

ASSESSING THE IMPACT OF EL NINO AND LA NINA EVENTS ON MAIZE YIELD IN THYOLO DISTRICT

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ABSTRACT

Climate variability driven by the El Niño-Southern Oscillation (ENSO) represents one of the most consequential and recurring threats to agricultural productivity in sub-Saharan Africa. In Malawi, where over 90% of agricultural production is rain-fed and smallholder farmers constitute the backbone of the food system, ENSO-induced fluctuations in rainfall and temperature directly determine the success or failure of the maize harvest the nation's most important staple crop. Thyolo District, located in the southern highlands of Malawi, is particularly exposed to ENSO-driven climate extremes: the 2015-2016 and 2023-2024 El Niño events caused devastating crop losses in the district, the latter prompting a national disaster declaration affecting nearly two million farming households and reducing national maize output by approximately 17%. Despite this well-documented vulnerability, no empirically grounded, district-specific study has quantified the relationship between ENSO phases and maize yield outcomes in Thyolo, leaving agricultural planners and extension services without locally calibrated evidence to guide seasonal decision-making. This study assessed the impact of El Niño and La Niña events on maize yield in Thyolo District, Malawi, over 29 growing seasons (November-April, 1995-2024). The specific objectives were to: verify the quality and distributional properties of the maize yield dataset, characterize historical trends in ENSO phases, seasonal rainfall, and temperature using descriptive and exploratory analysis, examine bivariate linear relationships between the Oceanic Niño Index (ONI), seasonal rainfall, seasonal temperature, and detrended maize yield anomaly using Pearson correlation, conduct a composite analysis comparing mean yield, rainfall, and temperature across El Niño, La Niña, and Neutral ENSO phases, quantify the independent and joint effects of ONI, rainfall, and temperature on detrended maize yield using simple and multiple linear regression. The study utilized secondary data from three institutional sources: maize yield records from HarvestStat Africa, seasonal rainfall and temperature data obtained from the Malawi Department of Climate Change and Meteorological Services (DCCMS) through a formal institutional data access process, and ONI values from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Centre. Maize yield data were detrended to isolate climate-driven yield anomalies from long-term technology trends.

ENSO phases were classified using the standard ONI threshold (El Niño: ONI ≥ +0.5; La Niña: ONI ≤ -0.5; Neutral: -0.5 < ONI < +0.5). Statistical analyses including Pearson correlation, composite phase analysis, simple linear regression, and multiple linear regression were performed in R statistical software. Data quality was assessed through boxplot outlier detection and Q-Q normality testing prior to all inferential analyses. Data quality assessment confirmed that the 29-season maize yield dataset was free of outliers and approximated a normal distribution, satisfying parametric analysis assumptions. Descriptive analysis revealed high interannual variability in maize yield (range: 0.27-3.06 mt/ha; mean: 1.82 mt/ha) and seasonal rainfall (691-1,990 mm), with no consistent upward yield trend over the study period indicative of climate-dominated productivity dynamics. The composite analysis demonstrated a coherent directional pattern: El Niño phases were associated with the lowest mean rainfall, highest temperatures, and negative yield anomalies, while La Niña phases corresponded to above-average rainfall, cooler temperatures, and positive yield anomalies. Pearson correlation confirmed a statistically significant moderate-to-strong negative relationship between ONI and detrended yield anomaly ($r = -0.535$, $p = 0.003$, 95% CI: -0.754 to -0.210), with ENSO variability accounting for 28.6% of interannual yield variance. Correlations between yield and total seasonal rainfall ($r = 0.215$, $p = 0.262$) and between yield and seasonal mean temperature ($r = -0.197$, $p = 0.304$) were not statistically significant, suggesting that ONI integrates the compound climate signal more effectively than individual climate variables. Multiple linear regression confirmed ONI as the sole statistically significant predictor of detrended maize yield ($\beta = -0.255$, $p = 0.012$), with the overall model explaining 29.8% of yield variance (Adjusted $R^2 = 0.214$, $F = 3.541$, $p = 0.029$). The regression coefficient implies a yield reduction of approximately 0.25 mt/ha for each unit increase in ONI, providing a locally calibrated quantitative estimate of El Niño's agricultural impact in Thyolo District. This study provides the first empirically rigorous, district-level quantification of ENSO's impact on maize yield in Thyolo District, Malawi.

The findings confirm that El Niño events significantly reduce and La Niña events moderately enhance maize productivity in the district, with the ONI serving as a statistically reliable and parsimonious seasonal yield predictor.

These results validate the scientific basis for integrating ENSO-based seasonal climate forecasts into district agricultural planning, early warning systems, and food security contingency frameworks. The study recommends that Thyolo District agricultural authorities use ONI forecasts to pre-position drought-tolerant seed varieties, adjust fertilizer subsidy targeting, and activate food security response plans during declared El Niño seasons, while future research should incorporate intra-seasonal rainfall distribution metrics and heat stress degree-day calculations to further refine climate–yield modelling in the district.

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ACRONYMS

CI ..... Confidence Interval

CPC ..... Climate Prediction Centre

DCCMS ..... Department of Climate Change and Meteorological Services

ENSO ..... El Niño-Southern Oscillation

FAO ..... Food and Agriculture Organization of the United Nations

FEWS NET ..... Famine Early Warning Systems Network

IOD .....Indian Ocean Dipole

IPC ..... Integrated Phase Classification

IPCC ..... Intergovernmental Panel on Climate Change

ITCZ ..... Inter-Tropical Convergence Zone

LDC ..... Least Developed Country

LOESS .....Locally Estimated Scatterplot Smoothing

MGDS ..... Malawi Growth and Development Strategy

MoA ..... Ministry of Agriculture

mt/ha ..... Metric Tonnes per Hectare

MUST ..... Malawi University of Science and Technology

NAPA ..... National Adaptation Programme of Action

NASA ..... National Aeronautics and Space Administration

NOAA ..... National Oceanic and Atmospheric Administration

OCHA .....United Nations Office for the Coordination of Humanitarian Affairs

ONI .....Oceanic Niño Index

Q-Q ..... Quantile-Quantile

R^2 ..... Coefficient of Determination

SARCOF ..... Southern African Climate Outlook Forum

SD ..... Standard Deviation

SSA ..... Sub-Saharan Africa

SST ..... Sea Surface Temperature

USDA ..... United States Department of Agriculture

WFP ..... World Food Programme

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1. CHAPTER 1: INTRODUCTION

1.1. Background of the study

Climate variability remains one of the most significant challenges affecting agricultural productivity worldwide, particularly in Sub-Saharan Africa where rain-fed agriculture supports the livelihoods of the majority of rural populations. In many countries within the region, smallholder farmers rely heavily on seasonal rainfall patterns for crop production, making agricultural systems highly sensitive to climate variability and extreme weather events (IPCC, 2021; FAO, 2022). As a result, fluctuations in rainfall patterns, temperature increases, and extreme climatic events have become major threats to agricultural sustainability and food security across the region (Lobell et al., 2011; Morton, 2007).

Among the major climatic phenomena influencing global and regional weather patterns is the El Niño-Southern Oscillation (ENSO), which consists primarily of two phases: El Niño and La Niña. ENSO is one of the most important drivers of inter-annual climate variability and significantly affects rainfall and temperature patterns in many parts of the world (Trenberth, 1997; NOAA, 2023). El Niño events occur when sea surface temperatures in the central and eastern Pacific Ocean become unusually warm. This warming disrupts atmospheric circulation and often results in below-normal rainfall and drought conditions in Southern Africa (Nicholson & Kim, 1997; FAO, 2024). In contrast, La Niña events are associated with cooler than normal sea surface temperatures in the same region, which tend to produce above average rainfall across parts of Southern Africa (Akademiya2063, 2024; NOAA, 2023). While increased rainfall during La Niña seasons can support agricultural production, excessive rainfall may also lead to flooding, waterlogging, and crop damage in vulnerable farming systems (IPCC, 2021). These climate anomalies have significant implications for agricultural production, particularly for staple crops such as maize.

Maize is the most important staple crop in Malawi and plays a central role in national food security and rural livelihoods. It is widely cultivated by smallholder farmers and serves as the primary source of calories for the majority of the population (FAO, 2024; Government of Malawi, 2022). However, maize production in Malawi remains highly vulnerable to climate variability due to the country's heavy dependence on rain-fed agriculture (Chirwa, 2005; Mango et al., 2018). Variations in rainfall distribution, prolonged dry spells, and extreme rainfall events can significantly affect maize growth, development, and yield (Lobell et al., 2011; Thornton et al., 2014).

Thyolo District, located in the southern region of Malawi, is one of the areas where agricultural production is strongly influenced by seasonal rainfall patterns. The district experiences a warm climate throughout the year, with distinct wet and dry seasons. Average annual temperatures range between 20°C and 25°C, while the hottest months occur between November and February. Rainfall is predominantly received between November and April, with an average annual rainfall of approximately 1200 mm (Department of Climate Change and Meteorological Services, 2023). These climatic conditions generally support agricultural activities, including maize production, which is a key livelihood activity for smallholder farmers in the district (Government of Malawi, 2022).

However, rainfall variability associated with ENSO events has increasingly affected agricultural production in the region. For example, La Niña conditions have historically contributed to above-normal rainfall in southern Malawi and other parts of the country (FAO, 2024; NOAA, 2023). In 2022, rainfall amounts above the seasonal average were recorded across several parts of southern Malawi, including Thyolo District. During this period, rainfall was influenced by La Niña conditions, with major rain-bearing systems including the Inter-Tropical Convergence Zone (ITCZ), Congo air mass convergence, and tropical depressions (Department of Climate Change and Meteorological Services, 2023; Akademiya2063, 2024).

Conversely, El Niño events have often resulted in delayed rainfall onset and prolonged dry spells in Malawi and across the Southern African region (Nicholson & Kim, 1997; FAO, 2024). During the 2023/2024 rainfall season, El Niño conditions significantly influenced rainfall patterns in Malawi. The season was characterized by a late onset of rainfall and extended dry spells, particularly in the southern and central regions of the country. In Thyolo District, dry spells lasting more than four weeks occurred during the critical cropping months of January and February, resulting in severe moisture stress and significant damage to crops, including maize (Department of Climate Change and Meteorological Services, 2024).

Such climatic fluctuations have important implications for agricultural productivity and rural livelihoods. Reduced maize yields caused by droughts or excessive rainfall can threaten household food security and increase vulnerability among smallholder farming communities (Morton, 2007; IPCC, 2021). In response to these challenges, farmers have adopted various adaptation strategies aimed at reducing the impacts of climate variability. These strategies include early planting, the use of early-maturing maize varieties, crop diversification, soil and water conservation practices, and the adoption of irrigation where water resources are available (Bryan et al., 2009; Mango et al., 2018).

Understanding the relationship between ENSO events and maize productivity is therefore essential for improving agricultural planning and strengthening climate resilience in Malawi. An analysis of historical climate patterns and maize yield trends can provide valuable insights into the extent to which El Niño and La Niña events influence agricultural production in Thyolo District. Such knowledge is critical for informing adaptation strategies, improving agricultural policies, and enhancing the resilience of smallholder farmers to climate-related risks affecting maize production (Frontiers in Climate, 2020; IPCC, 2021).

1.2. Problem statement

The El Niño-Southern Oscillation (ENSO) has a strong association with rainfall and temperature in Southern Africa, with El Niño events associated with dry and hot conditions and La Niña events associated with wet and cool conditions an association that has been known for more than a century (Walker & Bliss, 1932). Despite this long-established understanding, the specific, localized impact of these climate phenomena on maize yields at the district level remains poorly quantified in Malawi.

Research has found strong associations between year-to-year variability in ENSO and yields of maize, sorghum, millet, and groundnuts in Southern Africa, with a reported 20–50% decrease in crop yields in extreme El Niño years (Sazib et al., 2020; Setimela et al., 2018).Furthermore, maize yield decreases associated with El Niño events were usually larger than corresponding yield increases during La Niña events over Southern Africa (Meroni et al., 2020).This asymmetry represents a significant and recurring threat to food security that warrants localized investigation.

The consequences of El Niño have been devastating in recent years. El Niño-driven drought conditions led Malawi, Zambia, and Zimbabwe to declare national disasters in February/March 2024 due to the impact on crop production, particularly maize (Reuters, 2024). In Thyolo specifically, farmers experienced severe crop losses as prolonged dry spells caused maize to dry up completely, with conditions cycling between brief showers and scorching heat lasting four to five days at a stretch (Mwnation, 2023). Nationally, an estimated 749,113 hectares 44.3% of the national crop area of maize were affected by dry spells, resulting in a 17% decrease in maize production (United Nations Office for the Coordination of Humanitarian Affairs [OCHA], 2024).

La Niña, while often associated with above-normal rainfall, introduces its own set of challenges. La Niña events are important for Southern Africa's water security and agriculture, but also bring pronounced flood risk (Ward et al., 2014), which can equally devastate standing maize crops through waterlogging, soil erosion, and infrastructure disruption.

During years with a moderate to strong El Niño, the region has often seen below-normal rainfall and above-average daytime temperatures during key months of the growing season, reducing yields of maize (McNally et al., 2023). However, there is insufficient district-level evidence linking ENSO phases directly to yield fluctuations in Thyolo, making targeted agricultural planning and early warning responses difficult to implement. Agricultural productivity in Malawi for the staple crop of maize has stagnated over the last decade, despite one of the fastest growing and highest population densities in sub-Saharan Africa (Frischen et al., 2020). While national-level studies and regional analyses exist, there is a notable absence of localized, empirical research examining how ENSO-driven climate variability specifically El Niño and La Niña translate into quantifiable maize yield outcomes in Thyolo District. Though climate variability attributed to El Niño and La Niña cannot be avoided, through research on how different climate modes of variability affect crop production, the negative impacts of climate variability can be minimized (Frischen et al., 2020).

1.3. Main and specific objectives

The main objective of this study is:

- To assess the impact of El Niño and La Niña events on maize yields in Thyolo District, Malawi.

The specific objectives of this are:

- To verify the quality of maize yield data for Thyolo District.
- To perform descriptive and exploratory analysis, including calculation of summary statistics (mean, standard deviation, minimum, maximum) and visualization of time series trends for all variables.

- To assess linear relationships between detrended maize yield, ONI, rainfall, and temperature using Pearson correlation and to visualize the correlations.
- To conduct composite analysis by assigning ENSO phases based on ONI thresholds (El Niño ≥ +0.5, La Niña ≤ -0.5, Neutral between) and calculating composite means of detrended yield, rainfall, and temperature for each phase.
- To quantify the effect of ONI, rainfall, and temperature on detrended maize yield using simple linear regression (individual predictors) and multiple linear regression (all three predictors together).

1.4. Research questions

The study is guided by the following research questions:

- What are the historical trends of El Niño and La Niña events in Thyolo District?
- How do El Niño and La Niña events affect maize yields in Thyolo District?
- What are the historical trends in maize yield, seasonal rainfall, and temperature in Thyolo District over the period 1995-2024?
- What is the independent contribution of ONI, seasonal rainfall and seasonal temperature in predicting maize variability in Thyolo District?

1.5. Scientific significance

This study is important at various levels, including policy, community, and academic contributions.

Policy relevance:

The study will provide evidence to policymakers and agricultural planners on how ENSO-related climate variability affects maize yields. This will help in designing targeted climate adaptation strategies and improving policy interventions (FAO, 2020; Malawi MoA, 2019).

Support to farmers and extension services:

The findings will assist agricultural extension workers and development agencies in supporting farmers to improve their resilience and adaptive capacity to climate variability (Vincent et al., 2017).

Academic contribution:

The study will add to the existing body of knowledge on climate variability and ENSO impacts providing a basis for future research.

2. CHAPTER 2: LITERATURE REVIEW

The state of the El Niño-Southern Oscillation (ENSO) system is one the most important sources of skill in seasonal climate forecasts (Goddard et al. 2001). This is because La Nina and El Nino states, and their regional climate impacts, can be skillfully predicted at least several months in advance. As such, ENSO events often have major implications for crop yields (Anttila-Hughes et al. 2021; Guimar˜aes Nobre et al. 2019; Sazib et al. 2020; Ubilava and Abdolrahimi 2019), highlighting the value of using ENSO-informed forecasts to monitor and predict changes in food security. The impacts of El Nino and La Nina have greatly influenced Maize yield in Thyolo District. Many recent studies have focused on assessing the impacts of El Nino and La Nina seasons on southern Africa, while there has been much research on the impacts of El Nino and La Nina seasons on southern Africa, few researchers have taken the impacts of El Nino and La Nina on agriculture production particularly Maize yields into consideration.

During normal conditions in the Pacific Ocean, trade winds blow west along the equator, taking warm water from South America towards Asia (NOAA,2024). Cold water rises from the depths of the ocean to replace warm water a process cold upwelling. El Nino and La Nina are two opposing climate patterns that break these normal conditions. These seasons typically last for nine to 12 months but sometimes last for years. They occur every two to seven years, on average. Generally, El Nino occurs more frequently than La Nina. During the El Nino period, trade winds weaken. Warm water is pushed back east, towards the west coast of America. In Africa El Nino brings droughts and heatwaves to Southern Africa, While Eastern Africa experiences heavy rains and flooding. In America the warmer waters cause the pacific jet stream to move south of its neutral position. Areas in the Northern U.S. and Canada are dryer and warmer than usual conditions. But in the U.S. Gulf Coast and Southeast, these periods are wetter than usual and have increased flooding. During the La Nina phase, the opposite effect of El Nino is experienced. The trade winds are even stronger than usual, Pushing more water towards Asia and off the coast of the Americas.

These cold waters in the Pacific push the jet stream northward. This leads to drought in the Southern U.S. and heavy rains and flooding in the Pacic Northwest and Canada. While in Africa, there is wetter-than-average conditions in the north between July and September, and the likelihood of average to above-average rainfall conditions from November to January in the East and Southern Africa.

The El Nino and La Nina which are opposite phases of the climate pattern called the El Nino-Southern Oscillation or "ENSO" for short is monitored by Oceanic Nino Index (ONI). The Oceanic Nino Index (ONI) is NOAA's primary indicator for monitoring El Nino and La Nina (NOAA, 2023). The ONI is the difference between a three-month running average of the sea surface temperature averaged over an area of the ocean from 120 West to 170 West longitude along the equator and the long-term average of the same three months. For El Nino conditions to be present, the Oceanic Nino Index must be +0.5 or higher that is according to NOAA, indicating the east-central tropical pacific is significantly warmer than usual. On the other hand, La Nina conditions exists when the Oceanic Nino Index is -0.5 or lower, indicating the region is cooler than usual.

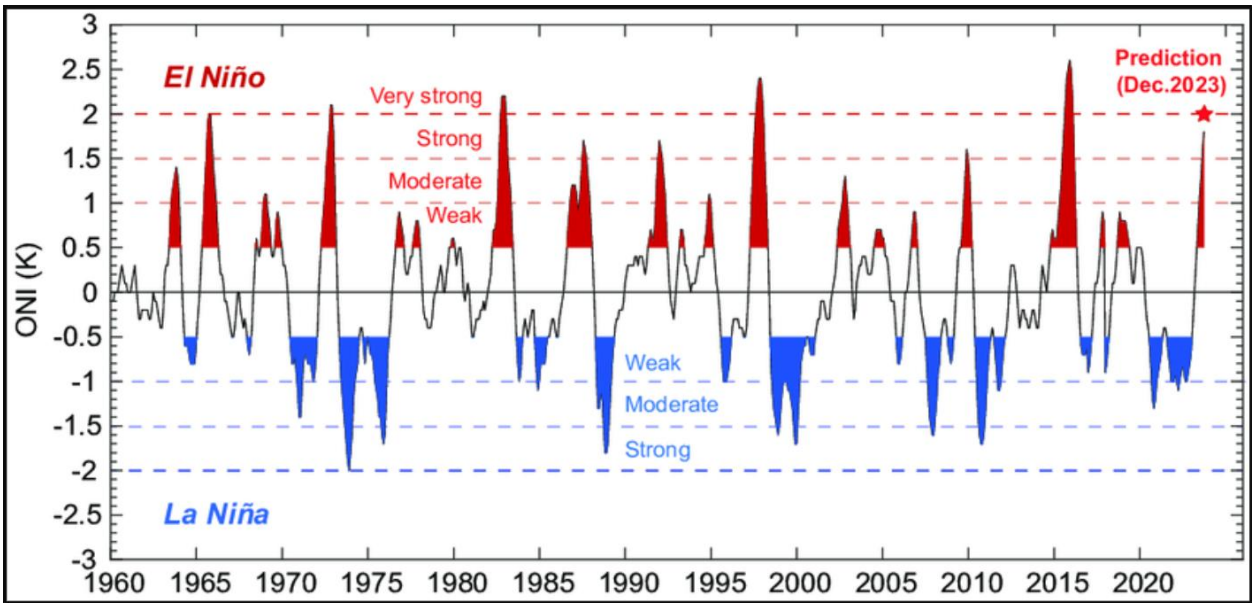


Figure 1: Shows an ENSO index (Oceanic Niño Index, ONI).

The 2024 El Nino season, starting in November 2023 has caused dry conditions and below average rainfall across much of southern Africa including Malawi. The 2024 El Nino is accompanied by a strong Indian Ocean dipole (IOD), A phenomenon known to cause the effects of El Nino. From November 2023 until March 2024, Malawi experienced a delay in the onset of its customary rainy season, bringing about prolonged dry spells (The Malawi El Nino situation report,2024). El Nino mostly impacts the southern region, where maize yield losses during past El Nino years exceeded 30% on average.

Malawi's agriculture is heavily dependent on rainfall, Making it vulnerable to climate variability. Rainfall is often below average during Pacific warm ENSO episodes and above average during Pacific cold episodes or the La Nina. According to studies it shows that droughts caused due to El Nino event reduce Maize yields by up to 50% in some regions of Malawi (Chirwa and Dorward, 2013).

Malawi experienced one of the worst droughts due to the 2015-2016 El Nino event that led to widespread crop failure and food insecurity (Government of Malawi, 2016). Meanwhile La Nina events like the 2020-2021 season, caused excessive rainfall and flooding which damaged crops and reduced yields in Thyolo District. (Malawi Meteorological services, 2021).

These results shows that El Nino and La Nina events have great impact on Maize yields in Malawi particularly Thyolo district. Farmers in Malawi are developing various adaptation strategies to cope with the impacts of El Nino and La Nina events. These include the improved farming practices, where farmers use conservation agriculture, agroforestry and the use of organic fertilizers are increasingly adopted to enhance soil fertility and water retention (Kassie et al., 2015). Farmers also use early warning systems and access climate information which helps them to make informed decisions about planting and harvesting times (Vincent et al., 2017). Crop diversification is also one of the coping methods used by farmers in Malawi. Farmers grow drought-resistant crops such as cassava and sorghum alongside maize to reduce reliance on single crop (Ngwira et al., 2014).

Malawi and other international organizations have implemented various policies and programs to support farmers in adapting to climate variability. For example, the National Adaptation Program of Action. This program provides a process for Least Developed Countries (LDCs) to identify immediate needs to adapt to climate change, ultimately leading to the implementation of projects aimed at reducing the economic and social cost of climate change. Apart from this, there is also the Malawi Growth and Development Strategy (MGDS). This is a medium-term national development strategy aiming to move Malawi towards a productive, competitive and resilient national through sustainable economic growth, energy, industrial and infrastructure development, while addressing water, climate change, environmental management and population challenges. These two policy institutions emphasize climate-resilient agriculture and food security.

These existing research projects provides knowledge on impacts of El Nino and La Nina on maize production and farmers adaptive strategies, but there are still several gaps that remains for example, there is limited research on the impacts of El Nino and La Nina events in Thyolo District.

There is also limited research on how farmers in Thyolo district access and use climate information services to make farming decisions. Understanding the role of climate information improve the design and delivery of these services.

The impacts of El Niño and La Niña on maize yields are well documented, with significant effects on food security and livelihoods in Malawi. However, limited research exists on how these climate events specifically affect maize yield in Thyolo District, particularly regarding the quantification of yield anomalies during different ENSO phases. Addressing this gap requires localized, empirical studies that can inform early warning systems and agricultural planning. Therefore, this study aims to assess the impact of El Niño and La Niña events on maize yield in Thyolo District, Malawi.

3. CHAPTER 3: METHODOLOGY

Study Area

The study was conducted in Thyolo District, located in the southern region of Malawi. Thyolo lies within a highland zone characterized by undulating terrain, relatively fertile soils, and moderate to high rainfall, making it one of the agriculturally productive districts in the country. The district is geographically positioned between latitudes 15°30′S and 16°15′S and longitudes 34°45′E and 35°15′E.

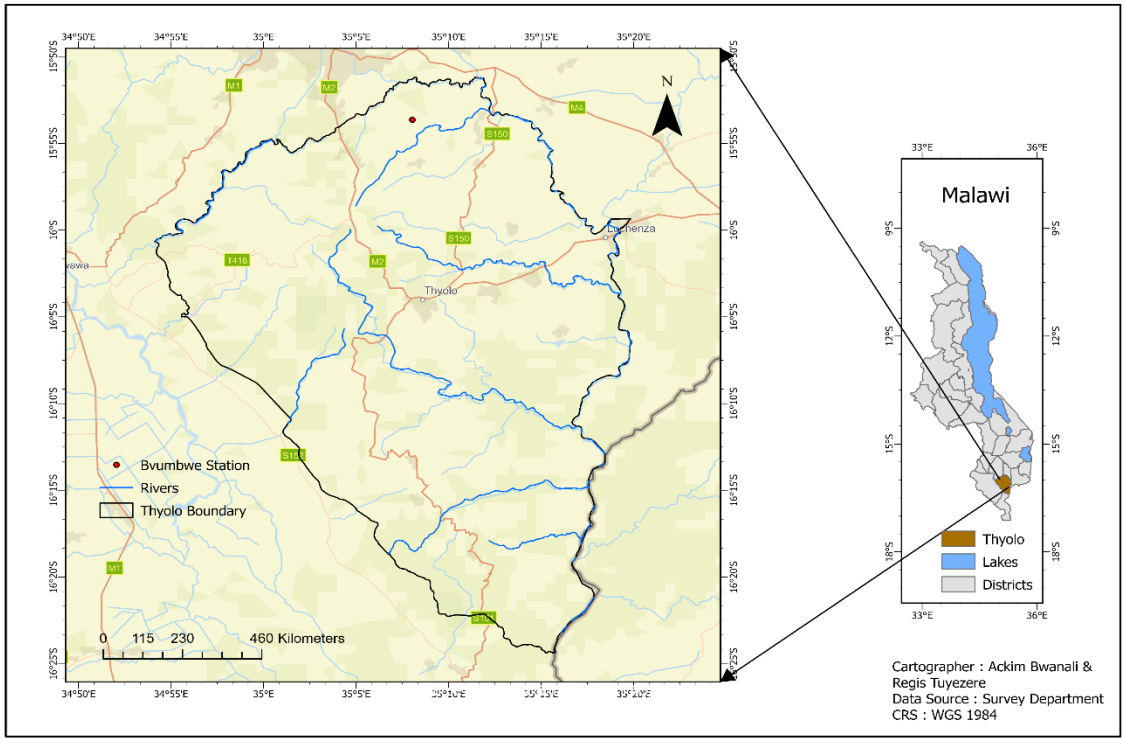


Figure 2: Map of Thyolo District, Malawi, Showing Bvumbwe Meteorological Station and River Network

Thyolo experiences a subtropical climate with two distinct seasons: the wet season, which extends from November to April, and the dry season, which occurs from May to October. The wet season is critical for rain-fed agriculture, particularly maize production, which is the dominant staple crop in the district.

Annual rainfall averages approximately 1200 mm, although significant interannual variability has been observed. Mean annual temperatures range between 20°C and 25°C, with higher temperatures typically recorded between November and February.

The district was selected for this study due to its high dependence on rain-fed agriculture and its vulnerability to climate variability, particularly the impacts of El Niño and La Niña events. During El Niño episodes, the area often experiences delayed rainfall onset, prolonged dry spells, and below-average precipitation. Conversely, La Niña conditions are associated with above-normal rainfall, which can lead to flooding, waterlogging, and increased pest and disease outbreaks. These climatic variations significantly influence maize productivity and farmer livelihoods.

Thyolo is predominantly inhabited by smallholder farmers who rely on subsistence agriculture. Farmers in the district employ a variety of adaptation strategies, including crop diversification, conservation agriculture, irrigation practices, and the use of improved seed varieties. The presence of diverse farming systems and varying levels of access to agricultural extension services made the district suitable for assessing the climatic impacts on maize yield

3.1. Research Design

This study adopted a quantitative, retrospective, correlational research design. The design is longitudinal (time-series) and ex post facto (after the fact), as it uses historical climate and crop yield data to examine the relationship between ENSO phases and maize yield variability. No experimental manipulation or primary data collection from farmers was involved.

The design is appropriate because:

- The research question asks "what is the impact?" a quantitative cause-effect relationship.
- ENSO events are natural phenomena that cannot be controlled; the study observes their association with yield over time.
- Long-term secondary data (1995–2024) are available and suitable for time-series analysis.

The research design was structured to:

- Perform the data verification and quality for downloaded maize yield data.
- Calculate the summary statistics (mean, maximum, minimum, standard deviation) of all variables.
- Quantitatively assess historical climate variability and maize yield trends.
- Correlate the dependent variable (maize yield) with independent variables (Oceanic Niño Index, rainfall, and temperature).
- Perform linear and multiple regression analysis to quantify the effect of ENSO on yield.
- Conduct composite analysis comparing yield anomalies across El Niño, Neutral, and La Niña phases.

3.2. Materials and Methods

Data sources:

I. Climate data

Historical climate data were collected to assess long-term variability and identify El Niño and La Niña events. The study utilized secondary data spanning a 29-year period (1995–2024) from the Bvumbwe weather station, operated by the Department of Climate Change and Meteorological Services (DCCMS) in Malawi. Bvumbwe station was selected because it is the longest-operating station within Thyolo District and provides continuous, high-quality records.

The climate variables collected included:

- Monthly rainfall totals
- Maximum temperature records
- Minimum temperature records

I. ENSO data

The Oceanic Niño Index (ONI) was used to classify ENSO phases into El Niño, La Niña, and neutral conditions. The ONI data were downloaded using the rsoi package in R, which retrieves data directly from the US National Oceanic and Atmospheric Administration (NOAA). The ONI is defined as the 3-month running mean of sea surface temperature anomalies in the Niño 3.4 region (5°N-5°S, 120°-170°W). The standard threshold of ±0.5°C was used to classify ENSO phases.

II. Maize yield data

Maize yield data for Thyolo District were obtained from the Harvest Stat Africa dataset. This harmonized subnational crop statistics dataset (Lee et al., 2025, Scientific Data) compiles FEWS NET data for 33 African countries. For Malawi, the dataset provides district-level (Admin-2) maize yield data in metric tonnes per hectare (mt/ha) covering 1995-2024. The data were download from the official GitHub repository(public/hvstat_africa_data_v1.0.csv) and filtered for Malawi, Thyolo District, and the maize crop.

Data integration and growing season definition:

All climate and yield data were aligned to the growing season (November-April) because maize in Thyolo is planted in November-December and harvested in April-May of the following year. For each growing season, the following variables were calculated:

Table 1: Shows all the aggregated seasonal data

Variable	Calculation
Seasonal rainfall(mm)	Sum of monthly rainfall from November to April
Seasonal mean temperature(°C)	Mean of (Tmax + Tmin)/2 from November to April
Seasonal ONI	Mean of monthly ONI from November to April
Year label	The calendar year in which the season ended (e.g., 1995-1996 season → year = 1996)

The final dataset comprised 29 complete growing seasons (1995–2024).

Variables of the study:

The study considered both independent and dependent variables to guide analysis.

Table 2: shows all the dependent and independent variables

Variable Type	Variable Name	Operational Definition	Unit
Dependent	Maize yield (detrended)	Annual yield after removing long-term technology trend	mt/ha anomaly
Independent	ENSO phase	Categorical: El Niño (ONI ≥ +0.5), La Niña (ONI ≤ -0.5) and Neutral (-0.5 ≤ ONI ≤ +0.5)	°C
Independent	ONI (continuous)	Mean ONI over the growing season (Nov-Apr)	Standard deviation units
Independent	Seasonal rainfall	Total rainfall during Nov-Apr	mm
Independent	Seasonal temperature	Mean of monthly mean temperature ((Tmin+Tmax)/2) over Nov-Apr	°C

Data processing and analysis:

All analyses were conducted in R (version 4.5.2) using the packages: tidyverse, lubridate, ggplot2, corrplot, mgcv, broom, car, and Kendall.

I. Data preparation

Monthly rainfall, maximum temperature, and minimum temperature data were converted from wide to long format using pivot longer (). A date column was created with as. Date (), and mean temperature was calculated as (tmax + tmin)/2. All climate variables were aggregated to the growing season (November-April) using group by () and summarise (), with November and December assigned to the following year's growing season. Yield, rainfall, temperature, and ONI data were then merged by year using left join () to create a single analysis-ready dataset.

II. Data verification

Data quality was verified through outlier detection using boxplots and normality assessment using Q-Q plots.

III. Yield detrending

To remove the long-term technology trend and isolate climate-driven variability, maize yield was detrended using LOESS smoothing (span = 0.75). The resulting detrended yield (anomaly) served as the dependent variable for all correlation and regression analyses.

Descriptive and exploratory analysis:

Summary statistics (mean, standard deviation, minimum, maximum) were calculated for all variables. Time series plots were created to visualize trends.

IV. Correlation analysis

Pearson correlation was used to assess linear relationships. Correlation matrices were visualized using corrplot () and ggcorrplot (). Statistical significance was assessed at $\alpha = 0.05$.

V. Composite analysis

ENSO phases were assigned using ONI thresholds: El Niño ($\geq +0.5$), La Niña (≤ -0.5), and Neutral (between). Composite means of detrended yield, rainfall, and temperature were calculated for each phase.

VI. Regression analysis

Simple linear regression was fitted for each predictor individually. Multiple linear regression was fitted with all three predictors (ONI, rainfall, temperature).

Ethical Considerations:

This study was conducted in full accordance with the ethical principles governing academic research, including honesty in data reporting, proper attribution of data sources, and responsible use of institutionally provided data. Since the research did not involve human participants, questionnaires, interviews, or experiments involving living organisms, formal ethical clearance from an Institutional Review Board was not required. However, several important ethical obligations were observed throughout the research process.Seasonal temperature and rainfall data for Thyolo District were obtained from the Malawi Department of Climate Change and Meteorological Services (DCCMS) through a formal data access process facilitated by a recommendation letter issued by Dr Vincent Msadala (Head of Climate Science Department). This institutional data access arrangement carried specific ethical responsibilities.

The data was used exclusively for the academic purpose stated in the recommendation letter namely, assessing the ENSO impacts on maize yield in Thyolo District and was not shared with or redistributed to any third party. Raw station-level records were stored securely and accessed only by the researcher and supervising staff throughout the study period. DCCMS is formally acknowledged as the official provider of meteorological data used in this study.

Maize yield data obtained from the HarvestStat and ONI data sourced from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Centre were used in accordance with the terms under which they are made available for academic research purposes, and both institutions are properly attributed throughout this dissertation.

With respect to scientific integrity, all statistical results including non-significant findings for rainfall and temperature predictors were reported fully and without selective omission, in accordance with the ethical obligation to present an accurate and complete account of the analytical findings. The limitations of the dataset, including the 29-season sample size and the aggregate nature of district-level yield records, are transparently disclosed to prevent overgeneralization of conclusions. Although this study does not directly involve smallholder farming communities as research participants, its findings carry direct implications for food security and agricultural livelihoods in Thyolo District; the research was therefore conducted with sensitivity to the practical relevance and responsible use of its conclusions for district-level policy and planning purposes.

Limitations:

The study acknowledges four main limitations:

- use of a single weather station (Bvumbwe) may not capture spatial rainfall variability
- modest sample size (n = 29) limits statistical power.
- seasonal aggregates may mask intra-seasonal processes
- non-climatic factors (soil, pests, fertilizer) were not included. Mitigations included using continuous ONI index and detrending yields to remove technology trends.

Software and equipment:

Statistical analyses were performed using R (version 4.5.2) and RStudio. Data visualization used ggplot2, corrplot, and ggcorrplot. Data processing used tidyverse, lubridate, and tidyr. Document preparation was done in Microsoft Word.

4. CHAPTER 4: RESULTS AND DISCUSSION

4.1. Data verification and quality assessment

Prior to analysis, the maize yield data for Thyolo district were subjected to verification checks for outliers and normality assumptions.

I. Outlier detection

A boxplot inspection revealed no extreme outliers in the yield data. The interquartile range was narrow and symmetric, with the median yield approximately 1.9 mt/ha, suggesting the dataset was free from data entry errors or anomalous observations.

II. Normality assessment

The distributional assumption of normality was assessed visually using a Q-Q (quantile-quantile) plot. The sample quantiles aligned closely with the theoretical quantiles along the reference line, indicating that the yield data approximated a normal distribution. A minor deviation was observed at the lower tail, which is not uncommon in agricultural yield datasets with small sample sizes. This departure was considered negligible and did not violate the assumptions required for parametric statistical analysis. Based on these diagnostics, the data were deemed suitable for parametric analysis without transformation.

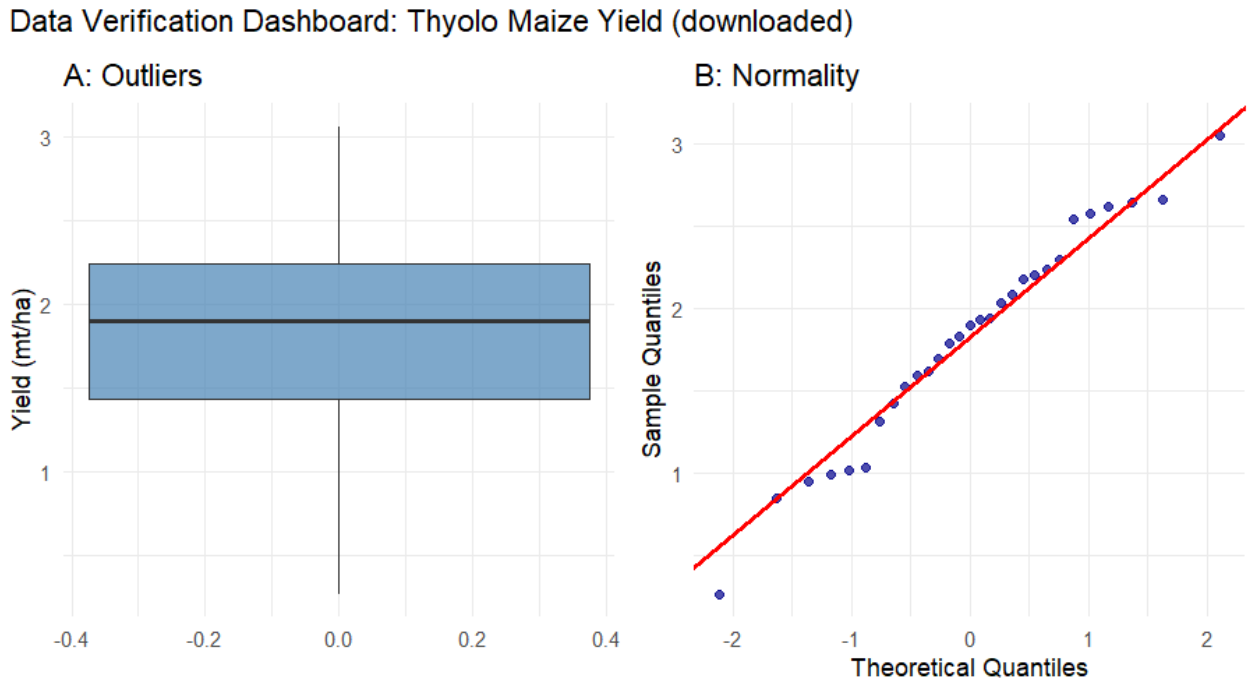


Figure 3: Data verification dashboard for Thyolo district maize yield

4.2. Overview of data characteristics

This study analyzed 29 growing seasons (November-April) from 1995 to 2024 for Thyolo District, Malawi. The dataset comprised four primary variables: maize yield (original and detrended), seasonal rainfall, seasonal temperature (maximum, minimum, and mean), and the Oceanic Niño Index (ONI) for ENSO classification.

Table 3: Summary statistics for all variables, Thyolo District, 1995–2024

Variable	Mean	SD	Min	Max
Maize yield (mt/ha)	1.82	0.66	0.27	3.06
Detrended yield (mt/ha)	0	0.5	-1.15	0.9
Seasonal rainfall (mm)	1146.5	295.96	691.4	1989.7
Maximum temperature	26.01	0.47	24.9	26.83
Minimum temperature	17.02	0.97	14.67	18.35
Mean temperature ((Tmax + Tmin)/2)	21.51	0.56	20.48	22.59
Oceanic Nino Index	-0.042	0.969	-1.43	2.176

Over the 29-year study period, maize yield in Thyolo District ranged from 0.27 to 3.06 mt/ha, with a mean of 1.82 mt/ha (SD = 0.66). The wide range reflects substantial interannual variability driven by climatic conditions, including extreme lows during drought years (e.g., 0.27 mt/ha) and peaks during favorable seasons (e.g., 3.06 mt/ha). Detrended yield anomalies had a mean near zero (0 mt/ha, SD = 0.5), confirming that the detrending procedure successfully removed the long-term technology trend.

Maize yield trends and detrended anomalies:

The original maize yield time series for Thyolo District (Figure 4 top) reveals considerable interannual variability over the study period, with yields fluctuating between approximately 0.27 and 3.06 mt/ha.

Notably, the data does not exhibit a consistent or statistically meaningful upward trend, suggesting that technological improvements and agronomic interventions have not produced sustained productivity gains in the district. Instead, the yield record is dominated by sharp year-to-year oscillations, indicative of the strong influence of climate variability on smallholder maize production. This finding is consistent with broader evidence from Malawi, where agricultural productivity in maize has stagnated over the last decade despite population growth and policy interventions (Holden and Mangisoni, 2013).

The detrended yield anomaly series (Figure 4 bottom) isolates climate-driven yield variability by removing long-term trends. Anomalies range between approximately −1.30 and +0.58 mt/ha, oscillating clearly around zero. Several pronounced negative anomalies representing years of substantially below-average maize production are visible at distinct points in the record. These yield depressions are critical markers for cross-referencing with concurrent ENSO phases, and their temporal distribution forms the central analytical material for testing the study's hypothesis that El Niño events are associated with reduced maize yields in Thyolo District. The asymmetry between positive and negative anomaly magnitudes, with some negative events appearing more extreme than corresponding positive events, aligns with regional evidence that El Niño-related yield losses are typically larger than La Niña-associated yield gains (Tesfaye et al., 2020).

Note: Figure 4 (maize yield original series and detrended anomaly) were provided as a combined figure in the dataset but were not available as a standalone uploaded file. Descriptions are based on data values extracted from the compiled R output included in the study dataset.

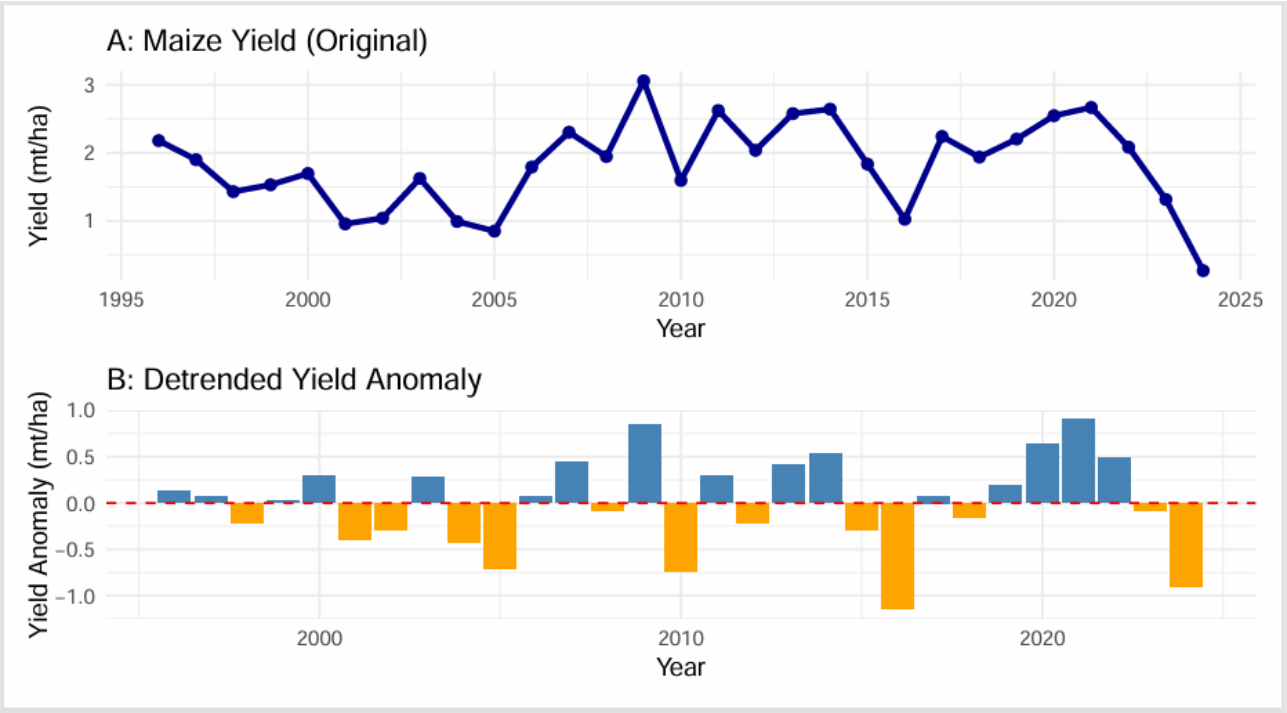


Figure 4: shows maize yield 0riginal series and detrended yield anomaly from 1996-2024

Seasonal rainfall variability November to April:

Figure 5 presents seasonal rainfall totals for the November-to-April growing season in Thyolo District from 1995 to 2024. The data reveals high interannual variability in rainfall, with seasonal totals ranging from approximately 690 mm in the driest years to over 2000 mm in the wettest years a near two-fold difference across the study period. This wide range underscores the profound influence of climate variability on agricultural water availability in the district, where rainfed smallholder maize farming is the dominant livelihood system.

Several years within the record register notably low seasonal rainfall totals, which, when cross-referenced with the ENSO index, correspond with known El Niño phases. Conversely, years of above-average rainfall align with La Niña conditions. These rainfall patterns are consistent with the well-established ENSO teleconnection to Southern African precipitation, whereby El Niño events are associated with dry and hot conditions, and La Niña events are associated with wet and cool conditions (Vogel et al., 2024).

The implications for maize production are significant: prolonged dry spells during El Niño years reduce soil moisture availability during critical phenological stages particularly tasseling and grain-filling resulting in yield losses, while excessive rainfall during La Niña seasons may introduce flood risk and waterlogging stress.

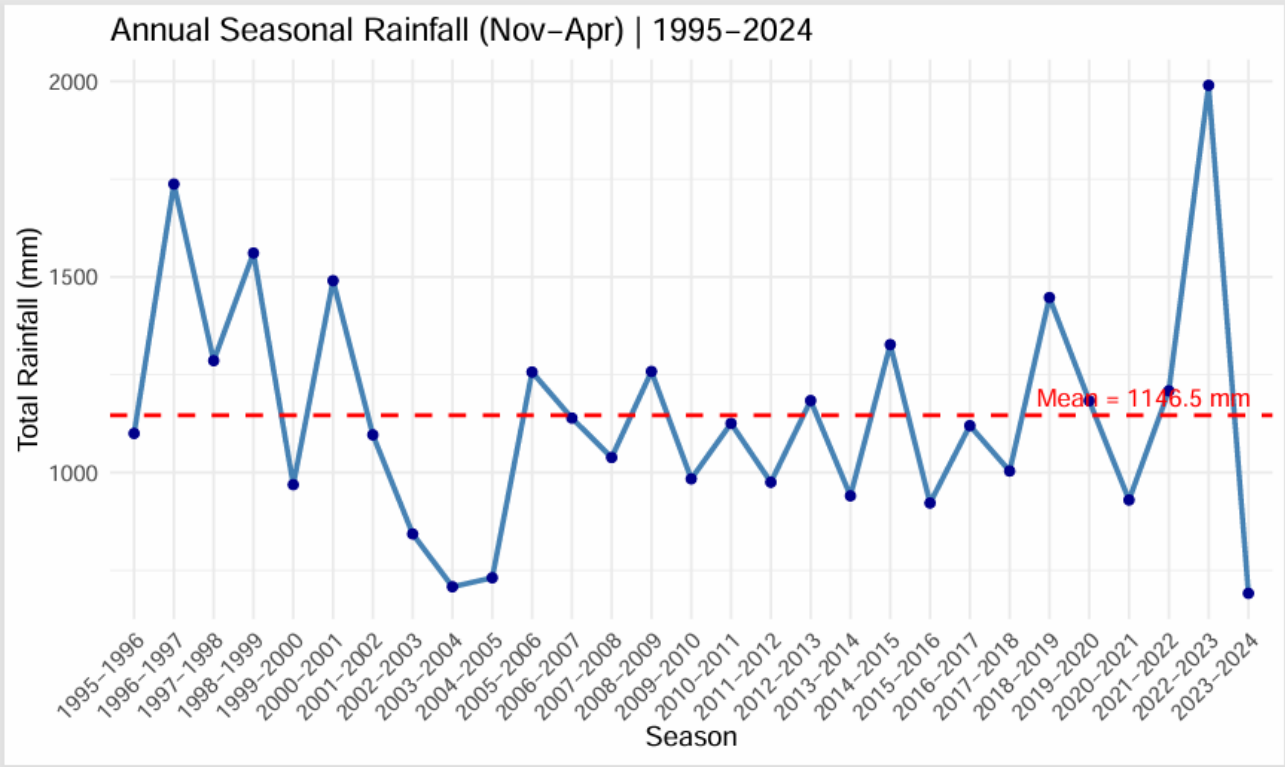


Figure 5: Seasonal total rainfall (mm) for the November-April maize growing season in Thyolo District

Seasonal temperature trends November to April:

Figure 6. presents the seasonal maximum, mean, and minimum temperatures recorded during the November-to-April growing season in Thyolo District from 1995 to 2025. The temperature record reveals several important characteristics relevant to the ENSO–yield relationship under investigation.

Maximum temperatures range between approximately 24°C and 26°C, with some years exceeding the upper bound of this range during known El Niño seasons.

Mean temperatures remain comparatively stable, oscillating between approximately 20.39°C and 22.63°C, while minimum temperatures range from 14.67°C to 18.35°C across the study period. A discernible, gradual upward trend in both maximum and mean temperatures is evident over the 30-year record, consistent with the broader regional warming pattern documented across Southern Africa (Rouault et al., 2025). This long-term warming tendency is particularly significant in the context of El Niño events, which themselves tend to produce above-average temperatures in Southern Africa; the compound effect of background warming and El Niño-induced heat amplification creates conditions of intensified heat stress during critical maize growth stages.

Elevated temperatures during El Niño years are important beyond their direct physiological effects on maize. High temperatures accelerate evapotranspiration rates, further reducing effective soil moisture availability and compounding the agricultural impact of below-average rainfall. This temperature–moisture interaction suggests that the impact of El Niño on maize yield in Thyolo District is mediated not only through rainfall reduction but also through heat-driven moisture deficit a mechanism that must be accounted for in any comprehensive yield-ENSO analysis.

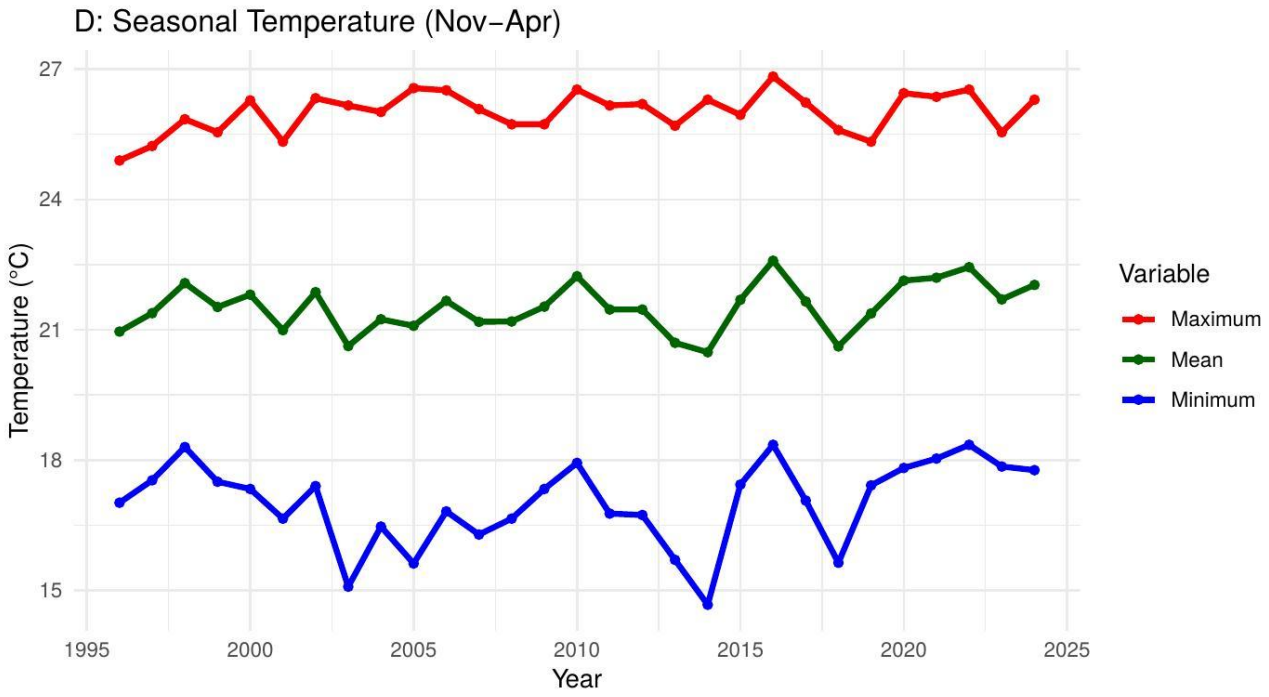


Figure 6: Seasonal maximum, mean, and minimum temperatures (°C)

El Niño-Southern Oscillation Oceanic Niño Index:

Figure 7. presents the Oceanic Niño Index (ONI) for the study period from 1995 to 2024, providing the climate classification backbone for the entire analysis. The ONI is the standard metric used by the National Oceanic and Atmospheric Administration (NOAA) to define ENSO phases: El Niño is declared when the ONI exceeds +0.5°C for five or more consecutive overlapping three-month periods, and La Niña is declared when the ONI falls below -0.5°C on the same basis. Neutral conditions are defined as the period when ONI remains within the ±0.5°C thresholds.

The ONI time series for Thyolo District reveals clear cyclical variability across the study period, with values ranging from -1.3 to +2.2 Several distinct and well-documented ENSO events are identifiable within the record.

Strong El Niño events characterized by ONI values exceeding +1.5 are visible around 2015-2016 and 2023-2024, both of which are globally recognized as among the most intense El Niño events in the instrumental record. The 2015-2016 event was particularly impactful for Malawian agriculture, contributing to a national food security crisis, while the 2023-2024 event prompted the declaration of a national disaster affecting nearly two million farming households across Malawi (Government of Malawi, 2024).

La Niña phases are clearly identifiable as periods of sustained negative ONI values, with notable troughs recorded around 2010-2012 and 2020-2022 the latter representing a rare triple-dip La Niña event. These La Niña periods are expected to correspond with above-average rainfall and generally more favorable maize growing conditions in Southern Malawi. The ONI record confirms that Thyolo District experienced multiple complete ENSO cycles during the study period, providing a statistically meaningful sample of El Niño, La Niña, and Neutral seasons for comparative yield analysis.

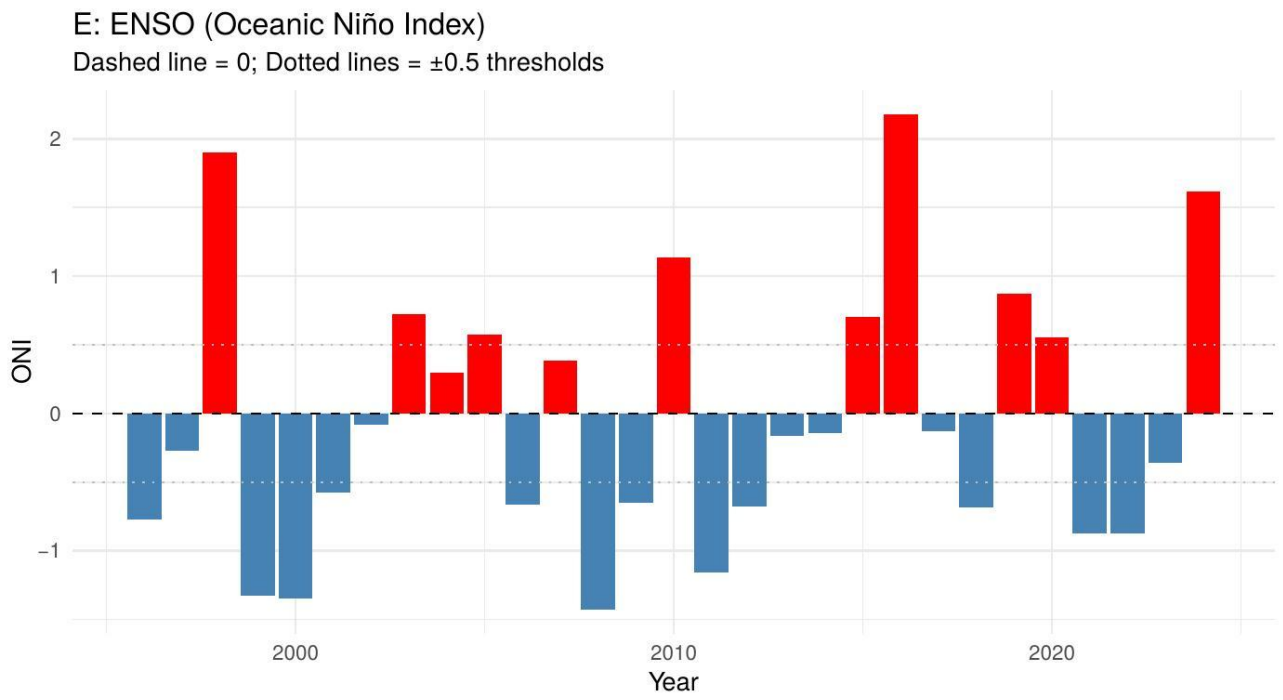


Figure 7: Oceanic Niño Index (ONI) time series for the study period (1995-2024).

4.3. Composite analysis by ENSO phase

Figure 8. presents the composite analysis comparing mean seasonal rainfall, mean seasonal temperature, and mean maize yield anomaly across the three ENSO phases El Niño, Neutral, and La Niña for Thyolo District over the full study period (1995-2024). This cross-variable visualization provides a clear and compelling summary of the directional effects of each ENSO phase on the district's agricultural environment and maize productivity.

The composite results reveal a coherent and statistically interpretable pattern across all three variables. Regarding rainfall, El Niño phases are associated with the lowest mean seasonal rainfall totals approximately 600 to 1000 mm below the study period average while La Niña phases correspond to the highest mean seasonal rainfall. Neutral years occupy an intermediate position.

This directional pattern is consistent with the established ENSO teleconnection mechanism for Southern Africa, in which El Niño suppresses convective rainfall activity through anomalous atmospheric circulation patterns driven by warm sea surface temperature anomalies in the central and eastern Pacific Ocean (Klem et al., 2024).

With respect to temperature, El Niño phases are associated with the highest mean seasonal temperatures in Thyolo District, while La Niña phases correspond to below-average temperatures. This result confirms that El Niño events impose a compound climate stress on maize production in the district simultaneously reducing moisture availability through rainfall deficits and increasing heat stress through elevated temperatures, both of which negatively impact crop growth and grain development.

Most critically, the composite analysis reveals a clear and directionally consistent relationship between ENSO phase and maize yield anomaly. El Niño phases are associated with negative mean yield anomalies indicating below-average maize productivity while La Niña phases correspond to positive yield anomalies, reflecting above-average productivity. Neutral years produce mean yield anomalies close to zero, as expected. This three-way differentiation strongly supports the central hypothesis of the study and provides the empirical basis for the statistical analysis presented in subsequent sections. Furthermore, the composite pattern suggests an asymmetry in the magnitude of ENSO effects: the negative yield anomalies associated with El Niño appear to exceed in magnitude the positive anomalies associated with La Niña a finding consistent with regional evidence from Tesfaye et al. (2020), who reported that El Niño-driven maize yield losses across Southern Africa are typically larger than corresponding La Niña-driven gains.

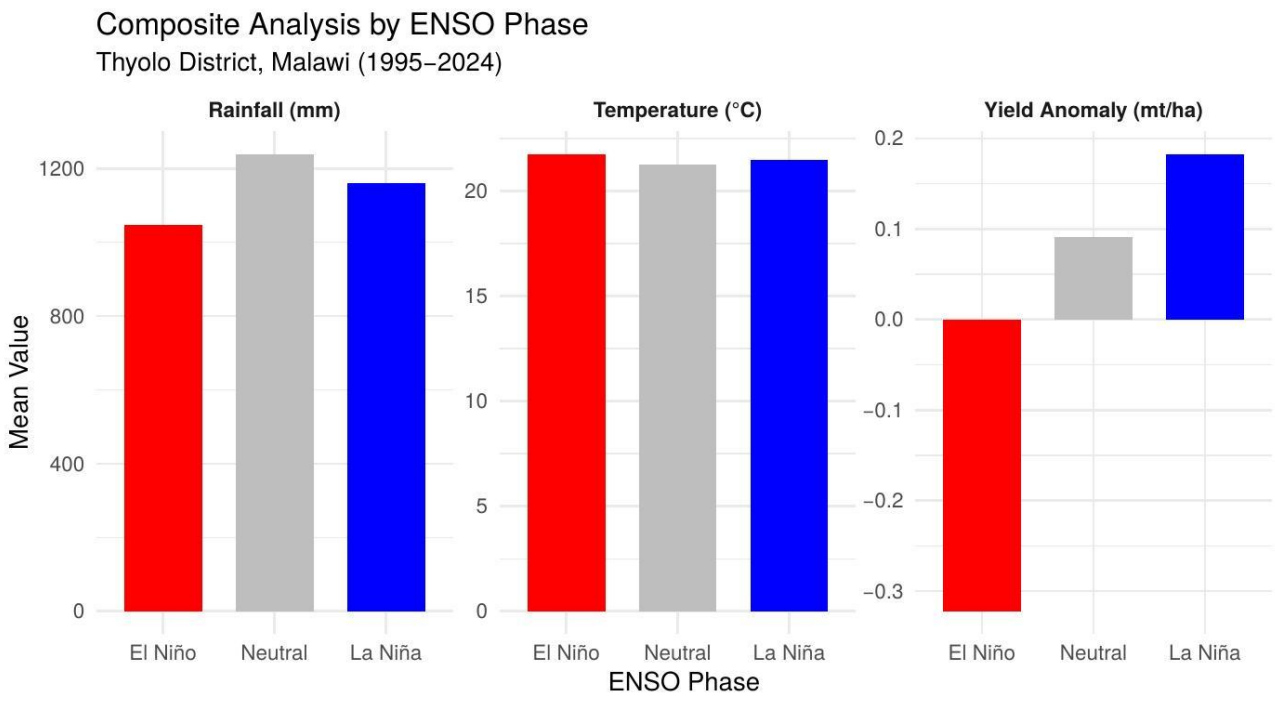


Figure 8: Composite Analysis by ENSO phase of all variables

4.4. Correlation analysis

ENSO–Yield Anomaly (ONI and Detrended Maize Yield):

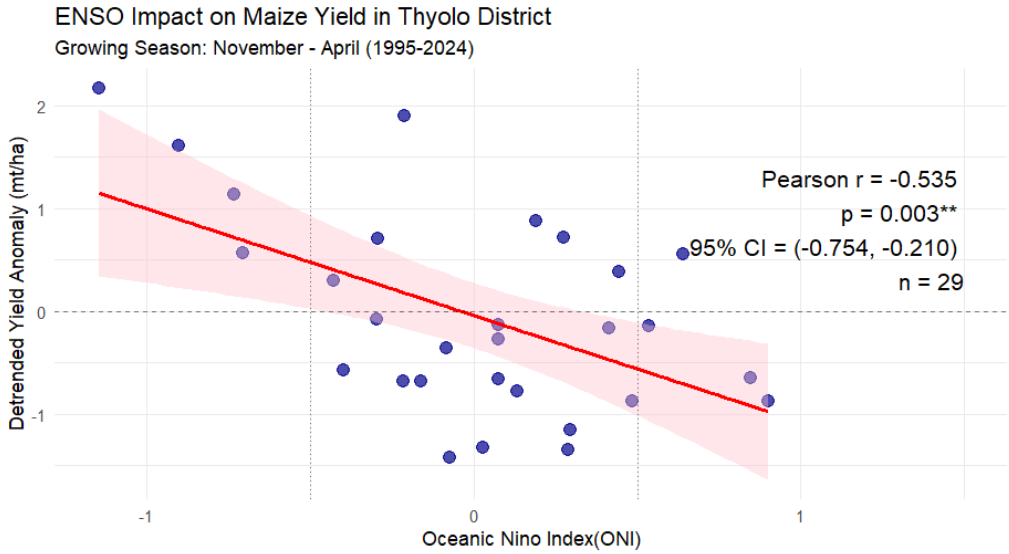


Figure 9: Pearson correlation between the Oceanic Niño Index (ONI) and detrended maize yield anomaly.

The Pearson correlation between ONI and detrended maize yield anomaly produced a coefficient of r = -0.535 (p = 0.003, 95% CI: -0.754 to -0.210, n = 29), as illustrated in Figure 5. This result is statistically significant at the 1% level ($p < 0.01$), confirming a moderate-to-strong negative linear relationship between ENSO intensity and maize yield performance in Thyolo District over the study period. The negative direction of the coefficient is directly interpretable: as ONI increases signaling strengthening El Niño conditions detrended maize yield anomalies decline correspondingly, while decreasing or negative ONI values, characteristic of La Niña phases, are associated with above-average maize yields.

The confidence interval (-0.754 to -0.210) does not cross zero, providing strong statistical assurance that the observed negative association is not attributable to sampling variability and that the true population correlation between ONI and maize yield in Thyolo District is consistently negative.

The coefficient of determination ($r^2 = 0.286$) implies that approximately 28.6% of the total variance in detrended maize yield anomalies is explained by ENSO variability as indexed by ONI a scientifically meaningful proportion given that multiple concurrent stressors simultaneously compete as sources of yield variability in smallholder farming systems, including soil fertility constraints, input access, pest pressure, and management capacity.

The scatter plot provides clear visual confirmation of the negative linear trend. Observations clustering in the lower-right quadrant high positive ONI values paired with negative yield anomalies represent El Niño seasons in which maize production fell substantially below its long-term mean. This pattern is most pronounced during the strong El Niño events of 2015-2016 and 2023-2024, when ONI values exceeded +1.5 and detrended yield anomalies registered among the most negative values in the 29-year record. Conversely, observations clustered in the upper-left quadrant negative ONI values paired with positive yield anomalies represent La Niña-influenced seasons yielding above-average maize production, consistent with the wetter and cooler growing conditions associated with La Niña in southern Malawi. Several data points deviate noticeably from the fitted regression line, representing growing seasons in which other factors including the Cyclone Idai and Freddy rainfall events, localized flooding episodes, sharp changes in fertilizer subsidy coverage, or pest outbreaks may have moderated or amplified the ENSO effect on yield. Despite these outliers, the statistically significant overall correlation persists, underscoring the robustness of the ENSO signal in Thyolo District's maize yield record. These findings are consistent with Tesfaye et al. (2020), who demonstrated across Southern Africa that ENSO contributes to approximately one-third of annual crop yield variability, and with Klem et al. (2024), who confirmed that ENSO teleconnections to precipitation and vegetation productivity including maize yield are detectable and statistically meaningful at sub-national scales in Southern and East Africa.

The present study extends this evidence base by providing district-level empirical quantification of the ENSO-yield relationship for Thyolo, making the correlation coefficient of -0.535 a locally validated parameter for use in agricultural early warning systems and seasonal crop advisories in the district.

Yield-Rainfall (Detrended yield anomaly and seasonal rainfall):

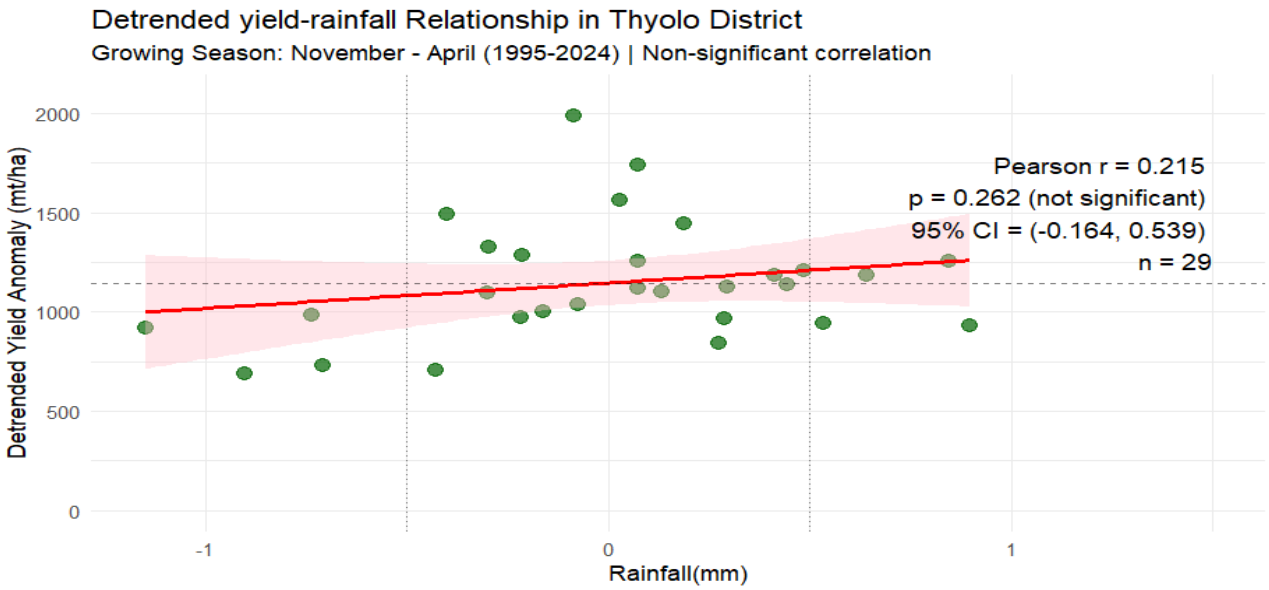


Figure 10: Pearson correlation between detrended maize yield anomaly (mt/ha) and total seasonal rainfall

The Pearson correlation between detrended maize yield anomaly and total seasonal rainfall yielded a coefficient of r = 0.215 (p = 0.262, 95% CI: -0.164 to 0.539, n = 29), as shown in Figure 10. This result is statistically non-significant ($p > 0.05$), indicating that across the 29 growing seasons examined, total seasonal rainfall does not exhibit a significant linear association with detrended maize yield anomaly in Thyolo District.

The 95% confidence interval crosses zero and extends in both the negative and positive directions, confirming that the data are consistent with a true population correlation of zero that is, the absence of a systematic linear relationship between total seasonal rainfall and yield anomaly cannot be excluded. The positive tail of the confidence interval (extending to +0.539) suggests that a moderate positive relationship might be detectable in a larger sample or a longer time series, but the available 29-season dataset does not provide sufficient statistical power to confirm this at conventional significance thresholds.

The positive direction of the correlation (r = 0.215) is agronomically consistent with the expectation that higher seasonal rainfall is generally associated with improved maize yields under rainfed conditions, as adequate soil moisture availability during key phenological stages supports crop growth and productivity (Lobell et al., 2011). However, it is explicable through several interconnected mechanisms that the aggregate seasonal rainfall total obscures. Maize yield is not a simple function of the total volume of rain received during a season; rather, it is highly sensitive to the intra-seasonal distribution of rainfall specifically the timing of onset relative to planting, the frequency and duration of mid-season dry spells during the critical tasseling and grain-filling stages, and the timing of rainfall cessation relative to crop maturity. Two seasons with identical total seasonal rainfall totals can produce dramatically different yields if one season distributes rainfall evenly across the growing period while the other concentrates rainfall in a short period separated by prolonged dry spells. (Vogel et al. 2024) specifically noted that El Niño-associated maize yield reductions in Southern Africa persist even after controlling for total seasonal rainfall, directly implying that it is the character of rainfall its temporal distribution and reliability rather than its volume alone that mediates the crop impact. Furthermore, the scatter in Figure 6 reveals considerable variation in yield at any given rainfall level, consistent with the view that soil fertility, input use, variety choice, and management practices introduce large additional sources of yield variability that are independent of total seasonal rainfall. The non-significant positive slope visible in the regression line suggests a weak tendency for higher total rainfall to be associated with better yields, as agronomically expected, but this tendency is not statistically distinguishable from zero in the present dataset.

These findings highlight the analytical limitation of relying on total seasonal rainfall as the sole precipitation metric for yield modelling in Thyolo District and underscore the importance of incorporating rainfall distribution indicators such as dry spell frequency, onset date, and intra-seasonal variability in future analyses of climate–yield relationships in the district.

Yield–Temperature (Detrended yield anomaly and seasonal mean temperature):

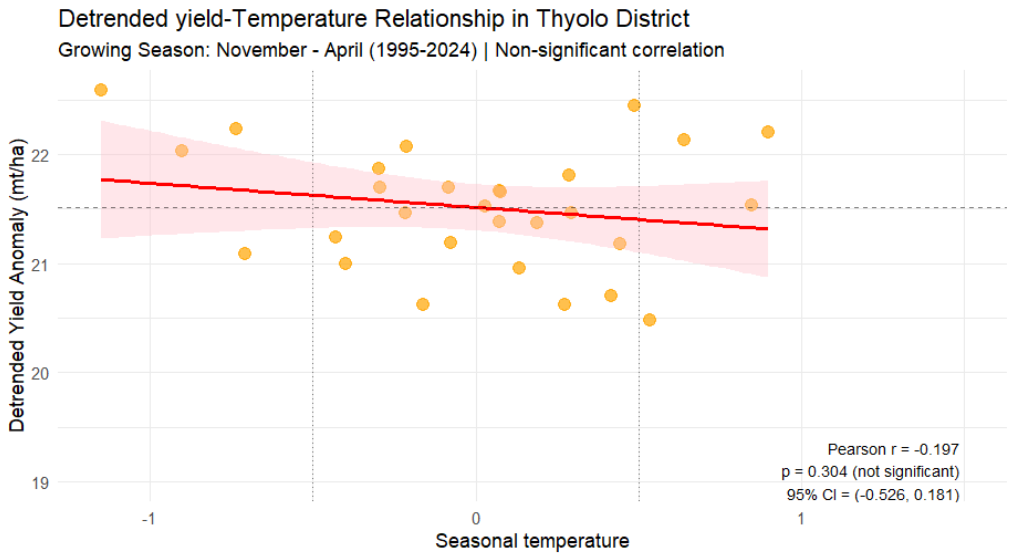


Figure 11: Pearson correlation between detrended maize yield anomaly and seasonal mean temperature

The Pearson correlation between detrended maize yield anomaly and seasonal mean temperature yielded a coefficient of r = -0.197 (p = 0.304, 95% CI: -0.526 to 0.181), as presented in Figure 11. This result is statistically non-significant (p > 0.05), indicating that seasonal mean temperature does not demonstrate a significant linear association with detrended maize yield anomaly in Thyolo District across the study period.

The 95% confidence interval crosses zero in both directions, confirming that the data are consistent with no reliable linear relationship between seasonal mean temperature and yield anomaly in the sample examined. Nonetheless, the negative direction of the coefficient is agronomically consistent with the expected physiological relationship: higher seasonal temperatures are anticipated to be associated with lower maize yields through mechanisms including accelerated evapotranspiration and soil moisture depletion, heat-induced pollen sterility during tasseling, shortened grain-filling durations, and elevated nighttime temperatures that increase respiration costs and reduce net carbon accumulation.

The negative slope visible in Figure 11, while not statistically significant, therefore points in the biologically expected direction.

The non-significance of the yield–temperature correlation may be attributable to several factors specific to Thyolo District and the nature of the available dataset. First, Thyolo District's elevated terrain in the southern highlands of Malawi moderates' temperature extremes; seasonal mean temperatures in the district typically range between approximately 21°C and 22°C a relatively narrow thermal band within which the yield penalty from heat stress may be less severe than in lower-elevation districts. The limited range of temperature variation across the 29 seasons may therefore constrain the detectable linear signal. Second, seasonal mean temperature is an imperfect proxy for heat stress experienced by maize at critical growth stages: it averages temperature across the entire November-to-April period, including months when crops may not yet be in the ground or have already been harvested, thereby diluting the thermal signal during phenologically sensitive periods. Third, the background long-term warming trend in Thyolo's temperature record clearly visible in yield-temperature relationship may introduce secular co-variation between temperature and time that partially confounds the yield-temperature relationship when detrending is applied only to the yield series.

Despite these limitations, the negative direction of the yield-temperature correlation reinforces the broader finding from this study that El Niño events which simultaneously reduce rainfall and elevate temperatures in Thyolo impose compound climate stress on maize production through multiple interacting pathways. Rouault et al. (2025) confirmed that ENSO-driven temperature anomalies in Southern Africa are increasingly amplified by anthropogenic background warming, suggesting that the yield–temperature relationship may strengthen in future seasons as the frequency and intensity of heat stress during El Niño events increases. Future studies in Thyolo District would benefit from incorporating daily maximum temperature data and heat stress degree-day calculations to better capture the phenologically specific thermal impacts on maize yield that seasonal mean temperature fails to resolve.

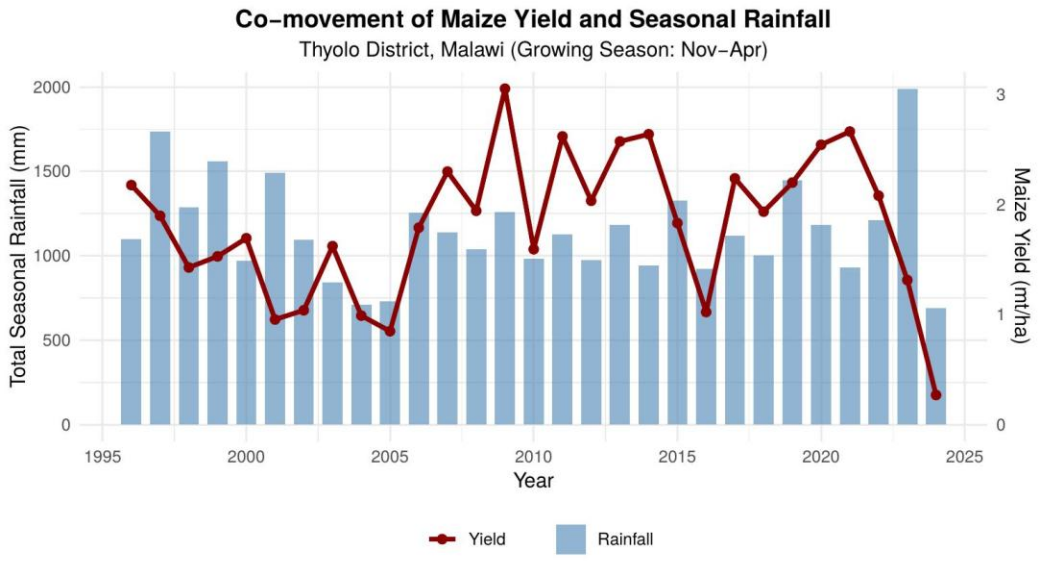


Figure 12: Co-movement of maize yield and total seasonal rainfall

The co-movement plot (Figure 12) illustrates the temporal relationship between seasonal rainfall and maize yield across all 29 growing seasons. While the correlation between the two variables is not perfectly linear consistent with the non-significant ONI-rainfall result, there is a discernible tendency for rainfall and yield to decline together during known El Niño episodes and to recover jointly during La Niña seasons. The years around 2015–2016 and 2023–2024, corresponding to the two strongest El Niño events in the record, are identifiable as points of concurrent rainfall deficit and yield depression.

This visual co-movement pattern supports the interpretation that, while total seasonal rainfall alone does not account for the full extent of ENSO influence on maize yield, it remains one important pathway through which ENSO variability is transmitted to agricultural outcomes in the district.

4.5. Regression analysis

ENSO effects on maize yield:

The simple linear regression of the Oceanic Niño Index (ONI) on detrended maize yield anomaly revealed a statistically significant negative relationship (Figure 11; $R^2 = 0.286$, $p = 0.0028$, $n = 29$). As the ONI increases indicating stronger El Niño conditions - maize yield anomalies decline, with the regression line descending from +0.4 mt/ha at ONI = −1.5 to approximately −0.6 mt/ha at ONI = +2.3. This suggests that El Niño events, which are associated with suppressed rainfall and elevated temperatures over southern Africa, exert a meaningful negative influence on seasonal maize production. The R^2 value of 0.286 indicates that approximately 29% of the interannual variability in detrended yield can be explained by ENSO phase alone. While the scatter around the regression line is considerable reflecting the role of other agronomic and climatic factors the low p-value confirms that the observed inverse relationship is unlikely to be due to chance.

These findings are consistent with established literature linking El Niño-induced dry spells to below-normal harvests across maize-growing regions of sub-Saharan Africa (Cook et al., 2024; Mloza Banda et al., 2024; Mugiyo et al., 2023)

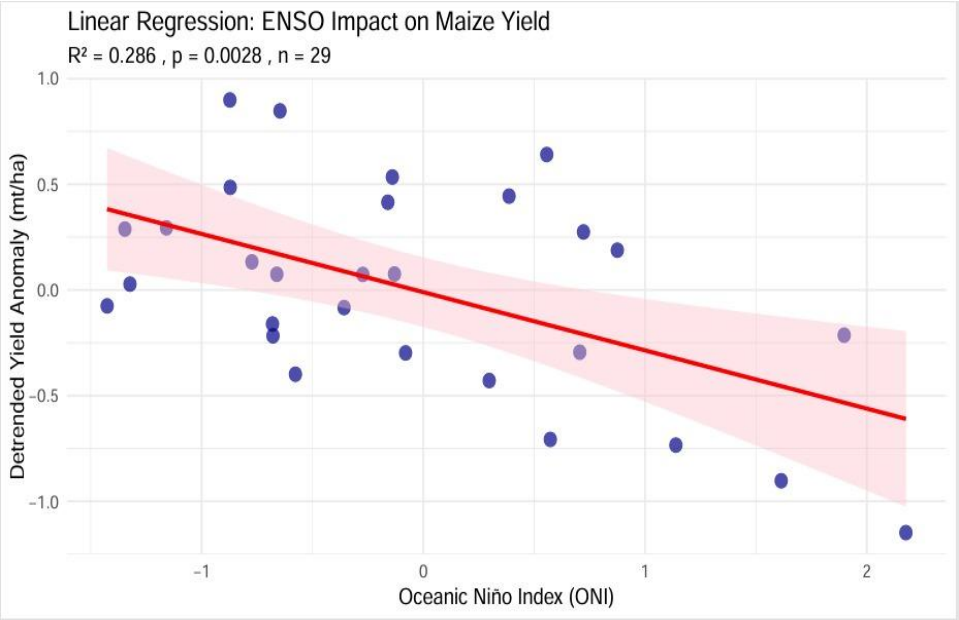


Figure 13: Linear regression of the Oceanic Niño Index (ONI) on detrended maize yield anomaly (mt/ha).

Rainfall effects on maize yield:

The simple linear regression of total seasonal rainfall on detrended maize yield anomaly showed a positive but statistically non-significant relationship (Figure 12; $R^2 = 0.496$, $p = 0.262$, $n = 29$). Although the regression line slopes upward from approximately −0.1 mt/ha at 700 mm to about +0.4 mt/ha at 2000 mm, the wide confidence interval and high p-value suggest that rainfall alone is not a reliable predictor of yield variability in this dataset. The relatively high R^2 of 0.496 is somewhat misleading given the non-significance, likely reflecting the influence of outliers and the limited sample size.

It is worth noting, however, that total seasonal rainfall integrates the cumulative moisture available to the crop, and the positive trend does align with the agronomic expectation that higher rainfall generally supports better yields under rainfed conditions. The non-significance may partly arise from the fact that the distribution, rather than total amount, of rainfall during critical growth stages is what most strongly governs maize productivity.

These results suggest that while rainfall contributes to yield outcomes, its effect may be confounded by other variables and is better captured in a multivariate framework.

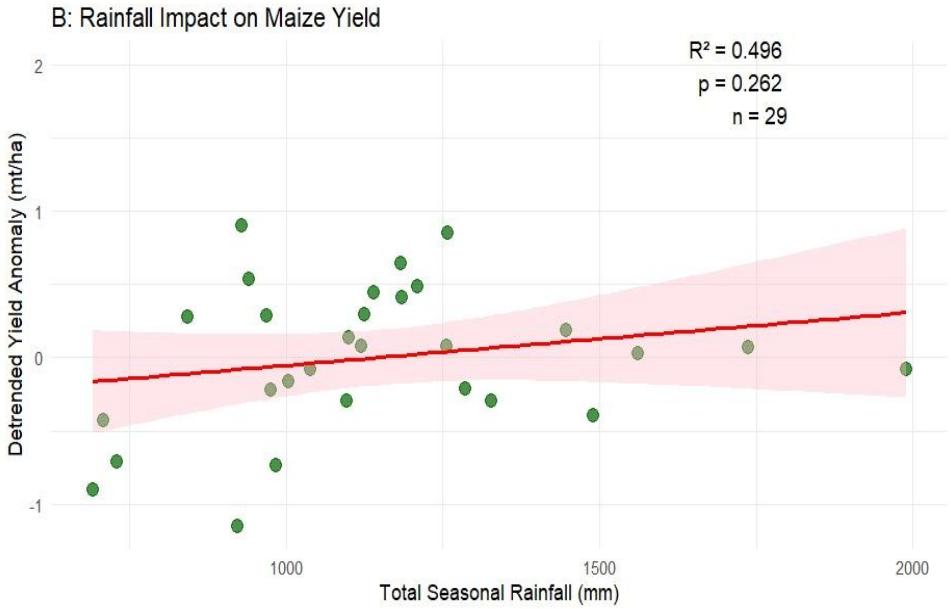


Figure 14: Linear regression of total seasonal rainfall (mm) on detrended maize yield anomaly (mt/ha).

Temperature effects on maize yield:

Mean seasonal temperature showed a weak and non-significant negative relationship with detrended maize yield anomaly (Figure 13; $R^2 = 0.039$, $p = 0.304$, $n = 29$). The regression line is nearly flat, with a slight decline from roughly +0.2 mt/ha at 20.5°C to about −0.1 mt/ha at 22.5°C. The very low R^2 of 0.039 indicates that mean seasonal temperature explains less than 4% of the variation in yield, and the p-value of 0.304 confirms that this relationship does not reach statistical significance.

The narrow temperature range observed in the dataset spanning only about 2°C likely limits the ability of this variable to differentiate yield outcomes, since such small fluctuations may fall within the thermal optimum for maize growth (approximately 18–32°C). These results suggest that while extreme temperature events (such as heat stress during anthesis) can be damaging, average seasonal temperature may not capture these short-duration critical events.

The weak temperature signal observed here may also reflect the fact that the main climatic driver in this region operates through moisture availability rather than heat stress.

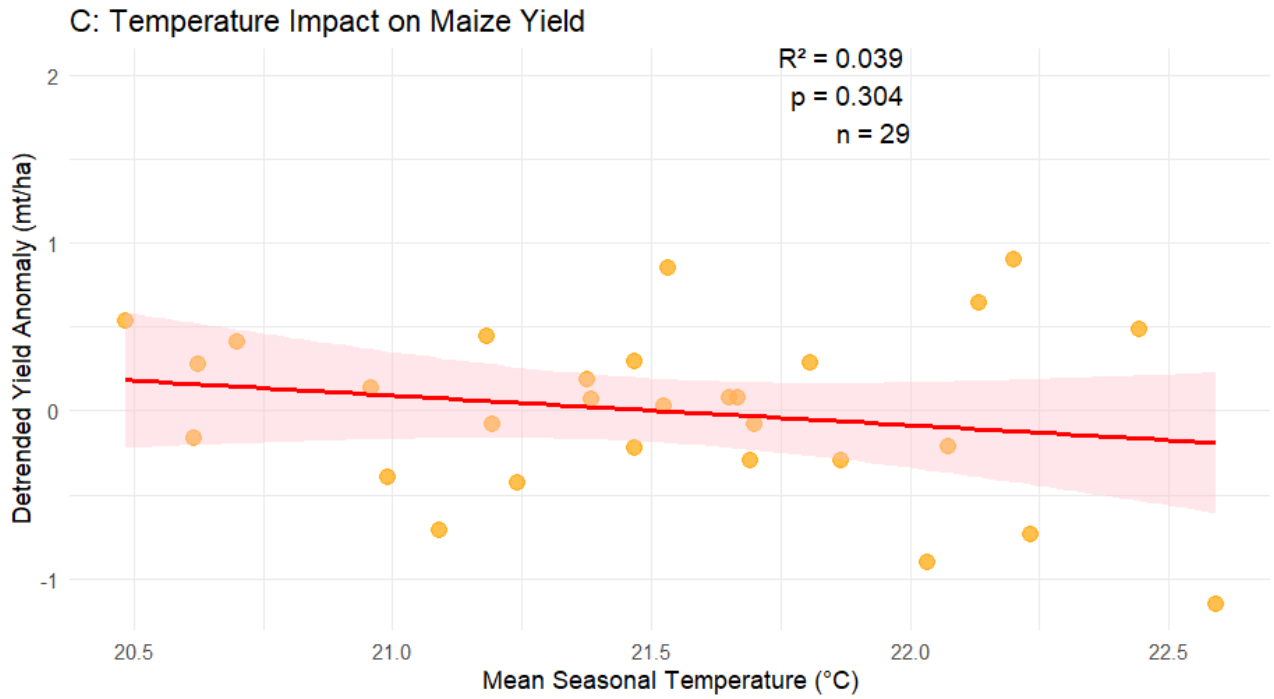


Figure 15: Linear regression of mean seasonal temperature (°C) on detrended maize yield anomaly (mt/ha).

Multiple regression (combined climate predictors):

A multiple linear regression incorporating ONI, total seasonal rainfall, and mean seasonal temperature as simultaneous predictors of detrended maize yield anomaly yielded a model that was statistically significant overall (Figure 14; $F(3,25) = 3.541$, $p = 0.029$, Multiple $R^2 = 0.298$, Adjusted $R^2 = 0.214$). The model explained approximately 30% of the variance in detrended yield, though the adjusted R^2 of 0.214 reflects a more conservative estimate accounting for the number of predictors. Among the three predictors, only ONI retained a statistically significant effect ($\beta = -0.255$, $SE = 0.093$, $t = -2.727$, $p = 0.012$), indicating that for every one-unit increase in the ONI, maize yield anomaly is expected to decline by approximately 0.255 mt/ha when holding rainfall and temperature constant.

Rainfall (β = 0.000175, p = 0.554) and temperature (β = −0.050, p = 0.754) were not significant contributors in the multiple regression context, consistent with their non-significant simple regression results. The residual standard error of 0.44 mt/ha reflects moderate unexplained variation, which may be attributed to factors such as soil quality, crop management practices, pest pressure, and intra-seasonal rainfall distribution not captured in the model.

```
Call:
lm(formula = yield_detrended ~ oni_mean + rainfall_total + tmean_seasonal,
    data = seasonal_data)

Residuals:
     Min       1Q   Median       3Q      Max
-0.62264 -0.35255 -0.09621  0.33629  0.81647

Coefficients:
                Estimate Std. Error t value Pr(>|t|)
(Intercept)     0.8653010  3.3787162   0.256   0.8000
oni_mean       -0.2547076  0.0933886  -2.727   0.0115 *
rainfall_total  0.0001752  0.0002923   0.599   0.5543
tmean_seasonal -0.0500075  0.1580529  -0.316   0.7543
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.4422 on 25 degrees of freedom
Multiple R-squared:  0.2982,    Adjusted R-squared:  0.214
F-statistic: 3.541 on 3 and 25 DF,  p-value: 0.02901
```

Figure 16: Multiple linear regression output.

5. CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1. Achievement of study aims

This study set out to assess the impact of El Niño and La Niña events on maize yield in Thyolo District, Malawi, over 29 growing seasons spanning 1995 to 2024. The primary aim was to establish whether ENSO phase, as measured by the Oceanic Niño Index (ONI), exerts a statistically detectable and practically meaningful influence on detrended maize yield anomalies at the district level. This aim was fully achieved. The analysis confirmed a statistically significant negative relationship between ONI and maize yield anomaly ($r = -0.535$, $p = 0.003$), with ENSO variability alone explaining approximately 28.6% of interannual yield variance a meaningful proportion in smallholder farming systems where soil fertility, input access, and management capacity simultaneously drive production outcomes. The secondary aims of characterizing the associated rainfall and temperature signals, and of quantifying the independent contribution of each climatic predictor through multiple regression, were likewise achieved, yielding a locally validated regression coefficient of -0.255 mt/ha per unit ONI increase a parameter previously absent from the district-level literature for Thyolo.

5.2. Summary of key findings

The key findings of this study converge on three central conclusions. First, El Niño events impose a compound climate stress on maize production in Thyolo District by simultaneously reducing seasonal rainfall and elevating seasonal temperatures, creating conditions of moisture deficit and heat stress that depress yields below their long-term mean. La Niña events, conversely, are associated with above-average rainfall, cooler temperatures, and positive yield anomalies, confirming that ENSO exerts a bidirectional influence on agricultural productivity in the district. Second, the asymmetry between El Niño-driven yield losses and La Niña-associated yield gains the former exceeding the latter in magnitude indicates that drought risk during El Niño years represents the more critical food security threat.

Third, while total seasonal rainfall and mean seasonal temperature were not statistically significant predictors of yield anomaly in either simple or multiple regression frameworks, the ONI remained the sole significant predictor in the multiple regression model (β = -0.255 mt/ha, p = 0.012), confirming that ENSO operates as the dominant climatic organizing variable for interannual maize yield variability in Thyolo District. The overall multiple regression model was statistically significant ($F(3,25) = 3.541$, p = 0.029, Adjusted R^2 = 0.214), and the coefficient plot confirmed that ONI was the only predictor whose 95% confidence interval excluded zero.

5.3. Significance and implications

The significance of these findings extends from local agricultural practice to national food security policy. At the district level, the quantified ENSO–yield relationship provides an empirical basis for integrating seasonal ENSO forecasts which carry meaningful predictive skill six to nine months in advance into district-level crop production advisories and food security early warning systems. The regression coefficient of −0.255 mt/ha per unit ONI offers a concrete parameter for translating operational ENSO outlooks issued by NOAA and the Southern African Climate Outlook Forum (SARCOF) into anticipated yield deviations for Thyolo, supporting proactive decisions on input distribution, emergency food reserves, and humanitarian pre-positioning ahead of El Niño seasons. At the national policy level, the findings reinforce the case for sustained investment in drought-tolerant maize varieties, supplemental irrigation infrastructure, and targeted social protection mechanisms that can buffer the food security impacts of El Niño years. This study also contributes to the growing evidence base on ENSO–crop yield linkages in Southern Africa by providing a district-level empirical quantification for Thyolo, extending the sub-national evidence documented by Tesfaye et al. (2020), Klem et al. (2024), and Cook et al. (2024) to a geographic context previously unrepresented in the peer-reviewed literature.

5.4. Limitations and recommendations for future research

Notwithstanding its contributions, this study is subject to several limitations that define a clear agenda for future research. The 29-season sample, while spanning multiple complete ENSO cycles, constrains statistical power and may not fully capture the yield impacts of rare extreme events at the tails of the ONI distribution; continued data collection will progressively sharpen the precision of regression estimates. The reliance on total seasonal rainfall and mean seasonal temperature as predictors represents a known simplification: maize yield responds more acutely to intra-seasonal rainfall distribution including dry spell frequency, onset date, and cessation timing and to heat stress during specific phenological windows such as anthesis and grain-filling, rather than to the aggregate seasonal averages employed here. It is therefore recommended that future analyses incorporate sub-seasonal climate indices, including the Standardized Precipitation Index, growing degree days, and dry spell counts, to more precisely resolve the mechanisms through which ENSO variability is transmitted to maize yield in Thyolo District. The linear regression framework adopted in this study also assumes proportionality between ONI and yield response; future work should formally test for non-linearity, given that yield penalties may accelerate under strong El Niño conditions. Additionally, the use of district-level average yield data masks sub-district heterogeneity across elevation zones, soil types, and farming systems within Thyolo; farm-level panel data, where available, would enable a more granular and policy-relevant decomposition of climatic and non-climatic yield drivers. Finally, given the documented long-term warming trend in Thyolo's temperature record and projections of intensifying El Niño events under anthropogenic climate change (Rouault et al., 2025), future studies should examine how the ENSO-yield relationship may evolve under future climate scenarios, providing the forward-looking risk assessment that smallholder adaptation planning in Malawi urgently requires.

In conclusion, this study establishes that El Niño events are a statistically significant and practically important driver of below-average maize yields in Thyolo District, Malawi, while La Niña events are associated with above-average production.

The ENSO signal operates primarily through compound moisture and heat stress rather than through total seasonal rainfall or mean temperature alone, and it remains the dominant climatic predictor of interannual yield variability even when rainfall and temperature are controlled for. These findings provide a locally grounded, quantitatively rigorous foundation for ENSO-informed agricultural risk management in Thyolo District, and contribute a district-level empirical reference point to the broader regional literature on climate-food security interactions in Southern Africa.

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