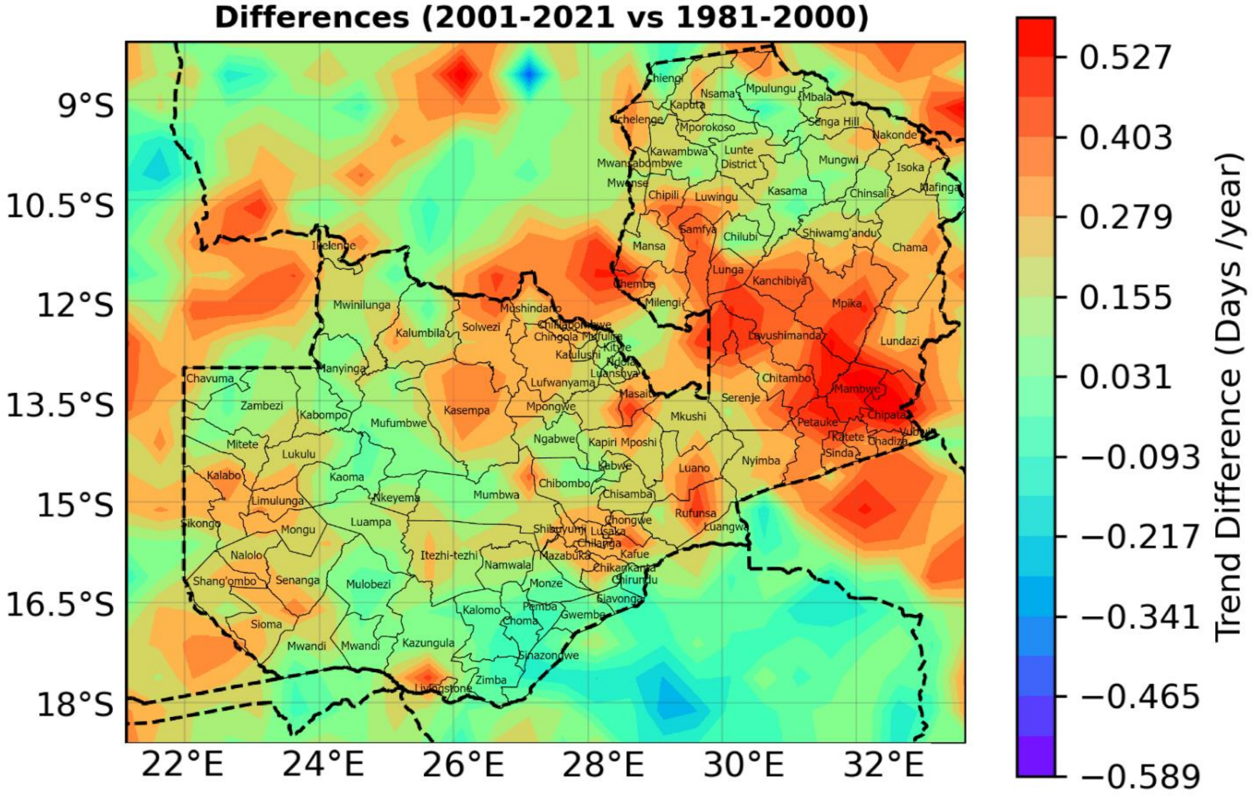


Figure 18: Difference in the annual trend of the number of days when daily rainfall exceeds 20mm for the period 2001-2021 from the period 1981-2000

The annual trend of heavy precipitation events (daily rainfall >20 mm) from the former period to the later period is increasing fastest in districts Solwezi, Kalumbila (partly), Kasempa, Mushindamo (partly), Chililabombwe, Chingola, Lufwanyama, Mpongwe, Njelenge, Chama (partly), Lundazi, Luano, Kalabo, Limulunga, Kazungula (partly), Kafue (partly), Serenje (partly), Sinda, Chadiza and Katete indicating that flash floods conditions in these districts are increasing with time (Fig. 18). The heavy precipitation days per year are also increasing in most of the remaining districts but at a slower rate as time increases.

4.3.5 Number of days when daily rainfall is exceeding 30mm

Daily rainfall exceeding 30 mm is labeled as a very extreme precipitation event by WMO. The difference in the annual trend of the number of days when daily rainfall exceeds the 30mm threshold for the period 2001–2021 from the corresponding trend for the period 1981-2000 is shown in Figure 19.

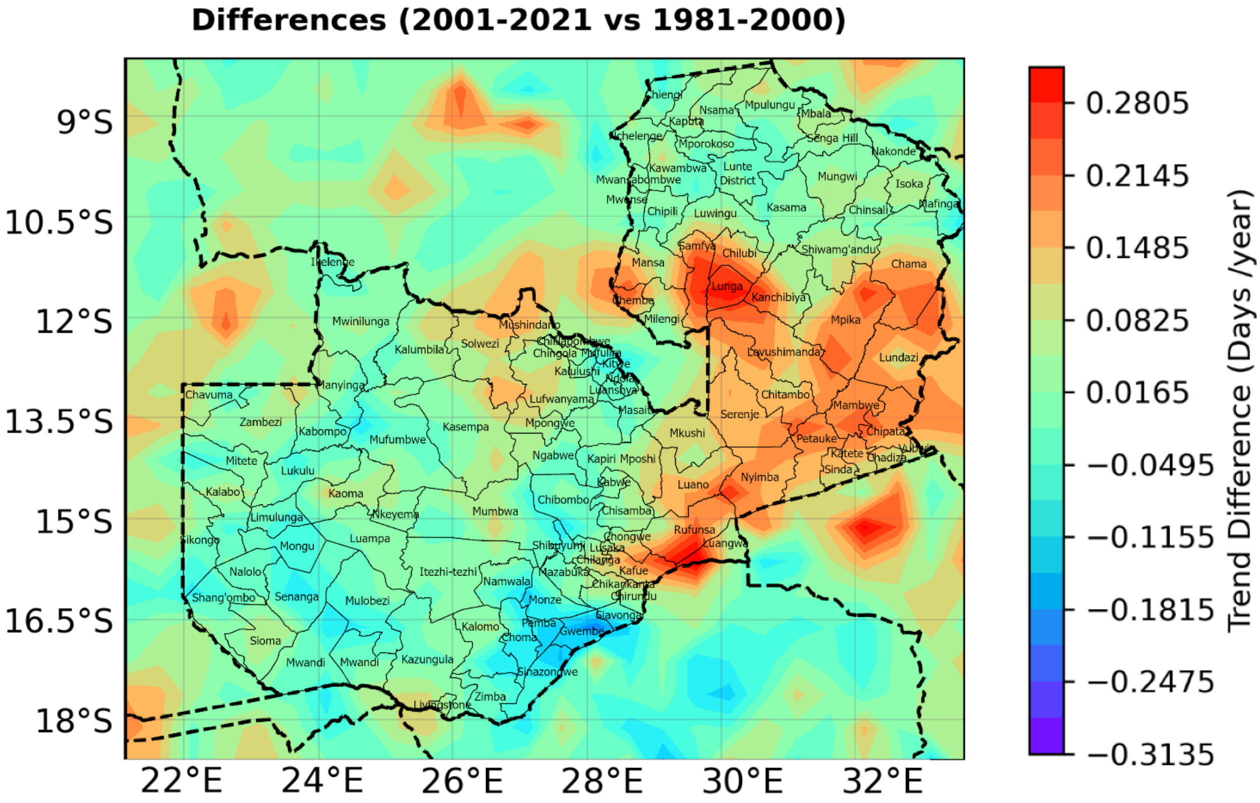


Figure 19: Difference of annual trend of the number of days when daily rainfall exceeds 30mm for the period 2001-2021 from the period 1981-2000.

Extreme weather events of very heavy daily precipitation are increasing for periods 1981-2000 and 2001-2100 over all the regions of Zambia but at different rates. The hot spots of this event are districts Mushindamo, Solwezi, Luano, Kafue, Rufunsa, Serenje, Lavushimanda, Chitambo, Chembe, Mansa, Samfya, Chilubi, Lunga, Kanchibiya, Mpika, Luangwa, Nyimba, Petauke, Sinda, Katete, Mambwe, Chipata, Lundazi and Chama where it is occurring at the fastest seasonal rate.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

In this chapter, a conclusion derived from the results discussed in Chapter 4 is presented. It also provides recommendations and suggestions for further studies.

5.1. Conclusions

The statistical analysis of ERA5 data showed that the five extreme weather events considered in this study have been getting more frequent and more severe over Zambia in recent years but with varied rates over the three climatic zones and two subperiods. The comprehensive examination of both the frequency of days with maximum temperature exceeding 35° C and annual maximum temperature trends in Zambia's three climatic zones has revealed significant shifts that necessitate urgent attention and strategic interventions. The escalating frequency of days with maximum temperatures exceeding 35°C, especially in Zone 1, highlights the intensification of temperature extremes with potential repercussions for agriculture and ecosystems. Consequently, the frequency of days with maximum temperatures exceeding 35°C showed districts Sinazongwe, Chirundu, Kafue, Rufunsa, Luano, Nyimba, Serenje(partly), Petauke, Sinda, Katete, Chipata, Chadiza, Vubwi, Mambwe, Lundazi, Mpika and Chama as hot spots.

The upward trajectory in annual maximum daily temperatures across all three zones further underscores the pervasive impact of climate change on Zambia's climate. The difference of annual trend in maximum daily temperature revealed districts including Mkushi, Serenje, Chitambo, Lavushimanda, Kanchibiya, Shiwang'andu, Mpika, Nyimba, Petauke, Sinda, Katete, Mambwe, Chipata, Chadiza, Vubwi, Lundazi and Chama as hot spots. The difference in annual trends unveiled through this study is that the daily maximum temperature is increasing over all the regions of Zambia but at different rates. These findings emphasize the need for targeted, region-specific adaptation strategies that consider the significant impacts of climate change. The insights gained from this research contribute to the broader understanding of climate change dynamics and provide a foundation for informed decision-making to enhance resilience in the face of evolving climatic conditions.

The examination of seasonal total rainfall trends across Zambia's climatic regions has revealed a dynamic interplay of climatic forces, providing valuable insights into the evolving precipitation patterns. There was a general decrease in seasonal total rainfall over the OND season and a generally fluctuating increase and decrease over the JFM season. This conclusion synthesizes local findings, offering a comprehensive perspective on the multifaceted nature of rainfall trends. The mixed trends observed in seasonal total rainfall underscore the localized and complex nature of precipitation dynamics within Zambia. The non-significant fluctuations, as evidenced by the Mann-Kendall statistical tests, emphasize the inherent variability in rainfall patterns. These observations resonate with the intricacies of regional climates, highlighting the need for tailored approaches to understanding and adapting to changing precipitation trends. The difference in annual trend patterns analyses have illuminated the shifting distribution of rainfall across Zambia's climatic zones revealing Ikelenge, Mwinilunga, Mwense, Chipili, Mwansabombwe, Kawambwa, Nchelenge, Nsama, Mpulungu, Mbala, Senga Hill, and Nakonde as hot spot districts. These spatial variations underscore the importance of localized assessments in developing effective water resource management strategies. The observed trends have implications for agriculture and water security, vital components of Zambia's socio-economic landscape. The evolving distribution of rainfall, coupled with the non-uniform changes in different regions, necessitates a nuanced understanding of water availability for sustainable farming practices. These local realities emphasize the significance of adaptive measures to safeguard food security and water resources.

Our detailed analysis, focusing specifically on the thresholds of 20 mm and 30 mm for daily rainfall, provides valuable insights into the changing precipitation patterns. Across the three climatic zones, our study reveals distinct trends and spatial variations, shedding light on potential implications for water resources, agriculture, and related sectors. The trends in the number of days with daily rainfall exceeding 20 mm indicate a general increase, particularly in the period 2001-2021. Zones 2 and 3 exhibit a statistically significant rise, emphasizing the changing precipitation dynamics. The difference in annual trend reveals a significant expansion of land experiencing rainfall exceeding 20 mm, particularly in the eastern parts of the three zones.

The difference in the seasonal trend of rainfall exceeding the 20mm threshold showed Mambwe, Chembe Chipata, and Petauke as districts with land areas that received the highest rainfall over the JFM season. Similarly, the trends for the 30 mm threshold highlight an overall increase, with statistical significance observed in Zones 2 and 3 during the latter period. Lunga and Samfya districts had the highest number of days with daily rainfall exceeding the 30mm threshold followed by parts of Mpika, Chembe, Kanchibiya, Rufunsa, Luangwa, Mambwe, Chipata, and Chama marking as hot spots. While the trends are less pronounced than the 20 mm threshold, they underscore the variability in heavy rainfall events. In conclusion, the observed trends in heavy rainfall events at both 20 mm and 30 mm thresholds suggest significant changes in Zambia's precipitation patterns. The extreme rainfall events of daily rainfall of more than 20 mm and 30 mm are increasing with time in all three climatic zones and the rate of increase also rises from south to north. The spatial analyses emphasize the need for localized assessments and adaptive strategies, considering the distinct characteristics of each climatic zone. These findings contribute to our understanding of the changing climatic conditions in Zambia and provide a basis for informed decision-making.

5.2. Recommendations

In light of the insights derived from the results, the following recommendations have been formulated for contemplation in subsequent research studies.

1. It is imperative to design and implement climate-resilient agricultural practices for each district that align with the observed and projected temperature trends. These practices should integrate adaptive measures, such as the cultivation of heat-resistant crop varieties, optimized irrigation strategies, and sustainable land management practices. Collaborative efforts between agricultural stakeholders, research institutions, and local communities are crucial to ensure the successful adoption of these resilient practices.
2. Strengthening regional climate monitoring and early warning systems is vital for timely response to emerging climate patterns. This includes the expansion and improvement of meteorological infrastructure, leveraging technology for real-time data collection, and enhancing community awareness and preparedness. By fostering a proactive approach to climate-related challenges, regions can better mitigate the potential impacts on agriculture, water resources, and overall socio-economic stability.
3. Implement tailored water resource management strategies that account for the regional nuances in precipitation patterns. This involves optimizing irrigation practices, promoting water-efficient technologies, and adopting sustainable water harvesting techniques.
4. Foster community-led climate resilience initiatives to empower local (district) populations in adapting to changing precipitation trends. This includes promoting sustainable farming practices, enhancing livelihood diversification, and establishing community-based early warning systems.

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APPENDICES

APPENDIX 1: The statistics (values) of annual cycles of monthly mean precipitation and temperatures for the ERA5 and the observed datasets.

1. The values of the annual cycle of monthly mean precipitation (mm) from ERA5, GPCC, CRU, and GPCP for the period 1981-2010.

	Datasets			
Months	**ERA5**	**GPCC**	**CRU**	**GPCP**
Jul	1.34	0.51	0.41	2.07
Aug	1.80	2.01	1.49	3.37
Sep	11.26	9.52	9.29	11.64
Oct	50.97	41.83	40.55	41.63
Nov	131.29	121.62	117.96	116.35
Dec	216.42	211.47	197.52	194.14
Jan	243.39	222.80	223.49	211.76
Feb	222.15	190.82	189.62	195.90
Mar	160.57	160.81	157.96	151.65
Apr	54.66	55.91	54.29	57.62
May	7.94	7.38	6.58	9.52
Jun	1.75	1.10	0.66	2.70

2. The values of the annual cycle of monthly mean temperature between ERA5 and observed CRU for the minimum temperature, maximum temperature, and average temperature over the period 1981-2010.

	Minimum Temperature		**Maximum Temp**	
Months	**ERA5**	**CRU**	**ERA5**	**CRU**
Jul	12.49	9.76	25.31	26.87
Aug	14.40	12.13	27.87	29.21
Sep	17.12	15.09	30.61	31.78
Oct	18.87	17.75	30.95	32.49
Nov	19.06	18.57	29.43	31.37
Dec	18.65	18.43	27.34	29.43
Jan	18.54	18.36	26.69	28.89
Feb	18.43	18.32	26.72	28.95
Mar	18.26	17.93	26.95	29.33
Apr	17.18	16.18	26.98	29.20
May	15.32	13.13	26.74	28.42
Jun	13.14	10.34	25.42	27.10

APPENDIX 2: Values of seasonal annual rainfall over ONDJFM for the period 1981-2010.

	Datasets			
Year	**ERA5**	**GPCC**	**CRU**	**GPCP**
1981	1104.9	1008.6	977.1	1008.9
1982	1164.1	1025.3	1019.7	1010.5
1983	1051.4	933.9	927.4	910.5
1984	1113.5	979.5	977.7	966.8
1985	1185.7	1016.6	1019.3	1031.3
1986	1277.3	1154.9	1130.8	1124.0
1987	996.8	884.8	862.9	868.4
1988	1133.0	1041.3	1002.4	1046.6
1989	1253.6	1116.8	1110.4	1128.6
1990	1044.0	995.0	970.8	942.1
1991	1078.8	1023.7	996.2	982.8
1992	919.2	871.5	840.3	824.8
1993	1196.4	1043.7	1029.8	991.6
1994	991.3	844.8	830.1	833.0
1995	945.9	818.9	819.0	791.9

1996	1057.9	1010.8	963.6	995.9
1997	1234.4	1147.2	1097.0	1151.9
1998	1114.2	1006.9	993.9	942.4
1999	1055.5	980.7	936.1	972.3
2000	1193.4	1109.2	1090.9	1116.4
2001	1171.0	1080.3	1105.6	1103.4
2002	1001.4	955.0	953.6	917.0
2003	1023.2	995.2	1044.9	917.9
2004	1134.8	1114.5	1121.8	1084.8
2005	896.5	919.6	913.3	875.8
2006	1151.1	1160.2	1070.0	1146.1
2007	1163.8	1151.3	1012.7	1099.4
2008	1134.3	1139.2	1038.7	1065.5
2009	1130.9	1123.2	1075.4	1056.0
2010	1188.3	1121.1	1063.2	1043.5

APPENDIX 3: Temperature anomalies for the minimum, maximum, and mean.

	Minimum Temperature		**Maximum Temp**	
Year	**ERA5**	**CRU**	**ERA5**	**CRU**
1981	−0.60	−1.26	−0.44	−0.62
1982	−0.21	−0.30	−0.37	−0.55
1983	0.37	0.28	0.53	0.44
1984	−0.16	−0.14	−0.23	−0.28
1985	−0.57	−0.53	−0.77	−.57
1986	−0.60	−0.51	−0.85	−0.81
1987	0.26	−0.26	0.56	0.60
1988	−0.02	−0.04	−0.22	−0.19
1989	−0.24	−0.37	−0.55	−0.54
1990	0.10	0.24	0.13	0.17
1991	−0.15	−0.40	−0.10	−0.19
1992	0.21	0.13	0.56	0.52
1993	0.03	−0.07	−0.19	−0.40
1994	−0.19	−0.20	0.21	0.08
1995	0.41	0.47	0.81	0.52

1996	0.00	−0.15	0.30	0.13
1997	0.16	0.25	−0.07	0.08
1998	0.45	0.48	0.69	0.44
1999	−0.08	−0.05	−0.20	−0.37
2000	0.00	0.18	−0.30	−0.43
2001	−0.01	0.31	−0.20	−0.13
2002	0.20	0.64	0.20	0.29
2003	0.07	0.03	0.28	0.41
2004	−0.06	−0.18	−0.24	0.14
2005	0.56	1.07	0.93	1.20
2006	0.02	0.11	−0.23	−0.24
2007	0.04	−0.08	−0.01	−0.01
2008	−0.24	−0.29	−0.09	−0.09
2009	−0.11	−0.06	−0.28	0.11
2010	0.37	0.70	0.14	0.32

APPENDIX 4: Seasonal (AMJJA) mean values for ERA5 and CRU Temperatures (Maximum and Minimum)

	Minimum Temperature		**Maximum Temp**	
Year	**ERA5**	**CRU**	**ERA5**	**CRU**
1981	16.18	11.04	27.15	28.80
1982	16.57	12.00	27.22	28.86
1983	17.15	12.58	28.12	29.86
1984	16.62	12.16	27.36	29.14
1985	16.20	11.77	26.82	28.84
1986	16.18	11.79	26.74	28.60
1987	17.04	12.04	28.14	30.02
1988	16.76	12.26	27.36	29.23
1989	16.54	11.92	27.04	28.88
1990	16.88	12.53	27.71	29.59
1991	16.63	11.90	27.49	29.22
1992	16.98	12.43	28.14	29.94
1993	16.81	12.23	27.40	29.02
1994	16.56	12.10	27.79	29.49
1995	17.20	12.77	28.40	29.94

1996	16.78	12.14	27.88	29.55
1997	16.93	12.55	27.52	29.50
1998	17.22	12.77	28.28	29.86
1999	16.70	12.25	27.38	29.05
2000	16.78	12.48	27.28	28.99
2001	16.77	12.61	27.38	29.29
2002	16.97	12.93	27.78	29.70
2003	16.85	12.33	27.87	29.82
2004	16.72	12.12	27.34	29.56
2005	17.34	13.36	28.52	30.62
2006	16.80	12.40	27.35	29.18
2007	16.81	12.22	27.58	29.41
2008	16.53	12.00	27.50	29.32
2009	16.67	12.24	27.30	29.52
2010	17.15	13.00	27.72	29.73

APPENDIX 5: Frequency of days with maximum temperature exceeding 35° C over ONDJFMA.

	Zone		
Season	1	2	3
1981/1982	10.05	5.26	0.944
1982/1983	8.39	2.05	0.48
1983/1984	9.96	5.46	1.12
1984/1985	6.04	3.64	0.56
1985/1986	2.67	0.85	0.31
1986/1987	5.26	0.77	0.18
1987/1988	17.25	7.48	0.86
1988/1989	6.44	1.92	0.50
1989/1990	11.63	3.21	0.50
1990/1991	16.53	7.12	1.04
1991/1992	14.05	3.93	0.47
1992/1993	14.98	7.56	0.93
1993/1994	10.94	4.38	0.93
1994/1995	22.88	6.	0.80
1995/1996	25.01	12.27	1.34

1996/1997	23.95	11.29	1.29
1997/1998	10.68	4.38	1.30
1998/1999	19.29	12.06	1.78
1999/2000	11.51	5.97	1.19
2000/2001	9.42	4.28	0.63
2001/2002	6.58	3.46	0.82
2002/2003	13.31	4.31	0.76
2003/2004	18.81	9.38	1.95
2004/2005	10.76	3.37	0.91
2005/2006	20.57	8.72	1.27
2006/2007	9.09	4.53	1.25
2007/2008	6.70	2.61	0.64
2008/2009	14.33	7.53	1.77
2009/2010	6.58	2.40	0.4
2010/2011	17.47	13.44	3.33
2011/2012	17.59	7.90	1.03
2012/2013	14.95	7.90	1.21
2013/2014	13.29	8.40	1.61
2014/2015	16.15	13.08	2.21

2015/2016	30.60	12.46	1.27
2016/2017	26.07	18.44	3.41
2017/2018	13.77	7.41	1.43
2018/2019	18.38	6.22	0.98
2019/2020	25.20	11.91	1.66
2020/2021	20.69	11.67	1.53

APPENDIX 6: Annual maximum daily temperature values

	Zone		
Season	**1**	**2**	**3**
1981/1982	36.894	35.602	32.417
1982/1983	35.260	34.008	31.508
1983/1984	36.240	35.692	32.778
1984/1985	35.544	34.795	32.358
1985/1986	34.591	33.963	32.053
1986/1987	35.129	33.618	31.284
1987/1988	38.161	35.936	31.964
1988/1989	35.799	34.423	31.839
1989/1990	36.426	35.107	32.329
1990/1991	37.783	35.929	32.799
1991/1992	36.299	34.646	32.323
1992/1993	36.929	35.642	32.305
1993/1994	36.341	35.431	32.914
1994/1995	37.471	35.532	32.042
1995/1996	38.139	36.331	32.949

1996/1997	36.986	35.980	32.699
1997/1998	36.787	35.756	33.973
1998/1999	37.591	36.625	33.456
1999/2000	36.560	35.751	32.443
2000/2001	35.800	35.071	32.969
2001/2002	35.864	34.902	32.985
2002/2003	36.531	35.359	32.937
2003/2004	37.951	36.637	34.235
2004/2005	36.194	35.508	34.035
2005/2006	37.917	35.889	32.940
2006/2007	36.408	35.132	33.506
2007/2008	35.941	34.684	32.164
2008/2009	36.408	35.772	34.319
2009/2010	35.381	34.572	32.659
2010/2011	37.411	36.381	34.973
2011/2012	38.642	36.830	32.928
2012/2013	36.851	35.755	33.268
2013/2014	36.871	36.050	33.953
2014/2015	36.778	36.368	34.240

2015/2016	38.110	36.277	33.128
2016/2017	37.904	36.810	34.509
2017/2018	38.277	37.149	34.067
2018/2019	36.838	35.662	33.347
2019/2020	39.225	37.080	33.033
2020/2021	37.950	36.633	34.094

APPENDIX 7:

1. Seasonal total rainfall values

	Zone		
Season	**1**	**2**	**3**
1981/1982	917.245	1020.179	1343.553
1982/1983	715.217	1222.083	1627.510
1983/1984	789.559	1113.825	1379.630
1984/1985	877.420	1228.929	1802.240
1985/1986	894.672	1206.069	1517.758
1986/1987	650.175	1016.080	1799.451
1987/1988	949.244	1173.609	1484.327
1988/1989	1041.406	1488.521	1780.944
1989/1990	1011.162	1514.911	1740.950
1990/1991	717.544	939.625	1205.992
1991/1992	1145.592	1881.252	2365.231
1992/1993	1446.257	1432.521	2216.832
1993/1994	723.775	933.072	1249.819
1994/1995	642.979	839.732	1421.072
1995/1996	858.537	990.479	1198.985

1996/1997	1039.373	1159.513	1226.135
1997/1998	740.772	1093.733	1725.618
1998/1999	890.961	1157.505	1297.804
1999/2000	931.171	1083.249	1200.488
2000/2001	960.739	1284.263	1436.589
2001/2002	618.509	967.333	1380.422
2002/2003	745.866	1115.658	1257.881
2003/2004	859.175	1047.180	1212.599
2004/2005	619.652	880.999	1302.815
2005/2006	985.537	1080.148	1204.979
2006/2007	763.414	1193.989	1543.555
2007/2008	1028.301	1084.631	1258.543
2008/2009	1000.368	880.999	1302.815
2009/2010	964.827	1080.148	1204.979
2010/2011	1188.709	1193.989	1543.555
2011/2012	862.500	1084.631	1258.543
2012/2013	857.817	880.999	1302.815
2013/2014	924.436	1080.148	1204.979
2014/2015	816.455	1193.989	1543.555

2015/2016	689.623	1084.631	1258.543
2016/2017	1150.801	880.999	1302.815
2017/2018	961.079	1080.148	1204.979
2018/2019	609.201	1193.989	1543.555
2019/2020	733.731	1084.631	1258.543
2020/2021	1423.008	880.999	1302.815

2. JFM seasonal total rainfall

	Zone		
Season	**1**	**2**	**3**
1981/1982	496.77607133	1061.92416149	1896.65418328
1982/1983	453.35229606	641.61249861	1526.24213736
1983/1984	2601.98064998	2711.80766946	2445.1590121
1984/1985	605.68564851	921.71979551	2885.41908541
1985/1986	547.06253394	1375.65704845	2646.94505775
1986/1987	347.6612173	1137.24993984	2778.95808957
1987/1988	609.22308249	768.29731362	1666.64978139
1988/1989	2790.13261798	2931.33770451	3196.1192312
1989/1990	838.91520464	1812.59874061	2128.27721282
1990/1991	585.7139412	728.0442696	2142.14503758
1991/1992	802.3623734	1464.44106148	2531.82024471
1992/1993	1501.70019051	3088.29939788	3531.02727983
1993/1994	459.89132439	1118.80067376	3231.26813032
1994/1995	777.05377675	633.28030763	1360.96639062
1995/1996	637.76476901	910.70372559	3132.77836584
1996/1997	2944.30561662	3342.2256979	3582.49676546

1997/1998	543.89481267	964.03789334	2871.13344153
1998/1999	761.85932898	1566.10433039	3356.55341006
1999/2000	1215.2724722	1405.92474589	1688.62844109
2000/2001	1246.0282473	2403.14584758	3277.36264348
2001/2002	287.00879966	846.08889668	1746.48825911
2002/2003	1789.80309649	3588.90724099	3533.09779378
2003/2004	1181.20904732	1753.46507	2701.69743905
2004/2005	1221.73464439	1166.36921517	1613.25160012
2005/2006	870.88751008	1577.03180341	1679.02522019
2006/2007	1737.4336553	1764.6671786	1286.19093025
2007/2008	596.94637974	627.93647336	1478.10046327
2008/2009	1138.1941427	1359.90118686	3026.88208766
2009/2010	1685.71468648	1907.32981246	1936.32221971
2010/2011	648.80405984	708.9005782	1877.14101385
2011/2012	3039.45041551	4243.45251443	4155.94889508
2012/2013	585.86863663	731.22726723	2272.38824669
2013/2014	719.11863992	1884.82612906	2301.99478097
2014/2015	3943.20900394	4221.30407154	2410.99296689
2015/2016	537.09662266	733.60633087	2895.24568471

2016/2017	777.24706574	987.3362474	2088.87432365
2017/2018	2018.76889929	2394.86594389	1999.00380071
2018/2019	368.93172335	599.17061172	1146.26092678
2019/2020	1055.08753708	1493.97427535	1989.3163095
2020/2021	657.008257	805.21546158	721.09781465

3. OND seasonal total rainfall

	Zone		
Season	**1**	**2**	**3**
1981/1982	4447.87158553	3701.2631162	3341.40101906
1982/1983	544.14272711	714.09387517	2710.81659974
1983/1984	1500.92545349	3102.72857087	3164.05244334
1984/1985	389.1770524	1203.34908381	2603.28473305
1985/1986	2863.82968226	2627.80720986	3352.08712546
1986/1987	2327.26551822	3979.33161679	3977.34241353
1987/1988	1760.23921166	4727.59880343	4983.32818905
1988/1989	3095.94493247	3364.16447244	3433.37079963
1989/1990	2487.89369508	7535.38821707	3457.61312119
1990/1991	1896.41327828	2643.07473334	1808.53398909
1991/1992	390.23634603	2206.81889236	4996.59765423
1992/1993	1712.76419868	1225.53697058	1137.25292287
1993/1994	1977.74986366	2273.58795949	1698.4176185
1994/1995	1975.15752556	2695.32893013	2996.100762
1995/1996	1109.59190817	3071.21221823	3133.95609994
1996/1997	1458.5337509	1764.75876274	2076.88961016

1997/1998	1460.0153754	1948.44837103	2313.53110877
1998/1999	2622.92643545	2502.61204037	3150.8020463
1999/2000	1146.28671652	978.62543222	1339.81024404
2000/2001	915.3007486	1884.35701769	2343.9433978
2001/2002	1655.48946655	3937.38100223	3182.27235565
2002/2003	682.9532934	3986.49957941	3368.92329208
2003/2004	1863.68338126	2739.6105865	3362.7144908
2004/2005	1508.0287171	4486.33756174	3063.40789849
2005/2006	1639.54757159	1928.48289255	2798.87368673
2006/2007	3615.52364578	3615.01775077	3270.43170402
2007/2008	4263.12767861	5056.45617992	3641.83101968
2008/2009	2836.21175099	3351.61365804	3735.04366212
2009/2010	1703.95224788	2061.04427424	2106.53758083
2010/2011	2074.24909243	3061.88817846	2116.7172861
2011/2012	3419.25045783	3708.11109167	3349.82059856
2012/2013	2513.66058686	1828.49442706	2213.9365905
2013/2014	4980.80372086	2254.28312496	2585.16642152
2014/2015	8784.6250623	4856.30313427	1218.50330206
2015/2016	263.8150574	682.73802666	3286.78580656

2016/2017	3072.23628854	3249.40784091	3265.06220737
2017/2018	527.86596499	915.59976121	2540.04604668
2018/2019	1928.83809958	2183.21015338	2315.8645492
2019/2020	1340.42210031	3031.04986358	3788.1559783
2020/2021	390.17534591	465.05289673	528.80442875

APPENDIX 8: Number of days when daily rainfall is exceeding 20mm

	Zone		
Season	**1**	**2**	**3**
1981/1982	4.36	6.05	4.13
1982/1983	4.95	6.17	4.84
1983/1984	4.09	4.79	4.73
1984/1985	6.47	7.50	7.75
1985/1986	6.63	5.24	5.09
1986/1987	4.29	4.92	6.66
1987/1988	6.86	6.99	5.68
1988/1989	8.32	10.14	7.12
1989/1990	5.22	6.77	5.60
1990/1991	3.72	4.09	4.68
1991/1992	3.60	2.31	3.82
1992/1993	7.01	7.65	6.25
1993/1994	5.34	4.87	4.41
1994/1995	3.05	4.47	6.29
1995/1996	6.34	4.24	4.07

1996/1997	10.28	7.82	3.65
1997/1998	6.04	5.92	11.46
1998/1999	5.24	5.55	5.48
1999/2000	6.82	4.75	4.39
2000/2001	6.62	7.08	6.58
2001/2002	2.07	3.26	4.80
2002/2003	5.89	6.71	5.64
2003/2004	5.47	4.41	4.28
2004/2005	3.43	3.88	4.99
2005/2006	7.16	4.68	3.68
2006/2007	6.02	10.45	7.66
2007/2008	11.97	7.31	5.10
2008/2009	8.74	8.67	5.19
2009/2010	7.69	8.94	7.95
2010/2011	5.69	7.44	5.59
2011/2012	6.47	5.83	4.76
2012/2013	8.70	9.85	8.57
2013/2014	7.40	7.05	6.25
2014/2015	7.78	6.88	5.08

2015/2016	5.37	7.50	7.68
2016/2017	9.65	8.03	4.08
2017/2018	8.48	8.06	8.68
2018/2019	4.95	6.27	5.17
2019/2020	6.03	8.30	13.29
2020/2021	10.69	11.36	9.54

APPENDIX 9: Number of days when daily rainfall is exceeding 30mm

	Zone		
Season	**1**	**2**	**3**
1981/1982	1.12	1.29	0.44
1982/1983	1.40	1.22	0.68
1983/1984	0.60	0.59	0.65
1984/1985	1.24	1.21	0.91
1985/1986	1.41	0.52	0.59
1986/1987	1.11	0.88	0.77
1987/1988	1.67	0.97	0.79
1988/1989	2.52	2.24	0.91
1989/1990	1.13	1.71	0.69
1990/1991	0.68	0.30	0.58
1991/1992	1.20	0.28	0.53
1992/1993	1.89	1.17	0.79
1993/1994	0.82	0.56	1.05
1994/1995	0.40	0.47	0.49
1995/1996	2.44	0.93	0.32

1996/1997	3.12	1.54	0.76
1997/1998	1.42	0.80	0.61
1998/1999	1.32	0.56	0.61
1999/2000	1.41	0.64	0.76
2000/2001	1.48	1.01	0.63
2001/2002	0.29	0.46	0.63
2002/2003	2.15	1.10	0.79
2003/2004	1.23	1.10	0.50
2004/2005	0.75	0.56	0.68
2005/2006	1.35	0.82	0.41
2006/2007	1.81	2.56	1.20
2007/2008	3.83	1.51	0.72
2008/2009	2.32	1.36	0.62
2009/2010	2.33	2.30	0.68
2010/2011	1.55	2.30	0.86
2011/2012	1.13	1.94	1.20
2012/2013	2.71	0.56	0.72
2013/2014	1.35	1.66	1.84
2014/2015	2.91	1.05	1.06

2015/2016	1.37	1.42	0.86
2016/2017	2.04	1.69	3.12
2017/2018	2.39	1.53	1.89
2018/2019	1.69	2.34	1.89
2019/2020	1.86	2.33	1.67
2020/2021	2.89	2.33	1.89