Influence of Major Climate Drivers (ENSO, IOD) on Eastern African Rainfall Regimes and Their Implications on Water Resources

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DECLARATION

I, **Moses David Tumusiime**, declare that this research report titled: **"Influence of Major Climate Drivers (ENSO, IOD) on Eastern African Rainfall Regimes and Their Implications on Water Resources"**, is my original work, it has neither been submitted to any University for any academic award, or publication nor published elsewhere in any print/electronic form.

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APPROVAL

This research report titled “Influence of Major Climate Drivers (ENSO, IOD) on Eastern African Rainfall Regimes and Their Implications on Water Resources”, has been submitted to the Faculty of life & Earth Science, Selinus University with our approval as University supervisors:

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ABSTRACT

Rainfall variability over Eastern Africa is influenced by several modes of climate variability, including the El Niño–Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), the Quasi-Biennial Oscillation (QBO) and the Madden–Julian Oscillation (MJO). This study explored factors Influencing Major Climate Drivers (ENSO, IOD) on the Variability and Trends of Rainfall in East Africa and Lake Victoria Catchment. Three objectives guided my study: to analyze rainfall variability and trends over El Niño - Southern Oscillation (ENSO) on the East African rainfall, to evaluate the contributions of Indian Ocean Sea Surface Temperatures to Enhanced East African Rainfall and to examine the Implication of climate drivers (ENSO, IOD) on water resources in Lake Victoria basin. I reviewed literature globally, in Sub-Saharan Africa, East Africa, and Uganda. Most studies revealed that Dipole Mode Index (DMI) have a significant influence on East Africa precipitation. This study used General Equation Framework, Trend analysis and Time series, Python programming tool, Pearson Correlation coefficient and ArcGIS tool methods. Chirps' precipitation dataset data was obtained from NOAA. Analysis proved that there is a significant negative correlation between MAM rainfall and DMI, parts of western Kenya and Uganda show a negative correlation, suggesting drier conditions during high DMI (positive IOD) El Niño years. However, OND season was proved with positive significance of increasing Sea Surface Temperature (SST) would increase precipitation in the region.

Results from analysis revealed that there is significant correlation between Dipole Mode Index and precipitation over East Africa and Water resources of Lake Victoria basin a shared resource of three countries and a direct beneficially of eleven countries of Nile Basin. The study concluded that East Africa rainfall regimes are influenced by both DMI and Bimodal of physical features. This research recommends further investigations to be carried out on other factors that influence East African precipitation since this study proved with evidence of zero correlation between DMI and rainfall during JJA.

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LIST OF ABBREVIATIONS

- ENSO) = El Niño–Southern Oscillation
- IOD = Indian Ocean Dipole
- pIOD = Positive Indian Ocean Dipole
- nIOD = Negative Indian Ocean Dipole
- DMI = Dipole Index Mode
- MAM = March April May
- SOND = September October November
- JJA = June July August
- WMO = World Meteorological Organization
- WIOD = Western Indian Ocean Dipole
- EIOD = Eastern Indian Ocean Dipole
- MJO = Madden–Julian Oscillation
- IOSST = Indian Ocean Sea Surface Temperatures
- LVB = Lake Victoria Basin
- ICPAC = IGAD Climate Prediction and Applications Centre
- NOAA = National Oceanic and Atmospheric Administration
- CHIRPS = Climate Hazards Group InfraRed Precipitation with Station data
- DAHIT= Database for Hydrological Time Series over Inland Waters
- Geosat = Geodetic/Geophysical Satellite
- G-REALM = Global Reservoir and Lake Monito
- TRMM = Tropical Rainfall Measuring Mission
- GPM = Global Precipitation Measurement
- ERA5 = ECMWF Reanalysis v5
- (ECMWF) = European Centre for Medium-Range Weather Forecasts
- NCEP = National Centers for Environmental Prediction
- NCAR = National Center for Atmospheric Research
- SOI = Southern Oscillation Index, or
- MEI = Multivariate ENSO Index

DEFINITION AND TERMINOLOGY

The El Niño–Southern Oscillation is a single climate phenomenon that periodically fluctuates between three phases: Neutral, La Niña or El Niño. La Niña and El Niño are opposite phases in the oscillation which are deemed to occur when specific ocean and atmospheric conditions are reached or exceeded.

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CHAPTER ONE: INTRODUCTION

1.0 Background

The relationship between East African rainfall patterns and the Western Indian Ocean Dipole (WIOD) is a well-documented phenomenon in climate science. This correlation is primarily driven by atmospheric and oceanic interactions that influence weather systems across the region. The WIOD, often referred to as the Indian Ocean Dipole (IOD), is an irregular oscillation of sea surface temperatures (SSTs) in the western and Eastern parts of the Indian Ocean. Positive and negative phases of this dipole significantly impact rainfall variability over East Africa. The DMI script explores the mechanisms behind this correlation, emphasizing how changes in SSTs associated with the IOD affect atmospheric circulation, moisture transport, and precipitation patterns as study by (YAN Xiao-yong, 2009) mentioned.

The overall aim of this study is to analyze the Influence of Major Climatic Drivers (El Niño–Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) also known as Dipole Index Mode (DMI) on Eastern Africa Rainfall Regimes (March April May (MAM), September October November (SOND) and their implications on water resources especially Lake Victoria basin. Report from (IPCC,2021), described that climate drivers are factors that influence the Earth's climate, both naturally and through human activities (IPCC, 2021). These factors, including solar radiation, greenhouse gases, and ocean currents, affect weather patterns, temperature, and precipitation over time that influence the Earth's climate system. Understanding these drivers is crucial for comprehending past climate changes, current state of climate, predicting future scenarios, and mitigating potential impacts (IPCC, 2021). Climate variability is driven by extensive processes (Kaye, 2024), the sun provides the primary source of energy driving Earth's climate system. The sun's energy, called solar radiation, isn't equally distributed across the globe because of Earth's spherical shape. This "unequal helping" of solar radiation across our planet is effectively what causes weather and climate (Trenberth, 2009).

Differences in solar radiation led to differences in temperature and differences in temperature ultimately lead to stormy weather – storms are Mother Nature's way of trying to minimize temperature differences. The part of the world where the sun shines the most are the tropics. Because of this, the ocean in the tropics is warmer than anywhere else in the world – sometimes over 30 degrees (Trenberth K. E., 2015), (Trenberth, Fasullo, & Shepherd, 2015).

El Niño Southern Oscillation (ENSO) is a climate pattern that influences rainfall, temperature, and wind patterns around the world. ENSO has three phases: El Niño, La Niña, and neutral. El Niño and La Niña events occur, on average, every few years and last up to around a year or (Li, Hu, McPhaden, Zhu, & Liu, 2023), (Islam, 2025).

El Niño; During an El Niño event, ocean water from the west coast of South America to the central tropical Pacific gets a lot warmer than usual because of changes in the wind. This unusually warm ocean water puts more energy into the atmosphere to form clouds, rainfall and thunderstorms – ultimately influencing weather patterns around the world (Trenberth, Fasullo, & Shepherd, 2015). During El Niño, East Africa tends to experience stronger, more frequent winds from the west Indian Ocean in summer, which can encourage dryness in eastern Indian Ocean areas like Indonesia and more rain in the west, like in the West Coast. In winter, the wind tends to blow more from the Eastern Indian Ocean, causing colder temperatures west ward of the region and coast of East Africa (Ogwang, Ongoma, Xing, & Ogou, 2015), (Nicholson, 2017).

La Niña; During a La Niña event, ocean water off the coast of South America to the central tropical Pacific gets cooler than usual. This cooling occurs because of strong winds that churn cooler, deeper sea water up to the ocean's surface (Nicholson, 2017).

Neutral; In the context of the El Niño-Southern Oscillation (ENSO), the "neutral phase" signifies a period where neither El Niño nor La Niña conditions are present as (Alizadeh, 2022) highlighted in the study. During neutral conditions, the tropical Pacific Ocean and the surrounding atmosphere exhibit near-average conditions for temperature, wind, rainfall, and convection, according to the Climate Prediction Center (NOAA). This means that neither the warmer-than-average El Niño nor the colder-than-average La Niña is in effect (McGregor & Ebi, 2018) .

According to Trenberth, K. E., & Fasullo, J. T. (2009) a negative phase exists when atmospheric pressure over Indonesia and the west Pacific is abnormally high and pressure over the east Pacific is abnormally low, during El Niño episodes, and a positive phase is when the opposite occurs during La Niña episodes, and pressure over Indonesia is low and over the west Pacific is high.

Several studies including (Cai, et al., 2025) indicates that rainfall variability over Eastern Africa is influenced by several modes of climate variability, including the El Niño–Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), the Quasi-Biennial Oscillation (QBO) and the Madden–Julian Oscillation (MJO). ENSO, which describes SST variability in the central and eastern tropical Pacific, is also connected to changes in the short rains (Ogwang, Ongoma, Xing, & Ogou, 2015) described that El Niño conditions, associated with warmer SST anomalies over the central and eastern Pacific, typically result in wetter short rains, whereas La Niña conditions, associated with cooler SST anomalies, result in drier short rains. Other studies' view (Trenberth, K. E., & Fasullo, J. T. (2009) was that ENSO's impact on Eastern Africa is, however, strongly mediated by the IOD.

1.1 El Niño Southern Oscillation (ENSO)

According to (Li, Cao, Gordon, Zheng, & Wang, 2023), the ElNino phase is characterized by the warming of the sea surface (above-average sea surface Temperatures (SST) over the central and eastern Pacific while LaNina is the cooling of the sea surface (below-average SST) over the same area). Historically, study reveals that, ElNiño and LaNiña events are known to occur every two to seven years, though not on a regular schedule (McPhaden, 2002). The ElNiño event is more frequent than the LaNiña. When they occur, ElNino and La Nina conditions last nine to twelve months but at times can last longer

East Africa is considered to be endowed with substantial freshwater resources though faced with climate change and variability generated extreme phenomenon, the rains are also influenced by atmospheric phenomena such as El-Nino Southern Oscillation (ENSO) studies from (Indeje, Semazzi, & Ogallo, 2000); (Ntale, 2004) and expressed that the Indian Ocean Sea Surface Temperature (SST) (Behera, et al., 2005); (Liu, Cook, & Vizy, 2020).

The El Niño Southern Oscillation (ENSO) phenomena are strongly associated with inter-annual variability of rainfall which has left unanswered questions to the community that attracted this research (including; what induces flood extreme over East Africa lakes catchment? what impacts of flood extreme on the socio-economic status of rural communities in East Africa? Saudi study revealed that changing precipitation patterns could be due to climate change or a connection with El Niño years, (Hasanean & Almazroui, 2015). It is also important to gather more information about weather extremes and disclose if they are tied to climate change or other factors. Food security is an important factor for the well-being of the community, a study by the Word Food Programme Team revealed that Floods and Drought extremely affected food production across East Africa in 2018 (Peters, et al., 2022), and Lake Victoria hit record height levels and a lot of destruction of livelihood infra-structures caused by floods. However, the study showed less on how the community could be resilient to the extremes of flooding.

1.2 Indian Ocean Dipole (IOD)

The IOD is a key driver of such inter-annual rainfall variability, describing differences in sea surface temperature (SST) anomaly between the western (50° E to 70° E, 10° S to 10° N) and eastern (90° E to 110° E, 10° S to 10° S) Indian Ocean. Research from (Palmer, et al., 2023). The positive IOD (signifying an SST anomaly difference of at least +0.4 °C for at least three months between the warmer west and cooler east) is linked with wetter short rains over Eastern Africa. During such phases, precipitation totals can be 2–3 times the long-term mean, as seen in 1997, 2006, 2012, 2015 and 2019. In contrast, the negative IOD (defined by a sustained negative SST difference of at least 0.4 °C) is associated with weaker short rains, resulting in 20–60% of the long-term mean rainfall, as evident during 1996, 1998, 2010 and 2016 (Khan, et al., 2021). (Hong, Lu, & Kanamitsu, 2008).

Indian Ocean Dipole or IOD is a phenomenon of ocean-atmosphere interaction in the Indian Ocean, the IOD can be identified using the Dipole Mode Index (DMI) mentioned by (Nurdiati, Sopaheluwakan, & Najib, (2019, October)); (Shi & Wang, 2022), DMI shows the difference between the western Indian Ocean Sea Surface Temperature (WIOSST) and Eastern Indian Ocean Sea Surface Temperature (EIOSST) (50°E-70°E,10°S-10°N) and (90°E-110°E,10°S-10°N) Indian Ocean Sea surface temperature anomaly. The positive DMI describes the sea surface temperature anomaly of the Western Indian Ocean (Africa) as warmer than the Eastern Indian Ocean.

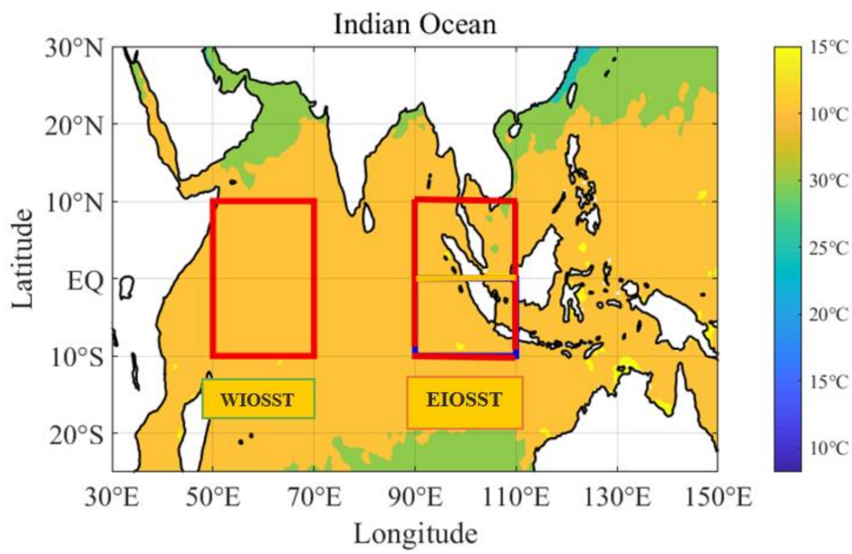


Figure 1: Location of Western IOSST and Eastern IOSST

The IOD and ENSO physically influence Eastern African short rains by modifying regional atmospheric circulation features (Endris, et al., 2019), Because ENSO events differ in their strength, coverage, and seasonality, there isn't unanimous agreement on what constitutes an ENSO event. But there are broad agreements and you can find some of the lists researchers have used along with how they chose those years. The list in table 1, right column represents ENSO years based on Physical Science Laboratory (PSL's) Extended Multivariate ENSO Index (MEI.ext) MEIV2.The Oceanic Niño Index (ONI) has become the de-facto standard that NOAA uses for classifying El Niño (warm) and La Niña (cool) events in the eastern tropical Pacific. It is the running 3-month mean SST anomaly for the Niño 3.4 region (i.e., 5°N-5°S, 120°-170°W). Events are defined as 5 consecutive overlapping 3-month periods at or above the +0.5° anomaly for warm (El Niño) events and at or below the -0.5 anomaly for cool (La Niña) events. The threshold is further broken down into Weak (with a 0.5 to 0.9 SST anomaly), Moderate (1.0 to 1.4), Strong (1.5 to 1.9), and Very Strong (≥ 2.0) events.

Table 1. Classifying El Niño (warm) and La Niña (cool) events

El Niño - 27				La Niña - 25		
Weak - 11	Moderate - 7	Strong - 6	Very Strong - 3	Weak - 12	Moderate - 6	Strong - 7
1952-53	1951-52	1957-58	1982-83	1954-55	1955-56	1973-74
1953-54	1963-64	1965-66	1997-98	1964-65	1970-71	1975-76
1958-59	1968-69	1972-73	2015-16	1971-72	1995-96	1988-89
1969-70	1986-87	1987-88		1974-75	2011-12	1998-99
1976-77	1994-95	1991-92		1983-84	2020-21	1999-00
1977-78	2002-03	2023-24		1984-85	2021-22	2007-08
1979-80	2009-10			2000-01		2010-11
2004-05				2005-06		
2006-07				2008-09		
2014-15				2016-17		
2018-19				2017-18		
				2022-23		

Source: (Voskresenskaya & Marchukova, 2017)

EL Nino events are associated with the warming of the Sea Surface Temperatures (SST) over the tropical Pacific Ocean, which significantly influences rainfall in various parts of the world. This study considered recent El Nino events occurred in (1991/92, 1997/98, 2002/03, 2004/05, 2006/07, 2009/10, 2014/16, 2018/19, 2023/24) but at varying strength as indicated in table one. In the eastern Horn of Africa, rainfall performance during El Nino events is associated with the perturbations in the Sea Surface Temperature (SST) over the Pacific Ocean in addition to the Indian Ocean Dipole (IOD) i.e., the warming of the sea surface temperatures in the western pole of the Indian Ocean relative to the (Singh, Thakur, & Adhikary, 2020).

1.3 Implication of Climate Drivers (ENSO, IOD) on Water Resources

The El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) are major climate drivers that significantly influence the water resources (Kebacho L. L., 2023) reported, Lake Victoria in East Africa through their impacts on regional rainfall patterns, lake levels, and associated hydrological processes. Below is a detailed examination by (Tumusiime, Aribo, Kalema, & Makula, 2025) of their implications, focusing on how these climate phenomena affect Lake Victoria's water resources, including precipitation, lake levels, water availability, and socioeconomic consequences.

ENSO is a coupled ocean-atmosphere phenomenon in the tropical Pacific, characterized by: El Niño: Warmer-than-average sea surface temperatures (SSTs) in the central and eastern Pacific, often leading to altered global weather patterns. La Niña: Cooler-than-average SSTs in the same region, typically associated with opposite effects. IOD is a similar phenomenon in the Indian Ocean, defined by the SST gradient between the western (near East Africa) and eastern (near Indonesia) Indian Ocean. Positive IOD (pIOD): Warmer SSTs in the western Indian Ocean and cooler SSTs in the eastern Indian Ocean, enhancing rainfall in East Africa (Kebacho, Ongoma, & Chen, 2024) described. Negative IOD (nIOD): Opposite SST pattern, leading to reduced rainfall in East Africa and increased rainfall in the eastern Indian Ocean region. Both phenomena interact through teleconnections, influencing rainfall and climate variability in East Africa, including the Lake Victoria basin, which spans parts of Kenya, Tanzania, and Uganda (Endris, et al., 2019) .

1.3.1 Impacts of Climate Drivers on Lake Victoria's Water Levels

El Niño events are frequently associated with enhanced rainfall during the October–December (OND) "short rains" season in eastern Africa, including the Lake Victoria basin. This is due to warmer SSTs in the central and eastern Pacific, which weaken trade winds and shift convective activity eastward, bringing moisture to East Africa (Amador, Alfaro, Lizano, & Magaña, 2006).

For example, the 1997/98 El Niño event (Table 1), one of the strongest on record, led to widespread flooding in East Africa, with rainfall up to 300% above average in some areas, significantly increasing inflow to Lake Victoria. Where thousands of people were displaced, distraction of property and death of life (Opere, 2004). (Pietroiusti, 2022).

However, the impact of El Niño can vary due to local drivers. For instance, the 2018 El Niño resulted in below-average rainfall in parts of the region, indicating that other factors, such as IOD or local atmospheric conditions, can modulate ENSO's effects. According to Awange, et al,2013, La Niña typically leads to suppressed rainfall in the equatorial parts of eastern Africa during the OND season, resulting in drought conditions and affecting resources (Awange, Anyah, Agola, Forootan, & Omondi, 2013) .This was observed during La Niña events of moderate category Table 1 in 2020, 2021, and 2022, which contributed to reduced inflows to Lake Victoria and lower lake levels. Prolonged La Niña events can exacerbate water scarcity, affecting agriculture, hydropower, and water supply in the basin (Nassali, Yongji, & Fangninou, 2020).

A positive IOD is strongly linked to increased rainfall during the East African Short Rains (EASR, October–December), as warmer SSTs in the western Indian Ocean enhance convection and bring

moisture-laden westerlies to East Africa. The 2019 positive IOD event led to rainfall 300% above normal, causing significant flooding around Lake Victoria and contributing to elevated lake levels. When positive IOD coincides with El Niño (e.g., 1997/98), the combined effect amplifies rainfall, leading to extreme flooding events that significantly increase lake inflows (Mutua, 2013).
Negative IOD events result in cooler SSTs in the western Indian Ocean and warmer SSTs in the eastern Indian Ocean, reducing rainfall in East Africa and increasing the risk of drought. This can lead to decreased inflows to Lake Victoria, lowering lake levels and affecting water availability (Funk, et al., 2014) .

1.3.2 Extreme ENSO and IOD events on Lake Level Fluctuations

Lake Victoria's water levels are highly sensitive to rainfall variability driven by ENSO and IOD. Historical records and limnological studies indicate that extreme ENSO and IOD events have caused significant lake level changes. For example, during the 1876–1878 El Niño and positive IOD, initial drought in 1876 was followed by floods in 1877–1878, leading to notable lake level rises. The 1997/98 El Niño and positive IOD event caused a rapid rise in Lake Victoria's water levels due to excessive rainfall as (Liu, Cook, & Vizy, 2020) mentioned that with lake levels reaching historic highs, leading to flooding of surrounding areas.

During La Niña and negative IOD events, reduced rainfall leads to lower inflows, causing lake levels to drop. This was evident in the early 2000s when prolonged dry conditions, partly influenced by La Niña, led to a significant decline in Lake Victoria's water levels, affecting hydropower generation at the Nalubaale and Kiira dams (Mahmoud, Gan, Li, & Funk, 2022).
Positive IOD and El Niño events, especially when co-occurring, can cause lake levels to rise dramatically. The 2019 positive IOD, combined with a weak El Niño, led to unprecedented lake level increases, causing flooding that displaced communities and disrupted livelihoods around the lake. In this study, we examined the extreme flood events, trends, and impacts on rural communities to improve the understanding of weather and climate extremes to formulate mitigation strategies for community resilience to floods. Flood-prone areas along Lake Victoria in East Africa, were the focus due to recent flood incidences that occurred in Uganda and claimed lives and property (the State of Climate in Africa 2019, pg. 17).

1.3.3 Enhanced Rainfall on Water Availability and Quality

Enhanced rainfall increases river inflows (e.g., from the Kagera, Mara, and Simiyu rivers) into Lake Victoria, improving water availability for domestic, agricultural, and industrial use.

However, excessive inflows can lead to flooding, which may contaminate water sources with sediments, pollutants, and pathogens, degrading water quality. Flooding events can also increase nutrient runoff, leading to eutrophication and algal blooms in Lake Victoria, which negatively impact fisheries and water treatment processes Roegner, A. F., et al. (2023), (Roegner & al., 2023). Drought conditions reduce inflows, limiting water availability for irrigation, domestic use, and hydropower. Lower lake levels can also concentrate pollutants, further degrading water quality and increasing treatment costs. Reduced water availability during droughts exacerbates competition for water resources among agriculture, fisheries, and urban centers in the Lake Victoria basin. Rainfall is very important for a lake's ecological system as it accounts for over 80% of its recharge (Awange et al., 2008); (Herrnegger, Stecher, Schwatke, & Olang, 2021).

1.3.4 El Niño and positive IOD impact on Socioeconomic and Ecological Impacts

El Niño and positive IOD events, by increasing rainfall, can boost agricultural productivity in the short term but often lead to crop losses due to flooding. For instance, the 1997/98 floods destroyed crops and infrastructure around Lake Victoria. La Niña and negative IOD-induced droughts reduce agricultural yields, threatening food security. The 1876 drought, linked to a La Niña-like event, caused widespread crop failures and famine in the region. triggered negative impacts on agriculture and food security Durodola, O.S. (2019).

Positive IOD and El Niño events are linked to increased incidences of waterborne diseases like cholera and malaria due to flooding and stagnant water pools. For example, the 2019 positive IOD was associated with malaria resurgence in East African highlands. Droughts during La Niña and negative IOD can lead to water scarcity, increasing the risk of water-related diseases due to reliance on contaminated water sources (Funk, et al., 2023).

Conflict and Migration; Extreme weather events driven by ENSO and IOD can lead to resource conflicts over water and arable land. Flooding and droughts displace communities, as seen during the 2019 floods, which forced thousands to relocate around Lake Victoria. This affected the livelihood of many people living around the Victoria basin, it was reported that over 200,000 in Uganda people were displaced because of the lake flooding (Mafaranga, 2020).

1.3.5 El Niño and positive IOD impact on Hydropower Generation

Lake Victoria is a critical water source for hydropower generation at the Nalubaale and Kiira dams in Uganda. High lake levels during El Niño and positive IOD events support increased power generation, while low levels during La Niña and negative IOD events reduce output, affecting energy supply in Uganda and neighboring countries. Lake Victoria supports a vital fishing industry. Flooding from El Niño and positive IOD can disrupt fishing activities due to turbulent waters and habitat changes, while droughts from La Niña and negative IOD reduce fish habitats and affect fish stocks due to lower water levels and increased water temperatures. Elsewhere it has been indicated that hydrological processes are characterized by high variability of rainfall both in space and time, making them sensitive to small-scale temporal and spatial rainfall variability (Cristiano, ten Veldhuis, & Van De Giesen, 2017).

The outstanding subsequent sections of the present study are structured as follows: the study domain, datasets, and methods. This is followed by another Section presenting the main results. Section 4 clarifies the conclusion and recommendations based on the endings of this research. The study domain is the Lake Victoria catchment located in the Eastern part of the African continent the region is enclosed within the geographical latitudes 5.1° N to 11.74° S and longitudes 28.86° E to 41.91° E. (Wasige, 2013).

1.2 Problem statement

Eastern Africa's rainfall seasons, critical for sustaining water resources, agriculture, and livelihoods, are significantly influenced by major climatic drivers such as the El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and Madden-Julian Oscillation (MJO), compounded by the effects of global climate change (Shongwe, van Oldenborgh, Van den Hurk, & van Aalst, 2011) Studies indicate that these climatic drivers cause shifts in rainfall, with long rains (March–May) decreasing and short rains (October–December) increasing. This variability results in more frequent droughts and floods, which can reduce river discharge into Lake Victoria (a shared water resource by East Africa countries) by up to 29% by 2060, according to projections, affecting the lake's water levels and availability. Research highlights that major climatic drivers, including (ENSO) and (IOD), play a dominant role in shaping rainfall patterns in Eastern Africa.

According to Kimuli 2023 review in Nature Reviews Earth & Environment (Kimutai, et al., 2023), these drivers contribute to high variability in precipitation patterns, leading to extreme weather events such as droughts and floods, which disrupt water availability, agricultural productivity, and ecosystem stability. Despite their importance, the complex interactions between these climatic drivers and their cumulative impact on Eastern African rainfall seasons remain inadequately understood, limiting the ability to predict and manage water resources effectively. This knowledge gap hampers the development of adaptive strategies to mitigate the socio-economic and environmental consequences of variable rainfall, particularly in the region of East Africa which is heavily reliant on rain-fed systems. Therefore, there is an urgent need to investigate how these climatic drivers shape rainfall patterns in Eastern Africa and to assess their implications for sustainable water resource management, food security, and resilience to climate variability. (Bhaga, Dube, Shekede, & Shoko, 2020).

1.3 Main Objective

The overall aim of this study is to analyze the Influence of Major Climate Drivers on Eastern African Rainfall Regimes and Their implications on Water Resources.

1.3.1 Specific Objective

i) To analyze seasonal rainfall variability and trends during El Niño - Southern Oscillation (ENSO) years on the East African rainfall 1990-2024).

ii) To evaluate the contributions of Indian Ocean Sea Surface Temperatures to Enhanced East African Rainfall (1990-2024).

iii) To examine the Implication of climate drivers (ENSO, IOD) on water resources in Lake Victoria basin (1990-2024).

1.4 Significance of the Study

Understanding Climate Variability in East Africa and Lake Victoria Basin, a vital ecological and economic region, is highly sensitive to climatic drivers such as the El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and other global and regional climate phenomena. This study elucidates how these drivers influence rainfall patterns, providing insights into the variability and predictability of precipitation, which is essential for effective water resource planning and management. The Lake Victoria Basin supports millions of people across multiple countries, providing water for domestic use, agriculture, fisheries, and hydropower generation. By examining the implications of rainfall variability on water availability, this study offers valuable data for optimizing water resource allocation, improving irrigation practices, and ensuring sustainable water supply under changing climatic conditions.

Agriculture in the Lake Victoria Basin is predominantly rain-fed, making it vulnerable to shifts in rainfall seasons. Understanding the influence of climatic drivers on rainfall can guide farmers and policymakers in developing adaptive strategies, such as improved crop selection and timing of planting seasons, to enhance agricultural productivity and ensure food security. Climate Change Adaptation: With climate change intensifying extreme weather events, this study provides a foundation for developing adaptive measures to mitigate the impacts of droughts, floods, and irregular rainfall patterns. It supports the formulation of policies and interventions to enhance resilience in communities dependent on the basin's water resources. Socioeconomic and Environmental Implications: The findings of this study can inform regional planning and disaster risk reduction strategies by highlighting how climatic drivers affect rainfall variability, water availability and related socioeconomic activities.

The study's outcomes can guide policymakers, water management authorities, and international organizations in designing evidence-based strategies for sustainable development. By linking climatic drivers to water resource dynamics, it supports informed decision-making to address challenges such as water scarcity, flood management, and transboundary water governance. In summary, this study is significant for advancing scientific understanding of climate-rainfall interactions, supporting sustainable water resource management, and fostering resilience in the Lake Victoria Basin, thereby contributing to the region's socioeconomic development and environmental sustainability.

1.6 Conceptual Framework

Below is a conceptual framework for the research objectives figure1, designed to guide the study of seasonal rainfall variability, the influence of Indian Ocean Sea Surface Temperatures (SSTs), and the implications of climate drivers (ENSO and Indian Ocean Dipole, IOD) on water resources in the Lake Victoria Basin from 1990 to 2024. The framework outlines the relationships between key variables, their interactions, and their impacts, providing a structured approach to addressing the objectives.

Independent Variables; (El Niño-Southern Oscillation (ENSO)) Measured through indices like the Niño 3.4 index, which tracks sea surface temperature anomalies in the Pacific Ocean. ENSO phases include El Niño (warm phase), La Niña (cool phase), and neutral conditions. Indian Ocean Sea Surface Temperatures (SSTs): Represented by SST anomalies in the Indian Ocean, particularly the Indian Ocean Dipole (IOD) index, which captures the dipole mode (positive and negative phases) influencing East African rainfall. Climate Drivers: Combination of ENSO and IOD, as they interact to modulate regional climate patterns.

Dependent Variables; **(**Seasonal Rainfall Variability and Trends) Measured as rainfall anomalies, seasonal precipitation totals, and trends in rainfall amount, intensity, and frequency in East Africa (1990–2024).

Enhanced East African Rainfall: Quantified by increased rainfall during specific seasons (e.g., short rains, October–December, or long rains, March–May) linked to SST anomalies. Water

Resources in Lake Victoria Basin: Indicators include lake levels, river discharge, groundwater recharge, and water availability for agriculture, domestic use, and hydropower.

Conceptual Framework

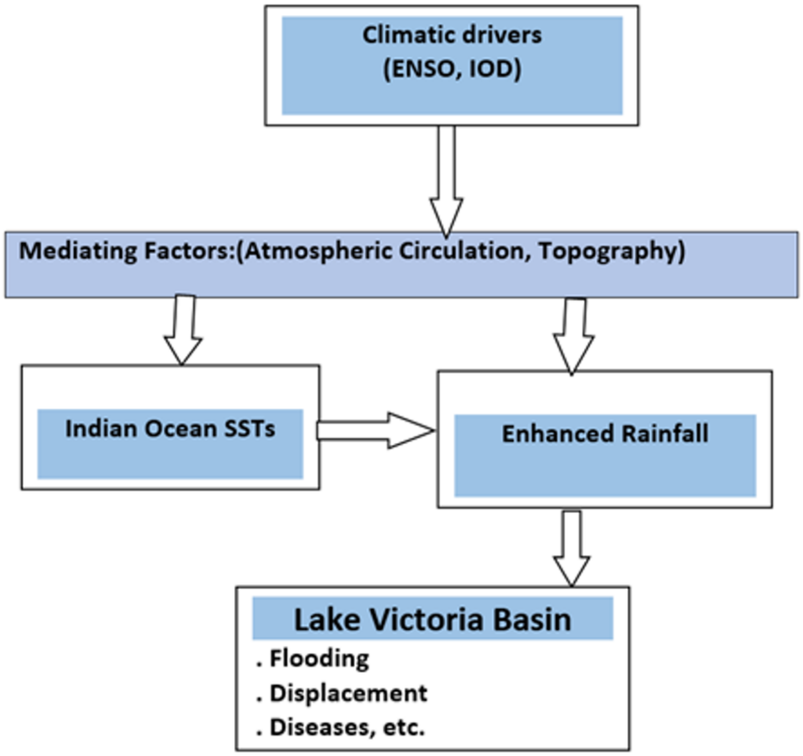


Figure 2: Conceptual framework for the research objectives

Past El Nino events led to significant climatic, environmental, and socio-economic impacts in the Greater Horn of Africa. This includes depressed rains during the June-September rainfall season in parts of Sudan, Ethiopia, Eritrea, and Djibouti. On the contrary, in the south (equatorial) of the region (Kenya, Somalia, south-southeast Ethiopia, Uganda and to some extent Burundi and Rwanda), enhanced/wetter-than-normal rains have been experienced during the October-December season (ICPAC, 2023), WMO State of the Climate in Africa 2023, East African countries are affected differently during EL Nino which requires serious attention for regional economic planning.

To understand the influence of climate drivers on rainfall, my study focused on the behaviors dipole mode index (DMI), The Dipole Mode Index is a measure of the temperature difference across the tropical Indian Ocean, specifically the east-west gradient of sea surface temperatures. It is a key indicator of the Indian Ocean Dipole (IOD) phenomenon. A positive DMI indicates a positive IOD, characterized by warmer-than-average waters in the western Indian Ocean and cooler-than-average waters in the east. Conversely, a negative DMI signifies a negative IOD, with cooler waters in the west and warmer waters in the east.

The Western Indian Ocean Dipole (WIOD), representing the western pole of the IOD, influences East African rainfall through its impact on the Walker circulation and moisture transport from the Indian Ocean. During SOND in El Niño years), warmer WIOD Sea Surface Temperatures (SSTs) enhances rainfall in some areas, particularly [e.g., coastal Kenya and southern Tanzania]. This pattern aligns with the expected influence of a positive IOD phase, often co-occurring with El Niño, where warmer WIOD SSTs strengthen convection over the western Indian Ocean, increasing moisture convergence over East Africa. The Eastern Indian Ocean Dipole (EIOD) representing the eastern pole of the IOD, is a well-documented driver of East African rainfall, particularly during the short rains (Nicholson, 2017).

CHAPTER TWO: LITERATURE REVIEW

2.0 Seasonal Rainfall Variability and Trends during El Niño - Southern Oscillation (ENSO)

The ElNino Southern Oscillation (ENSO) is an irregular periodic variation in winds and sea surface temperatures over the tropical eastern Pacific Ocean, which leads to significant influence on rainfall across the world as three (3) phases (ELNino, LaNina and Neutral) are among the leading natural climate indices that have a strong impact on global and regional average temperature and rainfall (Singh, Thakur, & Adhikary, 2021).

2.1. Global Teleconnections

Rainfall variability over Eastern Africa is influenced by several modes of climate variability, including the El Niño–Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), the Quasi-Biennial Oscillation (QBO) and the Madden–Julian Oscillation (MJO) (Nicholson, 2017).

The IOD is a key driver of such inter-annual rainfall variability, describing differences in sea surface temperature (SST) anomaly between the western (50° E to 70° E, 10° S to 10° N) and eastern (90° E to 110° E, 10° S to 0° S) Indian Ocean. The positive IOD (signifying an SST anomaly difference of at least +0.4 °C for at least three months between the warmer west and cooler east) is linked with wetter short rains over Eastern Africa. During such phases, precipitation totals can be 2–3 times the long-term mean, as seen in 1997, 2006, 2012, 2015 and 2019. In contrast, the negative IOD (defined by a sustained negative SST difference of at least 0.4 °C) is associated with weaker short rains, resulting in 20–60% of the long-term mean rainfall, as evident during 1996, 1998, 2010 and 2016 (Ashok Singh Samir Thakur Nirab C. Adhikary 2023).

ENSO, which describes SST variability in the central and eastern tropical Pacific, is also connected to changes in the short rains. El Niño conditions, associated with warmer SST anomalies over the central and eastern Pacific, typically result in wetter short rains, whereas La Niña conditions, associated with cooler SST anomalies, result in drier short rains. ENSO's impact on Eastern Africa is, however, strongly mediated by the IOD. The typical concurrence of positive IOD with East Pacific El Niño, and negative IOD with East Pacific La Niña, act to amplify precipitation responses. For instance, the coincidence of the 1997 El Niño with a strong positive IOD event led to short rain anomalies twice the climatological mean. In contrast, the strong central Pacific El Niño of 2015 coincided with a weaker IOD, producing anomalies ~50% above the climatological mean. However, these relationships are nonlinear, as demonstrated by extreme 2019/2020 rainfall that occurred during an anomalously positive phase of the IOD but neutral ENSO conditions.

The IOD and ENSO physically influence Eastern African short rains by modifying regional atmospheric circulation features (Ashok Singh Samir Thakur Nirab C. Adhikary 2023).

2.2 Climate Drivers

The ElNino phase is characterized by the warming of the sea surface (above-average sea surface Temperatures (SST) over the central and eastern Pacific while LaNina is the cooling of the sea surface (below-average SST) over the same area). Historically, ElNiño and LaNiña events are known to occur every two to seven years, though not on a regular schedule. The ElNiño event is more frequent than the LaNiña. When they occur, ElNino and LaNina conditions last nine to twelve months but at times can last longer (RAM,2023) .
lakes and rivers including wetlands which cover about 16% of the country (Uganda's) total surface area, with rainfall being the highest contributor disclosed (Nsubuga, 2014) With entire renewable water resources estimated at 66 km3/yr corresponding to about 2,800 m3/person/yr, East Africa is considered to be endowed with substantial freshwater resources though faced with climate change and variability generated extreme phenomenon, the rains are also influenced by atmospheric phenomena such as El-Nino Southern Oscillation (ENSO) (Indeje et al. 2000; Ntale and Gan 2004) and the Indian Ocean Sea Surface Temperature (SST) (Behera, et al., 2005). Weiran Liu.Kerry H. Cook. Edward K. Vizy 2020.

The El Niño Southern Oscillation (ENSO) phenomena are strongly associated with inter-annual variability of rainfall which has left unanswered questions to the community that attracted this research (including; what induces flood extreme over East Africa lakes catchment? what impacts of flood extreme on the socio-economic status of rural communities in East Africa? Saudi study revealed that changing precipitation patterns could be due to climate change or a connection with El Niño years, (Durodola, 2019), Staudt et al 2014. It is also important to gather more information about weather extremes and disclose if they are tied to climate change or other factors. Food security is an important factor for the well-being of the community, a study by the Word Food Programme Team revealed that Floods and Drought extremely affected food production across East Liu, W., Cook, K. H., & Vizy, E. K. (2020).

In this study, we examined the extreme flood events, trends, and impacts on rural communities to improve the understanding of weather and climate extremes to formulate mitigation strategies for community resilience to floods. Understanding variations in rainfall in tropical regions is important due to its impacts on water resources, health, agriculture and other services. Rainfall is one of the key climatic variables, and its temporal variability over East Africa has far reaching effects on the social, economic and ecological aspects of the region. The rainfall variability on different temporal scales, such as the inter-annual, seasonal, and inter-decadal, is extensively studied globally as observed by Barron et al. (2003).

Climate change is one of the global developmental and environmental challenges threatening the existence of humanity today. An unprecedented concentration of greenhouse gases in the atmosphere is linked to an overall warming of the planet, which has been affecting climate and weather patterns (Diaz, et al., 2016) taking into account that rainfall is one of the elements of weather and climate. Evidence is emerging that climate change is increasing rainfall variability and the frequency of extreme events such as drought, floods (Kansiime, et al., 2013; IPCC, 2007). Scientists around the world now agree that climatic changes occurring internationally are more the result of human activity (Tumusiime, 2018) which is common in lakes of Nile basin.

The cause of these major increases in rainfall in East Africa was attributable to ENSO and IOD a positive Indian Ocean Dipole (IOD) phase, a weather phenomenon caused by differences in sea surface temperatures between the eastern and western tropical Indian Ocean. In 2020, the differences in temperatures were higher than usual, causing much more rainfall (higher-than-average rainfall) over East Africa from September to January, resulting into floods in the region (Olaka, 2020). Although the rainfall caused by the dipole ended, the region then moved into its rainy season which typically runs from March to May (Olaka, 2020).

The typical concurrence of positive IOD with East Pacific El Niño, and negative IOD with East Pacific La Niña, act to amplify precipitation responses (Masood et al 2023) For instance, the coincidence of the 1997 El Niño with a strong positive IOD event led to short rain anomalies twice the climatological mean. In contrast, the strong central Pacific El Niño of 2015 coincided with a weaker IOD, producing anomalies ~50% above the climatological mean. However, these relationships are nonlinear, as demonstrated by extreme 2019/2020 rainfall that occurred during an anomalously positive phase of the IOD but neutral ENSO conditions.

Over the Lake Victoria basin, many studies about rainfall variability have been carried out for example Kizza et al., (2009) suggested the need of constantly carrying out temporal analysis of precipitation using updated datasets in order to analyze the current trends in precipitation over the basin, studies by (Nimusiima A, Basalirwa, & Majaliwa, 2013) established that the community believed there was a changing temporal and spatial rainfall pattern and that seasonal rainfall has become unpredictable. What is not clear are the intra-seasonal changes regarding wet and dry spells. The community perceives those dry spells have become longer, but is not sure which period (month) of the season is more affected than the other.

According to Ogega, Obed. (2021) a considerable increase in rainfall was experienced as unusually heavy June to December 2019. It was observed that October increased by 79%, in November by 56%, and in December by 74% compared to the long-term average. Observed rainfall in 2020 increased in January by 83%, in February by 25%, in March by 43%, and in April by 33% compared to the long-term average. However, May rainfall was less than the long-term average. Due to increases in rainfall, annual average river runoff and water availability are projected to increase by 10- 40% during the mid-century in some wet tropical areas and at high latitudes, and decrease by 10-30%over some dry regions (Parry, 2007).

2.2.1 The Impacts of Extreme Rainfall Events Over East Africa (EA)

Considering the impacts of extreme rainfall events over East Africa (EA) which range from loss of human and animal lives to the destruction of properties, it is important to understand previous climate events fully and their impacts to make more accurate and reliable forecasts to alleviate their impact (Ogwang et al. 2015b). While we acknowledge previous attempts aimed at generating information on extreme rainfall events over EA (e.g Ogwang et al. 2015b; Ongoma and Chen 2018; Kilavi et al. 2018; Nimusiima et al. 2019; Nkunzimana et al. 2019), in-depth and regular comprehensive analysis of extreme rainfall events which are required to support adaptation and mitigation of impacts is still insufficient. The present study is to analyze daily observed rainfall data and water levels to show the recent past occurrence of extreme rainfall events and their consistency in improving rural community livelihood and future development in East African countries.

2.3 To Examine the Implication of Climate Drivers (ENSO, IOD) on Water Resources in Lake Victoria basin (1990-2024)

2.3.1 Lake Victoria Water levels

A study carried out and witnessed that current rise in Lake Victoria water level started on 1st October 2019 and has consistently gone up from 12.00 meters to the current level of 13.32 meters as of 30th April 2020. This is a rise of 1.32 meters attained in only 6 months and the level is only 0.08 meters away from the highest level ever recorded (Cheptoris, 2020). Recently, and perhaps most threatening, Lake Victoria water level has been receding at an alarming rate (Awange, 2008). Although several studies have acknowledged that water levels of Lake Victoria have been threatening, there is still need to know why water levels raised so rapidly after a long time. Levels of these lakes, and other historical indicators in Africa, suggested that environmental conditions in the nineteenth century were much more extreme than anything evident in the modern record (Nicholson et al, 2001).

The fluctuations in water levels are attributed to several factors of which these factors may be anthropogenic factors or climatic factors. The lake's rise is due to increased runoff caused by human activities around Lake Victoria and the rivers that feed it. Twenty-three rivers feed the lake, some of these rivers originate hundreds of kilometers away; when it rains in Burundi, water finds its way to Lake Victoria. Human activities have accelerated the quick rise in Victoria's waters, (MWE, 2020). "Loss of forest cover, encroachment on wetlands, lakeshores, and river banks, including poor land use practices, have resulted in soil erosion, leading to siltation of our water bodies. Human impacts, nevertheless, are expected to continue from activities like sand mining, forestry, and agriculture, which all use water and encroach on the lake. Threats from climate change, such as more frequent instances of the El Niño–Southern Oscillation, also continue to disturb the shores of Lake Victoria (Twinomuhangi, 2020).

East Africa as a developing region, urbanization has increased the number of impermeable surfaces such as roads, roofs, and pavements, reducing water penetration into the soil and increasing the amount of runoff flowing to storm drains and other discharges (Okidi, 2020). Urbanization has also reduced the evapotranspiration capacity of forests and wetlands surrounding Lake Victoria. As lakes rise and fall more severely, experts say more consideration needs to be given to those creatures living along their shores. A growing number of communities-both coastal and inland—are finding themselves underwater. Extreme weather, sea level rise, and other climate change impacts are increasingly to blame (Mafaranga, 2020). During rainy season fish migrate to the newly inundated areas and shallow peripheries and escape from fishing gear because of the water level rise in the inland reservoirs (Patrick, 2016). This has caused a community outcry especially those involved in fishing to understand the water level changes and the possible factors responsible for these water level changes. This study therefore aims at analysing what influence rainfall leading to extreme rise of water levels of lake victoria ashared water body by three countries.

2.3.2 Fluctuations of Water level and Rainfall

Typically, water levels begin to rise in the spring when rain falls on the lakes or trickles in from the land and when snowmelt floods the tributaries that empty into the lake. Stronger storms and harsher cold snaps could mean more dramatic ups and downs for lake levels in the future. In the year 2020, after wetter-than-normal conditions, six rainfall events in May sent lake levels surging across the Great Lakes Basin. Uganda received the same amount of rainfall between 1961 to 1964 and 1996 to 1998, which resulted in a rise in the levels of rivers and lakes" in the region (Cheptoris,2020) but the current situation has been worsened by environmental degradation and urbanization associated with drought in 2016–2017 (Cheptoris,2020).

The Lake level rise in the early 1960s was a result of abnormally heavy rains; in the last six months of 1961, 2323 mm of rain were recorded, nearly 100% higher than its average value. Very high rainfall was recorded during the first six months of 1962 (1884 mm/year, about 50-60% above average), and 1963 (1739 mm), and 1964 (1739 mm). As a result, the lake level rose by 2.5 m by 1964 which was the historical highest level before 2020. From 1964 onwards, Lake levels continued falling with some isolated increases (e.g., in 1982 and 1997/98) until they reached a minimum of 10.4 m in 2006. Due to the recent heavy rains however, by May 2020 the water level had exceeded the historical mark and hit 13.42 m (Mafaranga, 2020).

Water level fluctuations have always been attached to climatic factors for example fall in water level to drought while rise in water level to increase in rainfall. The rise in lake level can be explained through rainfall and resulting tributary inflows, which would allow projections of possible future levels to be made by analysis of rainfall series. Eastern Africa is dominated by the Nile River basin but also encompasses tributaries of the Congo as well several regionally important rivers draining eastwards into the Red Sea, the Gulf of Aden and the Indian Ocean. Two endorheic rivers, the Awash and Omo, terminate in the Afar depression and Lake Turkana, respectively. The Nile basin contains several Rift Valley lakes, including Lake Victoria, which collects water from Burundi, Rwanda, northern Tanzania and the Kenyan Highlands, and has an important role in regulating flows in the White Nile downstream Paul et al 2023. The strong relationship between climatic indicators of drought and rainfall on one-hand and lake levels on the other hand signifies the need to incorporate climate information in predicting, monitoring and managing lake level changes (Awange, 2008).

Most of the studies have considered analyzing rainfall variability over Lake Victoria basin although not any has attempted to correlate rainfall with water level extreme rise so as to establish what relationship exists between the two variables on period of occurrence and return period. Mugume et al., (2016) aimed at identifying the periods within the MAM season that are becoming drier or wetter and considered variability in rainfall characteristics over the Lake Victoria basin because this variability is important due to its impact on water levels of the lake. Since it has been appreciated that rainfall variability has an impact on the water levels, it is therefore necessary to carry out this study in order to find out what influence could rainfall have on the lake levels.

Generally, most of studies have examined the relationship between rainfall and water levels though not identified the extreme return period and level of community damages along the lake shores.

A study on rainfall trends and temporal variations within seven sub-basins of Uganda from 1940 to 2009 using long-term observational data from 36 stations in different hydroclimatic conditions was conducted (Nsubuga et al., 2014) The results show decadal variability of rainfall with marked seasonal cycles and temporal variability of drought patterns over the region, such results are reflected in marked fluctuation in the lake water levels that greatly influence the socio-economic activities and the livelihood of the surrounding communities in East Africa (Nsubuga et al., 2014). Another study suggests that Lake Victoria's water level has been receding at an alarming rate and threatening all socio-economic activities associated with it (Awange et al., 2008). Over the last decade however several Lakes in the East African regions have witnessed an increase in their lake water levels, areas, and volumes, thus affecting the rich neighboring biodiversity, infrastructure, and livelihoods of the local communities (Herrnegger et al., 2021).

Rainfall is attested as one of the main sources of water that pours into the lake, therefore its variation in water levels should be of paramount importance. Perhaps, rainfall variability and the associated rainfall events have over several decades caused abrupt changes in water levels, transport difficulties, and socio-economic losses due to the loss of fish and famine. Recently, the water level of Lake Victoria (shared lake between three countries) has reached unprecedented heights as a result of heavy rains in the East African region which started in August 2019 (Mafaranga, 2020).

Water levels of Lake Victoria are susceptible to moderate changes in rainfall over the lake and rain catchment basin. Lake Victoria experienced drastic water level changes recently presenting a great threat to the community around the basin. The extreme rise in the water level of Lake Victoria involved looking at the effects of climate change. Changes in climatic conditions coupled with changes in land use around the continent, increased water demand from a growing human population, and depletion of groundwater resources remain issues of key concern amongst water managers (Fishman, 2018; Fl¨orke et al., 2018).

The Lake Victoria water levels have exhibited fluctuations since 1960. The highest rise in the lake water level was registered during the common El-Nino events early 60s and 1997/1998 (Nicholson,1998,1999), …2023. and is attributed to over-lake precipitation). From 2000 to 2005 Lake Victoria water levels fell drastically (USDA 2005) and it was suggested that the later water levels dropped well below more than 1.1meters below the previous 10-year average (Kull 2006).

The correlations between the Indian Ocean SSTs and EA short rains show interdecadal variability. Clark et al. (2003) studied the rainfall during October–December along the coast of Kenya and Tanzania, and found correlations between Indian Ocean SSTs and EA precipitation in

1950–1982 and 1983–1993 nearly reverse in sign. East Africa experiences varying rainfall associated with IOD, ENSO Ummenhofer et al. (2009) with some areas receiving heavy rains that in some instances have resulted in property destruction, and death of both livestock and human beings, while other areas have experienced drought and subsequently severe famine. This pattern of variance has prompted studies aimed at detecting whether rainfall patterns have been changing. There is a need to study how these changes are occurring or have occurred over the recent period. This study is therefore aimed at analyzing the variability of rainfall and how it influences the Lake Victoria water levels impacting socio-economic activities around the basin for the purpose of saving lives of the population, and prevent the destruction of properties by providing viable scientific evidence, about rainfall variability and its impacts on lake water levels to the communities.

CHAPTER THREE: DATA AND METHODS

3.1 Data and Analytical Methods

The East Africa (EA) region is located at the coast of Indian Ocean; its latitude extends 1.957709 and longitude 37.297204. This present work mainly focuses on analyzing the long-term pattern of rainfall and the effect of rising extreme water levels and climatic indices (ENSO and IOD) as the main driver of rainfall variability in the EA region.

The ENSO index for the period 1990–2024 (35 years) used in this study was derived from the SST (Sea Surface Temperature) in the Nino 3.4 region (1200–1700 W, 50 N–50 S) and collected from the Climate Predictor Centre of NOAA are available at the website http://origi n.cpc. ncep.noaa.gov/produ cts/analy sis_monit oring /ensos tuff/ detre nd. nino3 4. ascii .txt.

Chirps' precipitation data was downloaded from (Global/CHIRPS 2.0). Water level data set from satellite altimeters was collected from DAHIT, Geosat, G-REALM, HYDROWEB databases and Ministry of Water and Environment.

Analysing seasonal rainfall variability and trends during El Niño-Southern Oscillation (ENSO) years involves a combination of statistical, climatological, and modelling approaches. Below are the key methods used.

3.1.1 Data Collection and Preprocessing

Sources of data was use of historical rainfall data from meteorological stations, Water level from Ministry of Water and Environment, satellite observations (e.g., TRMM, GPM), and reanalysis datasets (e.g., ERA5, NCEP-NCAR). Quality Control: Remove outliers, fill missing data using interpolation or imputation techniques, and standardize data formats.

ENSO Identification: Classify ENSO phases (El Niño, La Niña, Neutral) using indices like the Oceanic Niño Index (ONI), Southern Oscillation Index (SOI), or Multivariate ENSO Index (MEI).

3.1.2 Time Series Analysis

Trend Analysis; Apply linear regression (Mann-Kendall test) was used to detect monotonic trends in rainfall during ENSO years.

Holt's Linear Trend Model (for trend):

$$S_t = \alpha Y_t + (1 - \alpha)(S_{t-1} + T_{t-1}) \quad \text{(i)}$$

$\boldsymbol{T}_t = \beta(S_t) + (S_{t-1}) + (1-\beta)\,T_{t-1}$ ……………………………………(ii)

T_t: Trend estimate

β: Trend smoothing factor ($0< \beta<1$)

Forecast: $\hat{Y}_{t+h} = S_t + hT_t$

Holt-Winters Seasonal Model (for trend and seasonal)

Level: $S_t = \alpha \frac{Yt}{It-L} + (1-\alpha) + (S_{t-1}+T_{t-1})$ ………………………….(iii)

Trend: $Tt = \beta\,(S_t - S_{t-1}) + (1-\beta)\,T_{t-1}$…………………..……………..(iv)

- Seasonal: $I_t = \gamma \frac{Y_t}{S_t} + (1-\gamma) I_{t-L}$
- Forecast: $\hat{Y}_{t+h} = (S_t + hT_t) I_{t+h-L}$
- (L): Seasonal period
- γ: Seasonal smoothing factor ($0 < \gamma < 1$)

3.1.3 Spatial Analysis

Spatial maps of rainfall anomalies were created using Python software applying libraries (cartopy, xarray, numpy, geopandas, pandas, regionmask, matplotlib. pyplot, pearsonr and pymannkendall) to visualize regional variability during ENSO phases.

3.1.4 Composite Analysis

Create composites of rainfall anomalies for El Niño and La Niña years to highlight typical patterns. Average rainfall data over multiple ENSO events to reduce noise and emphasize consistent signals.

3.1.4 Statistical Composite Analysis

In fields like meteorology or data science, composite analysis involves averaging data (e.g., measurements, signals) over multiple events to identify patterns. The equation for a composite mean is:

$\ddot{X} = \frac{1}{N}\sum_{i=1}^{N} X_i$ …………………..……………………………………..…..(v)

Where:

$\ddot{X}$: composite (average) value

X_1: individual data points (e.g., temperature, or signal at events)

(N): Number of events or samples

To evaluate the contributions of Indian Ocean Sea Surface Temperatures (SSTs) to enhanced East African rainfall, this research employs a combination of observational data analysis, statistical methods, and numerical modelling. Below is a summary of the key methods used, based on studies examining this relationship, particularly during the East African "short rains" season (October–November) and in the context of phenomena like the Indian Ocean Dipole (IOD):

3.1.5 Observational Data Analysis

Sea Surface Temperature (SST) and Rainfall Data Collection: Researchers use historical SST datasets (e.g., NOAA's Extended Reconstructed SST, ERSST5) and rainfall records from stations or gridded datasets like the Climatic Research Unit (CRU) to identify correlations between Indian Ocean SST anomalies and East African rainfall. For example, SST anomalies in the western and eastern Indian Ocean are compared with rainfall anomalies over East Africa (5°N–5°S, 35°–50°E)

Dipole Mode Index (DMI): The IOD is quantified using the DMI, which measures the SST gradient between the western (50°E–70°E, 10°S–10°N) and southeastern (90°E–110°E, 10°S–0°N) Indian Ocean. Positive IOD phases (warmer western SSTs, cooler eastern SSTs) are linked to enhanced rainfall.

To examine the implications of climate drivers like the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) on water resources in the Lake Victoria Basin, research employ a combination of methods. These methods integrate observational data analysis, modelling, and statistical techniques to assess impacts on rainfall, lake levels, and water availability. Below is a concise overview of commonly used methods based on available research approaches:

3.1.6 General Equation Framework

Lake water (H_t) at time (t) can be modeled as a function of climate drivers (ENSO, IOD), precipitation, evaporation, and other hydrological factors:

$$H_t = f(ENSO_t, IOD_t, P_t, E_t, Q_{in,t}, Q_{out,t}, \epsilon_t) \quad \text{……………..……………………..…..(vi)}$$

Where:

- H_t: Lake water Level at time (t)
- $ENSO_t$: ENSO index (e.g., NINO3.4 sea surface temperature anomaly or Southern Oscillation Index, SOI)
- IOD_t: IOD index (e.g., Dipole Mode Index, DMI)

- P_t: Precipitation overthe lake and its catchment
- E_t: Evaporation from the Lake surface

- E_t: Evaporation from the lake surface
- $Q_{in,t}$: Inflow from rivers or groundwater
- $Q_{out,t}$: Outflow (e.g., river discharge, withdrawals)
- ϵ_t: Error term or unexplained variability
- (f): Functional form (e.g., linear, nonlinear, or a hydrological model)

3.2 Scope of the study

The scope of the study for "East Africa and its Rainfall Seasons" defines the boundaries and focus of the research. Here’s a concise explanation of what the scope of this study entails:

Geographical Scope: The study focuses on East Africa, typically including countries such as Kenya, Uganda, Tanzania, Rwanda, Burundi

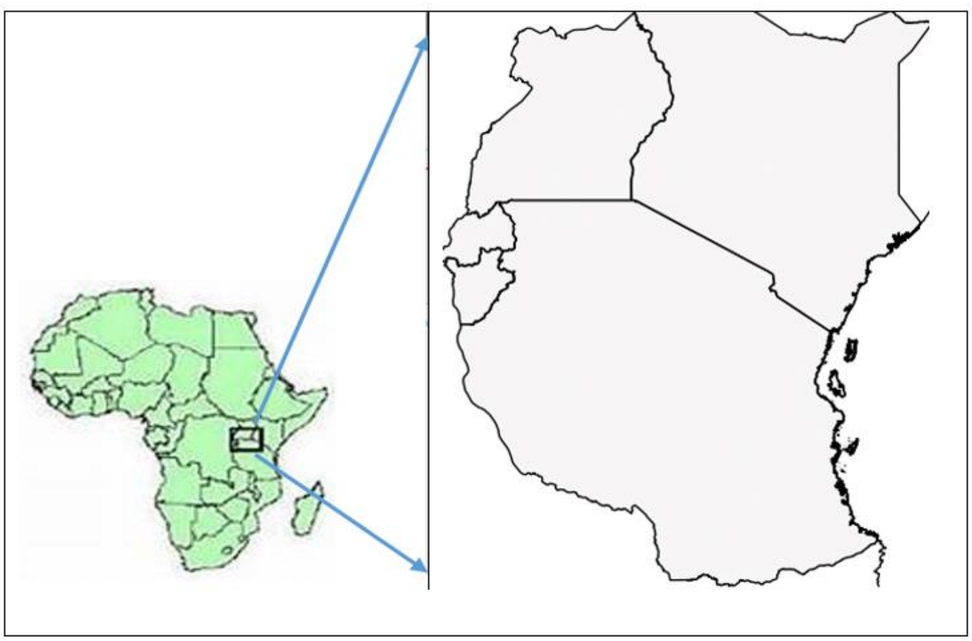


Figure 3: Map of Africa showing location of East Africa

Temporal Scope: The research examines rainfall seasons over a specific period, such as historical data (e.g., past 35 years), current patterns It focused on seasonal cycles, annual variations, or long-term trends.

3.2.1 Thematic Scope

The study centers on rainfall seasons, including: Seasonal Patterns: Analysis of the bimodal (two rainy seasons: "long rains" in March-May and "short rains" in October-December) and unimodal rainfall regimes in different parts of East Africa.

Climate Influences: Factors affecting rainfall, such as the Indian Ocean Dipole, El Niño/La Niña, and Inter-Tropical Convergence Zone (ITCZ) movements.

3.2.2 Climate of the Area

Geographically, Lake Victoria basin spans latitudes 0.33◦N–3◦S and longitudes 31.67◦E–34.88◦E and is the third largest lake in the world before Lake Superior the second and Caspian Sea the largest of the Great Lakes. It experiences annual rainfall of about 1200 mm throughout the year generally distributed into two distinct rainfall seasons Nicholson, 2017). The Lake Victoria basin has a bimodal rainfall structure, with one long rain season which approximately stretches from March to May (MAM) that coincides with the inter tropical convergence zone which follows the overhead sun around 21st-March Kizza et al., 2009; Nicholson, 2017) This is followed by a long dry season stretching from June to August (JJA). A short rain season is experienced during the period of September to November (SON) followed by a short dry season of the following month of December to January (DJF) (Ogwang et al., 2016).

Like most parts of East Africa, the lake basin climate is affected by synoptic system such as inter tropical convergence zone, subtropical anticyclones, tropical cyclones, monsoons, global sea surface temperatures, El-Nino and southern oscillation Cai, W., McPhaden, M.J., Grimm, A.M. et al., 2020. The inter tropical convergence zone is the main rain producing system in eastern Africa. Inter annual fluctuations in rainfall amount and distribution have in the past been generally attributed to anomalies in the large-scale factors that influence the characteristics of the inter tropical convergence zone in the (Nicholson, 2018).

The lake itself affects tremendously the climate over the lake basin and all the regions around the lake basin, a case in point Entebbe. The Lake Victoria basin has a population of about 340 million people with an annual growth rate of between 2.5% and 11.5%

3.3 Research Design and Sampling Methods

The study is a quantitative research type of study it involves two systematic measurable variables (water level of Lake Victoria basin and East Africa rainfall amounts). These variables can be measured and recorded at different points around Lake Victoria basin.

The two variables were analyzed differently first to establish the trends of the variable over the period of 35 years (1990 to 2024. There after correlation analysis was applied to the variables to establish if there exists a relationship between them. The research basically is of statistical methods involving real numbers of which these numbers change at a slow gradual rate thus a need to consider long period of years for study (35years).

3.4 Methods for Data Analysis

3.4.1 Trend Analysis and Time Series

Long term rainfall and water level records was collected and then used to calculate the mean monthly values and annual averages. Normalized values will also be used for both variables. Graphical methods were also being used to examine the general trend behavior of the two variables in the long time series of 60 years.

Time series statistical tests were applied to examine temporal trends in three segments of time interval of ten years (1962 – 1982, 1982 – 2002, 2002 - 2022). Time scale is classified into three-time segments to observe the trends in different time segments.

Seasonal trends were considered in this study in order to increase the validity and reliability of analysis as the annual rainfall patterns varies significantly across the four seasons. The seasons considered were March to May (MAM), June to August (JJA), September to November (SON) and December to February (DJF).

3.4.2 Python

Python is a high-level, versatile programming language known for its readability and simplicity. It's widely used in data analysis due to its extensive ecosystem of libraries and tools that simplify data manipulation, visualization, modelling and conduct data analysis. Python also has several libraries that enable coders to write programs for data analysis and machine learning more quickly and efficiently. Python 3.13 introduces some changes in behavior, i.e., new "well-defined semantics", fixing bugs, and removing many deprecated classes, functions and methods.

In this project, it was used for statistical computing and graphical presentation to analyze and visualize data also was used to calculate the Pearson correlation coefficient.

3.4.3 Pearson Correlation Coefficient

The name correlation suggests the relationship between two variables as their Co-relation. The correlation coefficient is the measurement of correlation. To see how the two sets of data are connected, we make use of this formula. The linear dependency between the data set is done by the Pearson Correlation coefficient. It is also known as the Pearson product-moment correlation coefficient. The value of the Pearson correlation coefficient product is between -1 to +1. When the correlation coefficient comes down to zero, then the data is said to be not related. While, if we are getting the value of +1, then the data are positively correlated and -1 has a negative correlation.

The Pearson correlation coefficient is denoted by the letter "r". The formula for Pearson correlation coefficient r is given by:

calculating the Pearson correlation coefficient (*r*):

$$r = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}} \quad \ldots\ldots\ldots\ldots\ldots\ldots(vii)$$

The Pearson's correlation coefficient formula is:

Where;

r = Pearson correlation coefficient

x = Values in the first set of data (independent variable)

y = Values in the second set of data (dependent variable)

n = is the sample size, and

Σ = represents a summation of all values.

3.5 ArcGIS Tool

ArcGIS is geospatial software to view, edit, manage and analyze geographic data. ArcGIS Spatial Analysis provided advanced spatial modeling and analysis. It helped us in modeling terrains, finding suitable locations and routes, discovering spatial patterns, and performing hydrologic and statistical analysis in this project it was used for spatial-temporal analysis of rainfall data collected from East Africa especially Lake Victoria water shade in regard to rainfall distribution and flooding of Lake Victoria basin.

CHAPTER FOUR: ANALYSIS AND RESULTS

4.1 Seasonal Rainfall Variability and Trend during ENSO years in East African

The El Niño-Southern Oscillation (ENSO) significantly impacts rainfall in East Africa, with distinct effects during its El Niño and La Niña phases: The Indian Ocean Dipole (IOD) or Dipole Mode Index (DMI) plays a pivotal role in modulating East African rainfall, particularly during El Niño events when teleconnections often amplify regional climate anomalies (Ashok et al., 2001). This study examines the composite correlation between DMI-SST anomalies and rainfall over core East Africa (25.5°E to 42.2°E, -12.5°S to 5°N, encompassing Kenya, Uganda, Tanzania, Rwanda, and Burundi) to understand the performance of El Niño years for instance (1991/92, 1997/98, 2002/03, 2004/05, 2006/07, 2009/10, 2014/16, 2018/19, 2023/24).

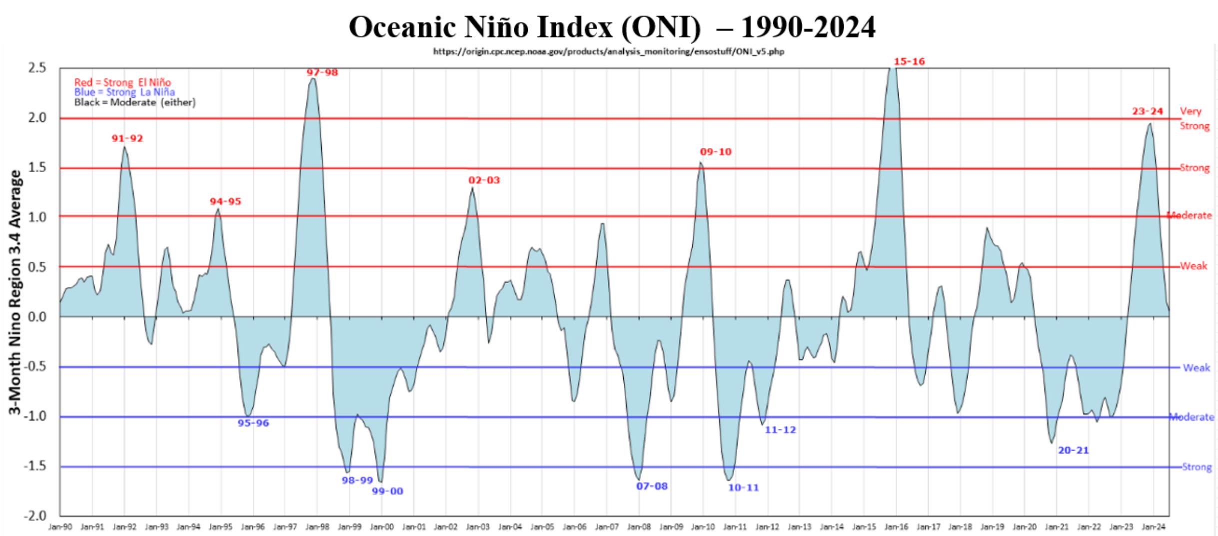


Figure 4.1 sea surface temperature anomalies in the Niño 3.4 region

The graph displays the Oceanic Niño Index (ONI) from 1990 to 2024, which measures sea surface temperature anomalies in the Niño 3.4 region to indicate El Niño and La Niña events. The x-axis represents time (years), and the y-axis shows the 3-month average temperature anomaly in degrees Celsius. Key thresholds are marked: ±0.5°C (weak), ±1.0°C (moderate), ±1.5°C (strong), and ±2.0°C (very strong), with red lines indicating El Niño (positive values) and blue lines indicating La Niña (negative values).

Interpretation:

El Niño Events: Notable peaks include 1997-98, 2009-10, 2015-16, and 2023-24, all exceeding 1.5°C, indicating strong to very strong El Niño conditions. The 1997-98 event reached approximately 2.3°C, the highest recorded.

La Niña Events: Significant troughs include 1998-99, 2010-11, 2011-12, and 2020-21, dipping below -1.0°C, with 2020-21 reaching around -1.5°C, indicating moderate to strong La Niña conditions.

Neutral Periods: The index often fluctuates around the 0°C line, with periods of weak El Niño or La Niña (e.g., 2002-03, 2014-15) interspersed between major events.

Recent Trends: The 2023-24 El Niño was strong, followed by a potential shift toward neutral or La Niña conditions by mid-2024.

The data highlights a cyclical pattern of El Niño and La Niña events over the 34-year period, with significant impacts likely during strong events (e.g., 1997-98, 2015-16, 2023-24). The recent 2023-24 El Niño suggests ongoing climate variability, with a possible transition to La Niña or neutral conditions in late 2024.

The study focused on two critical seasons: September-October-November-December (SOND, the "short rains") and March-April-May (MAM, the "long rains"), which are vital for agriculture and water resources in the region.

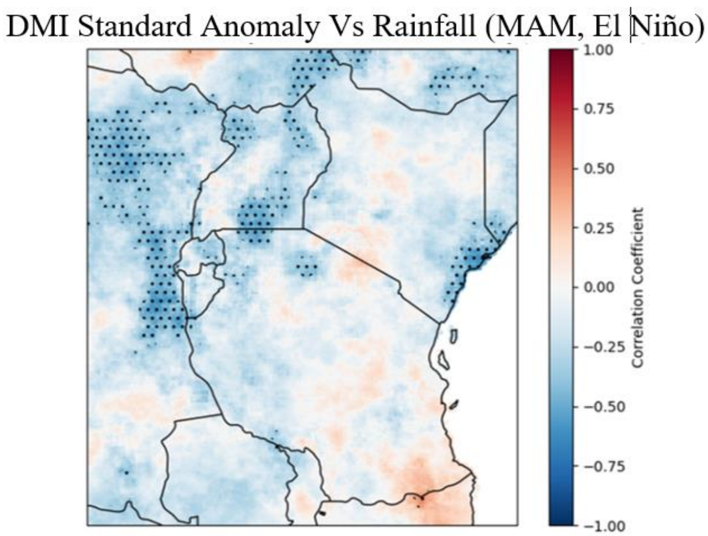


Figure 4.1.2: Correlation of DMI and MAM Rainfall El Niño years (1990–2024)

Figure 4.1.1 shows the statistical relationship (correlation coefficient) between the Dipole Mode Index (DMI) and the March-April-May (MAM) rainfall standard anomaly in East Africa during El Niño years over the specified period (1990 – 2024). The DMI is an indicator of the Indian Ocean Dipole, which affects climate patterns, including rainfall. The interpretation of the analysis is as follows:

Color Scale: The map uses a color gradient from blue to red, with values ranging from -1.0 to 1.0, representing the correlation coefficient. Blue shades (negative values, e.g., -1.0 to 0.0) indicate a negative correlation, meaning that as DMI increases, MAM rainfall tends to decrease. Red shades (positive values, e.g., 0.0 to 1.0) indicate a positive correlation, meaning that as DMI increases, MAM rainfall tends to increase. Values near 0 (light colors) suggest little to no correlation.

Geographical Variation: Areas with blue dots for instance parts of western Kenya and Uganda show a negative correlation, suggesting drier conditions during high DMI (positive IOD) El Niño years. Areas with red shades (e.g., southeastern Kenya and coastal regions) show a positive correlation, indicating increased rainfall with higher DMI values.

Black Dots represent specific data points or stations where the correlation was calculated, providing a detailed local perspective.

This map helps climatologists and researchers understand how the Indian Ocean Dipole interacts with El Niño events to influence seasonal rainfall patterns in East Africa. During El Niño years, the relationship between DMI and rainfall varies spatially, with some regions experiencing opposite effects (drier vs. wetter conditions) depending on their location. This information is crucial for predicting drought or flood risks and planning agricultural activities.

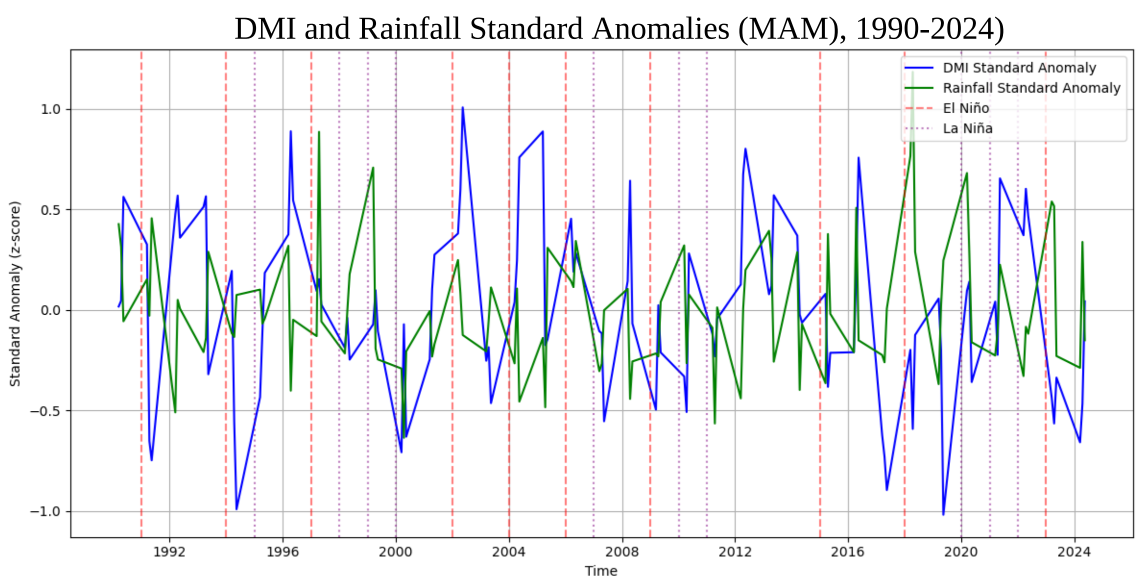


Figure 5: Correlation of DMI and MAM rainfall standard anomalies

The Indian Ocean Dipole (IOD), measured by the Dipole Mode Index (DMI), has a significant relationship with MAM (March-April-May) rainfall anomalies, particularly in East Africa, with positive DMI (warmer western Indian Ocean) often associated with increased rainfall anomalies and negative DMI (cooler western Indian Ocean) linked to decreased rainfall anomalies. This is because a positive DMI enhances atmospheric convection and moisture flux over the central Indian Ocean, leading to enhanced rainfall in the region, while the opposite occurs during a negative DMI.

Figure 5 displays the standardized anomalies of the Dipole Mode Index (DMI) and March-April-May (MAM) rainfall over a period from 1990 to 2024. Here's a breakdown:

The x-axis represents time (years from 1990 to 2024), while the y-axis shows the standardized anomaly score (in z-scores), ranging from -1.0 to 1.0.

The blue line represents the DMI Standard Anomaly, which is an indicator of the Indian Ocean Dipole (IOD), a climate phenomenon affecting rainfall patterns. The green line represents the Rainfall Standard Anomaly for the MAM season.

Shaded Regions; Red vertical bands indicate El Niño periods, while pink bands indicate La Niña periods, both of which influence global weather patterns.

Trends; Both DMI and rainfall anomalies fluctuate over time, with peaks and troughs corresponding to climatic events like El Niño and La Niña. Positive DMI anomalies (blue line above 0) often align with positive rainfall anomalies (green line above 0), suggesting a correlation during certain years. Negative anomalies in both DMI and rainfall are also observed, particularly during La Niña periods.

Correlation; Figure 5 suggests a relationship between DMI and MAM rainfall anomalies, where positive (or negative) phases of the IOD may correspond to increased (or decreased) rainfall, though the strength and timing of this correlation vary. The red and pink bands help contextualize these anomalies with El Niño and La Niña events, showing how these phenomena might influence the observed patterns.

DMI Standard Anomaly Vs Rainfall Anomaly (MAM, La Nina 1990-2024)

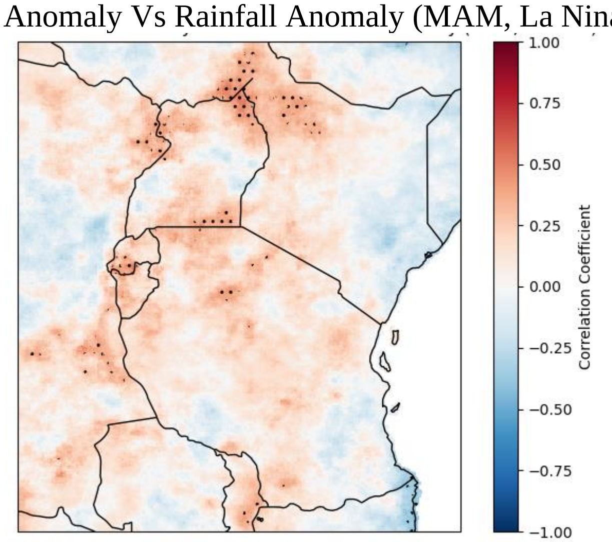


Figure 6: Correlation between DMI and rainfall MAM, La Nina years

The map figure 6 illustrates the correlation coefficient between the DMI (Dipole Mode Index) standard anomaly and rainfall standard anomaly across East Africa during the March-April-May (MAM) season in La Niña years from 1990 to 2024. The colour scale ranges from -1.0 (strong negative correlation, shown in blue) to +1.0 (strong positive correlation, shown in red), with 0.0 (no correlation) in white.

Positive Correlation (Red/Orange Shades): Areas with positive values, particularly in northern and central regions, indicate that higher DMI anomalies are associated with higher rainfall anomalies during La Niña years. The strongest positive correlations (up to 1.0) are concentrated in parts of northern Uganda and parts of Lake Victoria.

Negative Correlation (Blue Shades): Areas with negative values, such as parts of southern Kenya and Tanzania, suggest that higher DMI anomalies are linked to lower rainfall anomalies.

Neutral Correlation (White/Gray): Regions with values near 0.0, like central Uganda, show little to no consistent relationship between DMI and rainfall anomalies.

Black Dots: These likely represent specific data points or stations where measurements were taken.

This map highlights regional variations in how the Indian Ocean Dipole (reflected by DMI) influences rainfall patterns during La Niña events, with stronger effects in the north and weaker or opposite effects in the south.

DMI Standard Anomaly Vs Rainfall Anomaly (MAM, Neutral 1990-2024)

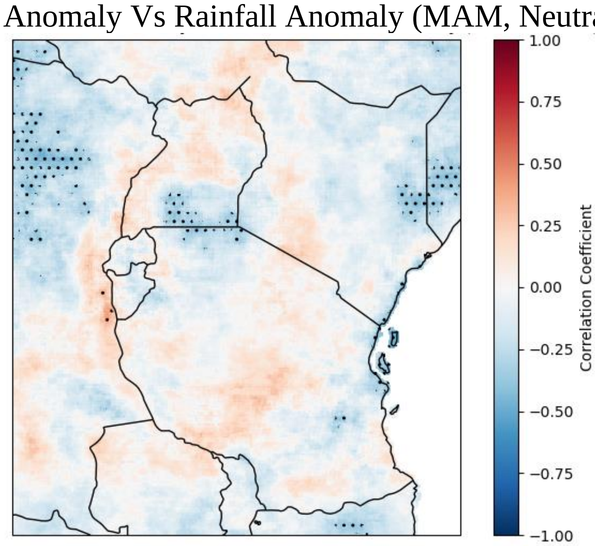


Figure 7: Correlation between DMI and rainfall MAM, during ENSO Neutral phase

Figure 7 explain the map 'Correlation between DMI standard anomaly and rainfall standard anomaly during (MAM, ENSO Neutral phase from 1990 – 2024), The map shows the correlation coefficient between the DMI (Dipole Mode Index) standard anomaly and the rainfall standard anomaly across a region (likely East Africa, given the shape) during the March-April-May (MAM) season under ENSO (El Niño-Southern Oscillation) neutral conditions from 1990 to 2024. The color scale ranges from -1.0 (strong negative correlation, in blue) to 1.0 (strong positive correlation, in red), with 0.0 (no correlation) in white.

Areas in red (e.g., parts of northern Uganda, southern Kenya and central Tanzania indicate a positive correlation, meaning that higher DMI anomalies are associated with higher rainfall anomalies.

Areas in blue (e.g., parts of western Kenya and Lake Victoria basin suggest a negative correlation, where higher DMI anomalies correspond to lower rainfall anomalies.

The dotted regions indicate areas where the correlation is statistically significant.

The neutral ENSO phase implies that the correlation is not influenced by strong El Niño or La Niña conditions, reflecting typical climate variability.

This map helps identify how the Indian Ocean Dipole (IOD), as measured by DMI, influences rainfall patterns regionally during the specified period.

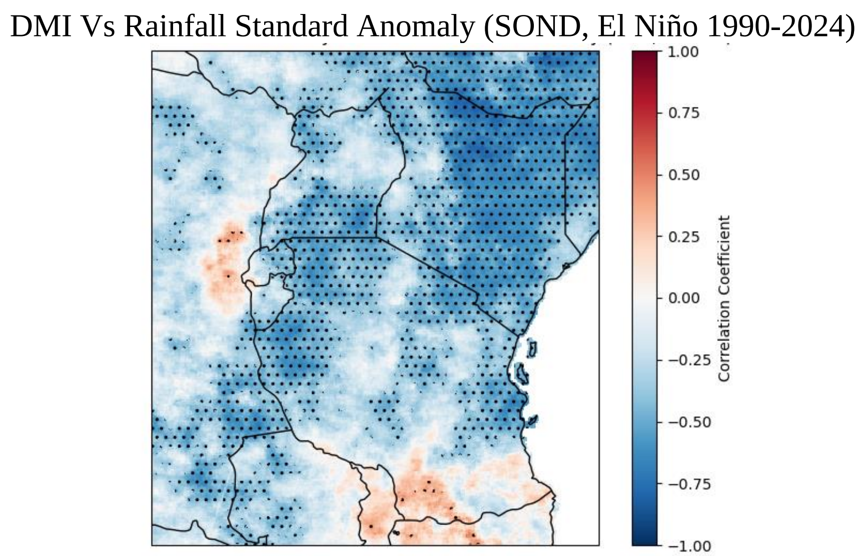


Figure 8: Correlation between DMI and rainfall during SOND, EL Nino years

Figure 8 the map explains 'Correlation between DMI standard anomaly and rainfall standard anomaly during (SOND, EL Nino years from 1990 – 2024)'

The map shows the correlation coefficient between the DMI (Dipole Mode Index) standard anomaly and rainfall standard anomaly during the September-October-December (SOND) season in El Niño years from 1990 to 2024. The colour scale ranges from -1.0 (strong negative correlation, in dark blue) to +1.0 (strong positive correlation, in dark red), with 0.0 (no correlation) in white.

Blue areas (negative correlation, e.g., -0.75 to -1.0) indicate that higher DMI anomalies are associated with lower rainfall anomalies, and vice versa.

Red areas (positive correlation, e.g., +0.75 to +1.0) indicate that higher DMI anomalies are associated with higher rainfall anomalies, and vice versa.

White areas (near 0.0) suggest little to no correlation between DMI and rainfall anomalies.

The map highlights regional variations, with some areas showing strong positive correlations (e.g., parts of southern and eastern regions) and others showing strong negative correlations (e.g., central and western regions), reflecting the complex influence of El Niño on rainfall patterns via the Indian Ocean Dipole (IOD).

From the analysis in figure 8 it is observed that most parts of East Africa have negative correlation between DMI of SOND season and rainfall while north eastern parts of Uganda and central Tanzania showed zero correlation.

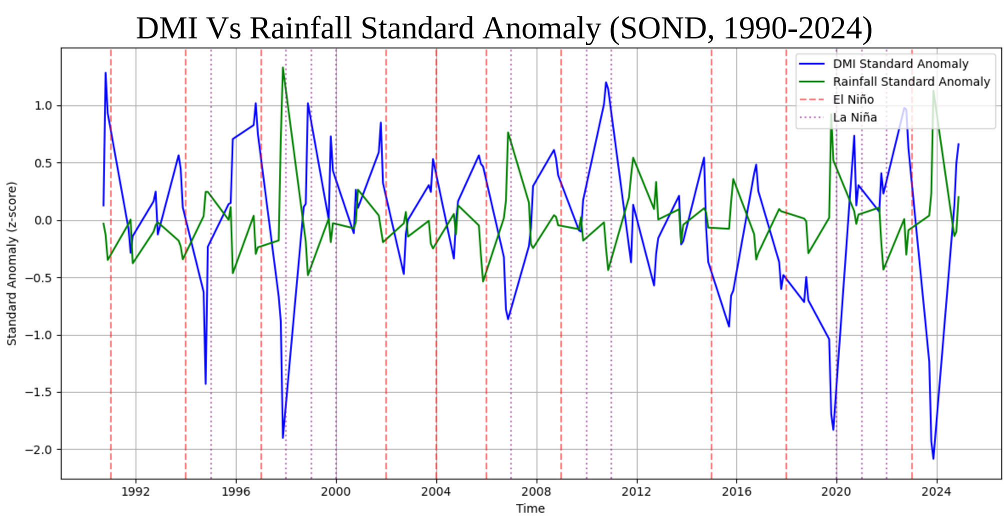


Figure 9: Time series analysis Dipole Mode Index (DMI) Vs rainfall

Figure 9 “DMI and Rainfall Standard Anomalies (SOND, 1990-2024)" shows the relationship between the Dipole Mode Index (DMI) and rainfall standard anomalies over the September-October-November (SOND) season from 1990 to 2024.

DMI Standard Anomaly (blue line) represents the standardized deviation of the Indian Ocean Dipole (IOD), which measures the sea surface temperature difference between the western and eastern equatorial Indian Ocean. Positive values indicate a positive IOD phase, while negative values indicate a negative IOD phase. Rainfall Standard Anomaly (green line) shows the standardized deviation of rainfall from the long-term average during the SON season.

El Niño and La Niña (red dashed lines) mark the periods when these climate phenomena occurred, which influence both DMI and rainfall patterns.

Key observations of figure 9 explains that; the blue and green lines generally show a positive correlation, meaning that positive DMI anomalies (e.g., around 1994, 1997, and 2019) often coincide with positive rainfall anomalies, and negative DMI anomalies (e.g., around 1992 and 2020) often align with negative rainfall anomalies. El Niño and La Niña events appear to modulate these anomalies, with El Niño often associated with positive DMI and rainfall anomalies, and La Niña with negative anomalies.

The correlation is not perfect, indicating other factors also influence rainfall. This suggests that the IOD, as measured by DMI, plays a significant role in modulating SOND rainfall patterns, with stronger effects during El Niño and La Niña years.

DMI Vs Rainfall Standard Anomaly (SOND, La Nina 1990-2024)

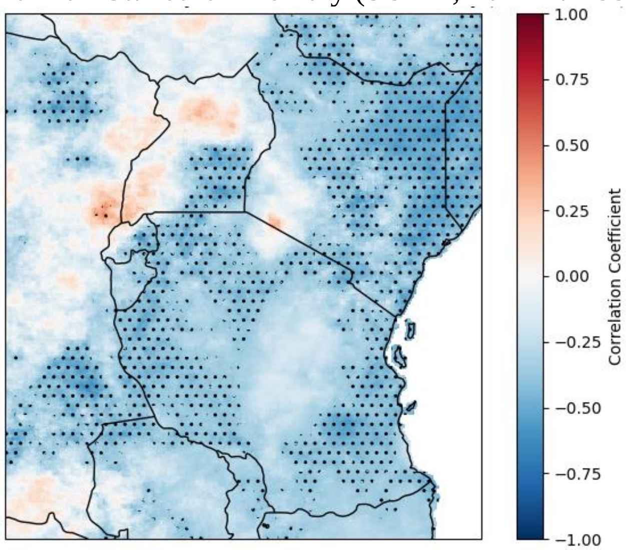


Figure 10: Correlation between DMI rainfall during SOND, La Nina years

Figure 10 explain and interpret the map 'Correlation between DMI standard anomaly and rainfall standard anomaly during (SOND, La nina years from 1990 – 2024)' The map illustrates the correlation coefficient between the DMI (Dipole Mode Index) standard anomaly and the rainfall standard anomaly during the September-October-November (SOND) season in La Niña years from 1990 to 2024. The DMI is an indicator of the Indian Ocean Dipole, which influences climate patterns, including rainfall.

The color gradient in figure 10 ranges from dark blue (-1.0) to dark red (+1.0), representing the strength and direction of the correlation. Positive values (red to orange) indicate a positive correlation (when DMI anomaly increases, rainfall anomaly also increases), while negative values (blue to light blue) indicate a negative correlation (when DMI anomaly increases, rainfall anomaly decreases). The correlation Strength is identified by values close to +1 or -1 indicated a strong correlation. While values near 0 indicate little to no correlation.

For the entire East Africa with exception of northern and south western Uganda there is a significance correlation: Areas with dotted patterns likely represent regions where the correlation is statistically significant. Regional Analysis of East Africa indicates that Western and Central Regions which are predominantly light blue to blue shades (correlation coefficients from -0.25 to -0.75) in figure 10 suggests a moderate to strong negative correlation. During La Niña years, higher DMI anomalies are associated with lower rainfall anomalies in these areas.

Eastern and Northeastern Regions shows mostly light blue to white (correlation coefficients near 0 to -0.25), indicating a weak or no significant correlation between DMI and rainfall anomalies. While Northwestern and Parts of Central show some areas of orange to red shades (correlation coefficients from +0.25 to +0.75), indicating a moderate to strong positive correlation, where higher DMI anomalies align with higher rainfall anomalies.

From the context of view, figure 10 covers East Africa (including countries like Kenya, Uganda, Tanzania, Rwanda and Burundi), and the patterns reflect how the Indian Ocean Dipole, modulated by La Niña conditions, impacts regional rainfall variability during the SON season. La Niña typically enhances rainfall in some parts of East Africa, but the figure 10 (map) shows a mixed response depending on the DMI, highlighting the complex interplay between these climate phenomena.

This map suggests that the relationship between DMI and rainfall anomalies varies spatially, with negative correlations dominating in the west and central regions, and positive correlations in the northwest during La Niña years.

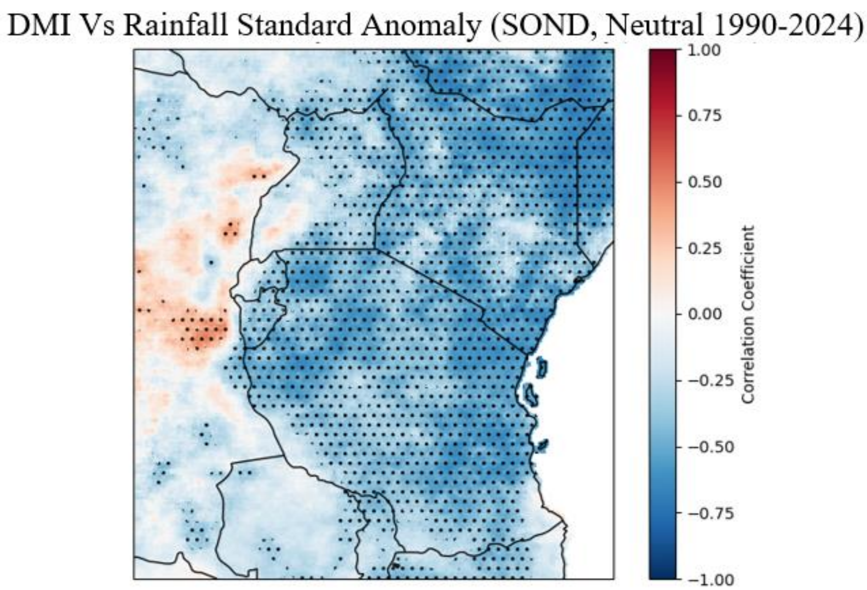


Figure 11: Correlation between DMI and rainfall during SOND, Neutral phase

Figure 11 explain and interpret the map 'Correlation between DMI standard anomaly and rainfall standard anomaly during (SOND, Neutral phase from 1990 – 2024)' The map illustrates the correlation between the Dipole Mode Index (DMI) standard anomaly and the rainfall standard anomaly across a region (likely East Africa) during the September-October-November (SOND) season in neutral phases from 1990 to 2024. The DMI is an indicator of the Indian Ocean Dipole (IOD), which influences rainfall patterns.

The interpretation of the map (Figure 11 explains the Color Scale, Spatial Patterns and Neutral Phase Context. The map uses a color gradient from blue (negative correlation, -1.0 to 0) to red (positive correlation, 0 to 1.0). A correlation coefficient close to 1 indicates a strong positive relationship (when DMI increases, rainfall increases), while a coefficient close to -1 indicates a strong negative relationship (when DMI increases, rainfall decreases). A value near 0 suggests little to no correlation.

Areas in blue, particularly in central and eastern parts, show negative correlations (e.g., -0.5 to -1.0), indicating that higher DMI anomalies are associated with lower rainfall anomalies during neutral IOD phases. Regions in red, mostly in the west and northwest, show positive correlations (e.g., 0.25 to 0.75), suggesting that higher DMI anomalies correlate with higher rainfall anomalies.

The dotted pattern indicates areas with significant correlation, while the background colors show the overall trend. Neutral Phase Context: During neutral IOD phases, the relationship between DMI and rainfall is less pronounced than during strong positive or negative IOD events, leading to varied local correlations.

Generally, the map highlights regional differences in how DMI anomalies affect rainfall during neutral SON seasons over the 1990-2024 period. Western areas tend to experience increased rainfall with positive DMI anomalies, while central and eastern areas see reduced rainfall, reflecting the complex influence of the IOD on regional climate.

4.2 The contributions of Indian Ocean Sea Surface Temperatures to East African Rainfall

The Indian Ocean Dipole often referred to as the IOD or Dipole Mode Index (DMI) is a climate phenomenon characterized by differences in Sea Surface Temperatures (SSTs) between the western and eastern parts of the Indian Ocean (50°E–70°E, 10°S–10°N) and southeastern (90°E–110°E, 10°S–10°N). This study focused on assessing contributions of Indian Ocean Sea Surface Temperatures to Enhanced East African Rainfall where correlation of DMI with East African precipitation and surrounding regions was mainly considered. Data sets were analyzed and results indicates significant correlation due to the influence of SST anomalies on regional atmospheric circulation and rainfall patterns. As illustrated in figure 12.

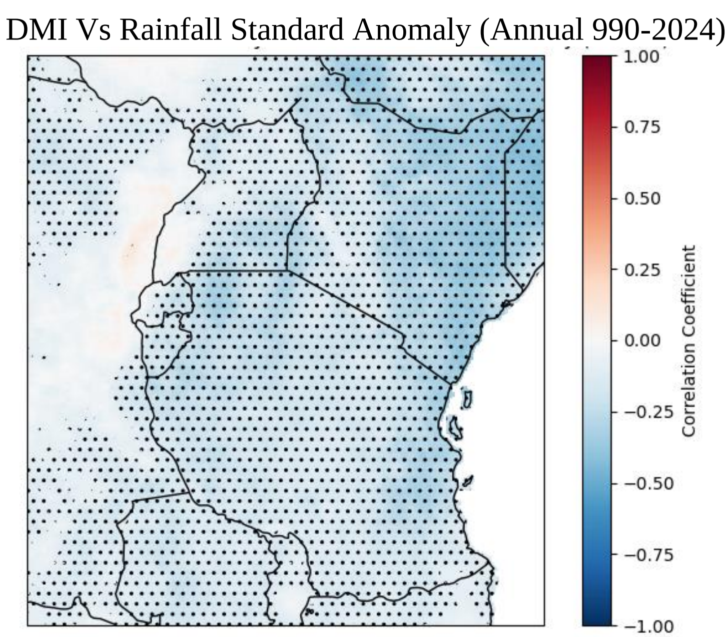
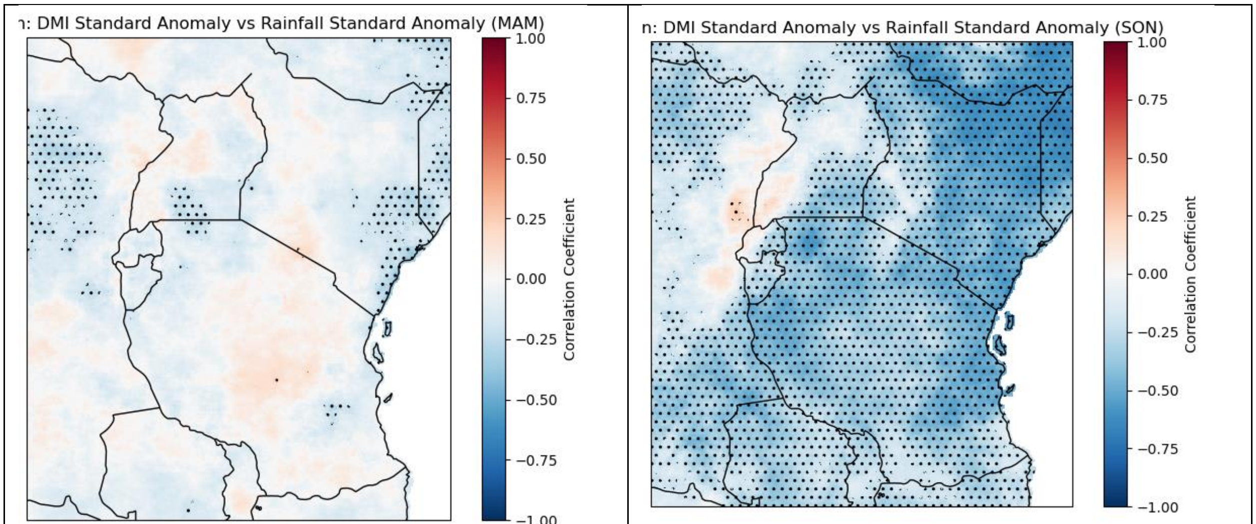


Figure 12: Correlation between DMI and annual rainfall of East Africa

Figure 12 illustrates the correlation between the Dipole Mode Index (DMI) Standard Anomaly and the Rainfall Standard Anomaly across the East Africa region on an annual basis. The DMI is a measure related to the Indian Ocean Dipole, which influences climate patterns, including rainfall. The color scale ranges from -1.00 (strong negative correlation, in dark blue) to +1.00 (strong positive correlation, in dark red), with 0.00 (no correlation) in white. Areas in red indicate a strong positive correlation, meaning that higher DMI values are associated with higher rainfall anomalies. Areas in blue indicate a strong negative correlation, meaning that higher DMI values are associated with lower rainfall anomalies.

Figure 12 shows that much of East Africa has a weak to moderate negative correlation (light blue to medium blue), suggesting that higher DMI values typically correspond to reduced rainfall. However, some regions, particularly along the eastern coast and Lake Victoria basin, show a transition toward positive correlations (yellow to red), indicating that higher DMI values may be linked to increased rainfall in those areas. This spatial variation highlights how the Indian Ocean Dipole's influence on annual rainfall differs across East Africa. Areas with dotes in thick blue color indicates significance negative correlation while areas no dote including western parts of Congo and south western Uganda indicates no correlation between DMI and East African annual rainfall.



(a) MAM (b) SOND

Figure 13: Correlation between DMI and East African Seasonal Rainfall (MAM and SOND)

Figure 13 Correlation of DMI and rainfall seasons (MAM) March-April-May rainfall anomaly over East Africa region" shows the correlation coefficient between the Dipole Mode Index (DMI) and rainfall anomalies during the March-April-May (MAM) season across East Africa. The DMI is an indicator of the Indian Ocean Dipole, which influences climate patterns.

The color scale ranges from -1.00 (blue) to +1.00 (red), representing the strength and direction of the correlation. Positive values (e.g., red areas) indicate that higher DMI values are associated with higher rainfall anomalies, suggesting a positive relationship. Negative values (e.g., blue areas) indicate that higher DMI values are associated with lower rainfall anomalies, suggesting a negative relationship. Values close to 0 (e.g., light colors) indicate little to no correlation.

Figure 13 helps identify regions in East Africa where the Indian Ocean Dipole significantly impacts MAM and SON rainfall patterns.

The Indian Ocean Dipole (IOD) is a significant driver of rainfall variability in East Africa specifically, positive DMI events, where the western Indian Ocean experiences warmer sea surface temperatures (SSTs) and the eastern part experiences cooler SSTs, are associated with increased rainfall over East Africa. Figure 13 indicates significant correlation (Corr) of sea surface temperature with blue line and rainfall (chirps V.2) with green line the results below indicates that an increase in average monthly sea surface temperature led to increase in precipitation from 1990 to 2024.

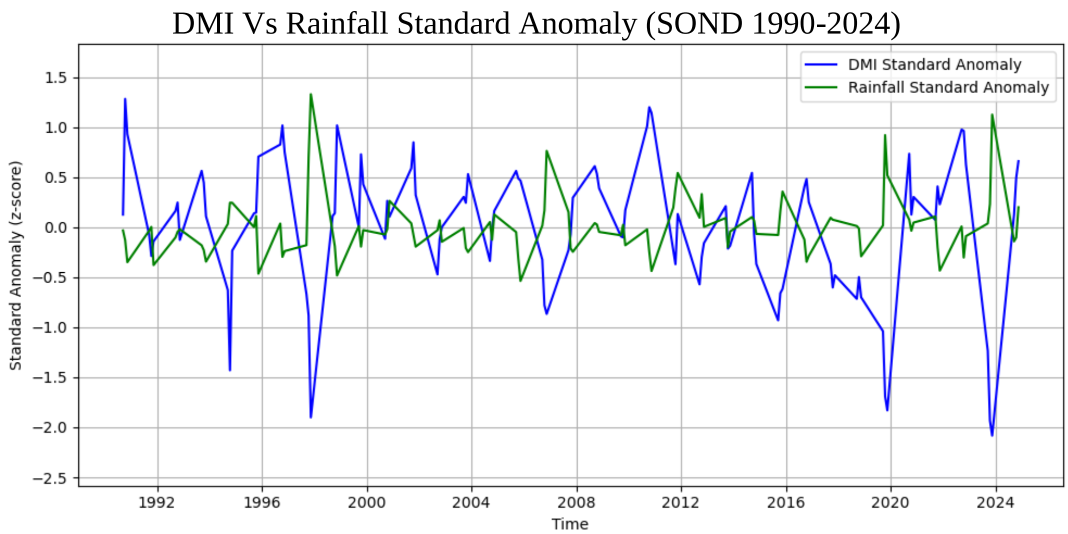


Figure 14: Shows DMI and Rainfall Standard Anomalies (SOND, 1990-2024)

The graph titled "DMI and Rainfall Standard Anomalies (SOND, 1990-2024)" illustrates the seasonal correlation between the Dipole Mode Index (DMI) and East Africa precipitation during the September-October-November (SOND) season over the period from 1990 to 2024. Here's a detailed explanation:

Axes: X-axis (Time): Represents the years from 1990 to 2024, showing the temporal progression of the data. Y-axis (Standard Anomaly Z-score): Measures the standard anomaly (in z-scores) of both DMI and rainfall, where positive values indicate above-average conditions and negative values indicate below-average conditions. A z-score of 0 represents the long-term average.

Data Lines: DMI Standard Anomaly (Blue Line): The DMI is an index used to measure the strength of the Indian Ocean Dipole (IOD), a climate phenomenon involving sea surface temperature differences between the western and eastern Indian Ocean. Positive DMI values indicate a positive IOD phase (warmer western Indian Ocean), while negative values indicate a negative IOD phase (Warmer Eastern Indian Ocean).

Rainfall Standard Anomaly (Green Line): Represents the deviation of rainfall from the long-term average for East Africa during the SON season, expressed as a z-score.
Correlation: The graph suggests a relationship between DMI and rainfall anomalies. Generally, when the DMI is positive (blue line peaks), the rainfall anomaly tends to be positive (green line peaks), indicating higher-than-average rainfall in East Africa. Conversely, when the DMI is negative (blue line dips), the rainfall anomaly tends to be negative (green line dips), indicating lower-than-average rainfall.

Variability: Both DMI and rainfall anomalies show significant year-to-year variability. Notable peaks and troughs occur, such as around 1994, 1997, 2010, and 2019-2020, reflecting strong IOD events and their impact on precipitation.
Extreme Events: Around 1997 and 2019, both DMI and rainfall show strong positive anomalies, likely corresponding to strong positive IOD events that brought above-average rainfall to East Africa. Around 1992 and 2016, both show strong negative anomalies, possibly linked to negative IOD events associated with drought conditions.
Contextual Meaning: The SON season is critical for East Africa, as it coincides with the short rains, a vital period for agriculture and water resources. The Indian Ocean Dipole influences these rains, with positive IOD phases typically enhancing rainfall and negative phases suppressing it.
The standard anomaly z-scores allow for a normalized comparison, highlighting how unusual the conditions were in a given year relative to the historical average (1990-2024).
Limitations: The correlation is not perfect, as seen in some years where DMI and rainfall anomalies diverge slightly, indicating other factors (e.g., local weather patterns or El Niño/Southern Oscillation) may also influence rainfall. The data ends in 2024, so it reflects trends up to that point but may not capture the most recent developments.
In summary, the graph demonstrates a general positive correlation between DMI and East Africa SON precipitation anomalies from 1990 to 2024, underscoring the IOD's role in modulating seasonal rainfall patterns in the region.

DMI Vs Rainfall Standard Anomaly (MAM, 1990-2024)

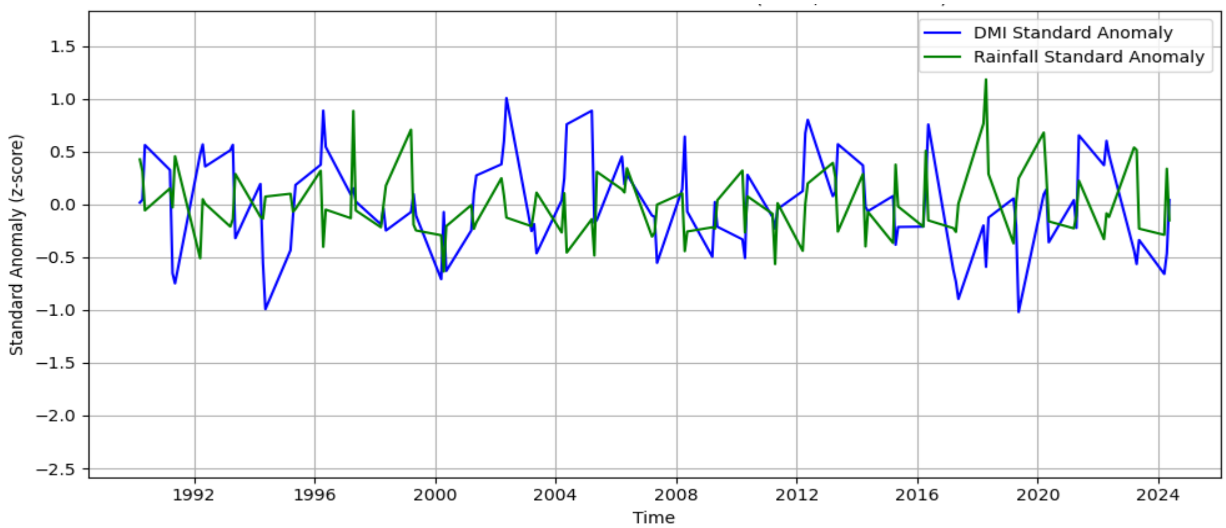


Figure 15: DMI and Rainfall Standard Anomalies (MAM, 1990-2024)

The graph displays the standard anomalies (z-scores) of the Dipole Mode Index (DMI) and rainfall in East Africa during the March-April-May (MAM) season from 1990 to 2024. The DMI, shown in blue, measures the strength of the Indian Ocean Dipole (IOD), a climate phenomenon affecting ocean temperatures. The rainfall standard anomaly, shown in green, indicates deviations from average precipitation levels.

Positive anomalies (above 0) suggest above-average conditions (e.g., warmer sea temperatures for DMI or higher rainfall). Negative anomalies (below 0) indicate below-average conditions.

The correlation between the two lines suggests a relationship: when DMI is positive (e.g., 1997, 2019), rainfall tends to be positive, indicating wetter conditions. Conversely, negative DMI (e.g., 1992, 2016) often aligns with negative rainfall anomalies, suggesting drier conditions.

This implies that a positive IOD phase may enhance rainfall in East Africa during MAM, while a negative phase may reduce it. However, the relationship is not perfectly linear, as some years show divergence, indicating other factors also influence rainfall.

The two graphs (Figure 15 and Figure 16 depict the standard anomalies of the Dipole Mode Index (DMI) and rainfall for two different seasons: March-April-May (MAM) from 1990 to 2024 and September-October-November (SON) from 1990 to 2024.

MAM Season (Figure 15), The DMI and rainfall anomalies show more frequent and pronounced fluctuations, with both lines often deviating significantly from the zero line (e.g., peaks around 1997 and 2010). There appears to be a moderate correlation between DMI and rainfall anomalies, with some years showing similar positive or negative trends (e.g., around 2005-2006), though the relationship is not consistently aligned. The amplitude of anomalies is generally higher, indicating more variability in both DMI and rainfall during the MAM season.

SON Season (Figure 15), The anomalies for DMI and rainfall are less variable compared to MAM, with fewer extreme peaks and troughs. There is a noticeable dip in DMI around the mid-1990s and a significant negative anomaly around 2020-2021, which is not as strongly mirrored in the rainfall data, suggesting a weaker correlation during this season. The rainfall anomalies tend to stay closer to the zero line, indicating more stable precipitation patterns compared to MAM.
Key Difference: The MAM season exhibits greater variability and a potentially stronger correlation between DMI and rainfall anomalies, while the SON season shows more stability and a weaker, less consistent relationship between the two variables.

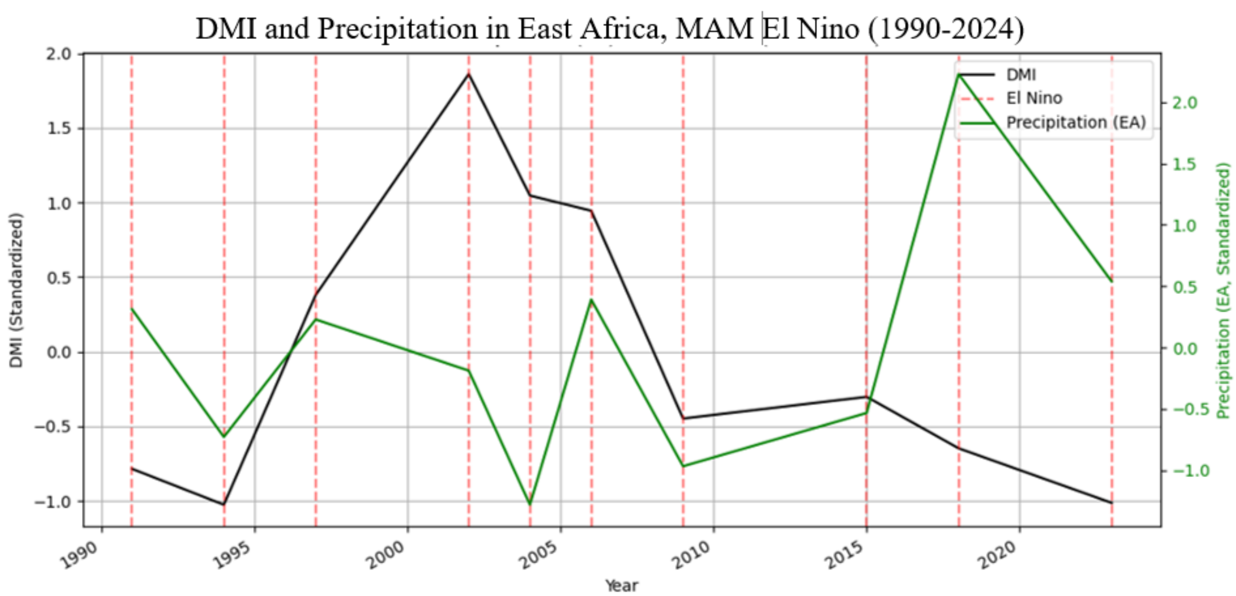


Figure 16: Correlation between DMI and Rainfall over East Africa MAM El Nino

The figure 16 is a line graph titled "DMI and Precipitation EA - MAM El Niño (1990-2024)," which compares the standardized values of the Dipole Mode Index (DMI) and precipitation in East Africa (EA) during the March-April-May (MAM) season over the period from 1990 to 2024.
The x-axis represents the years from 1990 to 2024, the y-axis on the left shows the standardized DMI values, ranging from -1.0 to 2.0. The y-axis on the right shows the standardized precipitation values for East Africa, also ranging from -1.0 to 2.0.
The black line represents the DMI, which measures the strength of the Indian Ocean Dipole (IOD), a climate phenomenon affecting ocean temperatures in the Indian Ocean. The green line represents

precipitation in East Africa, standardized to allow comparison with DMI. Both DMI and precipitation show fluctuations over time, with notable peaks and troughs.
A significant peak in DMI occurs around 1997-1998, reaching approximately 1.8, coinciding with a moderate increase in precipitation. Another prominent peak in DMI is observed around 2015-2016, reaching about 1.6, with a corresponding rise in precipitation to around 1.8.

The red vertical dashed lines likely indicate El Niño events, which are known to influence both IOD and precipitation patterns. The alignment of peaks with these lines suggests a correlation between El Niño, DMI, and increased precipitation in East Africa during MAM. Positive DMI values indicate a positive IOD phase, often associated with warmer sea surface temperatures in the western Indian Ocean, which can enhance rainfall in East Africa. The general trend shows that higher DMI values tend to correspond with higher precipitation levels, particularly during El Niño years, though the relationship is not perfectly linear.

After 2016, both DMI and precipitation show a decline, suggesting a weakening of the positive IOD influence on rainfall in recent years. This graph highlights the relationship between the Indian Ocean Dipole and East African precipitation, with El Niño events appearing to amplify this connection during the MAM season.

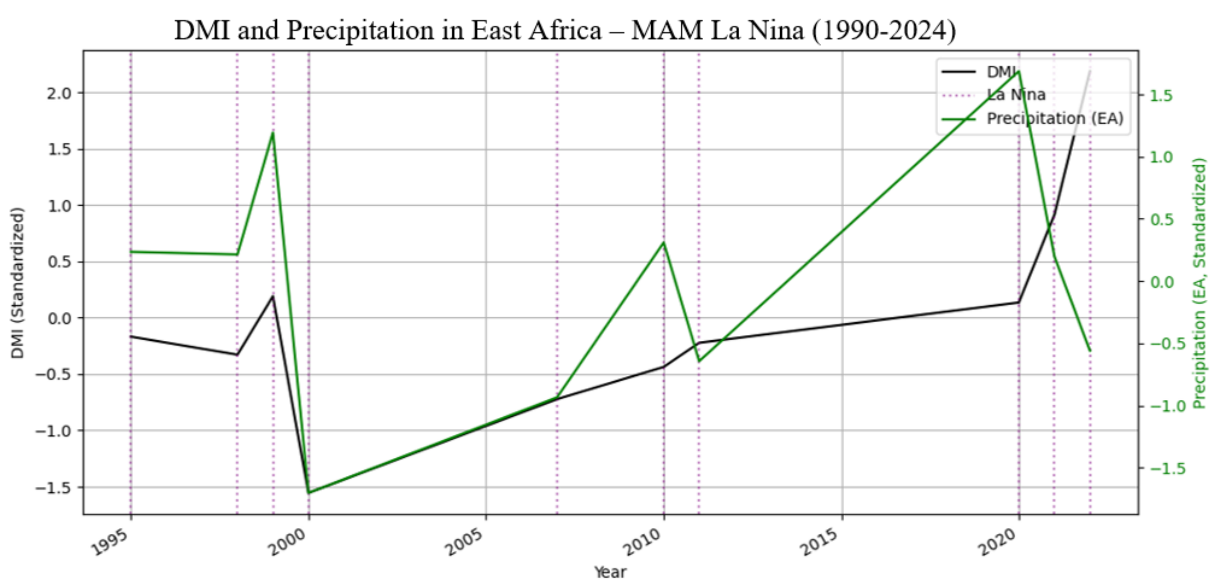


Figure 17: Correlation between DMI and Rainfall over East Africa MAM El Nino

The figure 17 is a line graph titled "DMI and Precipitation (EA) - MAM La Nina (1990-2024)," which compares the standardized values of the Dipole Mode Index (DMI) and precipitation in East

Africa (EA) during the March-April-May (MAM) season over the period from 1990 to 2024, specifically focusing on La Niña years. Detailed Meaning:

The x-axis represents the years from 1990 to 2024, the y-axis represents the standardized values (z-scores) of DMI and precipitation, ranging from -1.5 to 2.0. DMI (Dipole Mode Index): Represented by the black line, DMI measures the strength of the Indian Ocean Dipole (IOD), a climate phenomenon affecting weather patterns. Positive values indicate a positive IOD (warmer western Indian Ocean), while negative values indicate a negative IOD (cooler western Indian Ocean), often associated with La Niña conditions.

Precipitation (EA): Represented by the green line, this shows the standardized precipitation levels in East Africa during the MAM season.

In the early 1990s, both DMI and precipitation show moderate positive values, with a peak around 1995-2000 where precipitation rises sharply while DMI drops significantly negative.

From 2000 to 2010, precipitation gradually increases, while DMI fluctuates, showing a peak around 2010.

From 2010 to 2020, precipitation continues to rise steadily, peaking around 2015-2020, while DMI shows a more stable trend with a slight increase toward 2020.

There appears to be an inverse relationship between DMI and precipitation in some periods (e.g., 1995-2000), where a negative DMI coincides with higher precipitation. However, the relationship is not consistent across all years, suggesting other factors may influence precipitation.

The graph indicates that during La Niña years from 1990 to 2024, precipitation in East Africa during the MAM season has generally increased over time, with notable peaks around 2000 and 2015-2020. The DMI shows more variability, with significant negative values in some years (e.g., 2000) correlating with higher precipitation, consistent with the expected impact of a negative IOD during La Niña. However, the inconsistent correlation suggests that while the IOD influences East African rainfall, other climatic factors also play a role.

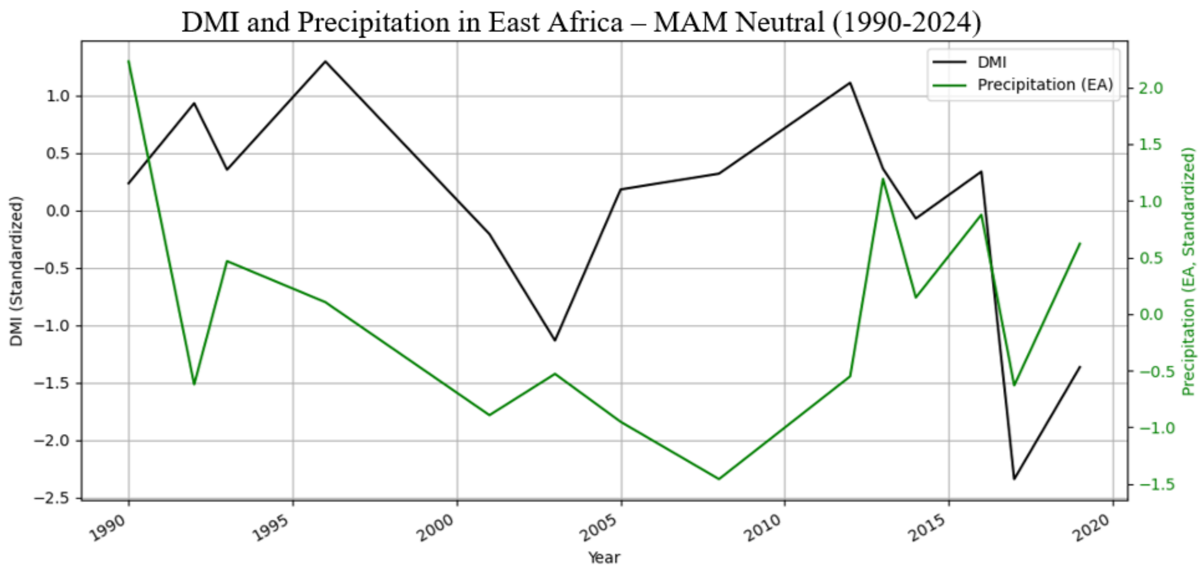


Figure 18: Correlation between DMI and Rainfall during MAM Neutral phase (1990-2024)

The figure 18 is a line graph titled "DMI and Precipitation (EA) - MAM Neutral)," which compares the Dipole Mode Index (DMI) and precipitation in East Africa (EA) during the March-April-May (MAM) season under neutral El Niño-Southern Oscillation (ENSO) conditions. The x-axis represents the years from 1990 to 2024, while the y-axis on the left shows the standardized DMI values (ranging from -2.5 to 1.0), and the y-axis on the right shows the standardized precipitation values (ranging from -1.5 to 2.0). The black line represents the DMI, and the green line represents precipitation.

DMI (Dipole Mode Index): This index measures the strength of the Indian Ocean Dipole (IOD), which reflects the difference in sea surface temperatures between the western and eastern Indian Ocean. Positive DMI values indicate a positive IOD phase (warmer western Indian Ocean), while negative values indicate a negative IOD phase (warmer eastern Indian Ocean). The graph shows fluctuations in DMI, with notable peaks around 1994, 2006, and 2015, and troughs around 1997, 2008, and 2022.

Precipitation (EA); This represents rainfall in East Africa, standardized to show deviations from the mean. Positive values indicate above-average rainfall, while negative values indicate below-average rainfall. The precipitation line shows variability, with peaks around 1990, 2010, and 2021, and dips around 1997, 2009, and 2023.

Correlation and Trends; The graph suggests a general lack of consistent correlation between DMI and precipitation during neutral ENSO years. For instance, high DMI values in 2006 correspond to moderate precipitation, while the peak DMI in 2015 aligns with a precipitation dip. Similarly, the low DMI in 1997 coincides with low precipitation, but this pattern does not hold across all years. Over the period from 1990 to 2024, during neutral ENSO conditions, there is no strong, consistent relationship between the DMI and precipitation in East Africa during the MAM season. The variability in both DMI and precipitation indicates that other factors, beyond the IOD, likely influence rainfall patterns in the region. Further analysis with additional data or statistical methods would be needed to identify specific drivers of these trends.

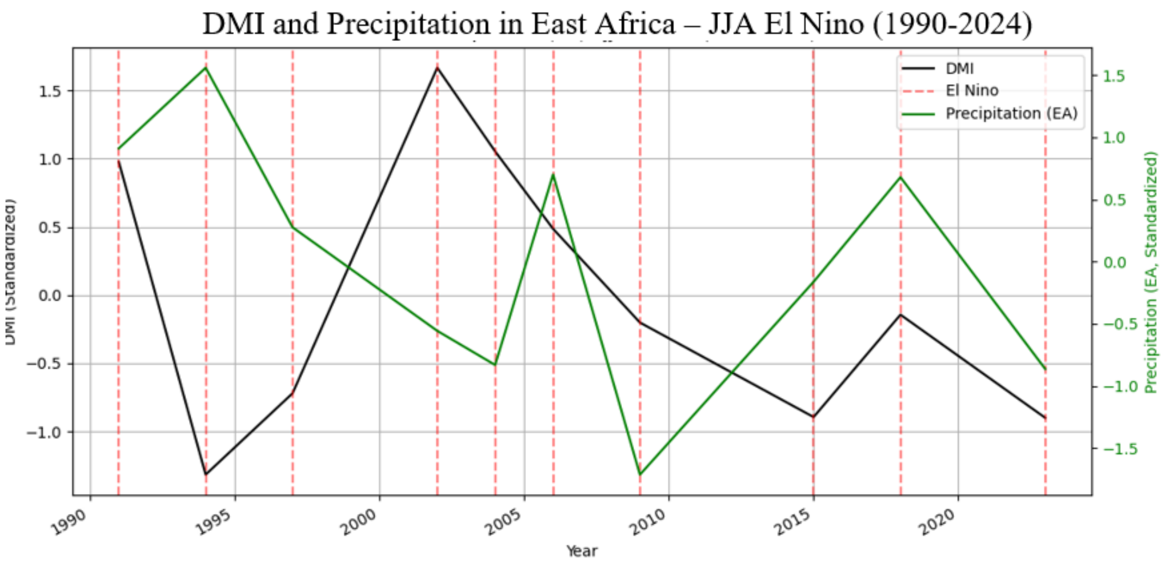


Figure 19: Correlation between DMI and Rainfall during JJA El Nino

The figure 19 is a graph titled "DMI and Precipitation (EA) - El Niño (1990-2024)," which plots the Dipole Mode Index (DMI) and precipitation (Eastern Africa, EA) over time from 1990 to 2024. The DMI, represented by the black line, measures the strength of the Indian Ocean Dipole (IOD), with positive values indicating a positive IOD phase (warmer western Indian Ocean) and negative values indicating a negative IOD phase. Precipitation (EA), shown by the green line, is standardized and reflects rainfall variations in Eastern Africa, with positive values indicating above-average rainfall and negative values indicating below-average rainfall. The red dashed lines mark El Niño events.

Figure 19, DMI (Black Line) fluctuates between positive and negative values, peaking around 1997-1998 and 2015-2016 (reaching 1.5), indicating strong positive IOD phases. Negative peaks occur around 1992 and 2010 (-1.0), suggesting strong negative IOD phases. These fluctuations correlate with climatic variability in the Indian Ocean.

Precipitation (EA, Green Line), Precipitation shows variability, with peaks around 1991-1992 and 2015-2016 (1.5), aligning with increased rainfall, and dips around 1997-1998 and 2019-2020 (-

1.0), indicating drought conditions. The data suggests a relationship between IOD phases and rainfall.

El Niño Events (Red Dashed Lines): These vertical lines highlight periods of El Niño, a warming of the central Pacific that influences global weather. Notable El Niño events occur around 1997-1998, 2010, and 2015-2016, often coinciding with significant DMI and precipitation shifts.

Correlation: There appears to be an inverse relationship between DMI and precipitation during some El Niño events (e.g., 1997-1998, where high DMI coincides with low precipitation), suggesting that a positive IOD may lead to reduced rainfall in Eastern Africa during El Niño.

Therefore, the Figure 19 indicates that the DMI and precipitation in Eastern Africa are influenced by IOD phases and El Niño events between 1990 and 2024. Strong positive IOD phases often correlate with reduced precipitation, particularly during El Niño years, while negative IOD phases may align with increased rainfall. This study suggests a complex interplay between IOD and El Niño that impacts Eastern African climate variability.

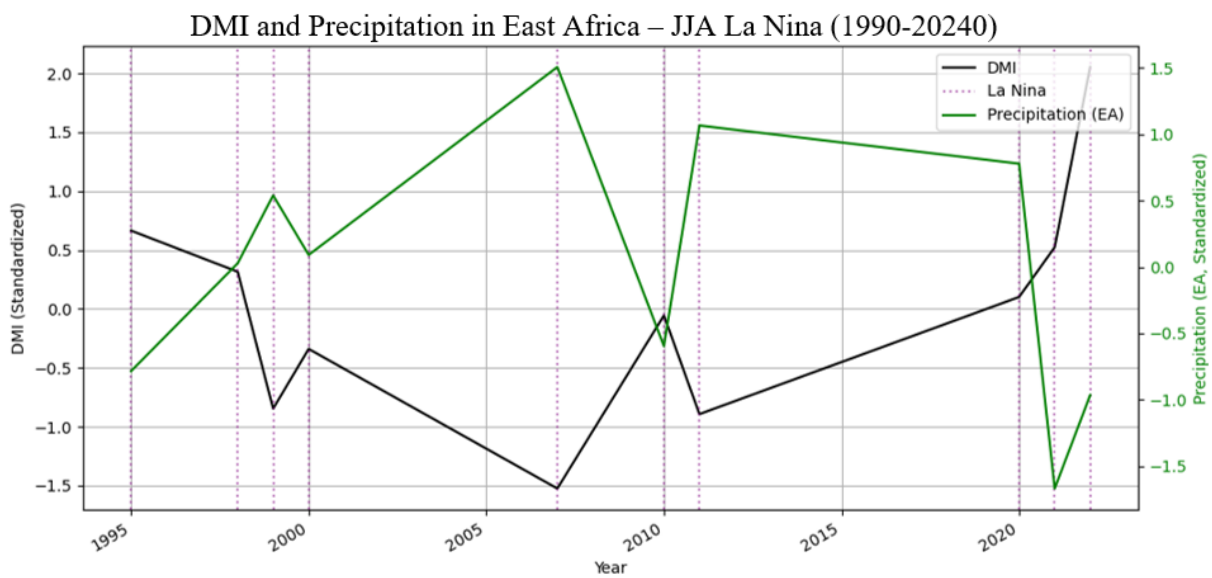


Figure 20: Correlation between DMI and Rainfall during JJA La Nina

Figure 20 is a line graph titled "DMI and Precipitation (EA) - JA La Nina (1990-2024)," which compares the Dipole Mode Index (DMI) and standardized precipitation in East Africa (EA) during June-August (JA) La Niña years from 1990 to 2024. The x-axis represents the years, while the y-axis on the left shows the standardized DMI values, and the y-axis on the right shows the standardized precipitation values (EA).

DMI (black line); The Dipole Mode Index measures the strength of the Indian Ocean Dipole, with positive values indicating a positive IOD (warmer western Indian Ocean) and negative values indicating a negative IOD (cooler western Indian Ocean, often associated with La Niña). The DMI fluctuates, showing peaks around 1995, 2007-2008, and 2020-2021, with dips around 2000 and 2010. Precipitation (EA) (green line): This represents standardized precipitation anomalies in East Africa. Higher values indicate above-average rainfall, while lower values indicate below-average rainfall. Precipitation shows peaks around 2006-2007 and 2017-2018, with a notable drop around 2020-2021.

From the analysis, figure 20 shows that two lines do not show a consistent direct correlation. For instance, high DMI values for instance 2007) correspond with high precipitation, suggesting a possible positive IOD influence on rainfall during La Niña. However, in 2020-2021, a high DMI coincides with a sharp drop in precipitation, indicating other factors for instance regional climate variability) may override the IOD effect. The data suggests that La Niña years, combined with IOD phases, create variable precipitation patterns in East Africa, with no uniform trend.

The Figure 20 indicates that the relationship between DMI and precipitation in East Africa during JA La Niña years (1990-2024) is complex and not consistently predictable. While some years show a positive association between DMI and rainfall, other factors likely influence precipitation, leading to significant variability.

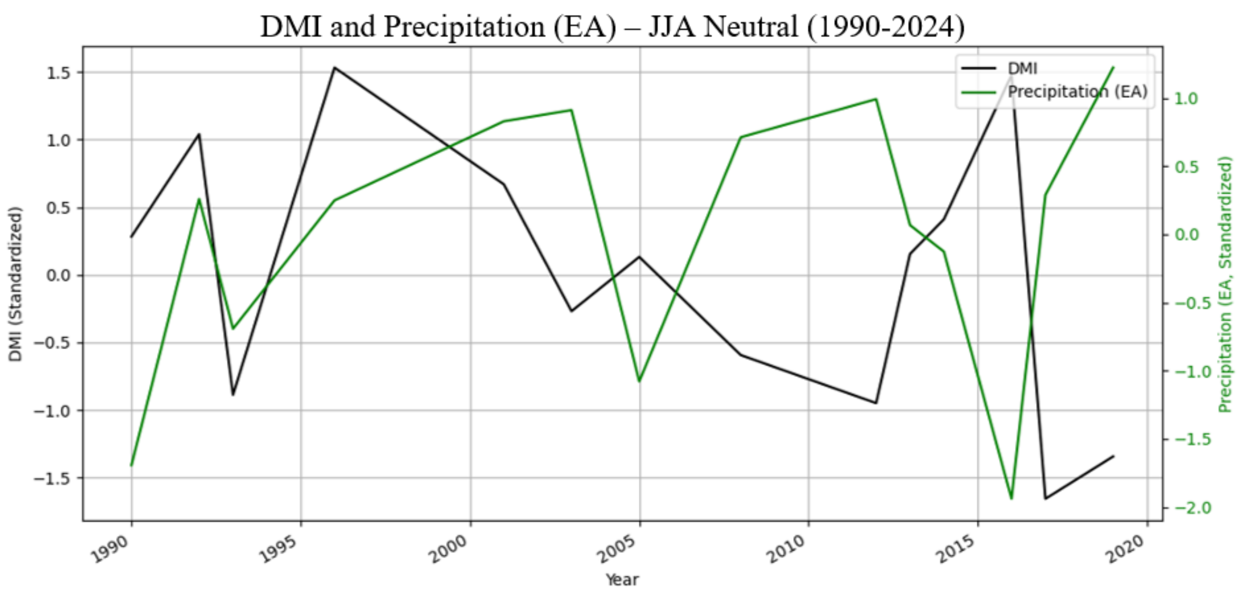


Figure 21: Correlation between DMI and Rainfall during JJA Neutral

The figure (21) shows a time series graph comparing the Dipole Mode Index (DMI) and Precipitation (EA) from 1990 to 2024 during JJA (June, July, August) neutral conditions. Both DMI and Precipitation are standardized, with values plotted on the y-axis ranging from -2.0 to 1.5, and years on the x-axis from 1990 to 2020.

DMI (black line); The Dipole Mode Index measures the east-west gradient of sea surface temperatures in the Indian Ocean, indicating the Indian Ocean Dipole (IOD). Positive values suggest a positive IOD phase (warmer west, cooler east), while negative values indicate a negative IOD phase. The graph shows significant variability, with peaks around 1994 and 2015-2016 (up to 1.5) and troughs around 1997 and 2019 (down to -1.5).

Precipitation (EA) (green line): This represents standardized precipitation in the East Africa (EA) region. Positive values indicate above-average rainfall, while negative values indicate below-average rainfall. The precipitation also fluctuates, with notable peaks around 1998 and 2015 (up to 1.0) and dips around 1997 and 2019 (down to -1.5).

This study observed that, there is a general trend of correlation between DMI and Precipitation, where positive DMI values often align with increased precipitation for instance 1994, 2015 and negative DMI values align with decreased precipitation for instance 1997 and 2019. This suggests that the IOD influences East African rainfall during neutral conditions.

The relationship is not perfectly linear, with some years showing divergence for instance in 2006, the DMI is positive but precipitation is near zero).

In summary conclusion the graph indicates a moderate correlation between the Indian Ocean Dipole (DMI) and East African precipitation during JJA neutral conditions from 1990 to 2024. Positive IOD phases tend to be associated with increased rainfall, while negative phases are linked to reduced rainfall, though other factors may also influence precipitation variability.

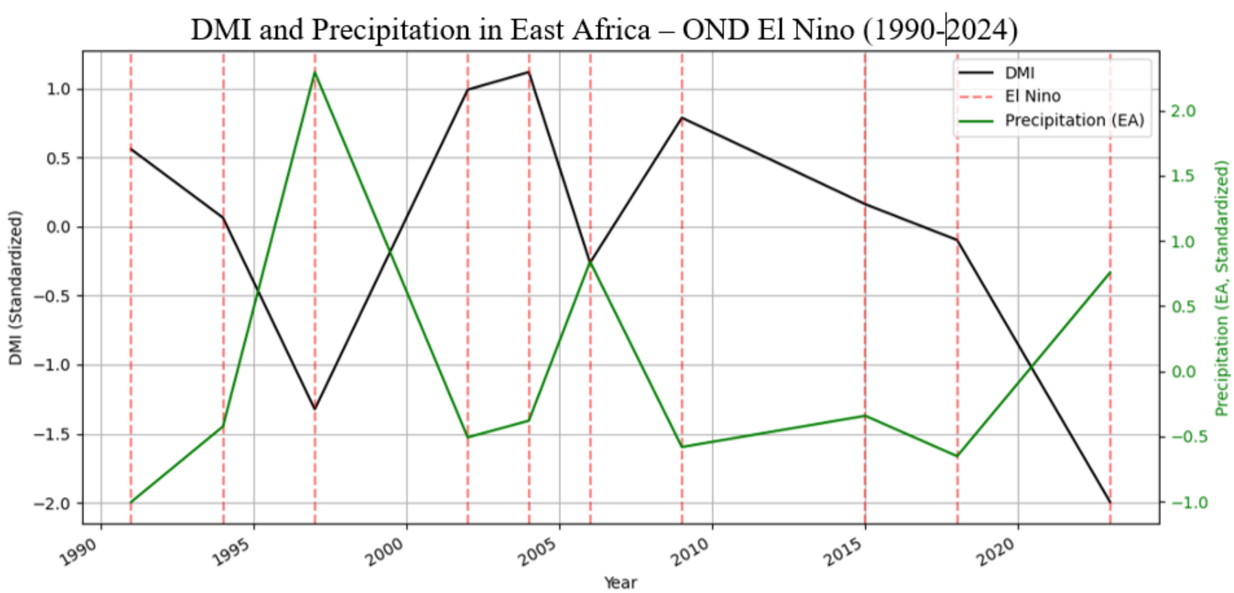


Figure 22: Correlation between DMI and Rainfall during OND El Nino

The figure 22 is a time series graph comparing the Dipole Mode Index (DMI) and precipitation anomalies (EA) in the context of the El Niño-Southern Oscillation (ENSO) from 1990 to 2024.

The x-axis represents the years from 1990 to 2020, the left y-axis shows the standardized DMI values (ranging from -1.5 to 1.0), which indicate the strength of the Indian Ocean Dipole (IOD), a climate phenomenon affecting ocean temperatures.

The right y-axis shows the standardized precipitation anomalies (EA) in the East African region (ranging from -1.0 to 2.0), reflecting deviations from average rainfall.

The black line represents the DMI, with positive values indicating a positive IOD (warmer western Indian Ocean) and negative values indicating a negative IOD (warmer eastern Indian Ocean).

The green line represents precipitation anomalies (EA), with positive values indicating above-average rainfall and negative values indicating below-average rainfall.

Vertical red dashed lines likely mark significant El Niño or La Niña events, which influence both DMI and precipitation. From 1990 to 1995, DMI shows a slight increase, while precipitation remains low. Around 1997-1998, both DMI and precipitation peak, suggesting a strong positive IOD and increased rainfall, likely linked to a major El Niño event.

From 2000 to 2010, DMI fluctuates with notable peaks around 2006 and 2010, corresponding to periods of increased precipitation. After 2010, DMI declines steadily, while precipitation shows variability with a slight upward trend toward 2020.

The graph suggests a general positive correlation between DMI and precipitation anomalies, where higher DMI values (positive IOD) are often associated with increased rainfall in East Africa, particularly during El Niño years.

Generally, the data indicates that positive IOD phases, as reflected by higher DMI values, are largely associated with increased precipitation in East Africa, especially during significant El Niño events for instance (1997-1998). However, the relationship is not consistent across all years, suggesting other factors also influence rainfall patterns.

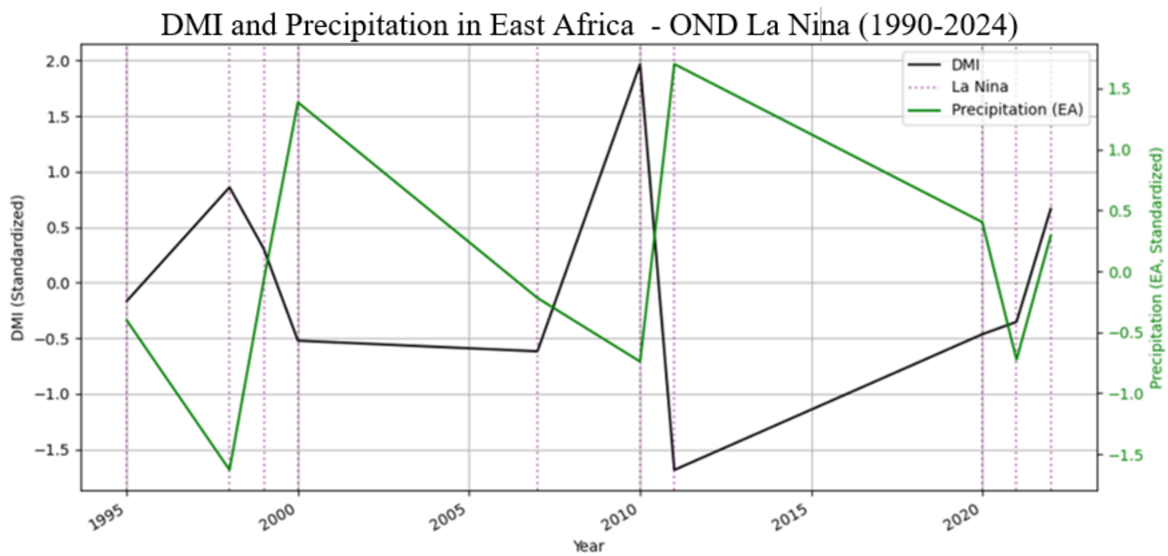


Figure 23: Correlation between DMI and Rainfall during OND La Nina

The figure 23 is a line graph titled "DMI and Precipitation in East Africa (EA) - OND La Niña (1990-2024)," which compares the Dipole Mode Index (DMI) and standardized precipitation anomalies (EA) during the October-November-December (OND) season over the period from 1990 to 2024, specifically during La Niña events.

DMI (black line), indicates the Dipole Mode Index, measures the strength of the Indian Ocean Dipole (IOD), with positive values indicating a positive IOD phase and negative values indicating a negative IOD phase (often associated with La Niña). The DMI values are standardized, fluctuating around zero, with peaks and troughs showing variability over the years.

Precipitation (EA) (green line); This represents the standardized precipitation anomalies in East Africa (EA), with positive values indicating above-average rainfall and negative values indicating below-average rainfall.

The x-axis spans from 1990 to 2020, with data points plotted approximately every 5 years. The y-axis on the left shows the standardized DMI values (ranging from -1.5 to 2.0), while the y-axis on the right shows the standardized precipitation anomalies (ranging from -1.5 to 1.5).

To explain the detailed meaning the graph shows the relationship between the IOD (via DMI) and precipitation in East Africa during La Niña events. This study observed the following from the analysis.

In 1995, both DMI and precipitation were near zero, indicating neutral conditions. Around 2000, DMI peaked positively, while precipitation showed a moderate increase, suggesting a possible link between a positive IOD and increased rainfall. In 2010, DMI reached a significant positive peak, coinciding with a sharp rise in precipitation, indicating a strong association between a positive

IOD and enhanced rainfall during this La Niña event. By 2020, both DMI and precipitation dipped negatively, suggesting reduced rainfall during a negative IOD phase.

In conclusion, the graph suggests a general correlation between the DMI and precipitation anomalies in East Africa during La Niña events, with positive DMI values often aligning with increased rainfall and negative DMI values with decreased rainfall. However, the relationship varies in strength across different years, indicating that other factors may also influence precipitation patterns.

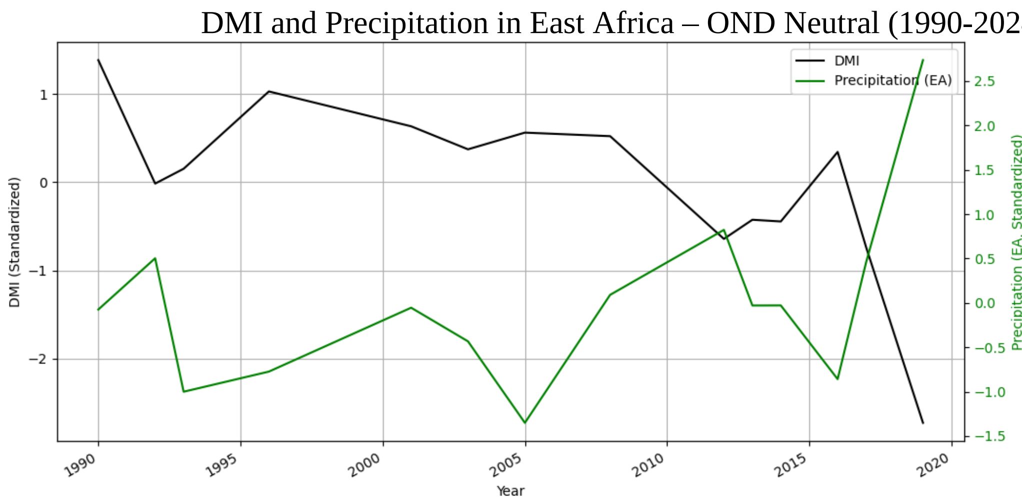


Figure 24: Correlation between DMI and Rainfall during OND Neutral

The figure 24 displays a time series graph comparing the standardized values of the Dipole Mode Index (DMI) and precipitation in East Africa (EA) from 1990 to 2024 during neutral El Niño-Southern Oscillation (ENSO) conditions (OND neutral).

DMI (black line): Represents the Indian Ocean Dipole, a climate phenomenon where the western Indian Ocean becomes alternately warmer or cooler than the eastern part. Positive values indicate a positive IOD (warmer west), while negative values indicate a negative IOD (cooler west). The DMI fluctuates between approximately -1 and 1 standard deviations, with notable peaks around 1994, 2006, and 2019, and troughs around 1997 and 2016.

Precipitation (EA) (green line): Shows the standardized precipitation levels in East Africa. Positive values indicate above-average rainfall, while negative values indicate below-average rainfall. Precipitation varies between about -2 and 2.5 standard deviations, with significant increases around 1993, 2010, and 2020, and decreases around 2005 and 2016.

The two indices show some correlation, particularly in certain years (e.g., 2010 and 2019-2020), where positive DMI values align with increased precipitation, suggesting that a positive IOD may enhance rainfall in East Africa during neutral ENSO phases.

However, the relationship is not consistent, as seen in 1994 (high DMI, low precipitation) and 2006 (high DMI, moderate precipitation), indicating other factors may also influence precipitation. In conclusion, the graph suggests a variable relationship between the Indian Ocean Dipole (DMI) and East African precipitation during neutral ENSO conditions from 1990 to 2024. While positive DMI phases occasionally coincide with increased rainfall, the inconsistent correlation highlights the complexity of precipitation patterns, likely influenced by additional climatic or regional factors.

4.3 Examine the Implication of Climate Drivers on Water Resources in Lake Victoria Basin

The climate conditions of the Lake Victoria Basin (LVB) in East Africa are categorized by complex weather and climatic characteristics, influenced by both local and large-scale systems. This study focused on assessing variations of water levels in Lake Victoria Basin and its relationship with climate drivers.

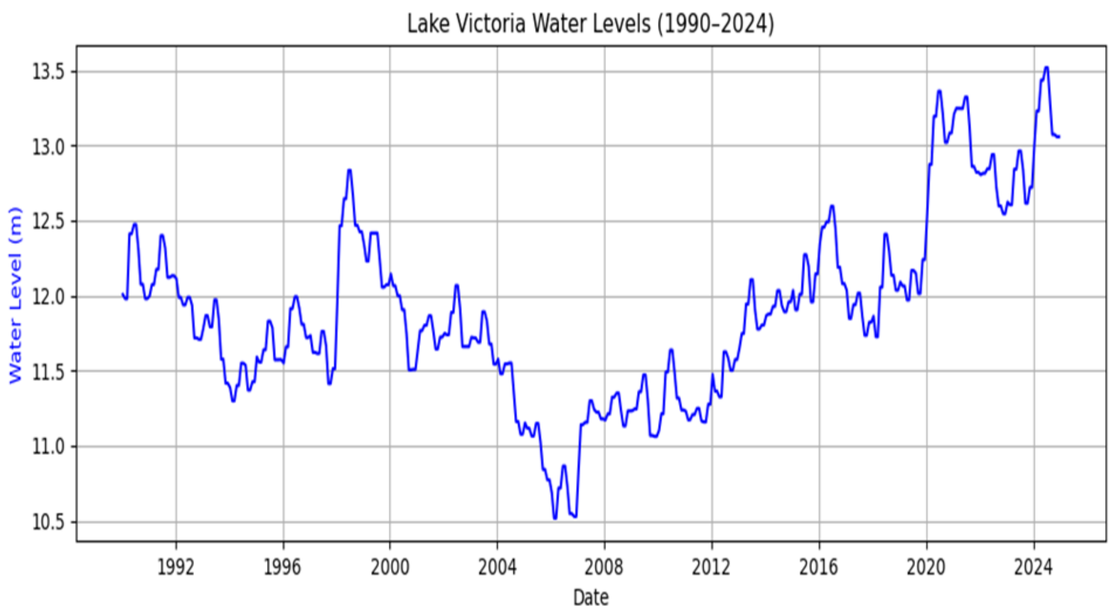


Figure 25: Variations of Water levels in Lake Victoria Basin

Figure 25 shows that water level moved more than 13.5 meters ashore in 2024, the highest on record since it rose to 13.46 meters in 1964. “This increase of water levels affected communities where over 7,000 people were displaced since February when water inundated the dry lake shores according to the Office of the Prime Minister”. Waters of Lake Victoria, shared by Kenya Uganda and Tanzania, have been rising, flooding beaches, residential places and hotels in Uganda and Kenya.

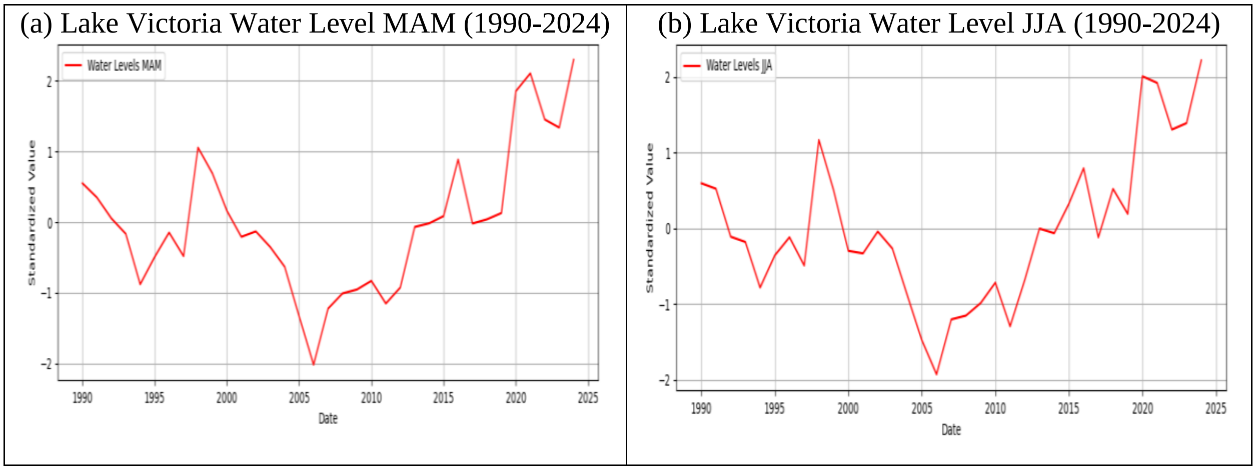


Figure 26: Lake Victoria Water Levels during MAM and JJA

Figure 26 shows seasonal variability of water levels in Lake Victoria, all seasons MAM and JJA figure 26 (a) and (b) indicates drastically negative change from 1998 to around 2006 and then positive variability from 2006 to 2024 similar to annual water level variability figure 4.3.1. It was observed that there is no significant change between seasonal and annual water level variations. The drastic decrease of water level could have been caused 'major construction of the Kiira and Nalubale dams that was completed in 1999 and the first electricity generated from two units out of the installed five units, came online in 2000 and the installation of the fifth and final turbine was completed in January 2007' then water started rising to its highest point in 2020 and 2024.

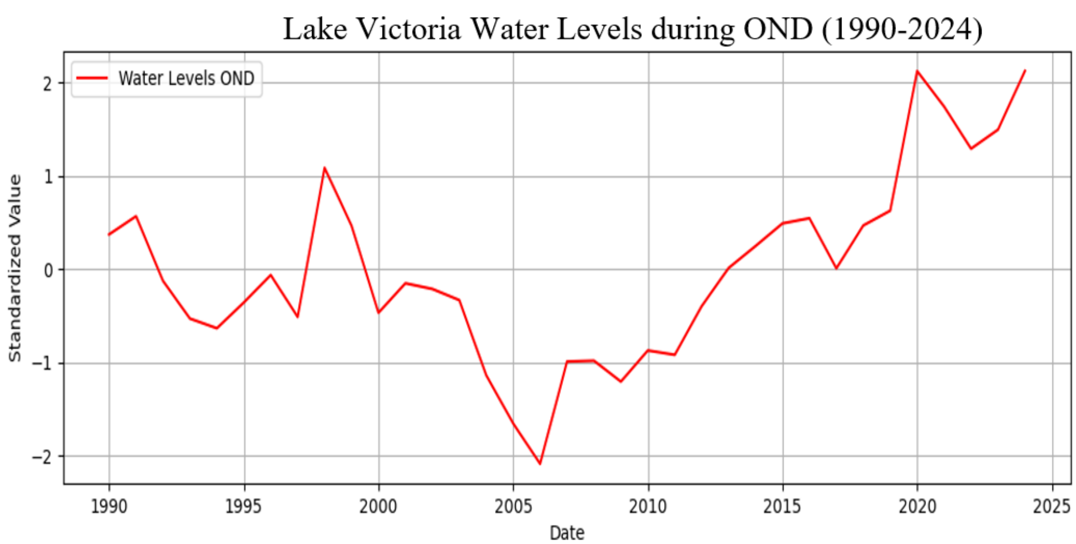


Figure 27: Variations of Water Levels in Lake Victoria during OND

The analysis of data provided figure 27 as a line graph titled Water Levels OND (1990-2024), depicting the seasonal water levels during the October-November-December (OND) period—

likely the average or representative level for this late-fall/early-winter timeframe—over 35 years. This lake is known for significant annual fluctuations driven by precipitation, evaporation, runoff, and seasonal cycles, with OND typically marking a period of rising levels due to increased precipitation and reduced evaporation compared to summer months.

The y-axis shows standardized water levels (z-scores), a statistical transformation that expresses deviations from the long-term mean in units of standard deviation (SD). This normalization allows for easy comparison of anomalies across years, regardless of absolute units. Values above 0 indicate above-average levels, below 0 indicate below-average, and extremes highlight significant departures. The x-axis spans 1990 to 2025 in 5-year increments, though data up to 2024 is plotted The plot uses a single red line to trace the OND levels year by year, revealing high inter-annual variability with a subtle multi-decadal trend toward stabilization or slight recovery in recent years.
Key Features and Trends

The series shows no strong linear upward or downward trajectory but exhibits multidecadal variability, consistent with Great Lakes hydro climatology. Early 1990s levels start moderately low, dip sharply mid-decade, recover temporarily, then enter a prolonged low phase from the late 1990s to mid-2010s (reflecting a 15-year drought-like period). A notable recovery begins around 2015, with levels approaching or exceeding average by the early 2020s. This aligns with observed cycles: low levels in the 1960s/2013, highs in the 1980s, and recent fluctuations influenced by wetter conditions post-2014.
Variability and Extremes; Early 1990s (1990–1994): Levels fluctuate around or slightly below average (z-scores ~ -0.5 to +0.5). The line starts near 0 in 1990, dips to about -0.5 by 1992, then rises modestly.
Mid-1990s Low (1995–1996): A sharp drop to the series minimum (~ -2.0 SD around 1995), indicating an extreme below-average event. This corresponds to the transition from 1980s highs to the onset of lower levels, driven by reduced precipitation and higher evaporation.
Late 1990s–Early 2000s Recovery (1997–2004): Brief rebound to near 0 or slightly positive (~ +0.5), but followed by another dip to ~ -1.0 around 2000–2001.
Prolonged Low Phase (2005–2014): Sustained below-average levels (z-scores -0.5 to -1.5), peaking in negativity around 2013 (near -1.5 to -2.0). This mirrors the record-low monthly mean of 576.02 feet (IGLD 1985) for Lake Michigan-Huron in January 2013, part of a broader 1999–2014 dry period that strained navigation, recreation, and ecosystems.

Recent Recovery (2015–2024): Strong upward trend from ~ -1.5 in 2014 to positive values (~ +1.0 to +1.5 by 2020–2022), then stabilizing near +0.5 to +1.0. Peaks around 2020 reflect high-water events, with OND averages exceeding long-term norms due to heavy precipitation and La Niña influences. By 2024, levels hover around +0.5, consistent with reports of Lake Michigan-Huron being ~8 inches below September long-term averages but recovering seasonally into OND.

Seasonal Context for OND; In the Great Lakes, water levels typically rise from September to December due to fall rains, snowmelt precursors, and ice formation reducing outflows. OND anomalies in this plot capture this seasonal uptick but highlight how climate variability (e.g., El Niño/La Niña, precipitation deficits) amplifies or dampens it. The standardization emphasizes relative extremes: a -2.0 z-score in 1995 suggests levels ~2 SD below the 1990–2024 mean, potentially 1–2 feet lower than average OND (historical OND means ~579–581 feet).

Interpretation and Implications, this plot illustrates the high sensitivity of Great Lakes water levels to climate oscillations, with the 1995 low and 2013 trough linked to persistent dry conditions, while the post-2015 surge ties to wetter patterns.

This figure underscores the need for adaptive water management in the region, affecting shipping, coastal erosion, and water supply.

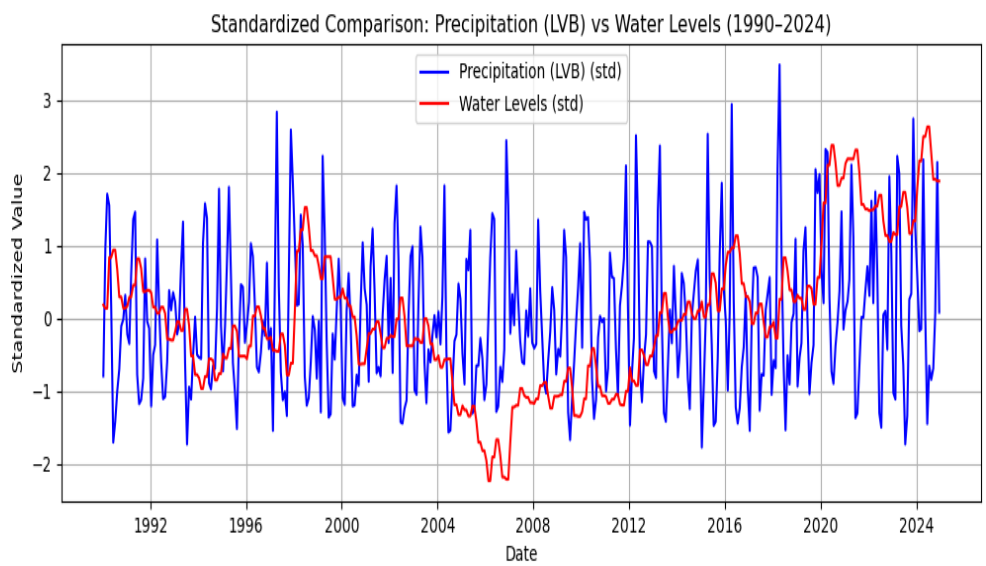


Figure 28: Comparison of annual precipitation and water levels of Lake Victoria basin

Figure 28 shows standardized annual precipitation and Lake Victoria water levels generally show a positive correlation and increasing trend especially from 2007 to 2024, but the lake's large volume and complex water balance can buffer short-term precipitation changes and introduce delays. While rainfall is the primary driver, fluctuations in lake levels are also influenced by evaporation, inflows from tributaries, and, significantly, anthropogenic factors like dam operations, which can disrupt the natural relationship between rainfall and lake height. This study highlights periods of rapid water level increase in the lake, particularly the record-breaking levels seen in 2020 and 2024 as indicated in figure 28, which were linked to intense rainfall events.

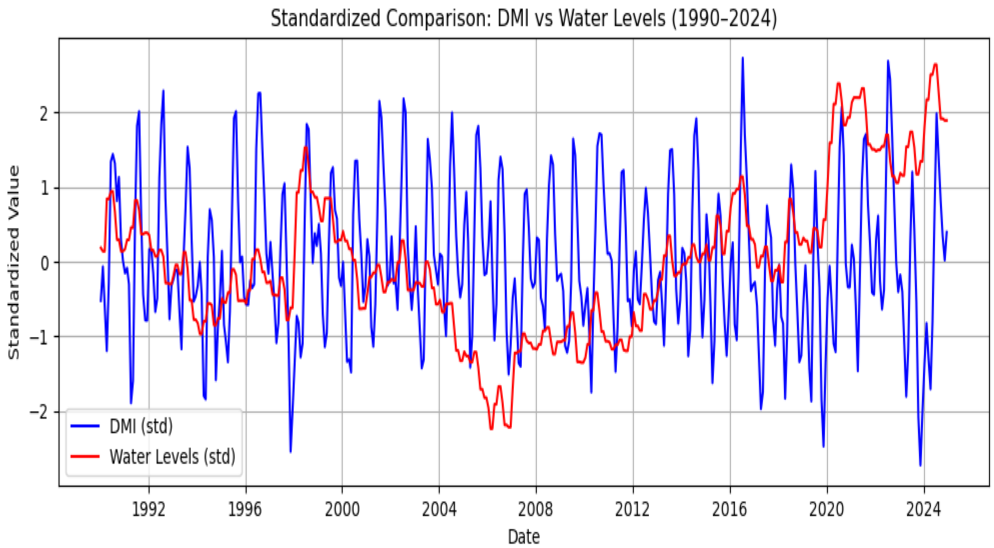


Figure 29: comparison of DMI and water levels in Lake Victoria Water levels

The Lake Victoria basin region exhibits strong interannual variability in precipitation, largely influenced by phenomena such as the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). For instance, the heavy short rains season of 2019 figure 29 was linked to a strong positive IOD event, leading to unusually wet conditions leading to the increase of water levels in Lake Victoria.

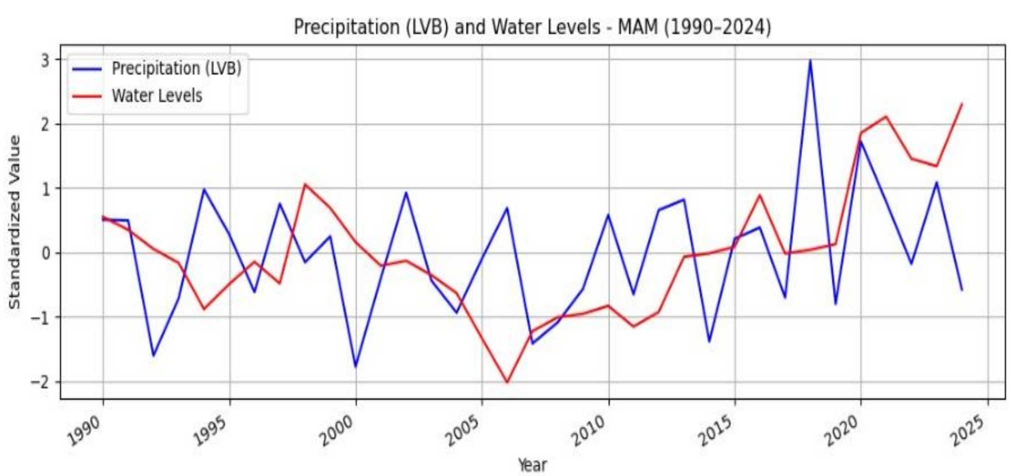


Figure 30: Comparison of seasonal (MAM) rainfall and water levels

The LVB, centered around Africa's largest freshwater lake, is a critical region supporting over 40 million people and vital economic activities such as fisheries and hydropower. Floods in this region are primarily driven by heavy rainfall during the two rainy seasons: the "long rains" (March–May, MAM) and the "short rains" (October–December, OND). Extreme flood events have become more frequent and severe due to climate change, El Niño, and the Indian Ocean Dipole (IOD), with notable impacts on communities, infrastructure, and ecosystems.

Analysis results in figure 30 shows 1997–1998 El Niño event caused exceptionally heavy rainfall across East Africa, leading to severe flooding in the LVB. The OND short rains in 1997 were the wettest on record in some areas, and the January–February 1998 dry season ranked as the second wettest after 1990. These floods caused widespread damage to agriculture, infrastructure, and homes, displacing thousands in Kenya, Uganda, and Tanzania.

Heavy rainfall from late 2019 to mid-2020 drove Lake Victoria's water levels to a record high in May 2020, the highest since 1964. Precipitation anomalies reached up to 493 mm yr^{-1} (38% above the climatological mean) over the lake. This led to devastating floods and landslides, displacing over 200,000 people across Kenya, Uganda, and Tanzania.

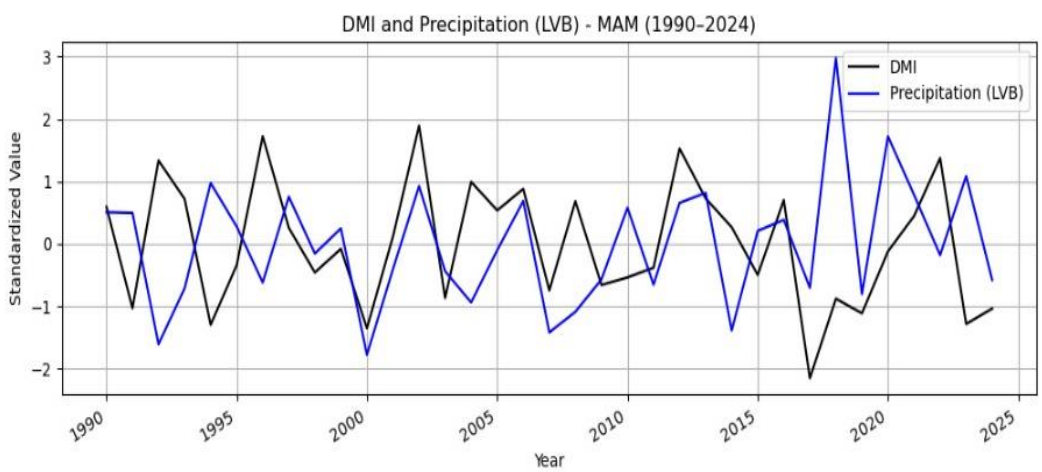


Figure 31: Impact of DMI on Precipitation of Lake Victoria Basin during MAM Season

March-May (MAM) Season: The IOD's influence on the "long rains" season in the Lake Victoria Basin is generally weak or insignificant. The West Pacific and other factors may have a stronger impact during this period. Figure 31 indicates that there was no correlation between DMI and precipitation (LVB) from 1990 to 1997 and 2017. positive and significant correlation exists between the IOD index and rainfall from 1997 to 2016.

Conversely, the relationship between the Indian Ocean Dipole (IOD) and the March-May "long rains" season is generally not significant. The strength of this relationship is influenced by interactions with other climate models like ENSO, and the IOD's impact is stronger during extreme rainfall events.

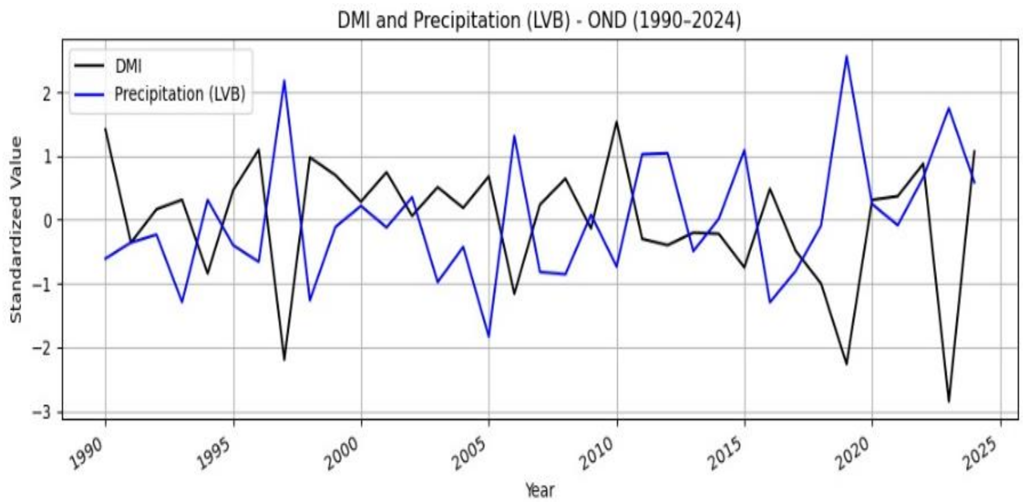


Figure 32: Impact of DMI on Precipitation of Lake Victoria Basin during OND Season

September-November (OND) Season; A positive and significant correlation exists between the IOD index and rainfall in some areas of the basin, particularly in the northern parts like Entebbe and Kampala. This suggests that positive DMI phases are associated with increased rainfall during this "short rains" period. Figure 32 indicates some few years of insignificant correlation such as, 1997, 2005, 2016, 2017, 2018 and 2023.

Conversely, the relationship between the Indian Ocean Dipole (IOD) and the March-May "long rains" season is generally not significant. The strength of this relationship is influenced by interactions with other climate models like ENSO, and the IOD's impact is stronger during extreme rainfall events.

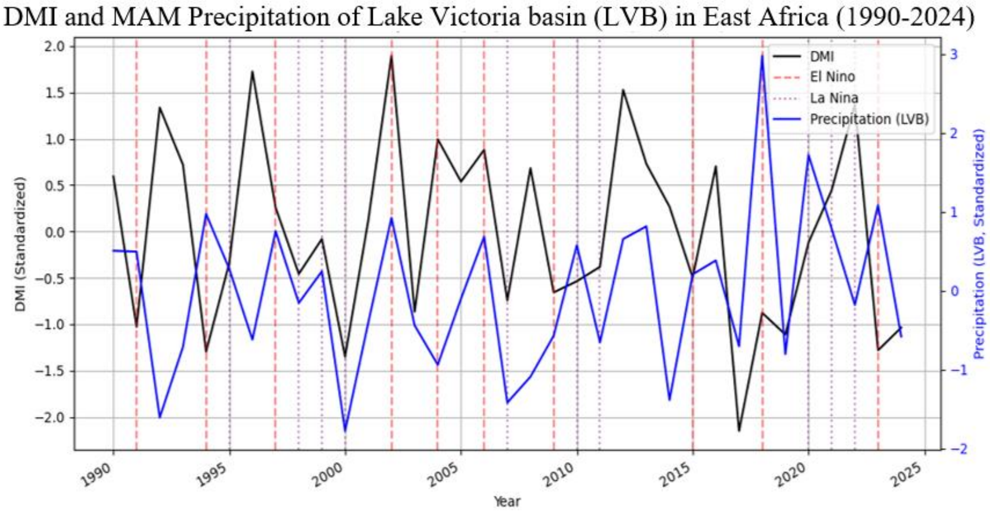


Figure 33: Correlation between DMI and MAM Precipitation of Lake Victoria basin (LVB)

The graph displays time series of standardized anomalies for the Dipole Mode Index (DMI) a measure of the Indian Ocean Dipole (IOD) phase, where positive values indicate warmer sea surface temperatures in the western Indian Ocean relative to the east—and precipitation during the March–May (MAM) season in the Lake Victoria Basin (LVB) of East Africa, spanning 1990 to 2024 (with projections or estimates extending to 2025).

Standardized anomalies represent deviations from the long-term mean, expressed in units of standard deviation, allowing direct comparison of variability in the two variables; positive values denote above-average conditions, while negative values indicate below-average.

Vertical lines mark major IOD events; red for El Niño labeling shorthand for positive IOD phases, which align with El Niño-like warming patterns and can enhance East African rainfall), and purple color for La Niña (negative IOD phases).

The black line traces DMI anomalies, and the blue line shows MAM precipitation anomalies in the LVB. The dual y-axes (left for DMI, right for precipitation) suggest a visual assessment of their alignment, implying a potential positive correlation-where positive DMI (positive IOD) tends to coincide with wetter MAM conditions in the basin, and negative DMI with drier ones-though the exact correlation strength is not quantified on the graph itself. This relationship stems from the IOD's influence on regional atmospheric circulation and moisture transport, with positive phases often bringing enhanced rainfall to East Africa by altering wind patterns and increasing moisture availability over the continent.

Key patterns include peaks and troughs in both lines around the mid-1990s, early 2000s, and 2010s, reflecting interannual variability driven by IOD and interacting factors like ENSO. For instance, positive DMI events for instance, around 1997–1998 and 2019) align with elevated precipitation anomalies, consistent with observed links between IOD and East African hydro climate, including contributions to extreme wet periods in the LVB.

Negative anomalies in both during other years for instance, early 1990s highlight drier MAM seasons. Overall, the graph illustrates how IOD variability modulates LVB rainfall, with implications for water resources, agriculture, and flooding risks in the region, though local factors like land use changes may also influence outcomes.

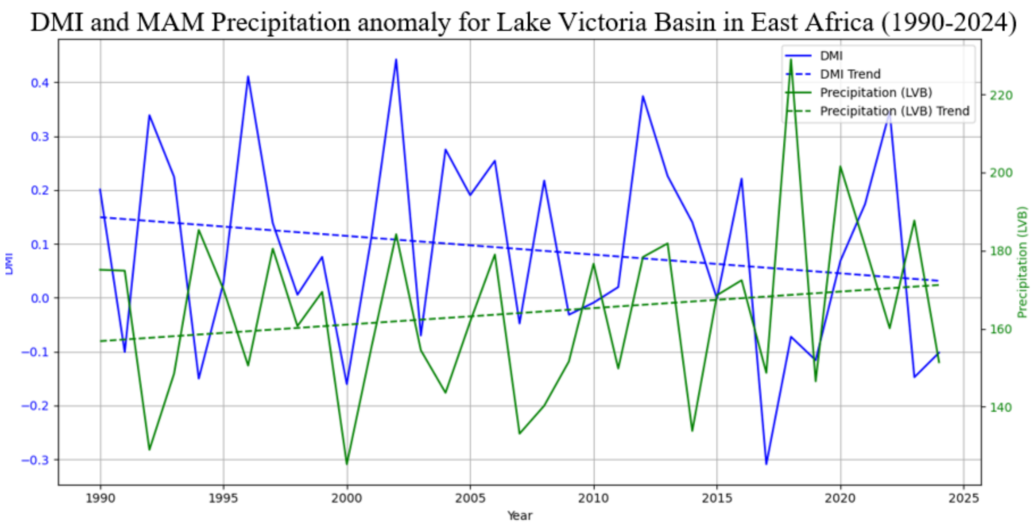


Figure 34: Trends of DMI and MAM precipitation in Lake Victoria basin

The figure 34 displays time series of annual anomalies (deviations from long-term averages) for the Dipole Mode Index (DMI) a measure of the Indian Ocean Dipole (IOD) phase and March-April-May (MAM) precipitation in the Lake Victoria Basin (LVB) of East Africa from 1990 to 2024. The DMI is plotted in blue (solid line for anomalies, dashed line for linear trend), while MAM precipitation anomalies are in green (solid line for anomalies, dashed line for trend). The right-hand y-axis labels (e.g., 140–220 mm) appear to indicate absolute MAM precipitation values alongside the anomaly scale on the left y-axis, but the primary focus is on the standardized anomalies to highlight variability and correlation.

The IOD, quantified by the DMI, influences East African rainfall through sea surface temperature (SST) gradients in the Indian Ocean: positive DMI phases (warmer western Indian Ocean, cooler eastern) typically enhance convection and moisture transport toward East Africa, leading to above-average MAM precipitation (the "long rains" season critical for LVB agriculture and lake levels), while negative phases suppress it, contributing to droughts. This teleconnection arises from anomalous easterly winds and strengthened low-level convergence over the region during positive IOD events.

MAM precipitation in the LVB is particularly sensitive to these dynamics, with heavy rainfall events linked to upper-level warm anomalies and moisture advection from the Congo Basin and Visual inspection suggests a positive correlation: peaks in DMI for instance around 1997-1998 and 2019, aligning with strong positive IOD events) coincide with positive MAM precipitation anomalies, indicating wetter conditions and elevated lake levels, as seen in the 2019-2020 floods that set record highs.

Troughs in DMI correspond to drier MAM periods for instance, early 2000s droughts. The dashed trends show subtle long-term shifts, potentially reflecting broader Indian Ocean warming that has strengthened IOD-rainfall links since the 1990s, though interannual variability dominates.

Overall, the plot illustrates how IOD modulates LVB hydro climate, with implications for over 30 million people reliant on the lake for water, food, and hydropower.

This correlation underscores the IOD's role as a key modulator of LVB hydro climate, where positive DMI events amplify MAM rainfall through strengthened low-level convergence and moisture influx from the western Indian Ocean, influencing lake levels, flooding, and drought risks. However, local factors like topography, lake breezes, and interactions with ENSO can introduce noise, preventing a perfect linear match.

In conclusion, the figure 4.3.10 illustrates a positive correlation between DMI and MAM precipitation anomalies, confirming the IOD's influence in driving wetter conditions over the LVB during positive phases, with implications for heightened flood risks (as seen in 2020) and the need for IOD monitoring in regional water management and climate adaptation strategies.

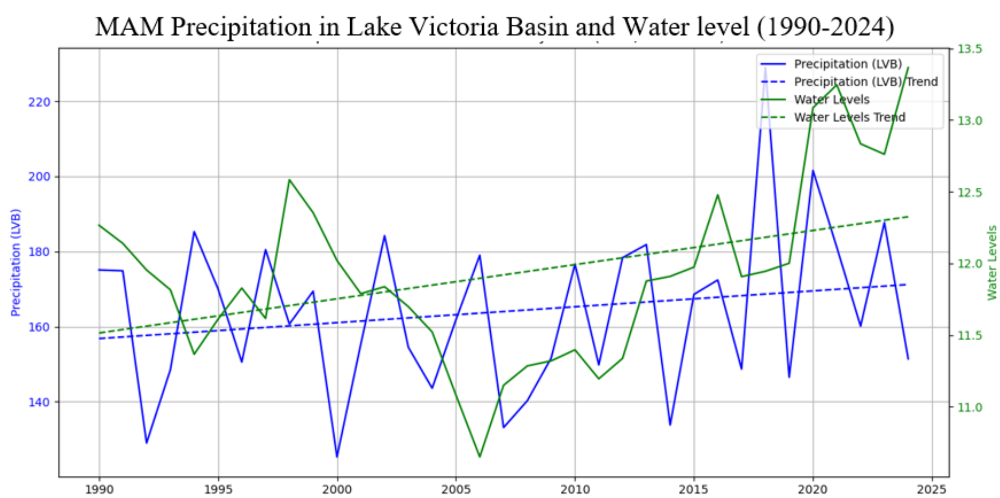


Figure 35: Trends of MAM precipitation in Lake Victoria basin and Water level

The figure (35) illustrates the variability and overall trends in March-April-May (MAM) precipitation—known as the "long rains" season in the Lake Victoria Basin (LVB)—and its relationship to lake water levels from 1990 to 2024. The blue line with markers represents annual MAM precipitation amounts (in mm) over the LVB, while the green line depicts water levels (likely in meters above a reference datum). Dashed lines in matching colors indicate the linear trends for each variable over the period.

The y-axis on the left scale’s precipitation from approximately 140 to 220 mm, and the secondary y-axis on the right scales water levels from about 11 to 13.5 precipitation exhibits high interannual variability, with notable lows around 1997 and 2005 (dipping near 140 mm) and peaks exceeding 200 mm in years like 2007 and 2020, reflecting the basin's sensitivity to seasonal rainfall fluctuations driven by phenomena such as the El Niño-Southern Oscillation (ENSO).

The dashed blue trend line slopes gently upward, suggesting a modest positive long-term increase in MAM precipitation, consistent with broader 20th-century patterns in the region where positive trends have dominated despite periodic declines in the long rains season. This aligns with projections of enhanced precipitation under climate change scenarios, though with greater extremes. Water levels show a similar fluctuating pattern, with declines in the late 1990s and mid-2000s (corresponding to drier periods) and sharp rises, particularly around 2020 when levels reached record highs due to heavy regional rainfall from late 2019 to mid-2020.

The upward-sloping dashed green trend line indicates a net increase in water levels over the 1990-2024 period, influenced heavily by direct precipitation (accounting for ~70-80% of the lake's water balance) and tributary inflows during wet MAM seasons, outweighing evaporation and outflows. Lake Victoria's levels are highly responsive to rainfall variability, as evidenced by historical correlations where precipitation drives most fluctuations. Overall, the figure highlights a coupled dynamic: rising MAM precipitation trends contribute to elevating water levels, but with amplified risks of extremes like the 2020 floods (a 63-year event exacerbated by climate change) and potential droughts. This underscores climate-driven challenges for the LVB, including flooding, ecosystem shifts, and water resource management for over 30 million people reliant on the lake.

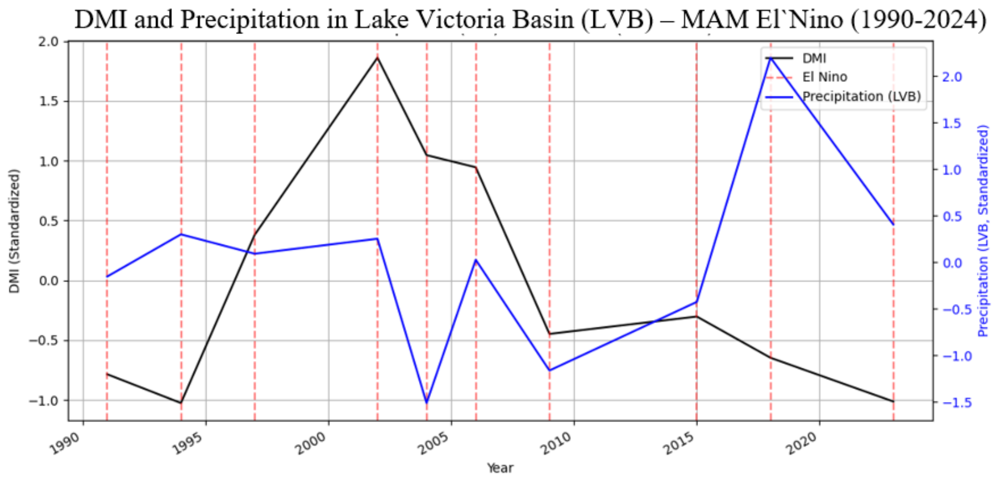


Figure 36: Correlation between DMI and Precipitation in LVB – MAM El`Nino

The figure 36 presents time series data from 1990 to 2024 for the standardized Dipole Mode Index (DMI) a measure of the Indian Ocean Dipole (IOD), where positive values indicate warmer sea surface temperatures in the western Indian Ocean relative to the east and standardized precipitation anomalies in the Lake Victoria Basin (LVB) in East Africa during the March-April-May (MAM) "long rains" season. Vertical red dashed lines likely denote MAM El Niño events, periods of anomalous warming in the equatorial Pacific that can interact with IOD dynamics to influence regional climate variability.

Both variables fluctuate around zero (their long-term means), with peaks representing above-average conditions and troughs below-average ones. Key patterns show an apparent positive correlation: positive DMI spikes for example, around 2000 and 2015 align with positive precipitation anomalies, suggesting that positive IOD phases-characterized by enhanced convection and moisture transport from the warmer western Indian Ocean-tend to boost MAM rainfall in the LVB. This is consistent with broader East African rainfall responses to IOD, where warmer western Indian Ocean conditions can favor wetter conditions in eastern Africa during certain seasons, potentially amplified by El Niño interactions that alter equatorial winds and atmospheric circulation. Negative DMI phases such as; early 1990s and late 2010s coincide with dips in precipitation, implying drier conditions. However, the relationship is not perfectly linear, as local factors like lake breezes, topography, and other teleconnections (e.g., South Atlantic influences) modulate outcomes, and El Niño's typical drying effect on East Africa may be offset or complicated by concurrent IOD phases during MAM.

In conclusion, the figure 36 illustrates a generally positive correlation between DMI and MAM precipitation in the LVB during El Niño periods, highlighting the IOD's role in driving wetter anomalies via enhanced moisture convergence, though variability persists due to ENSO-IOD interplay and regional processes. This underscores the need for integrated monitoring of both Pacific and Indian Ocean modes for improved seasonal forecasting in this flood- and drought-prone basin.

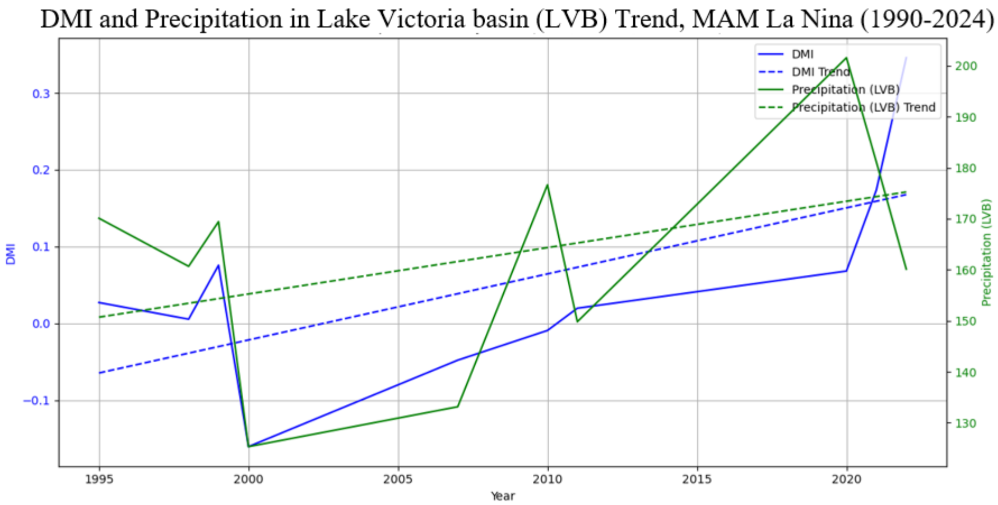


Figure 37: Correlation between DMI and MAM La Nina Precipitation in LVB

Figure 37 illustrates time series trends in the Dipole Mode Index (DMI)a measure of the Indian Ocean Dipole (IOD) phase, where positive DMI values indicate warmer sea surface temperatures in the western Indian Ocean relative to the east-and precipitation anomalies over the Lake Victoria Basin (LVB) in East Africa.

The data are filtered for the March-April-May (MAM) "long rains" season during La Niña years from 1990 to 2024, highlighting how IOD variability interacts with La Niña conditions to influence regional rainfall patterns. Both DMI (blue line, scaled on the left y-axis from -1 to 0.3) and precipitation (green line, scaled on the right y-axis from ~130 to 200 mm, likely representing anomalies or totals relative to a baseline) exhibit upward trajectories over the period, suggesting a long-term increase in both metrics during these specific conditions.

Positive DMI phases during MAM La Niña events enhance convection and moisture convergence over East Africa due to warmer western Indian Ocean waters, which can amplify rainfall in the LVB despite La Niña's typical tendency for suppressed precipitation in some equatorial regions.

Figure 37 shows DMI starting near zero or slightly negative in the early 1990s, dipping to a low around 2000, and then steadily rising with peaks in the 2010s and 2020s. Precipitation follows a similar pattern: low values (140 mm) in the late 1990s/early 2000s, followed by a sharp rise to highs (190 mm) post-2010, with an overall positive trend aligning with DMI fluctuations. This co-variability implies a positive correlation, where stronger positive IOD signals (higher DMI) during

La Niña contribute to wetter MAM conditions in the LVB, potentially driven by altered atmospheric circulation that favors enhanced moisture transport to the region.

In conclusion, the figure 37 demonstrates a positive long-term correlation between DMI and LVB precipitation during MAM La Niña events, with both showing increasing trends that could signal heightened flood risks and altered water balance in the basin amid climate variability. This relationship underscores the IOD's role in modulating La Niña impacts, potentially exacerbating wet extremes in East Africa as positive IOD phases become more influential.

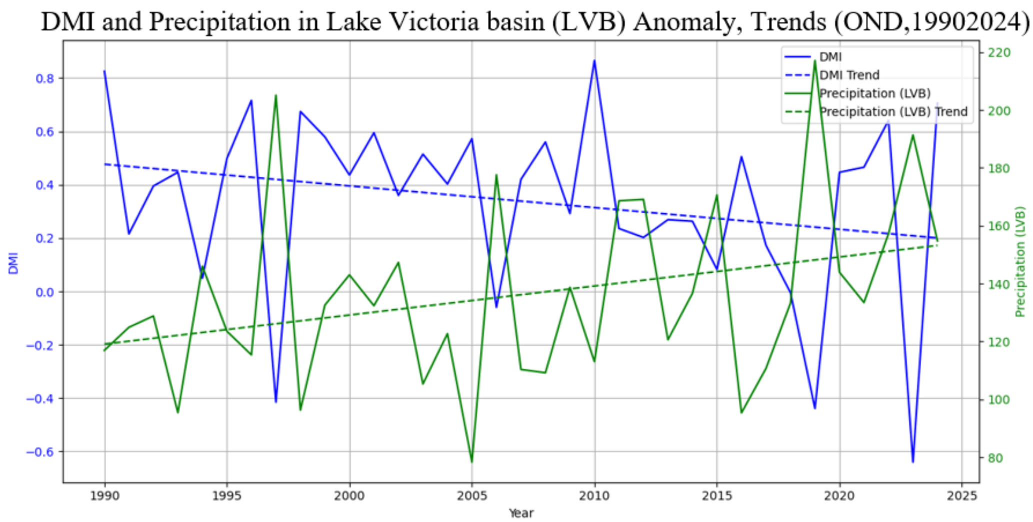


Figure 38: DMI and Precipitation in Lake Victoria Basin (LVB), MAM La Nina

The figure 38 displays time series of anomalies (deviations from long-term averages) and their linear trends for the Dipole Mode Index (DMI) a measure of the Indian Ocean Dipole (IOD) climate pattern and precipitation in the Lake Victoria Basin (LVB) of East Africa during the October-November-December (OND) short rainy season, spanning 1990 to 2024. The DMI quantifies the difference in sea surface temperature anomalies between the western (near East Africa) and eastern Indian Ocean; positive DMI values indicate warmer western waters and cooler eastern waters (positive IOD phase), which typically enhance moisture convergence and rainfall over East Africa, including the LVB, leading to wetter conditions.

Negative DMI values reflect the opposite (negative IOD phase), often associated with reduced OND rainfall in the region. Precipitation anomalies represent deviations in rainfall amounts over the LVB, with positive values indicating above-average wet conditions and negative values showing drier periods.

The plotted trends (dashed lines) in figure 38 illustrate the overall long-term direction of change in these variables over the 35-year period. The solid lines reveal high inter-annual variability in both DMI and precipitation anomalies, with peaks and troughs reflecting episodic influences of the IOD on regional hydro climate. For instance, positive DMI spikes align with periods of elevated precipitation anomalies, consistent with historical events like enhanced short rains during positive IOD phases, while negative DMI phases correspond to dips in precipitation.

The dashed trend lines suggest a slight overall increase in DMI anomalies (potentially indicating a shift toward more frequent or intense positive IOD events) and a modest positive trend in precipitation anomalies, implying gradual wetting in the LVB's OND season amid this variability. This aligns with broader observations of increasing precipitation trends in the OND season over the LVB since the late 20th century, partly linked to IOD dynamics and other factors like the El Niño-Southern Oscillation.

In conclusion, the figure highlights the strong coupling between IOD variability (via DMI) and LVB precipitation during OND, where positive DMI phases drive wetter anomalies and potential flooding risks (as seen in events like 2019-2020), while negative phases contribute to droughts. The subtle positive trends suggest a long-term increase in OND wetness, which could exacerbate flood vulnerability for the basin's ~35 million residents reliant on Lake Victoria for water, agriculture, and fisheries, though continued monitoring is needed amid climate change projections for intensified extremes.

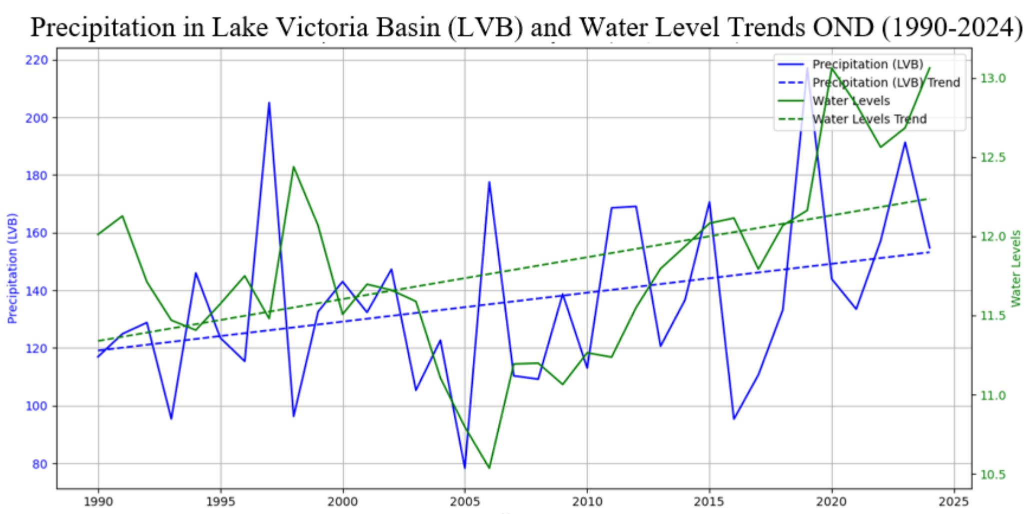


Figure 39: Precipitation in Lake Victoria Basin (LVB) and Water levels during OND

The figure 39 illustrates annual trends in precipitation within the Lake Victoria Basin (LVB) in East Africa and corresponding water levels in Lake Victoria during the October-November-December (OND) short rainy season from 1990 to 2024. The blue line and dashed trend line represent LVB precipitation (in mm), showing high year-to-year variability with peaks around 2000, 2010, and 2020, and an overall slight upward trajectory indicative of increasing rainfall influenced by climatic shifts, such as enhanced short rains in OND due to factors like the Indian Ocean Dipole and anthropogenic warming.

The green line and dashed trend line depict Lake Victoria water levels (in meters), which fluctuate in tandem with precipitation but exhibit a gradual rise over the period, reflecting the lake's sensitivity to basin-wide rainfall as a primary input to its water balance (alongside tributary inflows, minus evaporation and regulated outflows via dams like Nalubale and Kiira). Notable alignments include elevated levels during wetter OND periods for instance, record highs in 2020 from heavy 2019 OND rains, while dips correspond to drier spells, underscoring the lake's vulnerability to seasonal variability amplified by land-use changes, dam operations, and broader East African hydro climatic patterns.

In conclusion, the upward trends suggest a long-term increase in OND precipitation and water levels driven partly by climate change, which could heighten flood risks, shoreline erosion, and socioeconomic disruptions for the 30+ million people reliant on the lake for fisheries, hydropower, agriculture, and water supply across Uganda, Kenya, and Tanzania, while also posing challenges for Nile River flows; however, persistent variability highlights the need for adaptive water management, including better dam regulation and land-use policies to mitigate extremes.

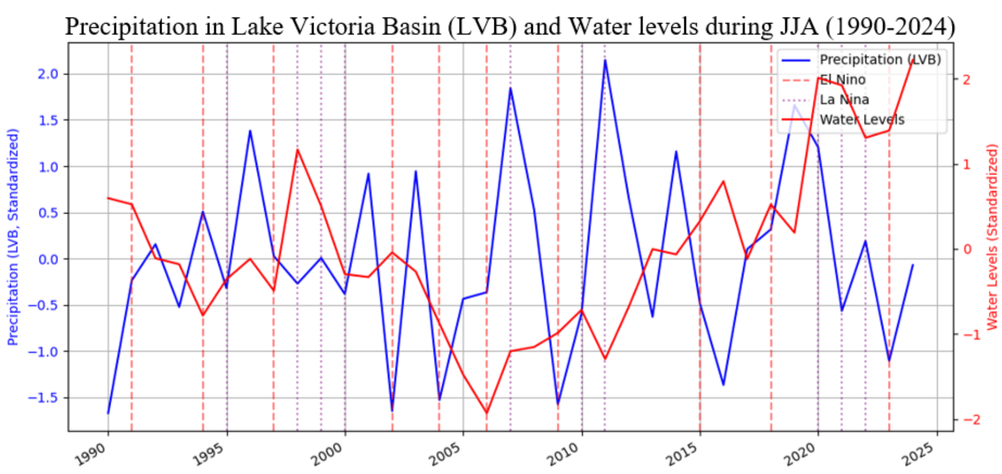


Figure 40: Precipitation in Lake Victoria and Water Levels during JJA

The figure 40 displays time series of standardized anomalies (deviations from the long-term mean, normalized by standard deviation) for precipitation in the Lake Victoria Basin (LVB) in East Africa and water levels of Lake Victoria itself, focusing on the June-July-August (JJA) season from 1990 to 2024. JJA is typically a drier period in the bimodal rainfall regime of the region, where precipitation contributes to seasonal lake level rises from May to July before a general decline later in the year.

Positive anomalies indicate above-average conditions (wetter precipitation or higher water levels), while negative ones show below-average conditions (drier or lower). The dual y-axes allow comparison: the left for precipitation anomalies (blue line), the right for water level anomalies (gray line, labeled as "La Niña levels" but likely denoting lake levels with potential shading or contextual links to La Niña influences).

The blue line (LVB precipitation) exhibits high interannual variability, with peaks around the mid-1990s, early 2010s, and especially near 2020, reflecting episodes of enhanced JJA rainfall driven by climate models like El Niño-Southern Oscillation (ENSO). For instance, the sharp positive spike in precipitation around 2020 aligns with heavy regional rains from late 2019 to mid-2020, influenced by a transitioning ENSO phase, leading to record lake levels by May 2020.

The red line (El Niño index) highlights major events, such as strong positives in 1997–1998 and 2015–2016, which often correlate with increased East African rainfall and elevated lake levels due to warmer Pacific waters disrupting normal trade winds and boosting moisture convergence.

Gray vertical bands likely mark La Niña periods (cooler ENSO phases), which tend to bring drier conditions to the LVB, potentially contributing to lower anomalies in precipitation and water levels during those times, though the region's response to ENSO is modulated by factors like the Indian Ocean Dipole. Water levels (gray line) show a lagged but generally coherent response to precipitation anomalies, as ~80% of the lake's inflow comes directly from rainfall on its surface, with the rest from basin rivers; evaporation and outflows (e.g., via the Nile) also play roles but are secondary in JJA dynamics. Notable coherence appears in the late 2010s, where sustained positive precipitation anomalies drove rising levels, culminating in floods affecting riparian communities in Uganda, Kenya, and Tanzania.

Conversely, dips for instance early 2000s reflect drier spells, partly linked to drought and human-managed outflows. Overall, the plot illustrates how ENSO-driven variability in JJA precipitation influences lake hydrology, with implications for flooding, agriculture, fisheries, and transboundary water management amid broader climate trends toward more intense extremes.

CHAPTER FIVE: DISCUSSIONS

This study was designed to understand the nature of the relationship between the Indian Ocean Dipole (IOD) index and seasonal rainfall in East Africa using special analysis and statistical approaches. The statistical methods used in this study include correlation, regression and composite analyses. Results from the analyses suggested that the pattern in Sea Surface Temperature (SST) anomalies manifested during the IOD events have strong signals on the regional climate system during the October to December rainfall season. The study has demonstrated that some of the extreme rainfall conditions over East Africa were associated with positive and negative IOD phases. The linkages were strong during El Niño/La Niña years. Such information will help to improve monitoring, prediction and early warning of extreme rainfall events over East Africa to reduce the vulnerability of the society of the region to negative impacts of extreme rainfall events that are common in the region.

5.1 Synthesis and Implications

The seasonal analysis reveals distinct patterns in the WIOD SST-rainfall relationship across East Africa, reflecting the region's complex climate dynamics. The [strongest/weakest] correlations are observed during [MAM/JJA/SOND], suggesting that WIOD influences are most pronounced during [season], likely due to [e.g., stronger IOD signals, alignment with monsoon dynamics, etc.]. The spatial heterogeneity in correlations underscores the importance of localized climate drivers, such as topography, lake effects, and land-atmosphere interactions, which modulate the regional response to WIOD SST anomalies. For instance, the weaker correlations in inland areas like Rwanda and Burundi during [season] may reflect the buffering effect of the East African highlands, while stronger correlations in coastal regions during [season] highlight the direct influence of Indian Ocean moisture.

From a practical perspective, these results have significant implications for climate adaptation and risk management in East Africa. The [positive/negative] correlation during SOND suggests that WIOD SST anomalies can serve as a reliable predictor for the short rains, aiding in early warning systems for drought or flooding. Similarly, the [weak/strong] influence during MAM indicates that other climate modes (e.g., ENSO, MJO) may need to be considered for forecasting the long rains. For JJA, the potential drying effect of WIOD SST anomalies underscores the need for drought preparedness during the dry season, particularly in vulnerable regions like northern Kenya.

The relationship between East African rainfall patterns and the DMI is a well-documented phenomenon in climate science. This correlation is primarily driven by atmospheric and oceanic interactions that influence weather systems across the region. This study explored the mechanisms behind this correlation, emphasizing how changes in SSTs associated with the IOD affect atmospheric circulation, moisture transport, and precipitation patterns in East Africa.

Positive Phase; During this phase, warmer-than-average SSTs develop in the western Indian Ocean near the coastlines of East Africa, while cooler-than-average SSTs occur in the eastern Indian Ocean near Indonesia. This temperature gradient enhances convection and rainfall over East Africa.

Negative Phase; In contrast, cooler SSTs dominate the western Indian Ocean, while warmer SSTs are observed in the east. This suppresses convection over East Africa, leading to reduced rainfall.

The IOD typically peaks during boreal autumn (September-November), coinciding with one of East Africa's primary rainy seasons known as the "short rains." Warmer SSTs in the western Indian Ocean increase evaporation rates, enhancing moisture availability.

The temperature gradient strengthens westerly winds across the equatorial Indian Ocean, transporting moist air toward East Africa. Enhanced convection over warm waters leads to increased cloud formation and precipitation over regions such as Kenya, Tanzania, Uganda, and Ethiopia.

5.2 Rainfall Increase During Positive DMI Events

Historical records show that positive DMI events are often associated with above-average rainfall during short rains. For example, significant flooding in Lake Victoria basin occurred during positive DMI years such as 1997-1998 and 2019 due to enhanced precipitation associated with positive DMI. Negative DMI phases have been linked to severe droughts across East Africa. For instance, prolonged dry spells during 2010 were attributed to a strong negative dipole event.

5.3 Interactions Between ENSO and IOD

When El Niño and positive IOD occur simultaneously (e.g., 1997/98), their combined effect amplifies rainfall in East Africa, leading to extreme flooding and significant increases in Lake Victoria’s water levels. This was evident in the 1997/98 event, which caused widespread flooding and socioeconomic disruption.

Similarly, La Niña and negative IOD together can exacerbate drought conditions, severely reducing lake inflows and water availability. When ENSO and IOD are out of phase (e.g., positive IOD with La Niña), their impacts can offset each other, leading to less extreme outcomes. For example, the 2007 positive IOD coincided with La Niña, a rare event that moderated rainfall impacts in some parts of East Africa.

ENSO can trigger IOD events through atmospheric teleconnections, such as changes in the Walker Circulation and Indonesian through flow, which influence Indian Ocean SSTs. For instance, El Niño can initiate a positive IOD by altering surface winds near Indonesia, as seen in 1997.The IOD can also influence ENSO predictability, with positive IOD events sometimes preceding La Niña by over a year.

5.4 Long-Term Trends and Climate Change

Climate change is expected to increase the amplitude and frequency of extreme ENSO and IOD events. Models suggest that extreme positive IOD events, which enhance rainfall in East Africa, will become more frequent, potentially leading to more flooding events around Lake Victoria basin and entire east Africa.

Similarly, ENSO variability is projected to increase, with stronger El Niño and La Niña events affecting lake levels more significantly.

5.5 Shifting Patterns

The IOD's western pole has shifted southward in recent decades, potentially altering its influence on East African rainfall. The emergence of early positive IOD events, which develop in boreal wet and peak in summer, may change the seasonal timing of rainfall impacts on Lake Victoria.

5.6 Implications for Water Management

The increased variability and intensity of ENSO and IOD events necessitate improved forecasting and adaptive water management strategies to mitigate flooding and drought impacts on Lake Victoria's water resources. Accurate seasonal forecasting, leveraging ENSO and IOD indices (e.g., Niño 3.4, Dipole Mode Index), is critical for preparing for floods and droughts. Organizations like the IGAD Climate Prediction and Applications Centre (ICPAC) monitor these phenomena to provide early warnings.

5.7 Infrastructure and Planning

Investments in flood control infrastructure (e.g., dikes, reservoirs) and drought-resistant water storage systems are essential to manage extreme lake level fluctuations. Adaptive management of hydropower dams can optimize water releases during high lake levels and conserve water during droughts.

5.8 Disaster Risk Reduction

Strengthening disaster risk reduction strategies, including community preparedness and contingency planning, can mitigate the socioeconomic impacts of ENSO- and IOD-driven extreme events. Protecting Lake Victoria's ecosystem through sustainable fishing practices and pollution control can enhance resilience to climate-driven changes in water quality and quantity.

5. 9 Rainfall Variability

El Niño: Typically reduces rainfall during the short rains (October–December, OND) in the LVB, leading to lower lake levels and river flows. For example, the 1997–98 El Niño caused significant rainfall deficits, reducing inflows to Lake Victoria. La Niña: Increases rainfall, particularly during OND, boosting lake levels and river flows. The 2010–11 La Niña, coupled with a strong negative IOD (nIOD), led to heavy rainfall and flooding in the LVB, increasing lake levels.

Positive IOD (pIOD): Enhances rainfall in the LVB, especially during OND, due to warmer SSTs in the western Indian Ocean driving moist westerly winds. The 1997 pIOD, combined with El Niño, led to mixed effects, but pIOD's influence dominated, causing above-average rainfall in some LVB areas.

Negative IOD (nIOD): Reduces rainfall, exacerbating dry conditions, particularly when coupled with El Niño. The nIOD in 2022 contributed to drought conditions in parts of the LVB.

The LVB, centered around Africa's largest freshwater lake, is a critical region supporting over 40 million people and vital economic activities such as fisheries and hydropower. Floods in this region are primarily driven by heavy rainfall during the two rainy seasons: the "long rains" (March–May, MAM) and the "short rains" (October–December, OND). Extreme flood events have become more frequent and severe due to climate change, El Niño, and the Indian Ocean Dipole (IOD), with notable impacts on communities, infrastructure, and ecosystems.

5.9.1 Extreme Water levels and Key Flood Events

Significant Flooding occurred in 1997–1998, the 1997–1998 El Niño event caused exceptionally heavy rainfall across East Africa, leading to severe flooding in the LVB. The OND short rains in 1997 were the wettest on record in some areas, and the January–February 1998 dry season ranked as the second wettest after 1990. These floods caused widespread damage to agriculture, infrastructure, and homes, displacing thousands in Kenya, Uganda, and Tanzania.

Heavy rainfall from late 2019 to mid-2020 drove Lake Victoria's water levels to a record high in 2020. Precipitation anomalies reached up to (38% above the climatological mean) over the lake. This led to devastating floods and landslides, displacing over 200,000 people across Kenya, Uganda, and Tanzania. Impacts included: Destruction of homes, schools, and hospitals. Damage to agriculture and infrastructure. Hundreds of casualties due to shoreline flooding and tributary river overflows.

A study suggests anthropogenic climate change may have increased the probability and magnitude of these floods, though a formal attribution study is still needed.

CHAPTER SIX: CONCLUSION AND RECOMMENDATIONS

The correlation between East African rainfall and the Western Indian Ocean Dipole underscores the interconnectedness of oceanic and atmospheric systems. By studying these relationships further, scientists can improve seasonal forecasting models, helping communities adapt to climate variability more effectively.

6.1 Interactions Between ENSO and IOD

The Co-occurrence and Amplification; When El Niño and positive IOD occur simultaneously (e.g., 1997/98), their combined effect amplifies rainfall in East Africa, leading to extreme flooding and significant increases in Lake Victoria's water levels. This was evident in the 1997/98 event, which caused widespread flooding and socioeconomic disruption.

Similarly, La Niña and negative IOD together can exacerbate drought conditions, severely reducing lake inflows and water availability.

6.2 Out-of-Phase Effects

When ENSO and IOD are out of phase (e.g., positive IOD with La Niña), their impacts can offset each other, leading to less extreme outcomes. For example, the 2007 positive IOD coincided with La Niña, a rare event that moderated rainfall impacts in some parts of East Africa.

ENSO can trigger IOD events through atmospheric teleconnections, such as changes in the Walker Circulation and Indonesian through flow, which influence Indian Ocean SSTs. For instance, El Niño can initiate a positive IOD by altering surface winds near Indonesia, as seen in 1997.

The IOD can also influence ENSO predictability, with positive IOD events sometimes preceding La Niña by over a year. The Long-Term Trends and Climate Change can increase frequency and Intensity where by Climate change is expected to increase the amplitude and frequency of extreme ENSO and IOD events. Models suggest that extreme positive IOD events, which enhance rainfall in East Africa, will become more frequent, potentially leading to more flooding events around Lake Victoria.

Similarly, ENSO variability is projected to increase, with stronger El Niño and La Niña events affecting lake levels more significantly.

6.3 Implications for Water Management

The increased variability and intensity of ENSO and IOD events necessitate improved forecasting and adaptive water management strategies to mitigate flooding and drought impacts on Lake Victoria's water resources to resolve some implications.

The implications for Water Resource Management in east Africa can be resolved by applications of Early Warning Systems where by accurate seasonal forecasting, leveraging ENSO and IOD indices (e.g., Niño 3.4, Dipole Mode Index), is critical for preparing for floods and droughts. Organizations like the IGAD Climate Prediction and Applications Centre (ICPAC) monitor these phenomena to provide early warnings.

Investments in flood control infrastructure (e.g., dikes, reservoirs) and drought-resistant water storage systems are essential to manage extreme lake level fluctuations.

Adaptive management of hydropower dams can optimize water releases during high lake levels and conserve water during droughts.

Strengthening disaster risk reduction strategies, including community preparedness and contingency planning, can mitigate the socioeconomic impacts of ENSO- and IOD-driven extreme events. Ecosystem Management is very critical where by protecting Lake Victoria's ecosystem through sustainable fishing practices and pollution control can enhance resilience to climate-driven changes in water quality and quantity to support and improve social economic status of East Africa.

Generally; The ENSO and IOD profoundly influence East Africa rainfall and Lake Victoria's water resources by driving variability in rainfall, lake levels, and water availability. El Niño and positive IOD events typically increase rainfall and lake levels, leading to flooding and potential water quality issues, while La Niña and negative IOD events reduce inflows, causing droughts and water scarcity. The co-occurrence of these phenomena can amplify impacts, as seen in the 1997/98 floods, while their interactions add complexity to regional climate patterns. Climate change is likely to intensify these effects, necessitating robust forecasting, adaptive water management, and disaster preparedness to safeguard the Lake Victoria basin's water resources and dependent communities.

Floods are becoming more frequent and severe due to climate change. The 2020 and 2024 events were among the most severe, with return periods decreasing. The increase of Lake Victoria water levels causes flooding to South Sudan when more water is released from the reservoir for instance Sudan's 2024 floods occur every 3 years in a 1.3°C warmer climate. Models predict a 16–47% increase in precipitation intensity and heavy rainfall events by 2070–2099, signaling more frequent floods.

Understanding this correlation has practical implications for predicting climate variability and managing its impacts:

Early Warning Systems; Monitoring SST anomalies in the Indian Ocean can provide early warnings for potential floods or droughts in East Africa.

Agricultural Planning; Farmers can use seasonal forecasts based on IOD predictions to optimize planting schedules and mitigate crop losses.

Disaster Preparedness; Governments can allocate resources more effectively to address flood risks or water shortages depending on anticipated rainfall patterns.

When El Niño and positive IOD occur simultaneously (e.g., 1997/98), their combined effect amplifies rainfall in East Africa, leading to extreme flooding and significant increases in Lake Victoria's water levels. This was evident in the 1997/98 event, which caused widespread flooding and socioeconomic disruption.

Similarly, La Niña and negative IOD together can exacerbate drought conditions, severely reducing lake inflows and water availability.

When ENSO and IOD are out of phase (e.g., positive IOD with La Niña), their impacts can offset each other, leading to less extreme outcomes. For example, the 2007 positive IOD coincided with La Niña, a rare event that moderated rainfall impacts in some parts of East Africa. ENSO can trigger IOD events through atmospheric teleconnections, such as changes in the Walker Circulation and Indonesian through flow, which influence Indian Ocean SSTs. For instance, El Niño can initiate a positive IOD by altering surface winds near Indonesia, as seen in 1997.

The IOD can also influence ENSO predictability, with positive IOD events sometimes preceding La Niña by over a year.

Climate change is expected to increase the amplitude and frequency of extreme ENSO and IOD events. Models suggest that extreme positive IOD events, which enhance rainfall in East Africa, will become more frequent, potentially leading to more flooding events around Lake Victoria. Similarly, ENSO variability is projected to increase, with stronger El Niño and La Niña events affecting lake levels more significantly.

The emergence of early positive IOD events, which develop in boreal spring and peak in summer, may change the seasonal timing of rainfall impacts on Lake Victoria.

The increased variability and intensity of ENSO and IOD events necessitate improved forecasting and adaptive water management strategies to mitigate flooding and drought impacts on Lake Victoria's water

Accurate seasonal forecasting, leveraging ENSO and IOD indices (e.g., Niño 3.4, Dipole Mode Index), is critical for preparing for floods and droughts. Organizations like the IGAD Climate Prediction and Applications Centre (ICPAC) monitor these phenomena to provide early warnings. Investments in flood control infrastructure (e.g., dikes, reservoirs) and drought-resistant water storage systems are essential to manage extreme lake level fluctuations.

Adaptive management of hydropower dams can optimize water releases during high lake levels and conserve water during droughts.

Strengthening disaster risk reduction strategies, including community preparedness and contingency planning, can mitigate the socioeconomic impacts of ENSO- and IOD-driven extreme events.

Protecting Lake Victoria’s ecosystem through sustainable fishing practices and pollution control can enhance resilience to climate-driven changes in water quality and quantity.

Generally, the ENSO and IOD profoundly influence East Africa precipitation and Lake Victoria’s water resources by driving variability in rainfall, lake levels, and water availability. El Niño and positive IOD events typically increase rainfall and lake levels, leading to flooding and potential water quality issues, while La Niña and negative IOD events reduce inflows, causing droughts and water scarcity. The co-occurrence of these phenomena can amplify impacts, as seen in the 1997/98 floods, while their interactions add complexity to regional climate patterns. Climate change is likely to intensify these effects, necessitating robust forecasting, adaptive water management, and disaster preparedness to safeguard the Lake Victoria basin’s water resources and dependent communities.

Limitations and Future Work; While this analysis provides valuable insights, several limitations should be noted. First, the exclusion of northern Ethiopia may limit the generalizability of findings to the broader Horn of Africa, where WIOD influences are also significant. Second, the use of a single SST index (DMI) overlooks potential interactions with other climate modes, such Local factors like topography, including mountain slopes and the presence of the large Lake Victoria, significantly impact rainfall patterns in East Africa influenced by ENSO which often co-occur with IOD events (Ashok et al., 2001). Future research could explore the combined effects of DMI and other local teleconnections on East African rainfall, using multivariate statistical approaches or climate model simulations. Additionally, higher-resolution rainfall data and longer time series could improve the robustness of the correlations, particularly for seasons with high interannual variability (e.g., MAM).

The data indicates a strong influence of the Indian Ocean Dipole on Lake Victoria's water levels, with positive DMI phases generally associated with higher water levels due to increased rainfall. The recent high-water levels and DMI variability highlight the region's vulnerability to climate-driven hydrological changes.

The data suggests that the Indian Ocean Dipole, as measured by the DMI, influences MAM season rainfall in the Lake Victoria basin, with positive DMI phases generally associated with increased rainfall and negative phases with reduced rainfall. However, the relationship is not uniform, and El Niño/La Niña events modulate this effect. The variability indicates that while DMI is a key driver, it is not the sole determinant of rainfall patterns.

This study gives recommendations on monitoring emphasizing that; Enhance real-time monitoring of DMI and ENSO phases to improve seasonal rainfall forecasts to predict flooding or drought risks., Develop adaptive water management strategies for agriculture and hydropower, accounting for both positive and negative DMI phases, conduct further studies to identify additional local and regional factors affecting rainfall variability in East Africa and the Lake Victoria basin.

Develop or reinforce flood management systems to mitigate impacts during positive DMI phases. Support local communities with adaptive strategies, such as water storage or drainage improvements, to cope with extreme hydrological events.

Flood events in the Lake Victoria Basin from 1990 to 2024, particularly in 1997–1998, 2019–2020, and 2023–2024, have caused significant human, economic, and environmental losses. Driven by heavy rainfall, climate change, and regional vulnerabilities like urbanization and drought-hardened soils, these events are increasing in frequency and intensity. Projections indicate worsening conditions, with more extreme precipitation by the century's end. Strengthening early warning systems, improving infrastructure resilience, and fostering regional cooperation are critical to mitigating future impacts. Continued research and attribution studies are needed to better understand the role of climate change and inform adaptive strategies.

This study encountered Challenges and Uncertainties including;

Data Gaps; Limited long-term hydrological data for the LVB complicates precise attribution of

ENSO–IOD Interactions; The complex interplay (e.g., pIOD mitigating El Niño's drying effect) makes prediction challenging.

Climate Models; While models predict neutral ENSO and IOD conditions into late 2025, uncertainties persist due to non-linear interactions and climate change.

ENSO and IOD significantly shape water resources in the LVB, with El Niño/nIOD driving droughts and La Niña/pIOD causing wetter conditions. Key events (1997–98, 2010–11, 2019) highlight their profound impacts on lake levels, river flows, and socioeconomic systems. Climate change has intensified these effects, increasing the frequency of extreme events.

This study further recommends that improved Forecasting is necessary and enhance regional climate models to better predict ENSO–IOD interactions, focusing on LVB-specific impacts.

Water Management; Develop adaptive water management strategies, such as improved reservoir operations and flood control, to mitigate extremes.

Community Resilience; Strengthen early warning systems and support agricultural adaptation to cope with rainfall variability. More research to expand monitoring of LVB hydrological responses to ENSO/IOD and integrate with climate change projections is required.

CHAPTER SEVEN: REFERENCE

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APPENDIX

Appendix 1. Certificate of Enrolment

UNISELINUS EUROPE

Accredited by WORLD CERTIFICATION INSTITUTE
Global Authority on Occupational Certification

Certificate
OF ENROLMENT AT
SELINUS UNIVERSITY

N° UNISE2240IT

DATE 28TH FEBRUARY 2023

STUDENT INFORMATION:
Name: **MOSES DAVID**
Surname: **TUMUSIIME**
Date of birth: **08/10/1976**
City of birth: **KAMPALA**
Country: **UGANDA**

CURRENT ADDRESS:
City: **KAMPALA**
Postal code: **256**
Street: **P.O. BOX 7025**
Country: **UGANDA**
Citizenship: **UGANDAN**

STUDY INFORMATION:
Program: **DOCTOR OF PHILOSOPHY**
Faculty of **LIFE & EARTH SCIENCE**
Major: **METEOROLOGY**
Study program: ☐ Bachelor ☐ Master ☒ PhD (Doctor of Philosophy)
☐ by APEL ☒ by Research
Study method: **by research**

TUITION INFORMATION
Last payment date: **08 AUGUST 2023**
Payment option: **6 INSTALMENTS**
Payment modality: **Bank remittance or PayPal**

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