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The Impact of Climate Variability on Yield and Export Volume in the South African Orange Industry

Sanele Kunene, Jan Johannes Hlongwane, Rudzani Nengovhela*

Department of Agricultural Economics and Animal Production, University of Limpopo, Polokwane, Sovenga, South Africa.
*Email: rudzani.nengovhela@ul.ac.za

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ABSTRACT

Agriculture lies at the heart of South Africa's economy, yet its performance is increasingly shaped by the unpredictable rhythm of the climate. Nowhere is this more evident than in the orange industry, a cornerstone of the nation's agricultural exports and rural livelihoods. This study sought to examine how climatic fluctuations have impacted orange yield and export volumes between 2000 and 2021. Using annual time-series data from the World Bank and Trading Economics, the study applies descriptive statistics, the Augmented Dickey-Fuller (ADF) unit root test, and the autoregressive distributed lag (ARDL) modelling framework to examine short-run and long-run relationships between temperature, precipitation, orange yield, and export volumes. The findings indicate that although climate variability has increased over the study period, its effect on orange yield is insignificant in both the short and long-run. However, a significant long-run relationship exists between orange yield and export volumes, emphasizing the dominant role of market dynamics in shaping production outcomes. This study contributes to the literature by distinguishing between climatic and market-driven influences on the industry's production performance. The findings suggest that policy efforts should prioritize export infrastructure development, logistics efficiency, market access expansion, and continued investment in climate-resilient technologies to ensure long-term industry sustainability.

Keywords: Climate Variability, Exports, Orange Industry, Autoregressive Distributed Lag, Orange Production Yield, Trade Performance
JEL Classifications: F1, Q17, Q54

1. INTRODUCTION

South Africa is one of the world's leading exporters of oranges, with its produce reaching markets in Europe, Asia, and the Middle East (Citrus Growers Association, 2020). Climate variability, characterized by fluctuations in temperature, rainfall patterns, and extreme weather events, has become a critical concern for agricultural stakeholders globally (Lobell et al., 2011). The South African orange industry has not been immune to these challenges. Yield variability has been observed over the years, partly attributed to climatic factors such as inconsistent rainfall and temperature extremes. These variations in yield affect domestic supply and South Africa's ability to compete in the global orange export market. Export competitiveness is determined by factors such as production costs, quality standards, and the reliability of supply chains, all of which can be undermined by the impacts of climate variability (CGA, 2020). According to Bulagi et al. (2015), South Africa's agricultural sector is characterized by a dual structure, where numerous small-scale farms operate alongside a well-established commercial farming sector. Approximately one-third of the nation's agricultural production is destined for export markets, highlighting the sector's increasing focus on exports (National Agricultural Marketing Council, 2023).

At the beginning of 2021, South African citrus was exported from the Port of Maputo in Mozambique, a breakthrough that reduced shipping costs and times to Asia and the Middle East (Zang, 2024). The north-eastern regions of South Africa, which are much closer to Maputo than the Port of Durban, produce a sizable portion of the nation's oranges (Moobi et al., 2024). Last season, only 0.6%

of oranges were shipped through Maputo; however, in marketing year (MY) 2023-2024, a larger percentage is anticipated to be exported through Maputo (South Africa's Citrus Market Outlook for 2023/2024 Season, 2024). Despite a 3% decline in MY 2022-2023 due to lower output, South Africa's exports to the US are predicted to keep increasing. Orange exports to the US reached a new high because of duty-free access provided by the African Growth and Opportunity Act (AGOA), which has increased by 25% from the 47,501 Metric Tons (MT) in MY 2020-2021 to 59,192 MT in MY 2021-2022 (Nhamo et al., 2025). Midnight oranges are South Africa's main export throughout the summer months in the United States. The 1st week of June saw the arrival of the first cargo of South African oranges to the US in MY2023/2024, and weekly exports were anticipated to last until the end of October (Zang, 2024). The production forecast for MY 2022/2023 remains unchanged, indicating stable growing conditions and consistent yields without significant changes in weather, input costs, or disease pressure (DALRRD, 2023). However, heavy rainfall and hailstorms in the Eastern Cape, Western Cape, and Limpopo regions have caused a 3% decline in production compared to the previous marketing year. Additionally, an inconsistent electricity supply has disrupted irrigation (Nhamo et al., 2025).

Despite these issues, above-average rainfall throughout the season has provided sufficient irrigation and improved yields, resulting in an 8% year-over-year increase in MY 2021/2022 (South Africa: Citrus Semi-annual, 2024). In light of expected smaller orange sizes, the forecast for orange exports has been revised downward to 1.1 million metric tons (MMT) for MY 2023-2024, reflecting a 12% decline. As processing prices rise, growers are increasingly sending more fruit for juicing, with some Class II fruit being redirected from exports to processing facilities (USDA, 2023). Finally, reports indicate that hail and strong winds have damaged fruit intended for export in the Western Cape and Limpopo provinces, particularly in Groblersdal, complicating the export outlook moving forward (DALRRD, 2023).

Research shows that South Africa's gross domestic product (GDP) is highly sensitive to rainfall fluctuations, leading to significant declines in agricultural output during droughts (Archer et al., 2002). With a large portion of agricultural activities reliant on rain-fed systems, the orange industry is especially vulnerable to these climatic changes (Goedhals-Gerber and Khumalo, 2019). Increased climate variability adversely affects production, directly influencing crop yields, disease prevalence, and fruit quality (Phaleng et al., 2024). These disruptions also have broader economic consequences, including reduced farmer incomes, job losses in citrus-growing regions, and decreased export earnings (Ojo et al., 2024).

A global review underscores the need for in-depth studies on competitive conditions and market dynamics (Phaleng et al., 2024). Understanding how climate variability affects production trends and market performance is essential for developing adaptive management strategies that mitigate risks in South Africa's citrus trade (Tshitavhe, 2022). This study fills the gap in analyses from 2000 to 2021 in South Africa. While some research has examined climate effects on agriculture (Zwane and Ferrer, 2024; Tshikovhi and Van Wyk, 2021), few have addressed the interactions among these factors or their economic implications for export volume. The findings will help policymakers and stakeholders develop effective adaptation strategies, ensuring the sustainability and growth of South Africa's orange sector amidst ongoing climate challenges.

The study is organized into five sections. Section 1 provides the introduction, outlining the background, problem statement, objectives, and significance of the study. Section 2 presents the literature review, which includes a comprehensive analysis of relevant studies conducted in South Africa, across Africa, and internationally. Section 3 describes the study area and details the analytical methods employed. Section 4 focuses on the presentation and discussion of the research findings. Finally, Section 5 provides the conclusion and offers recommendations based on the results of the study.

2. REVIEW OF ORANGE INDUSTRY STUDIES

Climate variability has become an increasingly significant factor affecting the performance of agricultural sectors globally, and the South African orange industry is no exception. South Africa remains the largest citrus exporter in the Southern Hemisphere and ranks second globally after Spain, making its orange sector vital to both national and international markets (Mashita and Hlongwane, 2024). The effect of climate conditions on yield and export dynamics has been the focus of several studies. Mashita (2024) assessed orange price behavior and forecasting from 2001 to 2021, employing ARIMA and ordinary least squares (OLS) models with secondary time series data. The findings revealed an upward trend in prices over time, which attributed to both rising demand and irregularities in supply caused by weather fluctuations. The study emphasized that increased collaboration between producers and advisors could help improve forecast accuracy, particularly in the face of unpredictable climatic events that influence orange yield.

Export competitiveness, a critical factor in the South African orange industry, is often linked to stability in production volumes. In a study aimed at identifying strategic export destinations, Kapuya (2023) used a combination of the growth-share matrix, indicative trade potential (ITP) analysis, and gravity modeling to evaluate 51 global markets. The study's results indicated that 44 of these are strategic, and 26 offer high growth potential. However, the study also noted that these opportunities are sensitive to the consistency of supply from South Africa, which is often disrupted by climatic factors such as drought and temperature variability. Consequently, stable production volumes linked to favorable climatic conditions remain central to maintaining and expanding export potential.

Complementing this, Kapuya (2023) examined the effect of technical barriers on export performance using a gravity model. The study projected modest gains in exports to the EU but much higher potential in emerging markets like China and the U.S. if trade constraints were removed. However, the realization of these gains remains dependent on stable production, which is often hindered by the effects of climate variability, particularly in key production areas such as Limpopo and the Eastern Cape. The findings underscore the notion that climate-induced yield instability can act as an indirect barrier to export growth, regardless of external market access improvements.

From a macroeconomic standpoint, Bulagi et al. (2015) analyzed the relationship between agricultural exports, such as oranges, and the contribution of agriculture to GDP in South Africa between 1994 and 2011. Applying the Granger causality test, the study found unidirectional causality from agricultural exports to agricultural GDP. This implies that if orange exports are reduced due to lower yields caused by climate variability, there may be broader negative effects on the agricultural sector's overall economic contribution. As such, yield variability driven by changing climate patterns not only affects producers but can have ripple effects across the national economy.

The competitive performance of the South African orange industry in the global market has also been shaped by environmental and climatic factors. Phaleng et al. (2024) conducted a systematic global review of the orange industry, emphasizing that climate change and disease outbreaks are among the most serious challenges to continued competitiveness. The study found that North America leads in citrus competitiveness due in part to robust adaptation strategies. For South Africa, maintaining its competitive advantage will depend on intensified research into adaptive production methods, better pest and disease control, and sustainable production practices. These adaptations are especially important given the increased unpredictability of climate conditions in recent years.

In a comparative study of Southern Hemisphere citrus exporters, Mokonyane (2024) assessed South Africa's relative strengths in the orange market. While the study confirmed the country's logistical and production advantages, it also raised concerns about long-term sustainability in the face of climate change. The study recommended a diversification of export markets, particularly into less saturated areas such as Russia and parts of Asia, but stressed that this strategy must be supported by consistent yields and quality, both of which are threatened by increasing climate variability.

At the farm level, the relationship between climatic changes and production efficiency has been further explored. Joseph et al., (2021) examined orange producers in Limpopo and reported that while adaptation strategies do exist, profit efficiency remains heavily influenced by rising input costs, particularly for fertilizer and irrigation water. The study showed that unpredictable weather events often exacerbate these costs, reducing farmers' ability to maintain yield levels. This implies that climate variability not only affects biological production outcomes but also has financial implications for producers attempting to remain profitable in a fluctuating environment.

Evidence from other African countries offers useful parallels. Achuu et al. (2022), in a study conducted in Uganda, found that 94.8% of orange farmers reported recognizing climate variability, noting a sharp decline in yields from 90% in 2015 to under 54% in 2016. Though conducted outside South Africa, the study demonstrates how climatic instability leads to yield reductions and points to group farming and increased irrigation access as key adaptation mechanisms. These findings hold relevance for South African producers, especially those in smallholder or resource-constrained contexts.

Environmental considerations in citrus farming have also been highlighted. Coltro et al. (2009), using ISO-aligned lifecycle assessments in Brazil, reported significant differences in environmental impact depending on farm size, water usage, energy consumption, and chemical inputs. The findings suggest that environmental sustainability is not just a climate mitigation tool but a yield-stabilizing strategy as well. Farms that adopt more efficient resource use are better positioned to withstand climatic stresses, which in turn supports consistent export volumes.

Farmer awareness and perceptions of sustainable practices were also assessed in a Nigerian study by Ogunbode et al. (2025), who surveyed 480 farmers across six states. The majority cited shifting rainfall patterns and declining production as major concerns. Although the study was not South African, it reinforces the broader continental trend of farmers acknowledging climate change and the need for support mechanisms to enable meaningful adaptation. The study's recommendations for climate-resilient agricultural frameworks are particularly relevant to South African citrus growers, who face similar challenges.

Fruit quality and its sensitivity to climatic conditions were addressed by Zekri (2011), who emphasized the importance of adequate irrigation, balanced nutrition, and cool winters for optimal citrus yield and quality. The study warned that failure to meet these requirements due to climatic variability may lead to declines not just in yield but also in marketability, thereby affecting export performance. These findings reiterate the complex interrelationship between climatic variables, production outcomes, and export potential in the orange sector.

The present review of the orange industry literature demonstrates the multifaceted influence of climate variability on both yield and export volume. While earlier studies have touched on production, pricing, sustainability, and trade, there remains a gap in fully integrating these aspects under the lens of climate variability. The reviewed studies make it clear that without stable yields, export growth is constrained, and without climate resilience, yields cannot be assured. Thus, the current study is well-positioned to contribute meaningfully by empirically investigating the extent to which climate variability has shaped the yield and export performance of South African oranges between 2000 and 2021.

In summary, the reviewed literature paints a comprehensive picture of the South African orange industry's current state, highlighting key factors such as price trends, strategic export opportunities, technical trade barriers, climate vulnerability, and employment dynamics, while also reflecting broader challenges faced by citrus farmers globally, including postharvest losses, climate variability, sustainability perceptions, and environmental concerns.

Collectively, these studies underscore the necessity for coordinated efforts in research, policy intervention, sustainability initiatives, improved management practices, technological investments, and market diversification to enhance the competitiveness, resilience, and sustainability of the orange sector. The findings emphasize the urgent need for supportive policy frameworks and continued innovation to strengthen the adaptive capacities of smallholder farmers and ensure the long-term sustainability of citrus production both in South Africa and worldwide.

3. DATA AND METHODOLOGY

This section outlines the research methods employed in the study, focusing on the selection of the study area, data collection, and the analytical approach used. Data on yield and orange prices were gathered annually, with a total of 22 observations. Furthermore, the chapter provides an overview of the study area, which encompasses all the provinces within South Africa's orange-producing regions. The methodology section begins with an analysis of orange price trends, followed by the introduction of the forecasting model.

3.1. Study Area

This study investigated the effect of climate variability on the yield and export competitiveness of the South African orange industry from 2000 to 2021, focusing on the relationship between orange production yield, export volume, average surface air temperature and average precipitation. South Africa is an important participant in the worldwide orange market, with its primary orange production regions spread across several provinces (CGA, 2019). These include Eastern Cape, KwaZulu-Natal, Limpopo, Mpumalanga, and Western Cape, where various climatic conditions influence yield and overall competitiveness. In the Eastern Cape, notable production areas include the Eastern Cape Midlands, Patensie, and the Sundays River Valley. KwaZulu-Natal's key areas are the KwaZulu-Natal Midlands, Nkwalini, and Pongola, while Limpopo's prominent production zones are Groblersdal, Hoedspruit, Letsitele, Vhembe, and Zebediela. Mpumalanga's main production areas consist of Nelspruit, Onderberg, and Senwes, with the Western Cape's production focused on Boland and Ceres (CGA, 2019).

3.2. Data Collection

The study relies on historical secondary data obtained from Trading Economics and the World Bank. Annual data from 2000 to 2021 (22 observations) were collected for orange production (metric tons), export volume (metric tons), temperature (°C), and precipitation (mm) (Trading Economics, 2025a; Trading Economics, 2025b; World bank, 2025). While the sources are highly reputable, potential limitations such as missing values or inconsistencies have influenced the analysis. Temperature (°C) and precipitation (mm) were identified as critical climatic variables, as they exert a significant influence on agricultural productivity, particularly in the cultivation of fruit crops such as oranges. These challenges were addressed through robust data imputation or exclusion methods. To ensure statistical reliability, the Augmented Dickey-Fuller (ADF) test was used to check for stationarity of the variables, preventing spurious regression results (Shrestha and Bhatta, 2017). The Autoregressive Distributed Lag (ARDL) model was used to analyse both short and long-run relationships between climate variability and industry performance. Additionally, descriptive analysis was used to assess the impact of climate trends on production and exports. The analysis was performed using Eviews 12 (student version).

This approach provided empirical insights into the role of climate variability in shaping orange production and export competitiveness, offering a foundation for further research and potential industry adaptation strategies.

3.3. VAR Lag Order Selection

Table 1 shows the lag order selection criteria (Endogenous: YIELD, EXPORT, PRECIP, TEMP; Exogenous: Constant) (Sample: 2000-2021, Included Observations: 22).

As shown in Table 1, the optimal lag length was selected using multiple lag selection criteria, including the Akaike Information Criterion (AIC), Schwarz Criterion (SC), Hannan-Quinn Criterion (HQ), and final prediction error (FPE). All four criteria identified lag 3 as the most appropriate, as it produced the lowest values across each criterion. Specifically, the AIC value at lag 3 was 46.52, the SC was 49.11, the HQ was 46.96, and the FPE was 6.38e + 15.

Based on these results, lag 3 was selected as the maximum lag length to be used in estimating the ARDL model. This ensures the model captures the necessary short-run and long-run dynamics among the variables without overfitting.

3.4. Unit Root Test

Table 2 illustrates the Augmented Dickey-Fuller (ADF) test for unit roots conducted at the first difference of the time series data for precipitation, temperature, yield, and export volume:

Based on the probability values presented in Table 2, all variables precipitation (P = 0.0001), temperature (P = 0.0055), yield (P = 0.0001), and export volume (P = 0.0000) have P < 0.01. Therefore, the null hypothesis of a unit root is rejected for all variables at the 1% significance level, leading to the conclusion that all series are stationary at the first difference.

Table 1: Lag order selection test

Lag	LogL	LR	FPE	AIC	SC	HQ
0	−476.6829	NA	1.11e+17	50.59820	50.79703	50.63185
1	−448.4652	41.58400*	3.22e+16	49.31213	50.30628	49.48038
2	−429.7105	19.74178	3.18e+16	49.02216	50.81162	49.32501
3	−389.9452	25.11494	**6.38e+15***	**46.52055***	**49.10533***	**46.95800***

Source: Own computation. Note: Asterisk (*) indicates the lag order selected by the respective criterion and bold values indicate the optimal lag length selected by each information criterion (LR, FPE, AIC, SC, and HQ)

Table 2: Augmented Dickey-Fuller (ADF) unit root testing results

Variable name	Lag length	Probability value	Conclusion
Precipitation	Automatic lag selection: Schwarz info criterion Maximum lags 3	0.0001	Stationary at 1% level
Temperature	Automatic lag selection: Schwarz info criterion Maximum lags 3	0.0055	Stationary at 1% level
Yield	Automatic lag selection: Schwarz info criterion Maximum lags 3	0.0001	Stationary at 1% level
Export volume	Automatic lag selection: Schwarz info criterion Maximum lags 3	0.0000	Stationary at 1% level

Source: Own computation

3.5. Analytical Techniques to Check the Short-Run and Long-Run Relationship

To effectively address the main objective of the study of analysing the long and short-run relationship between climate variability and orange production yield and orange export volume in South Africa from 2000 to 2021, the study adopted the autoregressive distributed lag (ARDL) modelling approach due to its suitability for time-series data characterised by non-stationary and mixed orders of integration. Unlike the Johansen cointegration technique, which requires all variables to be integrated of the same order, the ARDL framework allows variables to be integrated of order zero (I0), order one (I1) or a combination of both. The model incorporates lagged values of both the dependent and explanatory variables to account for dynamic adjustments over time (Shrestha and Bhatta, 2017).

The ARDL specifications follow a general to specific modelling approach, in which sufficient lag lengths were included to capture the underlying data generating process and to address the issue of spurious results. This approach enabled the modelling of both short and long-run relationships with a single unified framework (Shrestha and Bhatta, 2017).

The following straightforward model can be used to demonstrate the ARDL modelling approach:

$$Y_t = \alpha + \beta x_t + \delta z_t + e_t \quad (1)$$

The ARDL model's error correcting version is provided by:

$$\Delta y = \alpha_0 + \sum_{i=1}^{p} \beta \Delta y_{t-i} + \sum_{i=1}^{p} \delta \Delta x_{t-i} + \sum_{i=1}^{p} \varepsilon_i \Delta z_{t-i} + \lambda_1 y_{t-1} + \lambda_2 x_{t-1} + \lambda_3 z_{t-1} + u_t \quad (2)$$

The first part of the equation with β, δ, and ε represents the short-term dynamics of the model. The second section with λs represents long-term associations. The null hypothesis of the equation is $\lambda_1+\lambda_2+\lambda_3 = 0$, which indicates that there is no long-term relationship.

The study aimed to examine the effect of climate variability on yield and export competitiveness in the South African orange industry from 2000 to 2021. The study's objectives were to: (i) To describe and analyse trends in temperature, precipitation, orange production, yield and export volumes in the South African orange industry from 2000 to 2021. (ii) To analyse the long and short-run relationship between climate variability and orange production yield and orange export volumes in South Africa from 2000 to 2021. The study hypothesizes that climate variability, particularly temperature and precipitation fluctuations have no significant short and long-run impacts on the orange production and export volume in South Africa from 2000 to 2021.

4. EMPIRICAL RESULTS AND DISCUSSION

4.1. Summary Statistics Table

Table 3 presents the descriptive statistics for the key variables used in the study: Yield, export volume, precipitation, and temperature, over the period 2000-2021.

Descriptive statistics on Table 3 were computed for yield, export volume, precipitation, and temperature over the period 2000-2021. The mean orange yield was approximately 1,456,641 tons (SD = 227,207.50), while the mean export volume was 939.08 thousand tons (SD = 178.98). On average, the annual precipitation was 464.59 mm (SD = 68.94), and the temperature was 18.32°C (SD = 0.41).

The distribution of the variables was assessed through skewness and kurtosis. Yield (skewness = 0.04; kurtosis = 1.95), export volume (skewness = −0.28; kurtosis = 1.98), and temperature (skewness = 0.13; kurtosis = 2.99) were approximately symmetric with slight platykurtic tendencies. Precipitation was moderately positively skewed (skewness = 0.84) with a kurtosis of 3.13, indicating a distribution close to normal.

Normality was tested using the Jarque-Bera test. None of the variables had significant Jarque-Bera statistics at the 5% level, with all P-values exceeding.05 (e.g., P = 0.60 for yield, P = 0.97 for temperature), suggesting that the variables are approximately normally distributed. These results indicate that the data are suitable for further time series modelling.

4.2. Graphical Trends

Figure 1 displays the trend in South Africa's average annual temperature (in degrees Celsius reported on the y-axis) over a 22-year period, from 2000 through 2021 (reported on the x-axis). Figure 2 displays annual precipitation levels (reported on the y-axis in Mm) over the same period of 22 years, which appear to fluctuate significantly from year to year.

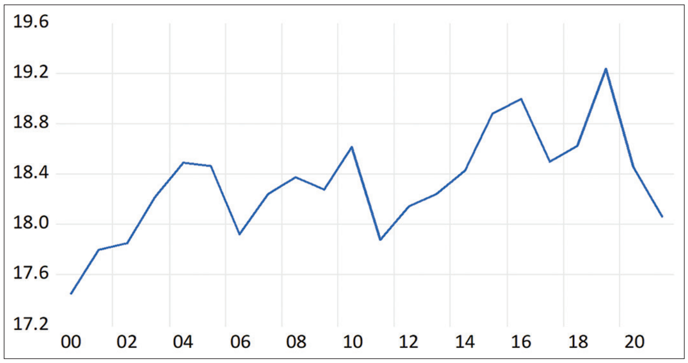
In Figure 1 the data reflect a steady and consistent rise in temperatures, beginning at approximately 17.2°C in 2000 and reaching nearly 19.5°C by 2021. This 2.3°C increase over two decades highlights a significant warming trend, supporting evidence of regional climate change as documented by Phaleng et al. (2024), who noted that climate shifts are becoming

Table 3: Summary statistics results

Statistic	Yield	Export volume	Precipitation (mm)	Temperature (°C)
Mean	1,456,641.00	939.08	464.59	18.32
Median	1,435,144.00	942.00	451.99	18.33
Maximum	1,808,142.00	1,173.10	639.02	19.23
Minimum	1,047,830.00	573.00	374.29	17.45
Std. Deviation	227,207.50	178.98	68.94	0.41
Skewness	0.04	−0.28	0.84	0.13
Kurtosis	1.95	1.98	3.13	2.99
Jarque-Bera	1.01	1.23	2.57	0.06
P-value (JB)	0.60	0.54	0.28	0.97
Sum	32,046,091.00	20,659.80	10,220.90	403.10
Sum Sq. Dev.	1.08×10^{12}	672,723.60	99,798.45	3.61

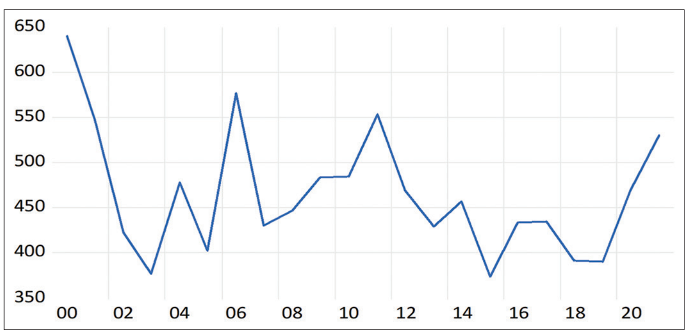
Source: Own computation

Figure 1: Average annual temperature (°C)



Source: Own illustration

Figure 2: Average annual precipitation (mm)



Source: Own illustration

increasingly critical in shaping citrus sector competitiveness. The gradual yet persistent increase in temperatures has direct implications for South African citrus production. As Kapuya (2023) observed, regions like Limpopo and the Eastern Cape, (key hubs of orange cultivation) are especially vulnerable to climatic extremes. Higher temperatures increase evapotranspiration rates, reduce soil moisture, and heighten dependence on irrigation systems, thereby increasing operational costs for farmers Joseph et al., (2024). These rising input demands, driven by warming conditions, reduce profit margins and amplify production risk. The long-term temperature trend illustrated in Figure 2 therefore underscores the growing climatic pressures that threaten yield stability and export consistency within the South African orange industry. In Figure 3 the early 2000s show a steep decline in rainfall, followed by alternating periods of high and low precipitation. There are sharp spikes and troughs, particularly around 2003, 2007, and 2016, suggesting the presence of climatic instability. This volatility aligns with broader regional climate trends and supports earlier literature, such as Joseph et al. (2024) and Phaleng et al. (2024), who documented unpredictable rainfall patterns as key constraints on orange yield.

Figure 3: Annual average export (MMT)

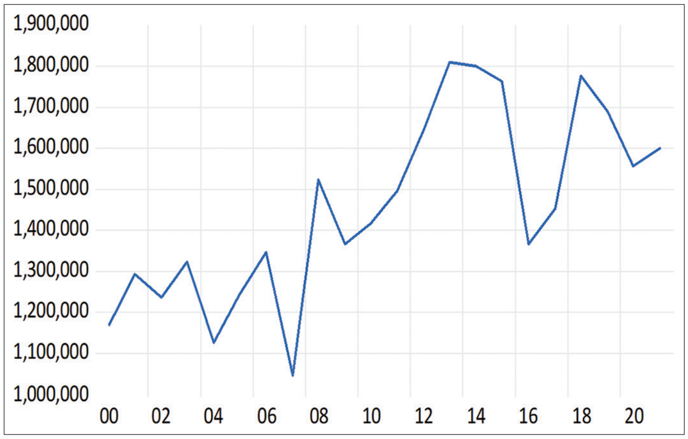
Source: Own illustration

Figure 3 shows a general upward trend in orange export volumes (reported on the y-axis) from 2000 to 2021(reported on the x-axis). Figure 4 illustrates the trajectory of South Africa's orange yield (measured in metric tons reported on the x-axis) over the 22-year period from 2000 to 2021 (reported on the y-axis).

In Figure 3 the increase in exports is not entirely smooth, as a few dips appear in the mid-2000s and early 2010s. However, beginning around 2009, exports start to rise more steeply, with peaks occurring between 2016 and 2021. The growth in export volumes over this period suggests an expanding global demand for South African oranges and possibly improved logistics, market access, or trade relations. This steady rise supports the earlier ARDL result showing that export volume significantly and positively influences orange yield. The upward trajectory also aligns with Kapuya (2023) and Mashita (2024), who report that South Africa has expanded its citrus export footprint significantly in recent years.

In Figure 4 the data reveal an overall upward trend, with national orange yields rising from approximately 1.1 million metric tons in 2000 to a peak of nearly 1.8 million metric tons around 2020. This

Figure 4: Average annual orange yield (mm)



Source: Own illustration

represents an increase of more than 60% over the observed period. While the general trajectory is positive, the graph also shows marked inter-annual fluctuations particularly around the mid-2000s and in the early 2010s suggesting that yield performance has not been uniformly stable.

These fluctuations align with the literature emphasizing the influence of climate variability on agricultural output. For instance, Mashita (2024) noted that supply irregularities often climate-driven can affect pricing and market planning. Similarly, Kapuya (2023) underscored that consistent yield levels are crucial for maintaining South Africa's strategic position in global citrus markets. However, inconsistent production volumes, such as those seen during drier years, undermine the country's ability to meet export commitments. These trends mirror findings in other African contexts, such as the study by Achuu et al. (2022) in Uganda, where yield dropped dramatically from 90% in 2015 to under 54% in 2016 due to adverse weather conditions.

The relationship between climate and yield is further supported by Zekri (2011), who found that citrus yield and quality depend on adequate irrigation, balanced nutrition, and favorable seasonal conditions. Therefore, while the long-term yield trend in Figure 4 is encouraging, its variability reflects the critical role that climate plays in shaping both production and export capacity in the South African orange sector.

4.3. ARDL Short-Run Results

This study employed an autoregressive distributed lag (ARDL) model to assess the short-run effects of climate variability and export volumes on orange yield in South Africa between 2000 and 2021. The results in Table 4 reveal that, in the short run, none of the climate-related variables, namely precipitation and temperature, exert a statistically significant effect on orange yield at the 5% level. The coefficient for current precipitation is −183.79 with a standard error of 2,614.49, yielding a t-statistic of −0.11 and a P = 0.913. This suggests an almost negligible and statistically insignificant short-run negative effect of precipitation on yield. Similarly, the coefficient for current temperature is −331,387.43 (SE = 264,077.00, P = 0.349), implying that a one-degree Celsius increase in temperature is associated with a decrease of approximately 331,387 tons in yield. However, this effect is also statistically insignificant.

Table 4: ARDL short-run results

Variable	Coefficient	Standard error	t-Stat	P-value
YIELD (−1)	−0.027	0.351	−0.076	0.942
YIELD (−2)	−0.439	0.298	−1.470	0.192
EXPORT (0)	647.403	866.979	0.747	0.483
EXPORT (−1)	149.900	666.482	0.225	0.830
EXPORT (−2)	2110.156	982.344	2.148	0.075
PRECIP (0)	−183.793	2614.493	−0.114	0.913
PRECIP(−1)	−1657.583	1279.741	−1.295	0.243
PRECIP (−2)	328.901	34134.110	0.290	0.781
PRECIP (−3)	−1862.109	1013.445	−1.837	0.116
TEMP (0)	−331387.43	26407.70	−1.015	0.349
TEMP(−1)	−525256.13	40269.00	−1.728	0.135
TEMP (−2)	−259496.42	12588.80	−1.221	0.268
Constant (C)	2.15e+10	1.83e+10	1.17	0.116

Source: Own illustration Model Statistics: adjusted R2=0.63, F (12, 6)=3.59, P=0.064 (marginal significance) Durbin-Watson=1.50

Further, the lagged values of yield, temperature, and precipitation likewise failed to demonstrate statistical significance in the short run. The first and second lags of yield have coefficients of −0.0266 (P = 0.9422) and −0.4387 (P = 0.1921), respectively. Among the export volume variables, the coefficient for the second lag (EXPORT (−2)) was 2,110.16 with a standard error of 982.34 and a P = 0.075. Although this result is not significant at the conventional 5% level, it is marginally significant at the 10% level, suggesting that increases in export volumes 2 years prior may positively influence current orange yield, possibly due to reinvestment in production infrastructure or market-driven efficiency improvements.

The overall explanatory power of the model is moderate, with an adjusted R-squared of 0.6328, indicating that approximately 63% of the variation in orange yield is explained by the included regressors. The F-statistic of 3.585 (P = 0.0639) is marginally significant, suggesting the joint relevance of the variables in explaining yield variation, albeit not robustly. The Durbin-Watson statistic of 1.497 indicates mild positive autocorrelation, which should be monitored in future modeling.

These findings support the null hypothesis of the study, which states that climate variability specifically fluctuations in precipitation and temperature has no statistically significant short-run impact on orange yield in South Africa. Despite the negative coefficients for both temperature and precipitation, the lack of statistical significance implies that, in the short term, orange production may be resilient to small or moderate variations in climate conditions, at least at the aggregate national level.

These results are largely consistent with studies that emphasize the more pronounced influence of climate variability over the long run or in local contexts. Mashita and Hlongwane (2024) found that climate irregularities impact orange price behavior rather than immediate yield outcomes, a finding that aligns with the present study's results. Similarly, Kapuya (2023) identified strategic export markets for South African oranges but highlighted that their viability is contingent on consistent production over time, again emphasizing the importance of long-term rather than short-term climate effects.

The current findings also indirectly align with Bulagi et al. (2015), who observed a causal relationship between agricultural exports and agricultural GDP in South Africa. The marginal significance of lagged export volume in the present study may reflect a delayed positive effect of trade success on production capacity, through mechanisms such as improved investment in farming inputs or infrastructure.

However, some micro-level studies do suggest more immediate climate effects. For example, Joseph et al. (2024) and Achuu et al. (2022) found that unpredictable weather conditions directly influenced yield and profit efficiency at the farm level. The current study, which relies on national aggregate data, may mask these localized short-run impacts, offering a partial explanation for the lack of significance. Additionally, although studies such as those by Phaleng et al. (2024) and Mokonyane (2024) emphasize climate change as a serious long-term threat to yield and export performance, the short-run ARDL model does not capture such gradual but compounding effects.

Overall, the short-run ARDL results suggest that climate variability does not significantly affect orange yield in the short term at the national level in South Africa. The only exception is a marginal effect of lagged export volumes, suggesting that market dynamics may play a more immediate role in influencing production decisions than climate variability. These results provide a nuanced view of the climate yield relationship, one that warrants further investigation through long-run modeling and disaggregated (regional or farm-level) analyses to better capture delayed and localized effects.

4.4. ARDL Long-Run Results

ARDL Long-Run Form and Bounds Test for Orange Yield (2000-2021). (Dependent Variable: D(YIELD); Selected Model: ARDL (2,2,3,2); n = 19).

Table 5: ARDL model long-run results

Variable	Coefficient	Stdandard error	t-statistic	P-value
Long-run coefficients				
EXPORT	1984.29	376.79	5.27	0.0019
PRECIP_	−2303.09	2457.00	−0.94	0.3848
TEMP_	−761,745.94	449,355.90	−1.70	0.1410
Constant (C)	14,678,187.00	9,013,073.00	1.63	0.1545
Error correction term				
YIELD (−1)*	−1.4652	0.5128	−2.86	0.0289
F-Bounds test				
F-statistic	2.41	—	—	—
Critical values (n=35)	I (0)/I (1)			
10%	2.618/3.532			
5%	3.164/4.194			
1%	4.428/5.816			

Source: Own computation

The ARDL long-run estimation investigates the influence of climate variability and export performance on orange yield in South Africa over the period 2000-2021. The long-run coefficients presented in Table 5 indicate that export volume (EXPORT) has a statistically significant and positive impact on orange yield. The coefficient for EXPORT was 1984.29 (P = 0.0019), suggesting that a one-unit increase in exports is associated with a 1,984-ton increase in orange yield in the long run, holding other factors constant. This strong significance highlights the importance of export-driven incentives in stimulating agricultural productivity.

Conversely, the climate variables precipitation (PRECIP) and temperature (TEMP) show negative but statistically insignificant relationships with orange yield. The coefficient for precipitation was −2303.09 (P = 0.3848), while temperature had a coefficient of −761,745.94 (P = 0.1410). These results indicate that increases in either precipitation or temperature may reduce yield over time, but the current data provide insufficient evidence to confirm a statistically meaningful long-run effect. The large negative coefficient for temperature is notable and suggests that, while not statistically significant at the 5% level, the biological and agronomic impact of warming trends may be economically relevant and merits further exploration.

The error correction term, YIELD (−1), is negative and statistically significant (coefficient = −1.4652, P = 0.0289), confirming the existence of a stable long-run equilibrium among the variables. The magnitude of the error correction coefficient suggests a relatively fast and strong adjustment toward long-run equilibrium, with approximately 146.5% of deviations corrected each year indicative of over-adjustment. This suggests that when short-term disruptions occur, the system tends to revert rapidly, and perhaps even excessively, to its long-run path.

However, the F-bounds test for cointegration does not support the presence of a long-run relationship. The calculated F-statistic of 2.41 falls below the lower critical bounds at all conventional levels of significance (e.g., for n = 35, the 5% critical bounds are I [0] = 3.164 and I [1] = 4.194). As a result, we fail to reject the null hypothesis of no cointegration, casting doubt on the long run cointegration among the variables. This inconsistency between the error correction term significance and the bounds test result is common in small samples and should be interpreted with caution.

These findings offer partial support for the study hypothesis, which proposed that climate variability does not have a significant impact on orange yield in the long run. While precipitation and temperature do not exert statistically significant effects, export performance clearly does. This aligns with studies by Kapuya (2023) and Mashita (2024), which emphasize the role of stable exports and trade opportunities in sustaining agricultural output. The negative sign and large magnitude of the temperature coefficient also echo concerns raised in Zekri (2011) and Phaleng et al. (2024) regarding climate threats, though statistical insignificance may reflect limitations due to sample size, data aggregation, or omitted adaptation mechanisms.

5. CONCLUSION

This study examined the impact of climate variability, proxied by inter-annual changes in temperature and precipitation, on orange yield and export volumes in South Africa from 2000 to 2021, addressing a gap in national-level empirical evidence within a sector critical to economic development and trade. The findings indicate that, despite rising temperatures and fluctuating rainfall patterns, climate variables did not exert a statistically significant short-run or long-run effect on orange yield or exports, suggesting resilience at the aggregate level, likely supported by improved agronomic practices, irrigation technologies, and structural adaptation within the citrus industry. In contrast, export volume was identified as a significant long-run determinant of yield, underscoring the dominant role of market access, trade performance, and global demand in driving production outcomes. While these results align more closely with literature emphasizing economic and trade factors over climatic drivers, they do not diminish the potential risks associated with long-term climate change, particularly at sub-national and smallholder levels where adaptive capacity may be constrained.

Accordingly, the study recommends prioritizing the strengthening of export capacity through improved trade infrastructure, logistics, and bilateral market access, alongside continued investment in climate-resilient agricultural technologies such as precision irrigation, drought-tolerant cultivars, and climate monitoring systems. Additionally, the development of spatially disaggregated agroclimatic data and the promotion of public–private partnerships across the citrus value chain are essential to enhance targeted policy interventions, support innovation, and ensure the long-term sustainability of South Africa's orange industry under evolving environmental and economic conditions.

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