

Impacts of the General Circulation Represented by the IOD on Maize Yield Anomalies in Zambia

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Abstract

Maize production in Zambia is highly sensitive to inter-annual climate variability during the austral summer growing season. Large-scale ocean-atmosphere circulation systems modulate moisture transport and convective activity across southern Africa. Among these systems, the Indian Ocean Dipole (IOD) plays a critical role in modulating moisture transport and precipitation patterns across Southern Africa. This study investigates the physical linkage between IOD-related general circulation and maize yield anomalies in Zambia. Using provincial Maize yield data (1993-2024), reanalysis data fields, and climatic suitability indices, we apply the Singular Value Decomposition method (SVD) to examine the coupled variability between the Indian Ocean Sea Surface temperature (SST) Anomalies and precipitation over Zambia. The results show that the leading SVD mode explains a dominant share of the covariance between SST and rainfall, indicating a strong coupling between Indian Ocean Variability and regional climate conditions. We trace a physically consistent pathway from the Indian Ocean's Sea Surface temperature anomalies to atmospheric circulation and climatic suitability, and yield a response over the study area. The Singular Value Decomposition (SVD) shows that there is a temporal correlation coefficient (TCC) of 0.48 for 31 years at a 99% confidence level. The associated precipitation pattern reveals spatial contrasts in rainfall distribution across Zambia that correspond closely to Maize yield anomalies, with precipitation suitability emerging as the dominant climatic control among the three selected variables in the country. The precipitant suitability index acts as a primary modifier, while sunshine duration and temperature play a compensatory role, thereby completing the climatic suitability of the crop. The IOD-related cir-

ulation variability significantly influences agricultural productivity. Our findings emphasize the method of forecasting the maize yield in Southern Africa.

Keywords

Indian Ocean Dipole, Maize Yield Anomalies, Zambia, Moisture Transport, Climatic Suitability, General Circulation

1. Introduction

Maize is Zambia's staple crop, accounting for more than half of the national calorie intake and occupying the largest cultivated land. Its productivity is strongly controlled by rainfall distribution, temperature, and total sunshine hours during the austral summer growing season (November-April). As Zambia relies predominantly on rain-fed agriculture, interannual climate variability frequently translates into yield fluctuations, thereby amplifying food insecurity and economic vulnerability. Large-scale circulation modes frequently lead to maize yield fluctuations, contributing to food insecurity and economic vulnerability. A dominant mode of tropical climate variability that plays a significant role in modulating rainfall is the Indian Ocean Dipole (IOD) pattern. The IOD represents a coupled ocean-atmosphere pattern characterized by an east-west SST gradient across the equatorial Indian Ocean (Saji et al., 1999). Through its influence on the walker circulation, low-level monsoon flow indicated by the westerlies and regional moisture pathways, the IOD can exert far-reaching effects on rainfall variability beyond the Indian Ocean basin, including eastern and Southern Africa. Previous studies have demonstrated robust linkages between Indian Ocean SST anomalies and rainfall variability over southern Africa, while analyses over Zimbabwe and neighboring countries show that a leading rainfall mode often explains spatially coherent signals across entire countries (Manatsa & Mukwada, 2012). Despite this growing body of climate literature, relatively few studies explicitly connected these circulation anomalies to crop yield responses in Southern Africa using a physically consistent link between the SST forcing, atmospheric circulation, agroclimatic suitability, and yield anomalies. Building on established methodologies applied in East Asia (Xu et al., 2021) and guided by regional rainfall SVD coupled mode analyses, this study adapts the framework to Zambia, focusing on Maize yield anomalies. Being the most widely cultivated crop in Zambia, maize yields are sensitive to climatic conditions such as rainfall, temperature, and sunshine duration during the growth stages, like any plant. It accounts for 80% of the country's grain production with a relatively stable cumulative planting area of 2.1 million hectares as at the 2023/2024 farming season (Mwape et al., 2025).

While the country's rainfall season is unimodal, there are problems arising from extreme events such as drought and floods, thereby affecting various activities that contribute to the country's Gross Domestic Product, with the 2010

floods when the country received the highest precipitation in the shift of the climatic period (Brigadier et al., 2016). Though the IOD's impact is less obvious in Zambia than in East Africa (Rwambo et al., 2025), recent studies show its influence is growing because of trends in temperatures with alternating warm and cool SSTs between the east and the west, thus resulting in wet and dry spells over Southern Africa, respectively causing crop yield anomalies (Ogwang et al., 2020). Understanding the relationship is crucial in climate-smart agriculture in the study area.

Persistent dry spells during the agriculture period have continued and with 2023/2024 farming season seeing the worst ever drought due to early cessation of rains, there is need to have an early warning tool to help the government make timely decisions and advise coping strategies with the situation about farming methods that will be accommodated by seasonal cumulative amounts of rainfall in each area (Mwape et al., 2025). Farmers plant a moderate variety that takes 130 - 150 days to mature, with a minimum amount of water required to support the crop ranging from 450 to 500mm from germination to the maturing stage. Planting mainly occurs in the third week of November, with the majority using conventional farming methods. This crop develops in five stages after being planted in the area. These are the initial (germination), the vegetative, tussling, grain filling stage, and maturing. Each phase has an ideal amount of water required, with a lower and upper limit, respectively. Therefore, the water requirement of a maize crop at each stage is determined by its coefficient. The absolute amount is also a function of seasonal demand. Previous studies indicate that Zambia, like any other part of Southern Africa, is experiencing unpredictable and declining precipitation and Temperature variations, resulting in high evapotranspiration across the country. Northwards and southwards rainfall variations induce early stoppage of rain in the Southern part of the country (Mohajan, 2013; Twaha et al., 2025).

The objectives are to 1) evaluate the relationship between precipitation variability associated with the IOD and maize yield anomalies; 2) assess how IOD-induced climate anomalies identify the most sensitive growth stages of maize to climatic extremes; 3) establish whether the Indian Ocean Dipole has a close relationship with maize yield anomalies through the climatic suitability in Zambia.

2. Study Area, Data Sets, and Methods

2.1. Study Area

Zambia lies in Southern Africa and has no seacoast, lying between latitudes -8° and -18.5° South and Longitudes 22° and 34° East (Figure 1), with a classified climate that is tropical wet and dry with minimal stretches of semi-arid climate to the Southwestern part and around the Zambezi valley. Elevation ranges from ≤ 371 m in low-lying Southern and eastern areas to >1729 m in the northern and north-eastern highlands. This pronounced topographic gradient influences the regional atmospheric circulation, rainfall distribution, and Agro-climatic conditions. These

are critical for understanding spatial variability in maize yield anomalies and their sensitivity to the Indian Ocean Dipole-related climate variability (Musonda et al., 2020). Located in the south, it boasts a wide range of natural features and ecological processes that support its abundant wildlife spread over 752,618 square kilometers. Knowing these characteristics of Zambia is clearly crucial for addressing conservation issues and promoting sustainable land management, considering the increasing environmental challenges. With these topographic gradient influences, Zambia's geology, geography, temperature, plants, and biodiversity are affected (Denison, 2011). Its topography modulates its rainfall distribution as the start of the season is October to March, with the austral summer being the peak of the rainy season.

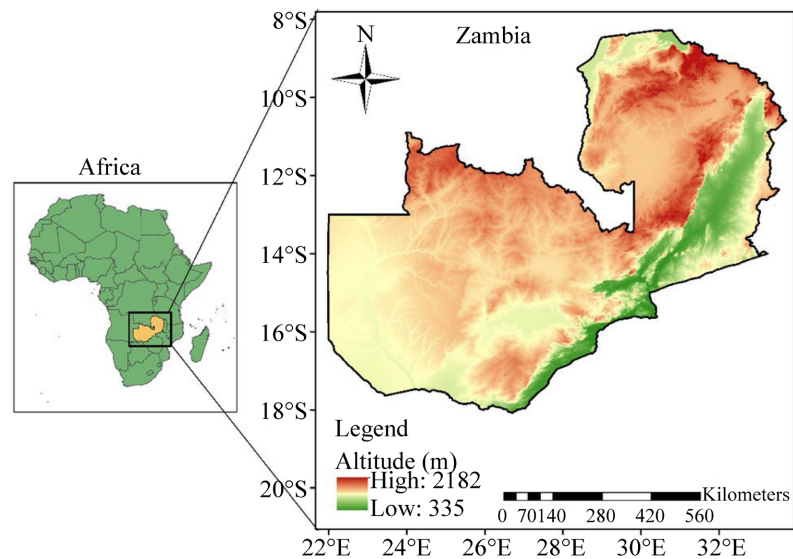


Figure 1. Zambia's boundaries in Southern Africa.

2.2. Data Sets

This study used various datasets, which include weather observations and Maize production, where meteorological yields were computed from data collected at the start of the task from the Zambia Statistics Agency, Ministry of Agriculture. Weather observations data sets were collected from the Zambia Meteorological Department headquarters in Lusaka. We used the provincial-level maize yield data for the last climatological period as of the 2024 crop marketing season in the post-rain season. The climatic upper and lower limits are computed by adopting some methods where similar studies were conducted at a provincial level on rice yield anomalies in China, based on the same climatic suitability methods (Xu et al., 2021).

The reanalysis data sets were drawn from various websites with different resolutions, including the interim <https://cds.climate.copernicus.eu/datasets/derived-era5-single-levels-daily-statistics?tab=download> with a resolution of $0.25^\circ \times 0.25^\circ$. Precipitation data were downloaded from CHIRPS V2, which is the Climate Haz-

ards Group infrared precipitation available at the data portal for the International Research Institute for Climate and Society. The dataset offers a high resolution of $0.05^\circ \times 0.05^\circ$ (Funk et al., 2015; Gebrechorkos et al., 2018). The Sea Surface temperature is the Hadley Centre global Sea Surface Temperature and Sea Ice (Rayner et al., 2003). The other dataset was downloaded from NOAA's website (<https://www.cpc.ncep.noaa.gov/products/wesley/reanalysis2/>) with a high resolution of $2.5^\circ \times 2.5^\circ$. The National Center for Environmental Prediction (NCEP)/National Centre for Atmospheric Research (NCAR) has a reanalysis of a global observation network that uses a data assimilation system of meteorological variables (Kalnay et al., 2018). Climate change on the Earth's surface is commonly quantified by the variations in the observed Sea Surface Temperature that drive other climate systems (Huang et al., 2018). For the total cloud amount, it was the vertical integral of clouds as classified as high, medium, and low clouds (Xu et al., 2021). The data used in the analysis spans from 1993 to 2024.

2.3. Methodology Used in the Research Paper

2.3.1. Calculation of the Indian Ocean Dipole

The Indian Ocean Dipole index was defined as the difference between the western Indian Ocean and the eastern Indian Ocean (Saji et al., 1999). The difference in the sea surface temperature anomalies is twofold, with positive and negative in a seesaw-like pattern. In this work, we selected the positive and Negative years by using ± 0.5 , dealing with the full rainy season from October to March. The IOD selected years the paper is working with are Positive IOD events being (1995, 1998, 2007, 2019, 2020, and 2024) and negative events being (1997, 1999, 2005, and 2006) respectively. The SVD was applied to area-weighted monthly anomalies to account for grid cell convergence to the poles. Following Bretherton et al. (1992), $\sqrt{\cos(\varphi)}$ weighting was applied to precipitation and SST fields prior to SVD decomposition. This ensures the cross-covariance matrix represents actual surface area rather than equal weighting at grid points. All other steps are the same. climatological monthly anomalies (1993-2024: no detrending), ONDJFM season, precipitation domain: $18.0^\circ\text{S} - 8.3^\circ\text{S}$, $22.0^\circ\text{E} - 33.7^\circ\text{E}$; SST domain: $30.0^\circ\text{S} - 20.0^\circ\text{N}$, $30.0^\circ\text{E} - 120.0^\circ\text{E}$. The formula used for the IOD is as follows.

$$\text{IOD} = \text{SST}_{\text{west IO}} - \text{SST}_{\text{east IO}} \quad (1)$$

2.3.2. Calculation of the Annual Maize Yield Anomaly

We followed some of the approaches from Xu et al. (2021) to calculate the annual maize yield anomalies. For a given year, provincial Agrometeorological Centre P, the percentage anomaly that deviates from a normal yield based on the country's production mean, whereby a defined 5-year running mean for the interval $t - 2$ to $t + 2$ was calculated. The 5-year running average means reducing technological trend bias and isolating climate-driven variability. The 5-year running mean interval was calculated as follows, aggregated as a country running mean based on the medium maturity maize variety.

$$Y'_{t,p} = \frac{y_{t,p} - \overline{y_{t,p}}}{y_{t,p}} \times 100 \quad (2)$$

2.3.3. Precipitation Anomaly Percentage

Precipitation Anomaly percentage was calculated as follows.

$$P'_i = \frac{P_{i-\bar{P}}}{\bar{P}} \times 100 \quad (3)$$

where \bar{P} is the average precipitation for the research period in Zambia, calculated for the entire country; P_i is the precipitation amount in a particular month, and P'_i is the anomaly percentage for a particular month in the agricultural season for the crop.

2.3.4. Climatic Suitability of Maize Yield Anomalies-Temperature Based

Earlier research (Xu et al., 2021) shows that climatic appropriateness has been demonstrated to be closely tied to crop yield. Hence, identifying climatic conditions is an excellent way of predicting crop yields and adaptability.

In a given year under a specific climate scenario (Teixeira et al., 2013), Climatic suitability is the best way to forecast crop yields as heat stress affects these crops in both sub-tropical and temperate regions. Most studies examine three forms of climatic suitability, and that is in accordance with temperature, duration of sunshine on the crop, and daily rainfall at early stages to maturation, with each stage varying (Xu et al., 2021).

The temperature is calculated using fuzzy mathematics (Cutforth & Shaykewich, 1990) as a nonlinear equation. The β -function can fairly depict the nonlinear relationship between the maize crop's development and temperature. The ideal temperature range varies above and below the mean suitability, with B being the temperature-dependent factor, and T_0 the time-dependent optimum observational temperature. The temperature suitability (ST) ranges from 0 to 1. When the temperature (T) is less than or equal to the lower limit or greater than or equal to the upper limit, the crop stops growing as temperature suitability is zero (Xu et al., 2021). defined as:

$$S_r = \begin{cases} \left[\frac{(T - T_1) \times (T_2 - T)^B}{(T_0 - T_1) \times (T_2 - T_0)} \right] & (T_1 < T < T_2) \\ B = \frac{T_2 - T_0}{T_0 - T_1} & \\ 0 & (T \leq T_1 \text{ or } T \geq T_2) \end{cases} \quad (4)$$

During growth stages of any crop, sunshine duration plays a pivotal role within a certain range, owing to the process of photosynthesis depending on the crop type and variety, with 70% daily duration being a critical value (S_6) and suitability is one (Shaw, 1964). The crop response to total sunshine hours on a daily basis explains the suitability of the growth state upon attaining and exceeding this value. The value b is an empirical parameter that varies with maize growth by stage for the

study period (Xu et al., 2021). Sunshine suitability (S_s) on maize was calculated as:

$$S_s = \begin{cases} e^{-\left[\frac{1-S_0}{b}\right]^2} & (S < S_0) \text{ or } (S \geq S_0) \\ 1 & \end{cases} \quad (5)$$

Precipitation suitability (S_p) is based on 10 days of precipitation meteorological Observations in millimeters (mm), with P being the actual precipitation. However, when precipitation is excessive, it harms the crop during the growth stages, and on the other hand, a lack of water balance at each stage results in crop failure, and the crop dies. In increased water vapor transport, the precipitation suitability is affected negatively towards the crop growth (Xu et al., 2021). The calculation was as follows:

$$S_p = \begin{cases} P/P_0 & (P < P_0) \\ P/P_0 & (P \geq P_0) \end{cases} \quad (6)$$

3. Results and Discussion

3.1. The Connection between the IOD and Maize Yield Anomalies

To arrive at the relationship between the Indian Ocean's SSTs and the maize yield, we employed the statistical method of Singular Value Decomposition (SVD) because it is selected as powerful in identifying coupling modes that are dominant between two (2) data set time series (Bretherton et al., 1992).

The dominant SVD mode represents the primary coupled variability of 82.7% between Indian Ocean SST anomalies and precipitation (**Figure 2(a)** and **Figure 2(b)**) over Zambia, consistent with the maximum covariance framework of (Bretherton et al., 1992). The precipitation pattern shows a clear dipole structure across Zambia, with positive rainfall anomalies dominating the southern and central regions, while negative anomalies appear over the northern sector (Saji et al., 1999). The results show that the SVD1 is associated with spatially contrasting rainfall responses over Zambia, suggesting a redistribution of moisture rather than uniform wet or dry conditions. The SST pattern displays predominantly negative SST anomalies across much of the equatorial and central Indian Ocean, with localized warm anomalies toward the Southwestern Indian Ocean. This pattern resembles an Indian Ocean Dipole-like structure where cooling over the central-eastern basin is linked to circulation changes that favor enhanced moisture transport toward southern Zambia. There is a variation (**Figure 2(c)**) coherence over time with a moderate positive correlation of $r = 0.48$, indicating a close relationship. This shows divergence between two series, implying that other climate drivers like ENSO also influence variability that is dominated by large-scale oscillations over the region (Nugroho & Nuraini, 2016). The spatial loading is uniformly positive across most of the country, demonstrating that both wet and dry years tend to occur synchronously across Zambia rather than exhibiting strong regional contrasts. The coherence is suggested to be spatially controlled by large-scale general circulation rather than either mesoscale or local processes, with variance that is attributed to basin-

scale circulation anomalies linked to tropical SST forcing (Manatsa & Mukwada, 2012). The consistency of these results in Southern Africa highlights the robustness of large-scale oceanic-atmosphere teleconnection in shaping the entire regional hydroclimate.

Table 1. Parameters used to determine the climatic variables S_T , S_P , and S_S during maize growth and development suitability stages were determined by 9 agrometeorological observations in Zambia.

Stage	S_T (Daily Temperature)				S_P (10 Days Mean Precipitation)	S_S (Daily Sunshine Hours)
	T_1/C	T_0/C	T_2/C	B	P_0/mm	S_s/h
Germination and Emergence	20	24	28	1	30.6	6
Early Vegetation	16	20	25	1.25	30.6	8
Tasseling Onset	21	25	30	1.25	35.5	9
Early Grain Fill	20	21	22	1	30.6	8
Late Grain Fill and Maturity	21	22	23	1	30.6	7

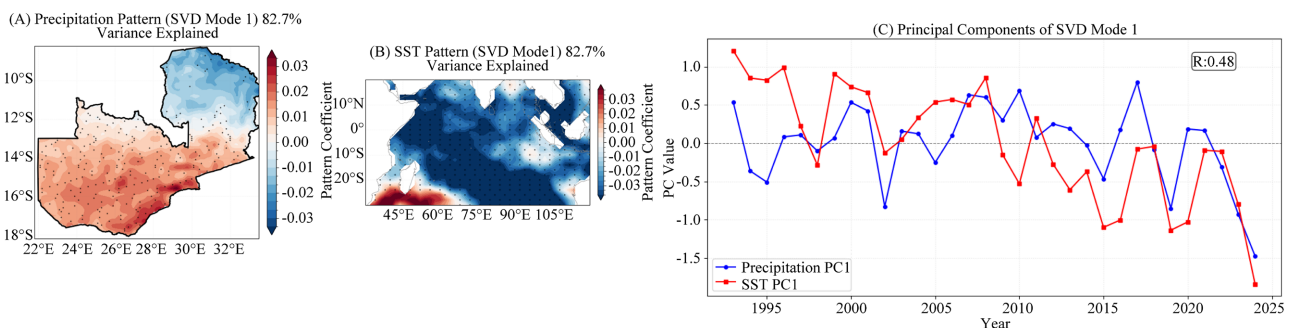


Figure 2. Coupled variability between the Indian Ocean (SST) anomalies and precipitation revealed by Singular Value Decomposition (SVD). (A) Precipitation anomaly pattern over Zambia and (B) Associated SST anomaly pattern over the Indian Ocean. The correlation coefficient of the (TCC) of the precipitation (blue line) and IOD-like SST (red) is 0.48. The stripling indicates statistically significant regions at the 99% confidence level. SVD1 describes 82.7% variance.

3.2. The IOD-Driven Circulation Anomaly

The IOD index is defined based on the SST anomaly as the difference between the western and the southeastern region within 10°S - 10°N, 50°E - 70°E, and 10°S to the equator, 90°E - 110°E regions, respectively. Attention should be drawn to the central, southern, and some parts of eastern Zambia (Figure 3), where there are more maize farmers, indicating a higher percentage in the total maize yield anomaly for the study area. Large-scale circulation anomalies associated with the IOD phases are illustrated. During the negative IOD events, anomalous cool SSTs in the western Indian Ocean and warm SSTs in the Eastern basin modify the zonal SST gradient. This alters the Walker circulation, thereby strengthening the easterly low-level inflow towards southern Africa (Saji et al., 1999; Behera & Yamagata, 2003).

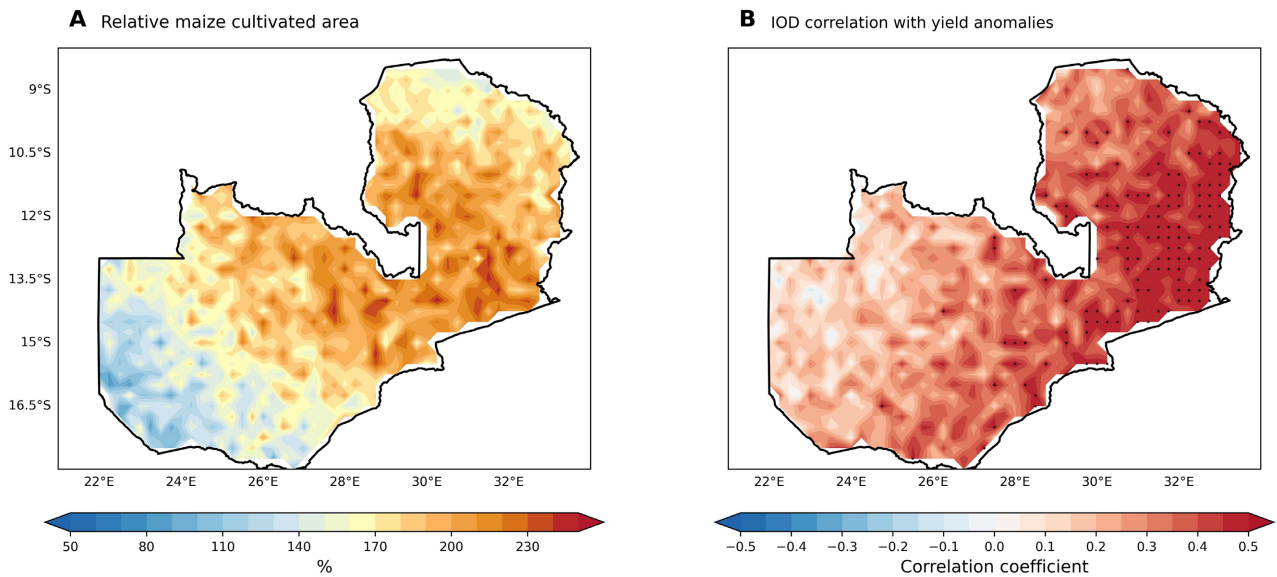


Figure 3. (A) Relative maize cultivated area intensity (% of maximum area) and (B) Pearson correlation coefficient between IOD index and maize yield anomalies in Zambia. Black dots in the panel indicate statistically significant correlations at a 95% confidence level from 1993 to 2024.

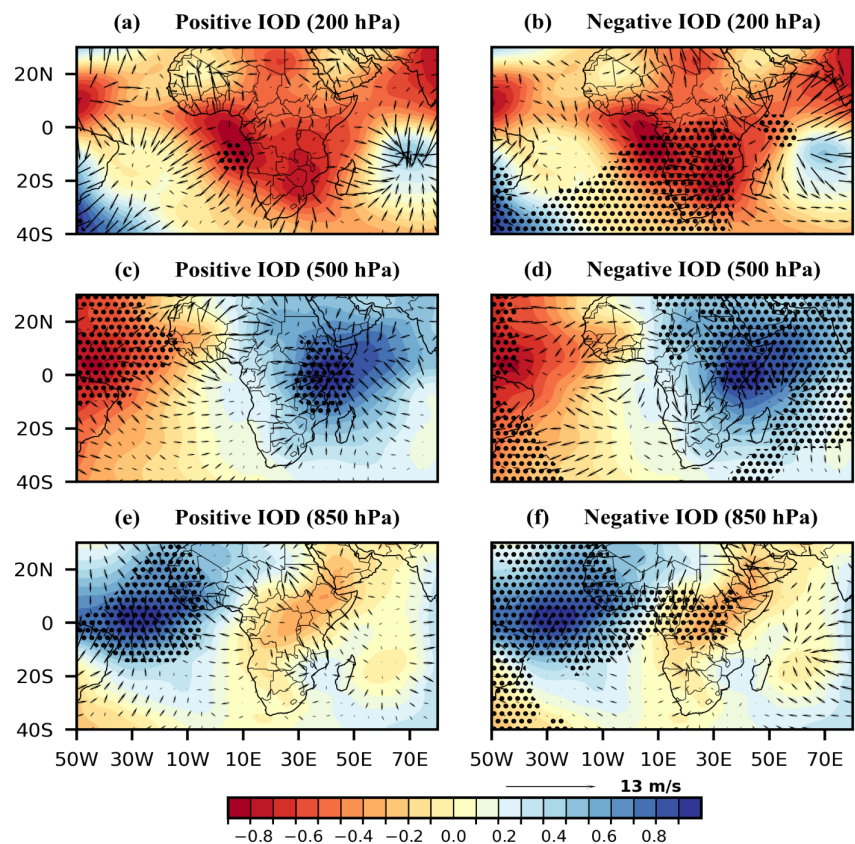


Figure 4. Composite anomalies during positive (left) and negative(right) Indian Ocean Dipole (IOD) phases: wind vectors and shaded anomalies (a, b) 200 hPa; (c, d) 500 hPa; and (e, f) 850 hPa. Shading indicated anomaly magnitude. Units consistent with the color bar and reference vector length corresponds to 13 m/s.

At 850 hPa, these conditions modulate enhanced moisture transport from the Southwest Indian into the Sub-continent over Africa, complemented by Northerly inflow from the Congo basin. The convergence of these moisture streams over the study area results in a strong low-level moisture convergence that creates (Figure 4) conditions that are favorable for an unstable atmosphere through enhanced convective developments following the rising motion. Vertically integrated moisture flux diagnostics confirm further moisture availability during negative IOD years, favoring wet conditions. At level 500 hPa, the negative phase is associated with anomalous cyclonic circulation and vertical motion supporting deep convection by facilitating moisture transport and cloud formation. At 200 hPa, enhanced divergence aloft indicates efficient mass evacuation from the upper troposphere, reinforcing sustained convective activity. These connections at low, mid, and high level upward coherence upper level divergence represent a dynamical configuration for wet austral summers over southern Africa classically (Washington & Preston, 2006; Nicholson, 2017). During the positive phase, in contrast, a weakened easterly moisture transport reduces inflow from the Congo Basin, and dominant low-level divergence over the study area is accompanied by anticyclonic circulation at mid-levels and pronounced subsidence that suppresses convection and limits rainfall. This underscores the sensitivity of Zambia's hydroclimate to the Indian Ocean SST gradients.

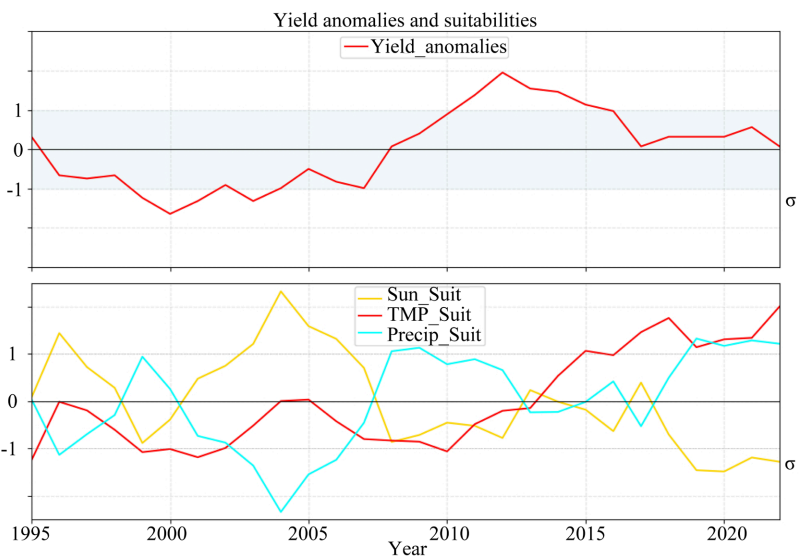


Figure 5. Time series of standardized maize yield anomalies (top orange) and agroclimatic suitability indices (bottom) for temperature (TMP_Suit, red), precipitation (Precip_Suit, blue), and sunshine duration (Sun_Suit, yellow). All variables are expressed in standard deviation from their long-term means.

3.3. Climatic Suitability and Maize Yield Response

Among the temporal evolution of the proposed climatic suitability variables based on precipitation, temperature, and sunshine duration, precipitation suitability exhibits the strongest and most immediate response to the general circulation (Fig-

ure 5) represented by the IOD. The negative phase is characterized by sustained improvement in precipitation over Zambia, particularly during the tasseling and grain-filling maize growth stage when moisture demand is at peak. Physiologically, water stress during these stages reduces kernel number and increases grain weight. This leads to substantial crop yield losses even when earlier growth conditions are analyzed as favorable (Lobell & Field, 2007; Cairns et al., 2012). The strong alignment between precipitation suitability and yield anomalies, therefore, reflects both climatic control and crop sensitivity with a correlation coefficient of 0.45, $p = 0.01$, and -0.21 for negative and positive IOD years, respectively. Temperature suitability shows a weaker but still notable influence on yield variability. Beyond the upper limit (Table 1), the flowering stage can exacerbate moisture stress and reduce pollen viability (Ombevah & Njeru, 2025). In this study, temperature suitability remains within an optimal threshold due to enhanced Total Cloud Cover and evaporative cooling conditions that reinforce the beneficial effects of increased rainfall. Sunshine duration on maize decreases during wet years because cloud amount increases; however, it does not offset the crop from improved soil moisture and reduces heat stress. These results are consistent with previous studies in rainfed agricultural tropical systems, which identify moisture availability as the primary limiting factor for maize production (Challinor et al., 2014a; Ray et al., 2015).

The compound effect of the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole interactions demonstrates that the impacts of the IOD on maize yield anomalies cannot be considered in isolation. Instead, it operates within a broader climate system where interactions with ENSO modulate both the magnitude and spatial expression. These interactions intensify, leading to severe droughts and widespread crop failures, while on the other hand, they improve yield potential. However, excessive rainfall may also increase risks of waterlogging, nutrient leaching, and crop disease, highlighting the nonlinear nature of climate-crop interactions (Behera et al., 2005; Funk et al., 2015).

The IOD exerts a statistically significant and spatially coherent control on Zambian precipitation, producing a meridional dipole characterized by enhanced rainfall in northern Zambia during the positive phase and suppressed rainfall in the southern part during negative IOD phases (Figure 6), with the opposite pattern during the negative phase (Saji et al., 1999). With the negative phase breaking the barrier, the country is considered saturated during the peak months, hence favorable for yield. This response reflects the large-scale reorganization of moisture transport and vertical motion (Figure 7) associated with Indian Ocean convection anomalies. This demonstrates that Zambia's hydro climate variability is strongly modulated by the tropical Indian Ocean circulation. For instance, the 1997-1998 El Niño and favorable IOD event resulted in a 50% drop in Zambian crop output (Lekprichakul, 2008) and attracted a severe drought. La Niña is, and IOD are capable of boosting rainfall, therefore increasing flood hazards as seen during the 2010/2011 farming season (Yamagata et al., 2004). Changes in atmos-

pheric circulation, including the subtropical jet stream and local low-pressure systems, mediate these interactions. Notwithstanding their importance, the combined impacts of ENSO and IOD on Zambian rainfall and maize yields are still understudied.

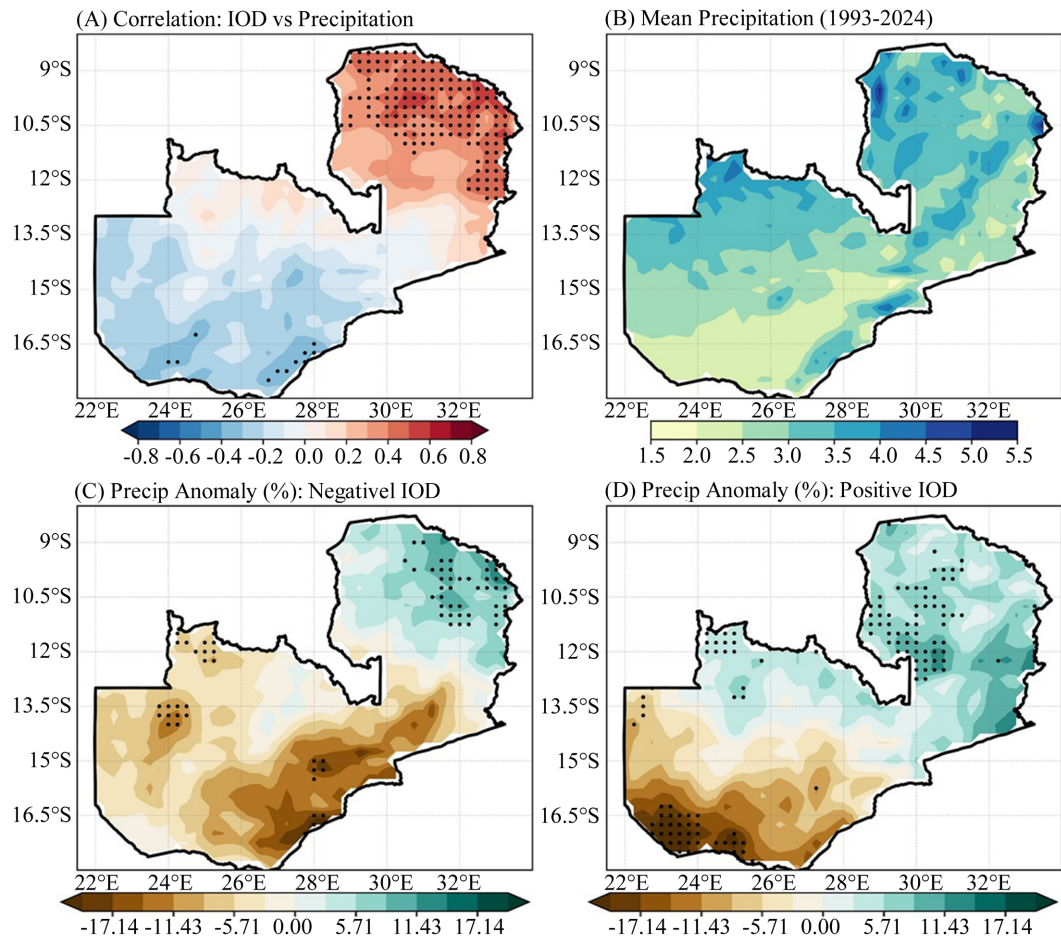


Figure 6. Indian Ocean Dipole influence on precipitation over Zambia: (A) Correlation coefficient between IOD index and seasonal precipitation; (B) Climatological mean precipitation from 1993-2024; (C) Composite anomalies for precipitation (%) during negative IOD phases, and (D) Composite precipitation anomalies (%) during positive IOD phases. Dots indicate statistically significant correlations at a 95% confidence level.

A key contribution of this study is the explicit demonstration of a physically consistent pathway linking general circulation, represented by the Indian Ocean Dipole, to maize yield anomalies in the study area. The negative Indian Ocean Dipole phase modifies the Walker circulation, enhances easterly moisture transport, and promotes vertically coherent ascent over southern Africa, resulting in improved precipitation during critical maize growth stages.

The water vapor transport is seen in the asymmetry in the circulation response over Zambia, with both the positive and the negative IOD years exhibiting a distinct pattern of moisture transport variability. The confidence levels differ markedly (**Figure 8**) between phases. During positive IOD years, significant anomalies

are more widespread and coherent along moisture transport pathways into central Southern Africa. This suggests that suppressed moisture inflow and enhanced subsidence associated with positive IOD phases constitute a robust and dynamically consistent circulation anomaly, leading to a reliable reduction in moisture deliver into Zambia while the negative phase shows enhanced moisture flux anomalies toward the region, the corresponding significant points are relatively sparse indicating that the wet circulation response is less stable and more influenced by interannual variability and interactions with other climate drivers like the ENSO and the Angola low pressure system. This asymmetric response implies that the drying influence of positive IOD is more systematic and reproducible than the wet phase of the negative IOD, thereby consistent with the previous studies emphasizing the dynamical impact of the tropical Indian Ocean variability on Southern African climate (Saji et al., 1999; Ogwang et al., 2020; Moihamette et al., 2024).

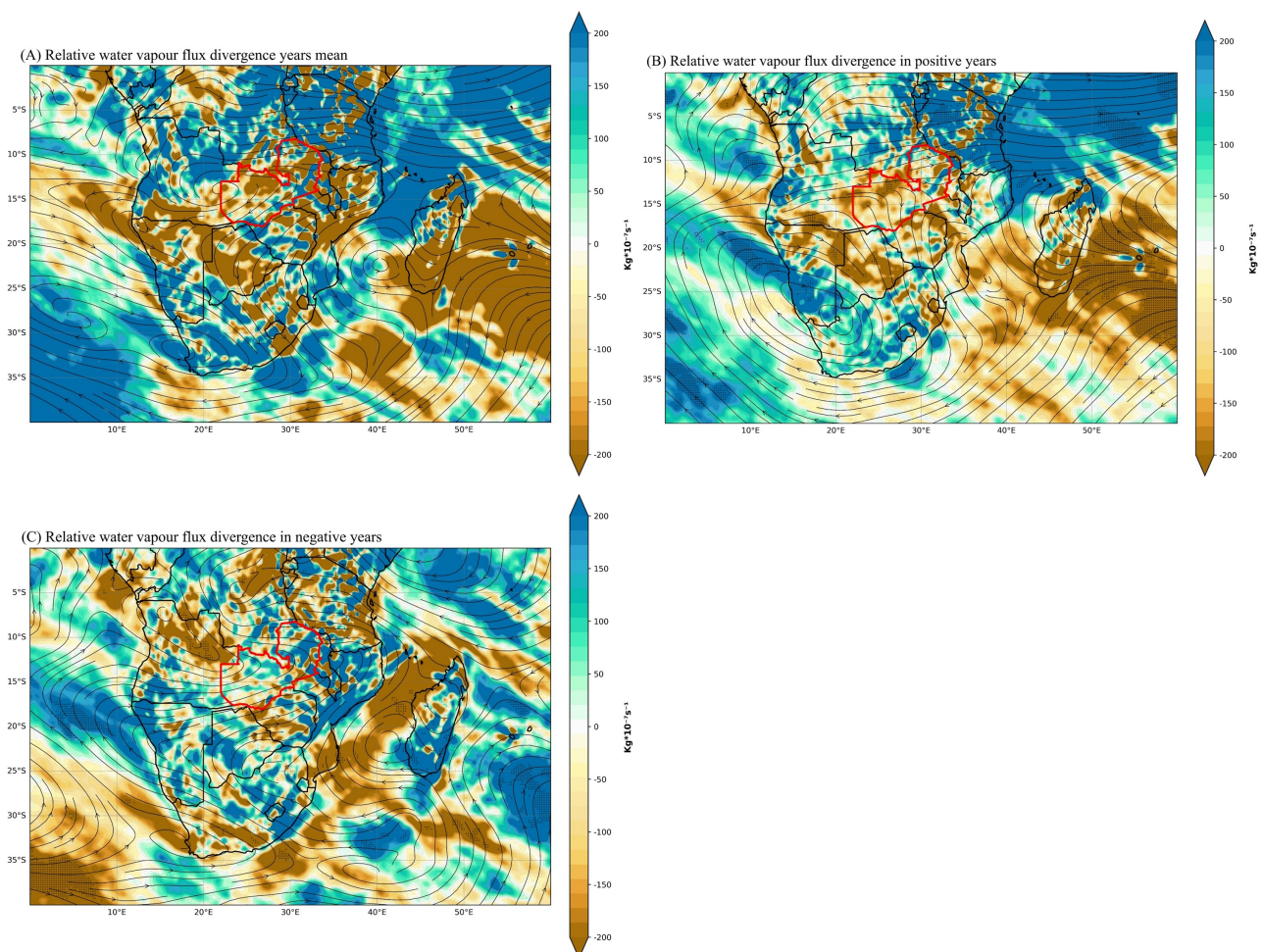


Figure 7. (A) Mean of vapour flux in the 1993-2024 rain season; (B) Relative bias of water divergence in positive IOD years; (C) Relative bias in IOD negative years. Water vapour flux divergence is indicated by depletion of more moisture in Zambia; Colours and the vectors indicate the pathway of water vapor flux. Dotted areas are significant points in a two-tailed t-test at a 95% confidence level.

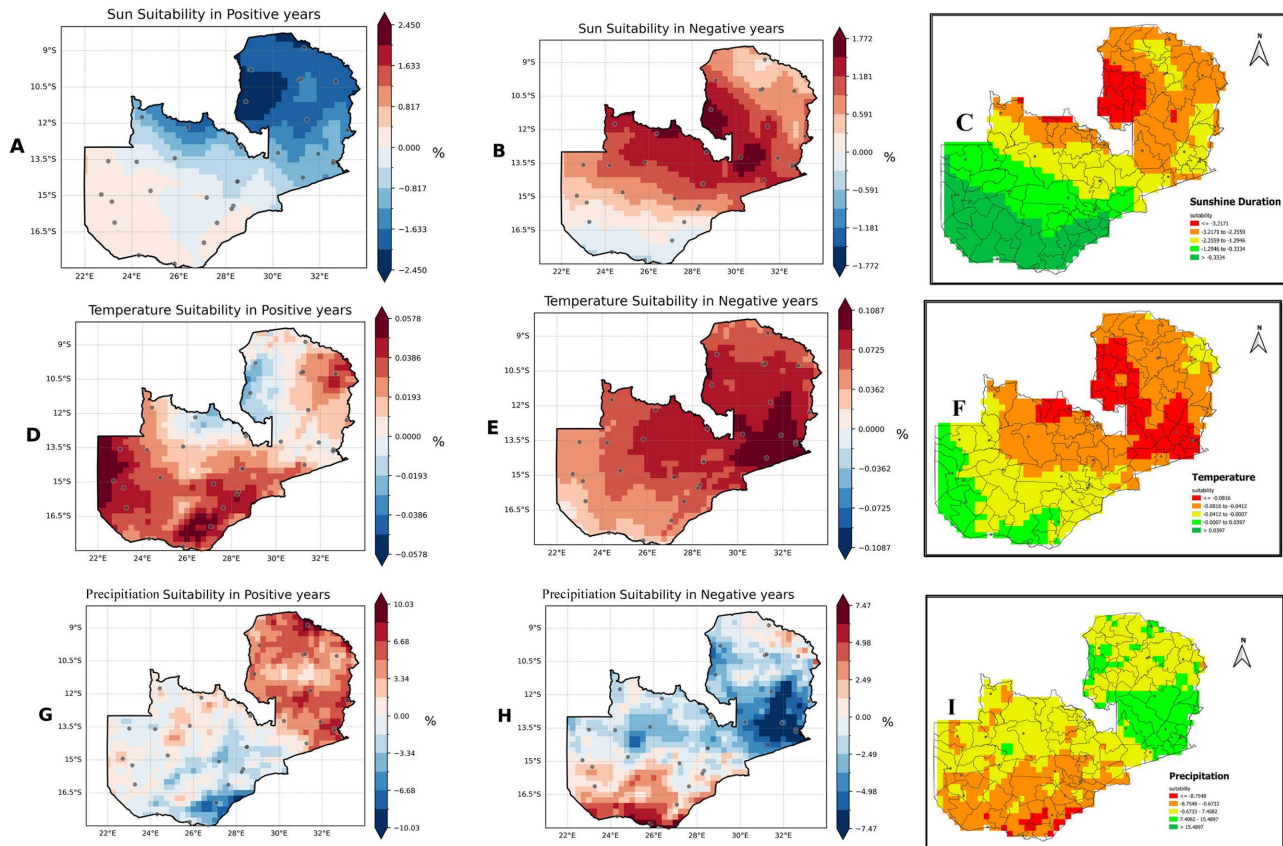


Figure 8. (A) Sunshine suitability relative bias in positive IOD years; (B) Negative IOD years; (C) Average sunshine duration in October-March from 1993-2024 in Zambia; (D) - (F) is for temperature, and (G) - (I) is for precipitation. The precipitation suitability has a close relationship with maize yield anomaly in Zambia.

3.4. Relationship between Precipitation and Maize Yield Anomalies

The relationship between monthly precipitation anomalies and annual maize yield anomalies was assessed by computing the correlation coefficient for a large range of precipitation anomaly percentages (0% - 200%) for the period from October to April (**Figure 9**). We see precipitation during the mid-late growing season (December through March) exhibits positive correlations with maize yield, with the strongest association appearing in February and March. Specifically, correlation coefficients in February increased progressively from moderate to high values ($r = 0.52 - 0.71$) with correlations statistically significant at the 95% confidence level. This indicates that above normal rainfall in this period is associated with positive yield anomalies. By contrast, early-season precipitation shows weak correlation with yield, and many of these correlations were not significant, suggesting limited effects of early rainfall on yield. April correlations were generally low and non-significant; hence, the study period and main season ended in March. In crop culture (*Xu et al., 2021*), there is a threshold in percentages, and only when a crop hits that threshold in extreme years will it have yield anomalies. In rice crop culture, an anomaly of 40% around July affects the crop.

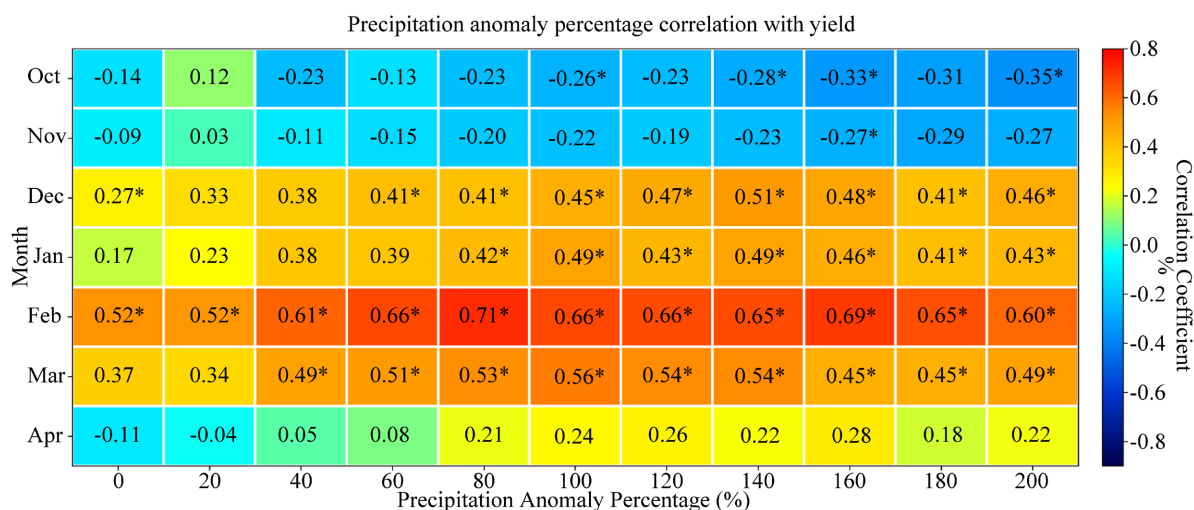


Figure 9. The annual precipitation anomaly in October-April, respectively, is compared with the annual maize yield anomaly. Boxes with (*) passed the significant test at the 95% level of significance.

4. Conclusion

This study provides evidence that IOD-driven general circulation significantly modulates maize yield anomalies in Zambia through its control on Moisture Transport and precipitation suitability among the proposed variables of the climate suitability based on temperature, sunshine duration, and precipitation. Negative IOD phases favor enhanced rainfall and positive yield anomalies, while positive phases increase drought risk. Integrating IOD signals into forecasts could improve early warning systems and climate-smart agricultural planning in Zambia and the wider Southern African region. Further integrating the IOD-informed climate outlooks into the national agricultural planning window, alongside other investments in drought-tolerant crop varieties apart from maize, improved water balance management, and climate-smart agronomic practices will be essential to mitigate future risks.

This study further demonstrates that the Indian Ocean Dipole functions as a major large-scale regulator of hydroclimate variability over Zambia, exerting its influence through modulation of atmospheric circulation, moisture transport pathways, and vertical motion anomalies. The strong association between the dominant rainfall mode and the IOD index confirms that Zambia's rainfall variability is dynamically linked to tropical Indian Ocean sea surface temperature gradients rather than solely being controlled by local processes. A key contribution of this work is the establishment of a physically consistent pathway connecting Oceanic forcing to agricultural outcomes. The sequence of IOD-induced SST gradients altering atmospheric circulation, which in turn modifies moisture convergence, precipitation suitability, and ultimately maize yield anomalies, strengthens confidence that the identified relationships are mechanistic and not merely statistical coincidences. Among all climatic suitability components, precipitation suitability emerges as the primary determinant of maize yield variability. This finding under-

scores the dominant role of water availability in Zambia's rain-fed agricultural systems while temperature and sunshine act as secondary modifiers. The results, therefore, highlight the continued vulnerability of maize production to circulation-driven rainfall fluctuations. The impacts of the general circulation represented by the IOD are especially pronounced when they coincide with maize growth stages, particularly tasseling and grain filling. This seasonal alignment explains differences in yield responses between IOD events and demonstrates that the timing of climate anomalies is as critical as their intensity. The spatial coherence of the leading mode suggests that maize yield often occurs simultaneously across provinces, increasing the likelihood of the nationwide production shocks rather than isolated local failures. This has important implications for food security, market stability, and national grain reserve management. Although the IOD exerts dominant control on the general circulation, its influence can interact with other climate systems, such as ENSO and regional circulation features like the Angola low-pressure system. Considering multiple climate modes together may therefore improve the skill of seasonal agricultural outlooks. Since the Indian Ocean Dipole develops several months before the peak maize growing season, it offers a suitable predictive window in the crop culture. Integrating the dipole monitoring into agrometeorological advisory systems across the country could positively enhance early warning capacity, guide planting decisions such as seed quality and variety, and support climate-informed agricultural investments while maintaining food security. The findings underscore the growing importance of the Indian Ocean-driven circulation to Zambia's economy and highlight the potential for integrating IOD signals into seasonal forecasting and agricultural risk management. The analyses in this paper verify the significance of the Indian Ocean Dipole index on the spatial distribution of rainfall over Zambia. The observed dipole emphasizes the need to include IOD monitoring in the forecasting and management of climate risks. Further research is needed to explore the relationships between IOD-related sea surface temperature gradients and the regional circulations and moisture transport over southern Africa, so as to track the rainfall pattern very well while keeping in check other suitability variables influencing maize yield anomalies.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- Behera, S. K., & Yamagata, T. (2003). Influence of the Indian Ocean Dipole on the Southern Oscillation. *Journal of the Meteorological Society of Japan. Series II*, *81*, 169-177. <https://doi.org/10.2151/jmsj.81.169>
- Behera, S. K., Luo, J., Masson, S., Delecluse, P., Gualdi, S., Navarra, A. et al. (2005). Paramount Impact of the Indian Ocean Dipole on the East African Short Rains: A CGCM Study. *Journal of Climate*, *18*, 4514-4530. <https://doi.org/10.1175/jcli3541.1>
- Bretherton, C. S., Smith, C., & Wallace, J. M. (1992). An Intercomparison of Methods for Finding Coupled Patterns in Climate Data. *Journal of Climate*, *5*, 541-560. [https://doi.org/10.1175/1520-0442\(1992\)005<0541:aiomff>2.0.co;2](https://doi.org/10.1175/1520-0442(1992)005<0541:aiomff>2.0.co;2)
- Brigadier, L., Ogwang, B. A., Ongoma, V., Ngonga, C., & Nyasa, L. (2016). Diagnosis of the 2010 DJF Flood over Zambia. *Natural Hazards*, *81*, 189-201. <https://doi.org/10.1007/s11069-015-2069-z>
- Cairns, J. E., Sonder, K., Zaidi, P. H., Verhulst, N., Mahuku, G. et al. (2012). Maize Production in a Changing Climate: Impacts, Adaptation, and Mitigation Strategies. *Advances in Agronomy*, *114*, 1-58.
- Challinor, A. J., Watson, J., Lobell, D. B., Howden, S. M., Smith, D. R., & Chhetri, N. (2014). A Meta-Analysis of Crop Yield under Climate Change and Adaptation. *Nature Climate Change*, *4*, 287-291. <https://doi.org/10.1038/nclimate2153>
- Cutforth, H. W., & Shaykewich, C. F. (1990). A Temperature Response Function for Corn Development. *Agricultural and Forest Meteorology*, *50*, 159-171. [https://doi.org/10.1016/0168-1923\(90\)90051-7](https://doi.org/10.1016/0168-1923(90)90051-7)
- Denison, K. M. (2011). *Farmer Land Allocation for Maize, Groundnut and Cotton Production in Chipata District, Eastern Province, Zambia*. Michigan Technological University. <https://search.proquest.com/openview/b6d27b51d2c6888b9a48b50ea80183bd/1?pq-origsite=gscholar&cbl=18750>
- Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S. et al. (2015). The Climate Hazards Infrared Precipitation with Stations—A New Environmental Record for Monitoring Extremes. *Scientific Data*, *2*, 1-21. <https://doi.org/10.1038/sdata.2015.66>
- Gebrechorkos, S. H., Hülsmann, S., & Bernhofer, C. (2018). Evaluation of Multiple Climate Data Sources for Managing Environmental Resources in East Africa. *Hydrology and Earth System Sciences*, *22*, 4547-4564. <https://doi.org/10.5194/hess-22-4547-2018>
- Huang, J., Zhang, F., Zhou, L., Hu, Z., & Li, Y. (2018). Regional Changes of Climate Extremes and Its Effect on Rice Yield in Jiangsu Province, Southeast China. *Environmental Earth Sciences*, *77*, Article No. 106. <https://doi.org/10.1007/s12665-018-7295-8>
- Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L. et al. (2018). The NCEP/NCAR 40-Year Reanalysis Project. In *Renewable Energy* (pp. 146-194). Routledge. <https://doi.org/10.4324/9781315793245-16>
- Lekprichakul, T. (2008). *Impact of 2004/2005 Drought on Zambia's Agricultural Production and Economy: Preliminary Results*. Working Paper on Social-Ecological Resilience Series No. 2008-002. <https://www.chikyu.ac.jp/resilience/files/WorkingPaper/WP2008-002.Thamana.pdf>
- Lobell, D. B., & Field, C. B. (2007). Global Scale Climate-Crop Yield Relationships and the Impacts of Recent Warming. *Environmental Research Letters*, *2*, Article 014002.

- <https://doi.org/10.1088/1748-9326/2/1/014002>
- Manatsa, D., & Mukwada, G. (2012). Rainfall Mechanisms for the Dominant Rainfall Mode over Zimbabwe Relative to ENSO and/or Iodzm. *The Scientific World Journal*, 2012, 1-15. <https://doi.org/10.1100/2012/926310>
- Mohajan, H. (2013). *Declining Economy in Zambia and Its Impact in Food Security*. <https://mpira.ub.uni-muenchen.de/id/eprint/50683>
- Moihamette, F., Pokam, W. M., Diallo, I., & Washington, R. (2024). Response of Regional Circulation Features to the Indian Ocean Dipole and Influence on Central Africa Climate. *Climate Dynamics*, 62, 1-21. <https://doi.org/10.1007/s00382-024-07251-w>
- Musonda, B., Jing, Y., Iyakaremye, V., & Ojara, M. (2020). Analysis of Long-Term Variations of Drought Characteristics Using Standardized Precipitation Index over Zambia. *Atmosphere*, 11, Article 1268. <https://doi.org/10.3390/atmos11121268>
- Mwape, A., Hayes, M., Bathke, D. J., Smith, K. H., Mahmood, R., & Jones, E. (2025). Drought Management in Zambia: Insights from the 2023/2024 Drought. *Climate*, 13, Article 227. <https://doi.org/10.3390/cli13110227>
- Nicholson, S. E. (2017). Climate and Climatic Variability of Rainfall over Eastern Africa. *Reviews of Geophysics*, 55, 590-635. <https://doi.org/10.1002/2016rg000544>
- Nugroho, B. D. A., & Nuraini, L. (2016). Cropping Pattern Scenario Based on Global Climate Indices and Rainfall in Banyumas District, Central Java, Indonesia. *Agriculture and Agricultural Science Procedia*, 9, 54-63. <https://doi.org/10.1016/j.aaspro.2016.02.124>
- Ogwang, B. A., Ongoma, V., Shilenje, Z. W., Ramotubei, T. S., Letuma, M., & Ngaina, J. N. (2020). Influence of Indian Ocean Dipole on Rainfall Variability and Extremes over Southern Africa. *Mausam*, 71, 637-648. <https://doi.org/10.54302/mausam.v71i4.50>
- Ombevah, A. K., & Njeru, M. K. (2025). Impact of Annual Temperature and Rainfall Anomalies on Maize Yields in Machakos County: An Analysis from 1993 to 2023. *International Journal of Latest Technology in Engineering Management & Applied Science*, 14, 264-271. <https://doi.org/10.51583/ijltemas.2025.140300030>
- Ray, D. K., Gerber, J. S., MacDonald, G. K., & West, P. C. (2015). Climate Variation Explains a Third of Global Crop Yield Variability. *Nature Communications*, 6, Article No. 5989. <https://doi.org/10.1038/ncomms6989>
- Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P. et al. (2003). Global Analyses of Sea Surface Temperature, Sea Ice, and Night Marine Air Temperature since the Late Nineteenth Century. *Journal of Geophysical Research: Atmospheres*, 108, 1-37. <https://doi.org/10.1029/2002jd002670>
- Rwambo, I., Fan, Y., Yu, P., Chu, C., Nyasulu, M., & King'uzza, P. (2025). Interannual Variability of Short Rains in Tanzania and the Influences from ENSO and the Indian Ocean Dipole. *Atmospheric and Oceanic Science Letters*, 18, Article 100614. <https://doi.org/10.1016/j.aosl.2025.100614>
- Saji, N. H., Goswami, B. N., Vinayachandran, P. N., & Yamagata, T. (1999). A Dipole Mode in the Tropical Indian Ocean. *Nature*, 401, 360-363. <https://doi.org/10.1038/43854>
- Shaw, L. H. (1964). The Effect of Weather on Agricultural Output: A Look at Methodology. *Journal of Farm Economics*, 46, 218-230. <https://doi.org/10.2307/1236485>
- Teixeira, E. I., Fischer, G., van Velthuisen, H., Walter, C., & Ewert, F. (2013). Global Hot Spots of Heat Stress on Agricultural Crops Due to Climate Change. *Agricultural and Forest Meteorology*, 170, 206-215. <https://doi.org/10.1016/j.agrformet.2011.09.002>
- Twaha, M., Semgomba, D., Ndabagenga, D., & Mwinjuma, M. (2025). Temporal and Spatial Variation Characteristics of March-April-May Precipitation in Tanzania and Its Relationship with SST. *Journal of Geoscience and Environment Protection*, 13, 130-150.

<https://doi.org/10.4236/gep.2025.1312008>

- Washington, R., & Preston, A. (2006). Extreme Wet Years over Southern Africa: Role of Indian Ocean Sea Surface Temperatures. *Journal of Geophysical Research: Atmospheres*, *111*, D15104. <https://doi.org/10.1029/2005jd006724>
- Xu, J., Koldunov, N. V., Xu, M., Zhu, X., Fraedrich, K., Jiang, X. et al. (2021). Impacts of Indian Ocean Dipole-Like SST on Rice Yield Anomalies in Jiangsu Province. *Frontiers in Earth Science*, *8*, Article 568365. <https://doi.org/10.3389/feart.2020.568365>
- Yamagata, T., Behera, S. K., Luo, J., Masson, S., Jury, M. R., & Rao, S. A. (2004). Coupled Ocean-Atmosphere Variability in the Tropical Indian Ocean. In *Geophysical Monograph Series* (pp. 189-211). American Geophysical Union. <https://doi.org/10.1029/147gm12>