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Our journal strives to contribute essential research findings to the international community, aiding researchers, scientists, institutions, and societies in staying abreast of new developments in theory and applications. We welcome experimental, computational, and theoretical studies that enrich the understanding of climate-related challenges.

Focal areas of interest include, but are not limited to, climate adaptation, mitigation strategies, interdisciplinary studies, climate trends, climate data analysis, climate modeling, climate economics, and the impact of climate change on agriculture, water resources, health, and the environment. We emphasize the integration of climate science into various fields and the collaboration needed to address the complex challenges posed by climate change.

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# Analysis of Drought Characteristics and their relationship with Crop yield in Northwestern Nigeria

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## Abstract:

*Drought affects virtually all climate regions, with a profound impact on arid and semi-arid regions worldwide. This study examines drought characteristics and their relationship with crop yield estimation in Northwestern Nigeria, using monthly rainfall and minimum and maximum temperatures from 1980 to 2021, while crop yield information is from 2009 to 2021. The Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI) were used to characterize drought. Correlation and regression analyses were performed with SPI SPEI and crop yield estimation. Results of correlation and regression analysis show the behavior of drought indices varies: SPEI better predicts yield at Kaduna ($R^2$ = 80.3%) and Kano ($R^2$ = 56.7%), while SPI performs better at Jigawa ($R^2$ = 66.6%) and Kano ($R^2$ = 66.6%). Hence, it is sensitive to drought quantification, whereas SPI can serve as an indicator of regional crop production. Crop yield of maize shows a highly positive linear correlation with SPEI in Kaduna (0.774) and a very low correlation in Jigawa (0.191). These factors can be used effectively to monitor and assess food grain production, thereby enabling the adoption of appropriate agricultural practices to minimize the effects of drought.*

**Keywords:** Drought, Crop yield, SPI, SPEI, Relationship.

* Corresponding author

## 1. Introduction

Climate change increases the frequency and magnitude of hydro-meteorological hazards, such as drought and floods, that affect virtually all regions of the world. Drought has a profound impact on crop yield and the subsistence farming economy in arid and semi-arid lands of developing countries. (Hamal et al., 2020). Global assessment report on disaster risk reduction (2023) observed that drought phenomena are dramatically increasing with great effect on global food security, employment, education and about two billion people are now living under water stress condition and where 80% are at the risk of crop failure, resulted to the hunger in sub- Saharan Africa and South east Asia reported by United Nations Office for Disaster Risk Reduction (UNDRR, 2023). Drought has long been recognized as one of the most insidious causes of human misery, and it is a natural disaster that annually causes economic losses for farming communities worldwide (Narasimhan & Srinivasan, 2005; Qaisrani et al., 2021). Worldwide, drought accounts for 7.5% of natural disasters and is considered the second-most geographically widespread hazard after floods (UNDRR, 2007). The percentage of areas affected by serious drought doubled from the 1970s to the early 2000s (Nagarajan, 2009). Understanding the mechanisms underlying these climate features can improve the ability to make timely seasonal predictions of drought events and provide useful insights for resource planners, system managers, and policymakers to help mitigate drought impacts. (Vogt and Gordon, 2021). The study conducted by (Das et al., 2020) revealed an increase in the mean yield of crops, which was attributed to the suitable temperature profile and the lack of significant water stress during the growing seasons of different crops. Recent scientific evidence underscores the alarming acceleration in drought trends. According to the Intergovernmental Panel on Climate Change (IPCC), global warming of 1.1°C above pre-industrial levels has already intensified hydrological extremes such as droughts (IPCC, 2023).

There is practically no climatic region in which droughts of varying intensities have not occurred in recent decades, largely due to climate change. According to Tadić et al (2015), the UN considers drought to be the greatest threat facing the world in the 21st century. In Africa, rising global temperatures accompanying climate change have intensified the hydrological cycle and led to drier dry seasons, thus increasing the risk of more extreme and frequent droughts. To validate this fact, the World Meteorological Organization (WMO, 2022) confirmed that the past seven years have been the warmest period. This has significantly increased the frequency and severity of extreme hydrological events, such as floods and droughts, worldwide (Leng et al., 2016). The Sudan Sahelian Zones (SSZ) in West Africa (including Northwestern Nigeria) are characterized by alternating periods of extreme dryness (i.e., drought) and wetness on annual and decadal time scales. Based on previously reported consequences of catastrophic droughts, it is clear that climatic variability, especially droughts, has made it difficult for most rural dwellers (farmers and herders) in the SSZ, including Northwestern Nigeria, to sustain their livelihoods. Tarhule & Lamb (2003) highlighted that the droughts that ravaged the area in the period 1960s-1990s led to a very serious ecological decline, the decimation of livestock herds, widespread food scarcity, mass migrations, and the great loss of human lives.

A recent study (Okoduwa & Mokhtarisabet, 2025) observed significant fluctuations in drought severity and vegetation stress in the Sahelian region, with critical periods and persistent aridity in Borno, Yobe, and Gombe States. The impact of climate variability, especially droughts, has created food crises in arid lands, which are always linked to high vulnerability to acute health crises (Pérez-Sánchez & Senent-Aparicio, 2018). Persistent drought in Northwestern Nigeria delays the onset of rains, leads to early cessation of the rains, and shortens the rainy season, including pronounced dry spells, which have caused low agricultural productivity in the region, since it is mostly dependent on rain-fed agriculture.

Drought is classified into four main types: meteorological, hydrological, agricultural, and socioeconomic droughts (WMO, 2006). A study by Mishra & Singh (2010) introduced the term groundwater drought as a distinct type and considered it an aspect of hydrological droughts (Zhu et al., 2016). In general, meteorological drought is followed by agricultural drought, then hydrological drought. (Wilhite & Glantz, 2019). A prolonged hydrological drought will then lead to socioeconomic changes that may reach the level of famine, triggering migration and large-scale refugee situations. (Mishra & Singh, 2010; Abdourahamane, 2018). It is very difficult to provide a precise, universally accepted definition of drought due to its varying characteristics and

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impacts across regions worldwide, including rainfall patterns, human responses, resilience, and diverse academic perspectives. (Belal et al., 2014) attributed the obstacle of having a precise definition for hydro-meteorological variables and socioeconomic factors to the stochastic nature of water demand in different regions around the world.

The indicators commonly used to identify droughty conditions are vegetation health, rainfall, evaporation, streamflow, temperature, crop information, and soil moisture (Svoboda & Fuchs, 2016). Studies have shown that farmers plant their crops about 3-4 times due to early-season drought (Turco et al., 2013). Reports on crop conditions also indicate the severity of the drought. When crops are wilting, it indicates soil moisture stress. Other factors that affect crop yield were grouped into three basic categories. (Ngoune Liliane & Shelton Charles, 2020): technological (agricultural practices, managerial decisions), biological (diseases, insects, pests, and weeds), and environmental (climatic conditions, soil fertility, topography, and water quality).

The assessment of drought impacts on specific crops under certain conditions is a key factor in identifying farm-level adaptability and estimating the viability of alternative crop yield options. (Tigkas et al., 2020). Several studies have examined the impacts of droughts on crop growth and development at different levels, including soil moisture uptake, shoot and root growth, several plant processes such as photosynthesis, respiration, and plant water uptake, and final yield. (Dalezios et al., 2017). The detrimental effects of drought on rice, maize, and soybean yields in Southern Brazil were measured in a related study (Miyamoto & Hackmann, 2025). They found that drought negatively affected rice, maize, and soybeans. The Standardized Precipitation Index (SPI) was used to assess the impacts of extreme events on agricultural productivity without incorporating the Standardized Precipitation Evapotranspiration Index (SPEI). Findings reveal a consistent negative association between drought and crop yields, with each crop exhibiting a distinct sensitivity profile.

Recent studies have examined crop damage using drought indices such as the Standardized Precipitation Index (SPI) (Barideh & Nasimi, 2025). In a related analysis, Bezdan & Bezdan (2019) employed multiple regression techniques to assess the relationship between crop yield and drought, incorporating the Standardized Precipitation Index (SPI), Standardized Temperature Index (STI), and Standardized Precipitation Evapotranspiration Index (SPEI). Their findings demonstrate that SPEI exhibits a stronger correlation with de-trended crop yields than SPI or STI. Specifically, SPEI showed greater sensitivity during critical crop growth stages and explained between 40% and 74% of the variability in de-trended yields.

Furthermore, studies such as Shiru & Shahid (2018) utilized satellite-derived rainfall and temperature data, while others, including Adepoju et al. (2022), focused primarily on rainfall data in relation to crop yield estimation. However, reliance on precipitation-only indices such as SPI may be inadequate, as they do not account for temperature effects, which are critical for understanding evapotranspiration and the overall water balance. As highlighted by Svoboda & Fuchs (2016), integrating both precipitation and temperature provides a more comprehensive assessment of drought impacts on agricultural productivity.

Early studies primarily focused on the influence of climatic variables on crop yields, either by analyzing long-term trends in mean climatic conditions or by examining the effects of short-term climate variability. (Miyamoto & Hackmann, 2025). Including temperature alongside precipitation data enables the Standardized Precipitation Evapotranspiration Index (SPEI) to better capture the role of evapotranspiration in drought dynamics. Given the significant capabilities of both the Standardized Precipitation Index (SPI) and SPEI to detect and characterize drought events globally, their application provides valuable insights into drought behavior. Consequently, such analyses contribute to a more comprehensive understanding of drought impacts on crop productivity, particularly during critical stages of the growing season. This study seeks to examine the effect of drought indices on the yield of maize, rice, and millet in the Northwestern part of Nigeria.

## 2. Materials and Methods

### 2.1. Study area

The Northwestern part of Nigeria is situated between Latitudes 9° 0 ′ 00 ″ and 13° 49 ′ 30 ″ North of the Equator and Longitudes 3° 45 ′ 00 ″ and 10° 20 ′ 00 ″ East of the Greenwich Meridian. It shares borders with the Republic of Niger to the North and the Republic of Benin to the West, around Kebbi

State (Figure 1). It is the most populous part of Nigeria, accounting for 25.75 percent of the Nigerian population. It is the third-largest region, in terms of geographical coverage, with an estimated area of 216,065 square kilometers (National Population Commission (NPC), 2006). Northwestern Nigeria is traditionally renowned for agriculture and aquaculture, which remain the main livelihoods of about 80% of the region's inhabitants. The states of Kaduna, Kano, Jigawa (Dutse), Katsina, Sokoto, and Kebbi have been major producers of food crops such as cereals, rice, maize, millet, and other staples, while vegetables such as onion, pepper, and watermelon. Because of the increasing cases of banditry, partly induced by drought, most farmers have relocated to other parts of Nigeria. (NAERLS, 2021).

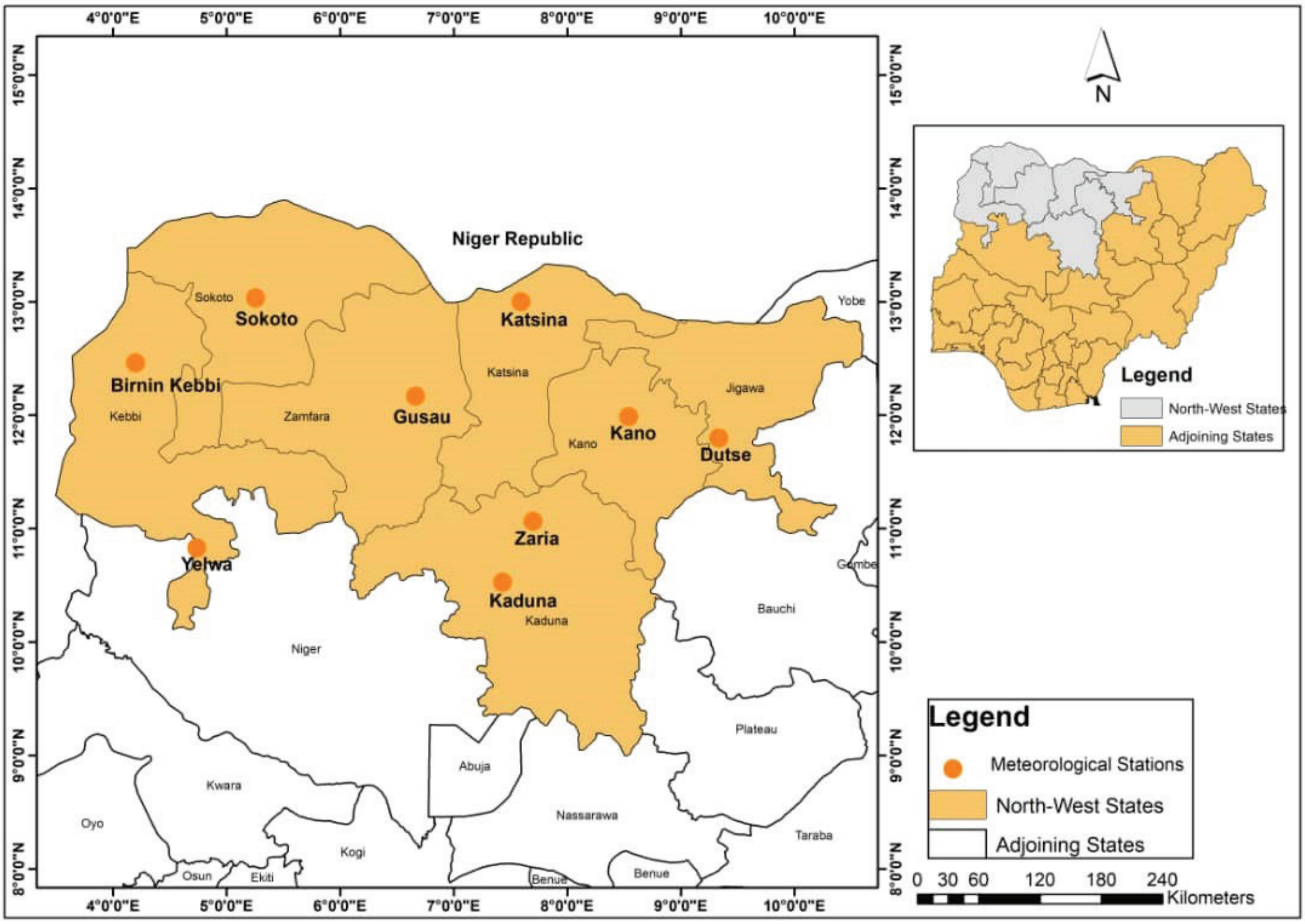


Figure 1: Study area

## 2.2. Climate

Northwestern Nigeria technically falls under Koppen's $A_w$ classification, a hot, dry climate with no precipitation in the cold season and a mean annual temperature of 28 °C. However, in December and January, the night and early-morning temperatures could be well below 20°C. The average Maximum temperature ranges between 32 °C and 35 °C across the study area. The study area, in its southern parts, is situated in a dry sub-humid zone with an annual rainfall of over 1,000mm, while its northern part is semi-arid with an annual rainfall range of between 600 and 800mm. The northern part is arid with an annual rainfall of between 400mm and 600mm; this confirms that the study area has a dry climate. (Abdullahi and Ismail, 2019). Rainfall in the area is concentrated only from June to September, sometimes extending into October in the Southern parts, during which the humidity exceeds 60%. Rainfall in the study area is characterized by a few extremely high and torrential episodes. (Umar and Ismaila, 2017). The nethermost part of northwestern Nigeria's seasonal rainfall regime is

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more important than the annual total and a major controlling factor in the calendar of agricultural activities.(Li, et al., 2021).

## 2.3. Data collection

Six synoptic stations across Kebbi, Zamfara, Kano, Katsina, Sokoto, and Kaduna States were selected for this study. The selection criteria were based on the availability of long-term, consistent records of rainfall and temperature, as well as the stations' location within drought-prone areas. Additional spatial coverage was also considered. Monthly rainfall and temperature data spanning 42 years (1980–2021) were obtained from the archives of the Nigerian Meteorological Agency (NiMet). These data provided the basis for assessing climatic variability and drought conditions in the study area. Crop yield data for rice, maize, and millet were sourced for the period 2009–2021. Long-term time-series data on crop yields (1980–2021) were not readily available, which necessitated the use of secondary data from the National Agricultural Extension and Research Liaison Service (NAERLS). Consequently, the analysis of crop yield response to drought indices was limited to the period for which reliable agricultural data were accessible.

## 2.4. Standardized Precipitation Index (SPI)

Monthly rainfall was used for SPI analysis. The SPI compares precipitation over a specific period with the same period's total precipitation across all years in the historical record. (Alamgir et al., 2015). It is an easily calculated, flexible, and universal index that requires only precipitation data, which are the main reasons for its wide applicability in various drought-related applications worldwide. Several scholars have used the SPI for meteorological drought. (Abdulrahim et al., 2016; Chunming, 2010; Diani et al., 2019; Guenang & Kamga, 2014). Although it is primarily considered a meteorological drought index, it has also been used in many studies on hydrological and agricultural drought. (Tigkas et al., 2019). Positive SPI values indicate greater than median precipitation, and negative values indicate less than median precipitation. (Tigkas, et al 2015). It also allows the user to confidently compare historical and current droughts across different climatic and geographic locations when assessing the rarity or frequency of a given drought event (WMO, 2012). SPI equation is written below:

$$\text{SPI Formula: } \frac{xi - x}{\partial} \quad (1)$$

Where,

$x$ = the mean annual rainfall; $xi$ = the annual rainfall at any year. $\partial$ = the standard variation

## 2.5. Standardized Precipitation Evapotranspiration Index (SPEI)

Monthly minimum and maximum temperatures collected from the Nigerian Meteorological Agency were used for SPEI analysis. A relatively new drought index, developed by Vicente-Serrano et al. (2010). SPEI uses the SPIs but includes a temperature component, allowing the index to account for the effect of temperature on drought development through a basic water balance calculation (Svoboda & Fuchs, 2016). SPEI has an intensity scale in which both positive and negative values are calculated, identifying wet and dry events. It can be calculated for time steps as short as 1 month and as long as 48 months. The input parameters are monthly precipitation, minimum temperature, and maximum temperature data. Including temperature alongside precipitation data allows SPEI to account for its impact on drought. The output is applicable across all climate regimes, with results comparable because they are standardized (Svoboda & Fuchs, 2016). SPEI = P- PET, where monthly PET is calculated using Hargreaves' method (1985). The method requires monthly temperature and precipitation. The equation is written below:

$$\text{SPEI Formula: } di = pi - PET \quad (2)$$

Where,

$di$ = difference of precipitation,

$pi$ = a precipitation,

$PET$ = potential evapotranspiration for a month.

## 2.6. Correlation and regression analysis

Crop production is highly dependent on weather parameters. The purpose of the correlation is to examine the relationship between drought indices and crop yield. Variability in meteorological parameters affects crop production and productivity (Bhattacharyya et al., 2021). Crops grown during the seasons were considered for regression, including maize, rice, and millet. Seasonal crop calendars remain a vital tool for the Nigerian agricultural sector, enabling farmers to synchronize planting and harvesting with ecological realities by optimizing yields, reducing losses, and strengthening food security. Figure 2 presents the main crops cultivated, which are maize, rice, groundnut, cowpea, millet, sorghum, soybean, and vegetables during the growing season, with the expected duration from planting to harvesting period in the study area. A multiple regression analysis was conducted to assess the effects of drought indices on crop yield. The independent variables are SPEI and SPI, and the dependent variable is crop yield. The stepwise regression method was used to obtain the desired equations using Minitab Statistical Package version 18. To assess model accuracy and predictive performance, three statistical metrics were used: Mean Squared Error (MSE), Root Mean Squared Error (RMSE), and Mean Absolute Percentage Error (MAPE). These measures are widely recognized. Their application in this study is consistent with previous research, as demonstrated in studies by Mahmood et al. (2019), Olanrewaju & Shitu (2021), and Wichitarapongsakun et al. (2016), where similar metrics were used to evaluate model reliability and forecasting precision.

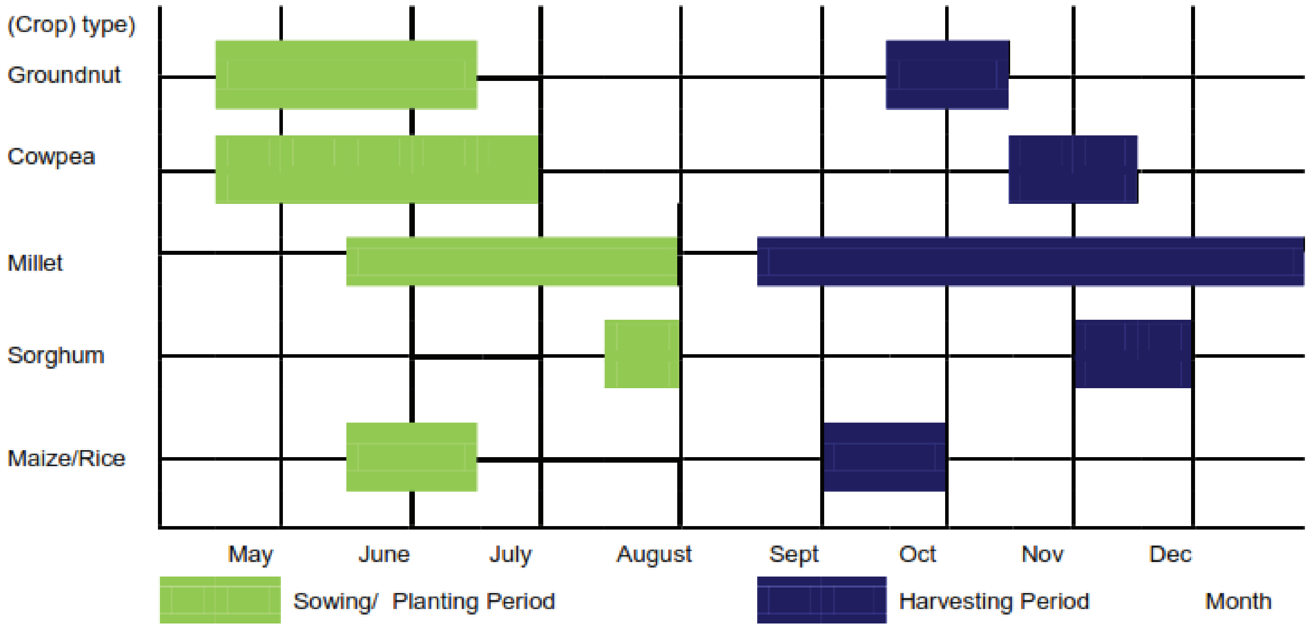


Figure 2: Crop calendar (Ndamani & Watanabe, 2015)

## 3. Results and Discussion

### 3.1. Regression analysis

To determine the effect of meteorological drought on crops, SPI, SPI, and estimated crop yield per hectare were used in a regression analysis. Findings revealed that in Kaduna, the $R^2$ values are 73.3% (SPI) and 80.3% (SPEI), indicating that more than 73.3% and 80.3% of the yield can be explained or predicted by these variables. Crop yield is significantly influenced by drought indices in Kaduna. For Jigawa, R2 is 66.65% (SPI) and 56.1% (SPEI), indicating that 66.6% and 56.1%, respectively. The yield is explained by these variables. The result indicates that rainfall and temperature positively influenced crop yield. This is because there are major inputs determining drought. These findings are consistent with (Bhattacharyya et al., 2021) who reported that crop production is highly sensitive to rainfall characteristics—particularly onset timing and the length of the growing period, as well as temperature variability. Regression results for rice, maize, and millet in Sokoto indicate that SPI and SPEI explain only 7.7% and 6.5% of yield variability, respectively, suggesting limited predictive capacity of these indices in isolation. The observed decline in average yields may therefore be attributed not only to drought conditions but also to other influencing factors, including soil texture, fertilizer application levels, pest infestations, diseases, and weed pressure.

The variation observed in the results of the multiple regression across locations is due to many factors. First, Kaduna and some parts of Kebbi are situated in the Guinea Savanna agro-ecological zone, whereas Jigawa, Zamfara, Kano, and Katsina are in the Sudan and Sahel Savanna agro-ecological zones. Gadedjisso-Tossou et al. (2021) supported this conclusion. They reported that crop development is expected to differ across agro-ecological zones. In addition, edaphic conditions vary across agro-ecological zones. Also, the availability of agricultural inputs such as fertilizer, labor, and seed varieties, which depend on farmers' socioeconomic characteristics, will also contribute to output. Moreover, in a related study, AbdulKadir et al. (2013), the appraisal of the eco-climatic characteristics in Northern Nigeria confirmed that the dynamics in the eco-climatic parameters, moisture effectiveness zone, is fundamental to the identification of the current state of the environment in Northern Nigeria.

Table 1: Summary of multiple regression equation and percentage of explanation

| States | Indices | Regression Equation | $R^2$ (%) | Adjusted $R^2$ |
|---|---|---|---|---|
| Jigawa | SPI | Y= -1.28 + 0.430 RICE + 0.22 Maize + 0.339 Milet | 66.6 | 55.4 |
| | SPEI | Y= 0.70 - 0.242 RICE - 0.27 Maize + 0.206 Milet | 56.1 | 41.6 |
| Gusau | SPI | Y= 5.38 - 0.1463 RICE - 2.162 Maize - 1.746 Millet | 30.5 | 7.4 |
| | SPEI | Y= 8.51 - 0.232 RICE - 3.40 Maize - 2.77 Millet | 6.0 | 0.0 |
| Kaduna | SPI | Y= 0.79 - 1.201 RICE + 1.654 Maize + 1.033 Millet | 73.4 | 66.2 |
| | SPEI | Y= 6.33 - 1.084 RICE + 3.870 Maize + 2.095 Millet | 80.3 | 74.9 |
| Kano | SPI | Y= 0.071 - 0.106 RICE + 0.226 Maize - 0.315 Millet | 36.6 | 19.3 |
| | SPEI | Y= 1.38 - 0.445 RICE + 0.134 Maize - 0.469 Millet | 56.7 | 44.9 |
| Kastina | SPI | Y= 0.817 - 0.798 RICE + 1.42 Maize - 1.64 Millet | 15.9 | 0.0 |
| | SPEI | Y= 0.701 - 1.258 RICE + 1.480 Maize - 0.67 Millet | 37.5 | 16.6 |
| Sokoto | SPI | Y= 1.55 + 1.11 RICE - 0.27 Maize + 0.27 Millet | 7.7 | 0.0 |
| | SPEI | Y= -1.58 + 0. 77 RICE - 0. 75 Maize + 1.05 Millet | 6.5 | 0.0 |
| Kebbi | SPI | Y= 0.41 + 0.010 RICE + 0.980 Maize - 1.06 Millet | 21.7 | 0.0 |
| | SPEI | Y= 4.40 - 1.85 RICE - 0.338 Maize - 0.09 Millet | 15.9 | 0.0 |

*Note: Yields are for Rice, Maize, and Millet. Y represents SPI and SPEI.*

## 3.2. Modeling the relationship between crop yield and drought indices using regression techniques

According to Table 2, the model explains 52.4% of the total variation in maize yield in Kaduna State, as reflected by the coefficient of determination ($R^2$). After adjusting for the number of predictors in the stepwise regression model, the adjusted $R^2$ decreased slightly to 48.1%, indicating a moderate level of explanatory power and suggesting a moderate relationship between drought conditions and maize yield. The results demonstrate that both SPI and SPEI account for 11.6% and 10.6% of the variance in maize in Kastina and Kebbi, respectively. It is clear that these two indices jointly account for the lowest variance in rice production across the state, with 0% in Katsina. This may be attributed to the fact that rice is cultivated under conditions where water is available for a substantial portion of the growing season; consequently, drought may not serve as a primary determinant of yield variability. The adjusted $R^2$ measures the proportion of explained variation relative to the total variation and helps identify non-significant explanations. Based on this, it can be inferred that a relatively meaningful explanation was observed in Kaduna, with a value of 0.48. This indicates that the model explains more of the variance in maize in Kaduna than in other crops. The relatively low Mean Squared Error (MSE) values further support the model's adequacy, with a notably low value of 0.040 for maize in Jigawa State. In contrast, moderately higher MSE values were observed for millet in Zamfara (0.632) and Sokoto (0.613). Furthermore, Sokoto State recorded the highest MSE value (0.907) for maize, indicating comparatively lower predictive accuracy of the model in that context. The Root Mean Squared Error (RMSE) is another key measure of model fit, as it accounts for unexplained variation. The lower RMSE values recorded in Jigawa (0.201) and Kaduna (0.250) indicate a smaller deviation between dependent variables, maize, rice, and millet, and suggest a better model fit. This further confirms the influence of drought indices in the study area. In a related study, Raha & Gayen (2020) reported that areas with extreme to severe drought exhibited higher RMSE values.

Mean Absolute Percentage Error (MAPE) measures the average magnitude of error produced by the model. The findings revealed the three highest MAPEs across states as follows: Zamfara 83.968% (millet), 76.616% (maize), and 173.144% (millet) recorded in Sokoto, while the lowest values were recorded in Jigawa 9.491% (maize), Kaduna 7.741% (maize), and Kebbi 9.460% in (rice). Higher values of the Mean Absolute Percentage Error (MAPE) suggest that the model may have inadequately captured critical crop growth stages, which also confirms the nature of the data used. Conversely, lower MAPE values indicate improved predictive accuracy of the Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI) for maize and rice in Jigawa, Kaduna, and Kebbi States, whereas higher MAPE values reflect reduced model performance and less reliable predictions. "Recent studies (Ng et al., 2023) assessed the performances of the predicting models using root-mean-square error (RMSE), mean absolute error (MAE), and Mean Absolute Percentage Error (MAPE). The accuracy of drought forecasting was associated with a lower MAPE, and SPI indices were used as the standard model for evaluating drought accuracy. A critical look revealed that the majority show positive autocorrelation across states; this is because the values are less than 2, except in Jigawa (2.094), Kaduna (2.52), and 2.089, which indicate negative autocorrelation, respectively. This finding further confirms that the weather requirements of the dependent variables used differ remarkably. The greater the F-values, the more accurate the regression. Kaduna has the highest F-value, with 12.112, while the lowest was zero, recorded in Kano. This could imply that the regression fits Kaduna better than other states.

Table 2: Summary of the goodness of fit for the regression model between crop yield and drought indices

| States | Crops | $R^2$ | Adjusted $R^2$ | F values | MSE | RMSE | MAPE |
|---|---|---|---|---|---|---|---|
| Jigawa | Rice | 0.023 | -0.065 | 0.263 | 0.566 | 0.753 | 55.395 |
| | Maize | 0.050 | -0.037 | 0.573 | 0.040 | 0.201 | 9.491 |
| | Millet | 0.038 | -0.050 | 0.430 | 0.060 | 0.245 | 21.320 |
| Gusau | Rice | 0.017 | -0.072 | 0.189 | 0.580 | 0.223 | 36.757 |
| | Maize | 0.050 | -0.036 | 0.580 | 0.079 | 0.282 | 17.038 |
| | Millet | 0.020 | -0.069 | 0.223 | 0.632 | 0.795 | 83.968 |
| Kaduna | Rice | 0.030 | -0.059 | 0.335 | 0.090 | 0.299 | 8.037 |
| | Maize | 0.524 | 0.481 | 12.112 | 0.063 | 0.250 | 7.741 |
| | Millet | 0.064 | -0.021 | 0.752 | 0.092 | 0.303 | 37.210 |
| Kano | Rice | 0.000 | -0.091 | 0.000 | 0.344 | 0.586 | 19.417 |
| | Maize | 0.080 | -0.003 | 0.961 | 0.094 | 0.306 | 9.327 |
| | Millet | 0.098 | 0.016 | 1.201 | 0.281 | 0.530 | 53.331 |
| Kastina | Rice | 0.003 | 0.003 | 0.326 | 0.251 | 0.501 | 25.118 |
| | Maize | 0.116 | 0.116 | 0.293 | 0.179 | 0.423 | 27.277 |
| | Millet | 0.078 | 0.078 | 0.625 | 0.044 | 0.210 | 25.104 |
| Sokoto | Rice | 0.108 | 0.027 | 1.337 | 0.127 | 0.357 | 19.479 |
| | Maize | 0.022 | -0.067 | 0.252 | 0.907 | 0.953 | 173.144 |
| | Millet | 0.110 | 0.029 | 1.353 | 0.613 | 0.783 | 76.616 |
| Kebbi | Rice | 0.012 | -0.077 | 0.138 | 0.094 | 0.306 | 9.460 |
| | Maize | 0.106 | 0.025 | 1.304 | 0.280 | 0.529 | 34.999 |
| | Millet | 0.032 | -0.056 | 0.360 | 0.070 | 0.264 | 33.498 |

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### 3.3. Assessment of the linear relationship between drought indices and crop yield

Correlation analysis measures the strength and direction of the linear relationship between the independent and dependent variables. Table 3 shows the estimated crop yield distribution observed on annual production for each of the major rainfed crops cultivated during the rainy season. These are rice, maize, and millet. The analysis of correlation coefficients revealed that the Standardized Precipitation Index (SPI) exhibited both positive and negative relationships with the annual yield of the studied crops, with comparatively stronger associations than those observed for the Standardized Precipitation Evapotranspiration Index (SPEI) in some cases. Notably, strong positive relationships were observed in Kaduna State between SPEI and maize yield (r = 0.77), SPI and maize yield (r = 0.647), and SPEI and rice yield (r = 0.66). In contrast, a strong negative correlation was identified in Kano State between SPEI and millet yield (r = -0.684), indicating an inverse relationship between drought conditions and millet production in that location. The analysis implied that as the number of positive SPEI values increased, crop yields also increased, except for SPEI and millet, for which yields decreased. The correlation statistics between SPEI and Rice in Zamfara showed a negative correlation (r = -0.43), suggesting a weak relationship. As the SPEI value increases, rice yield decreases. This result is expected, given that cultivating rice requires more water. In a related study, Elagib (2013) reported a strong positive correlation between the Standardized Precipitation Index (SPI) and crop yield during the early to mid-growing season in the semi-arid area of Sudan.

However, the correlation coefficients may not be statistically significant; it should be noted that the correlation values between drought indices and crop yield indicate that climate variables such as rainfall and temperature are sensitive to agricultural production. Previous studies confirmed that agriculture is perhaps the most weather-sensitive of all man's economic activities (Ayoade, 1993). Report by Agricultural Extension and Research Liaison Services (NAERLS, 2021) in an assessment of the recent decrease in land cultivated and yield witnessed in some states could be traced to incessant kidnapping and bandit activities that make it difficult for farmers to move freely to perform agricultural activities, especially in Zamfara, Katsina, Niger, Sokoto, and Kebbi. Some farmers have outrightly left farming, while many have relocated to Internally Displaced People's (IDP) camps for safety and humanitarian support. In view of the foregoing, one can infer that the total devoted to wet-season farming also played a significant role in annual crop yield. Previous studies (Adepoju et al., 2022) reported that drought is a key abiotic stress affecting maize yield and production in Sub-Saharan Africa, contributing between 44% to 58% grain yield decline in West and Central Africa. The negative relationship observed in SPEI (Table 3) further confirmed the impact of temperature and potential evaporation on the index's use. The related study conducted in America (Hatfield & Prueger, 2015) showed that the major impact of warmer temperatures was during the reproductive stage of development, and in all cases, grain yield in maize was significantly reduced by as much as 80-90% from a normal temperature regime.

The results of the linear relationship between drought indices and crop yield (Figures 3, 4, 5, 6, 7, 8, and 9) clearly demonstrated a pattern of heterogeneous variance (non-constant variance) across SPI, SPEI, and crop yield. It should be noted that there is a relationship between the drought indices and crops, as adequately explained earlier in Table 2 above, except that the general pattern follows a linear trend. These could be a result of their responses to temperature and rainfall, which differ among crop species throughout their life cycle, particularly during stages of plant development, which is consistent with other findings (Gebremichael et al., 2014; Salack et al., 2015). It can also be seen that SPEI exhibits greater variation in many instances than SPI, which only quantifies precipitation deficit or surplus at different time scales. The results are in line with the studies of (Gadedjisso-Tossou et al., 2021), who assessed that the variation of rainfall and temperature has a significant effect on the cereal crop yields in Togo.

Table 3: Correlation between drought indices and crop yield

| States | Variables | SPEI | SPI | RICE | Maize | Millet |
|---|---|---|---|---|---|---|
| Gusau | SPEI | **1.000** | 0.453 | -0.143 | -0.185 | 0.085 |
| | SPI | 0.453 | **1.000** | 0.497 | 0.318 | 0.460 |
| | RICE | -0.143 | 0.497 | **1.000** | 0.681 | 0.519 |
| | Maize | -0.185 | 0.318 | 0.681 | **1.000** | 0.160 |
| | Millet | 0.085 | 0.460 | 0.519 | 0.160 | **1.000** |
| Jigawa | SPEI | **1.000** | 0.453 | -0.278 | 0.191 | -0.412 |
| | SPI | 0.453 | **1.000** | 0.386 | 0.243 | -0.213 |
| | RICE | -0.278 | 0.386 | **1.000** | 0.240 | 0.03* |
| | Maize | 0.191 | 0.243 | 0.240 | **1.000** | -0.871 |
| | Millet | -0.412 | -0.213 | 0.03* | -0.871 | **1.000** |
| Kaduna | SPEI | **1.000** | 0.702 | -0.088 | 0.774 | 0.314 |
| | SPI | 0.702 | **1.000** | -0.328 | 0.647 | 0.287 |
| | RICE | -0.088 | -0.328 | **1.000** | 0.065 | 0.129 |
| | Maize | 0.774 | 0.647 | 0.065 | **1.000** | -0.047 |
| | Millet | 0.314 | 0.287 | 0.129 | -0.047 | **1.000** |
| Kano | SPEI | **1.000** | 0.852 | -0.661 | -0.224 | -0.684 |
| | SPI | 0.852 | **1.000** | -0.385 | 0.023 | -0.568 |
| | RICE | -0.661 | -0.385 | **1.000** | 0.502 | 0.628 |
| | Maize | -0.224 | 0.023* | 0.502 | **1.000** | 0.186 |
| | Millet | -0.684 | -0.568 | 0.628 | 0.186 | **1.000** |
| Kastina | SPEI | **1.000** | 0.642 | -0.284 | 0.107 | 0.152 |
| | SPI | 0.642 | **1.000** | -0.074 | 0.087 | -0.064 |
| | RICE | -0.284 | -0.074 | **1.000** | 0.778 | 0.414 |
| | Maize | 0.107 | 0.087 | 0.778 | **1.000** | 0.750 |
| | Millet | 0.152 | -0.064 | 0.414 | 0.750 | **1.000** |
| Sokoto | SPEI | **1.000** | -0.381 | 0.156 | 0.180 | 0.212 |
| | SPI | -0.381 | **1.000** | 0.272 | 0.161 | 0.132 |
| | RICE | 0.156 | 0.272 | **1.000** | 0.625 | 0.459 |
| | Maize | 0.180 | 0.161 | 0.625 | **1.000** | 0.937 |
| | Millet | 0.212 | 0.132 | 0.459 | 0.937 | **1.000** |
| Kebbi | SPEI | **1.000** | 0.007* | -0.470 | -0.229 | -0.117 |
| | SPI | 0.007* | **1.000** | 0.096 | 0.401 | 0.086 |
| | RICE | -0.470 | 0.096 | **1.000** | 0.152 | 0.003* |
| | Maize | -0.229 | 0.401 | 0.152 | **1.000** | 0.661 |
| | Millet | -0.117 | 0.086 | 0.003* | 0.661 | **1.000** |

**95% confidence level, *Significant 0.05*

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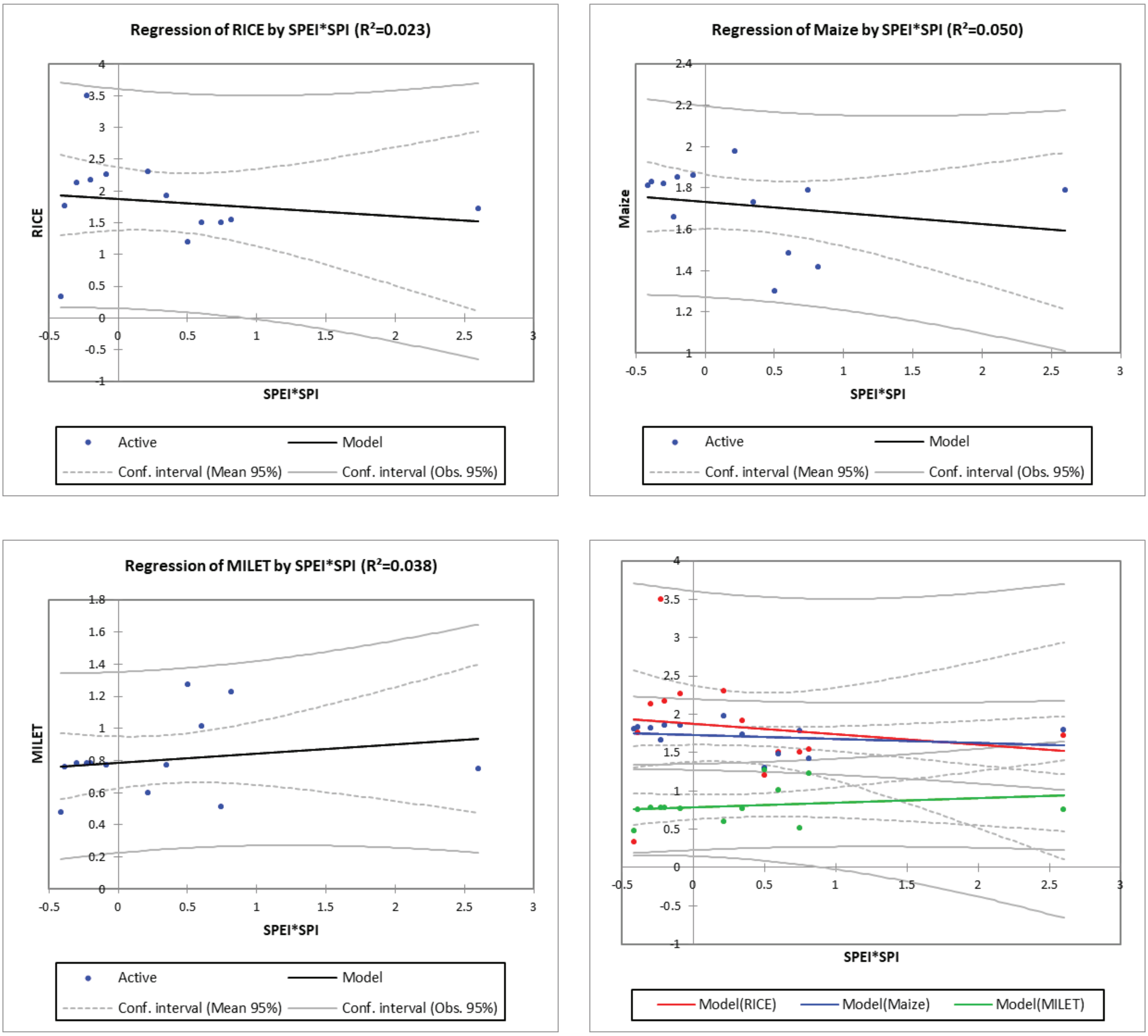


Figure 3: Linear relationship between drought indices and crop yield in Jigawa

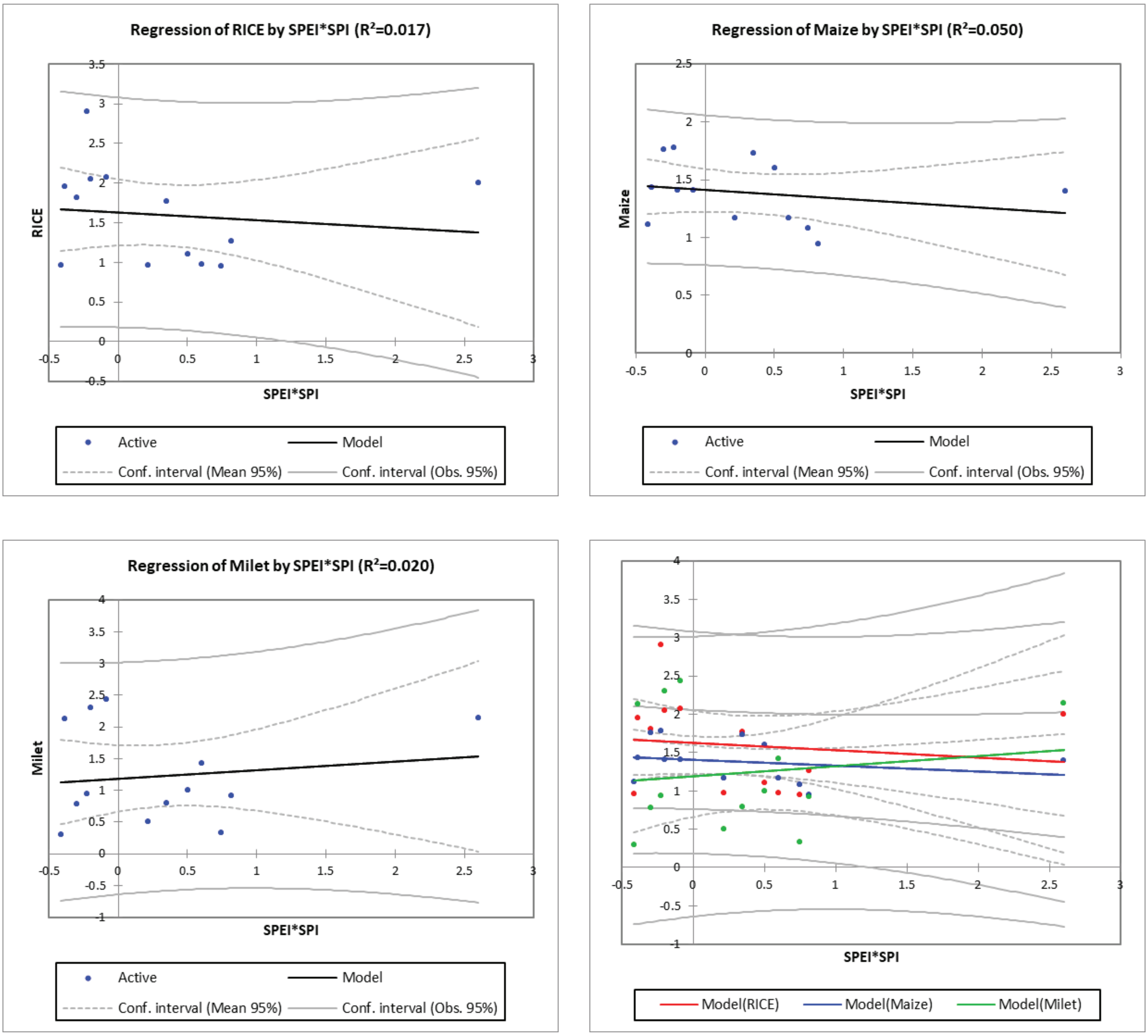


Figure 4: Linear relationship between drought indices and crop yield in Zamfara

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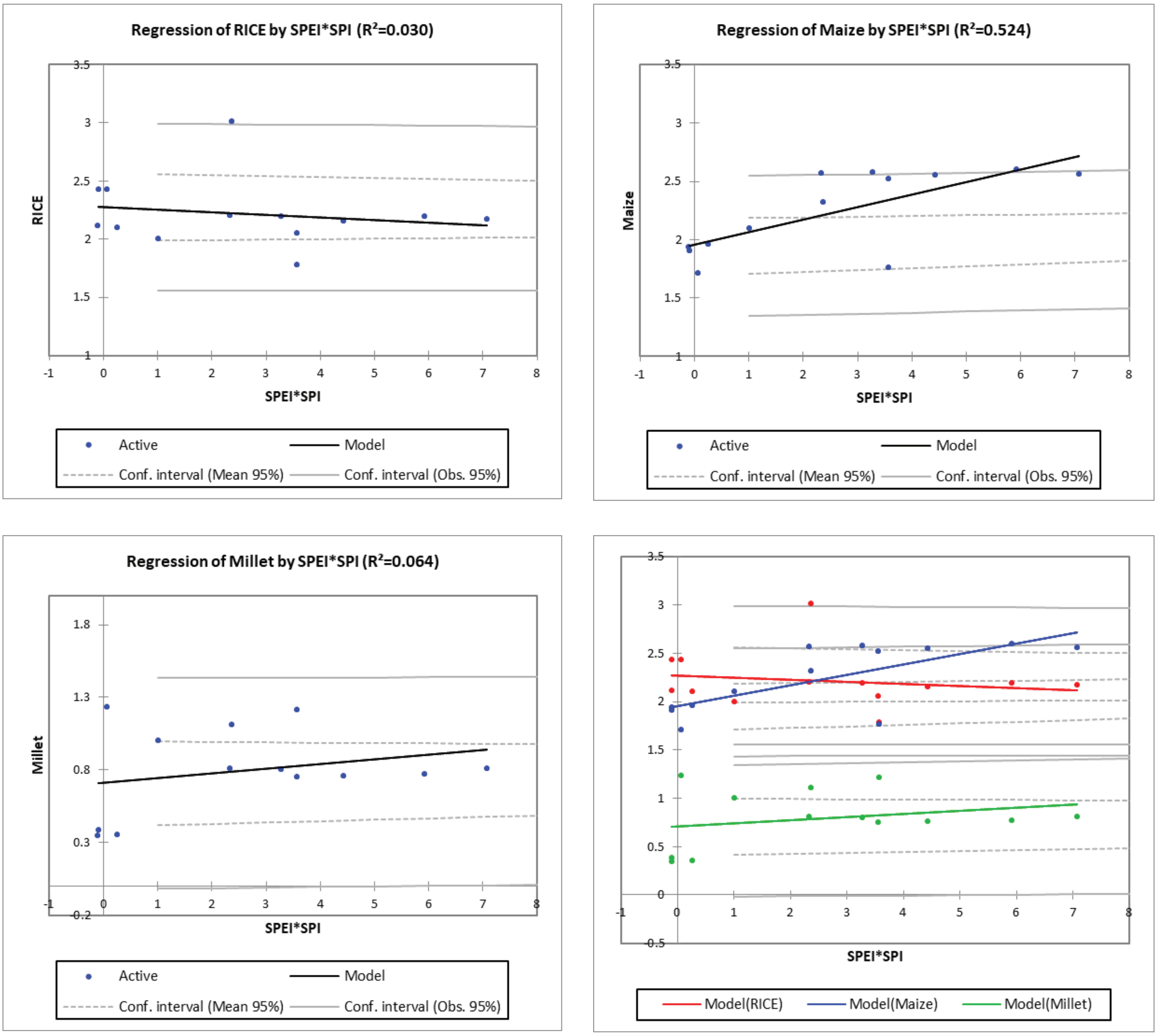


Figure 5: Linear relationship between drought indices and crop yield in Kaduna

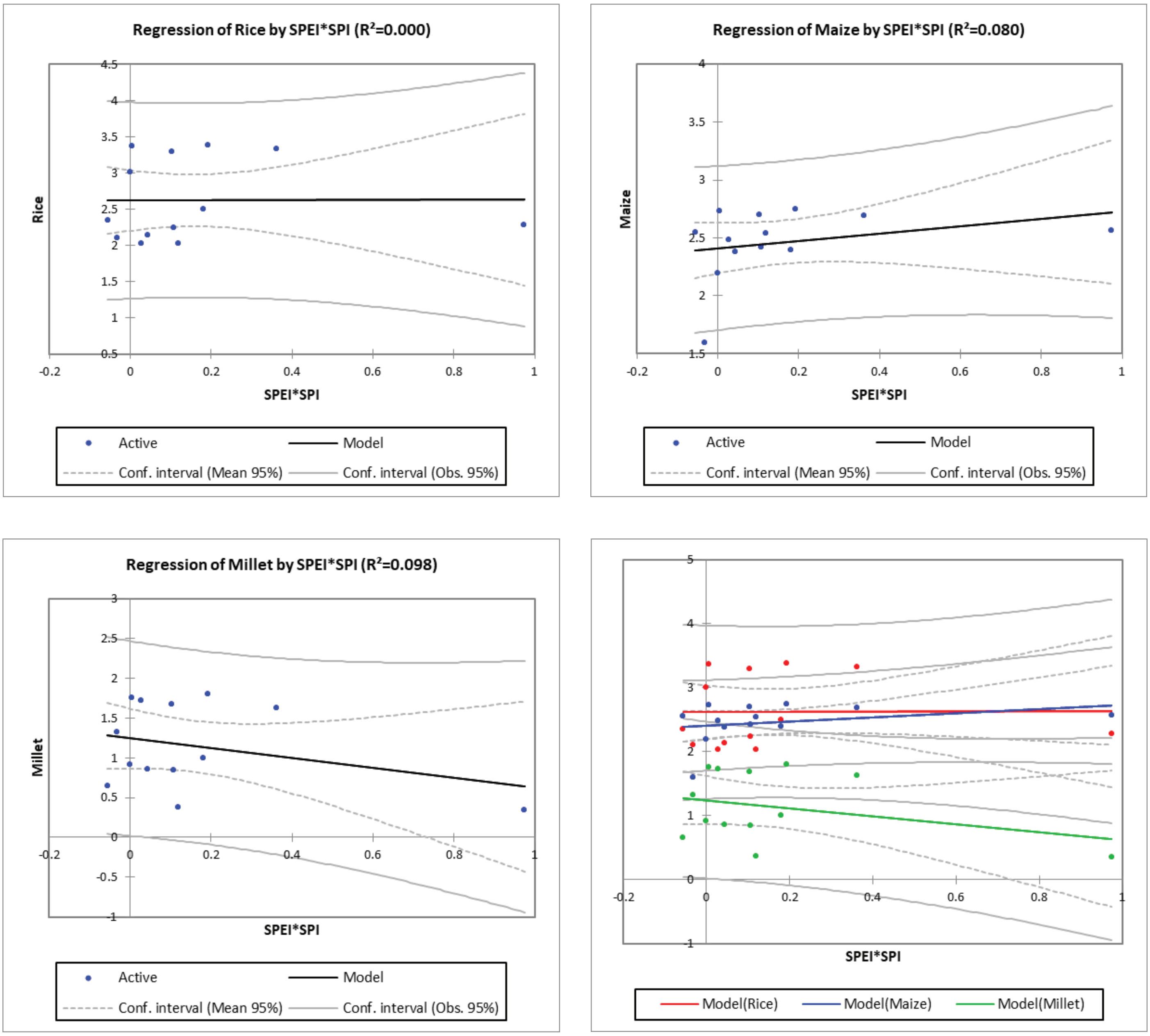


Figure 6: Linear relationship between drought indices and crop yield in Kano

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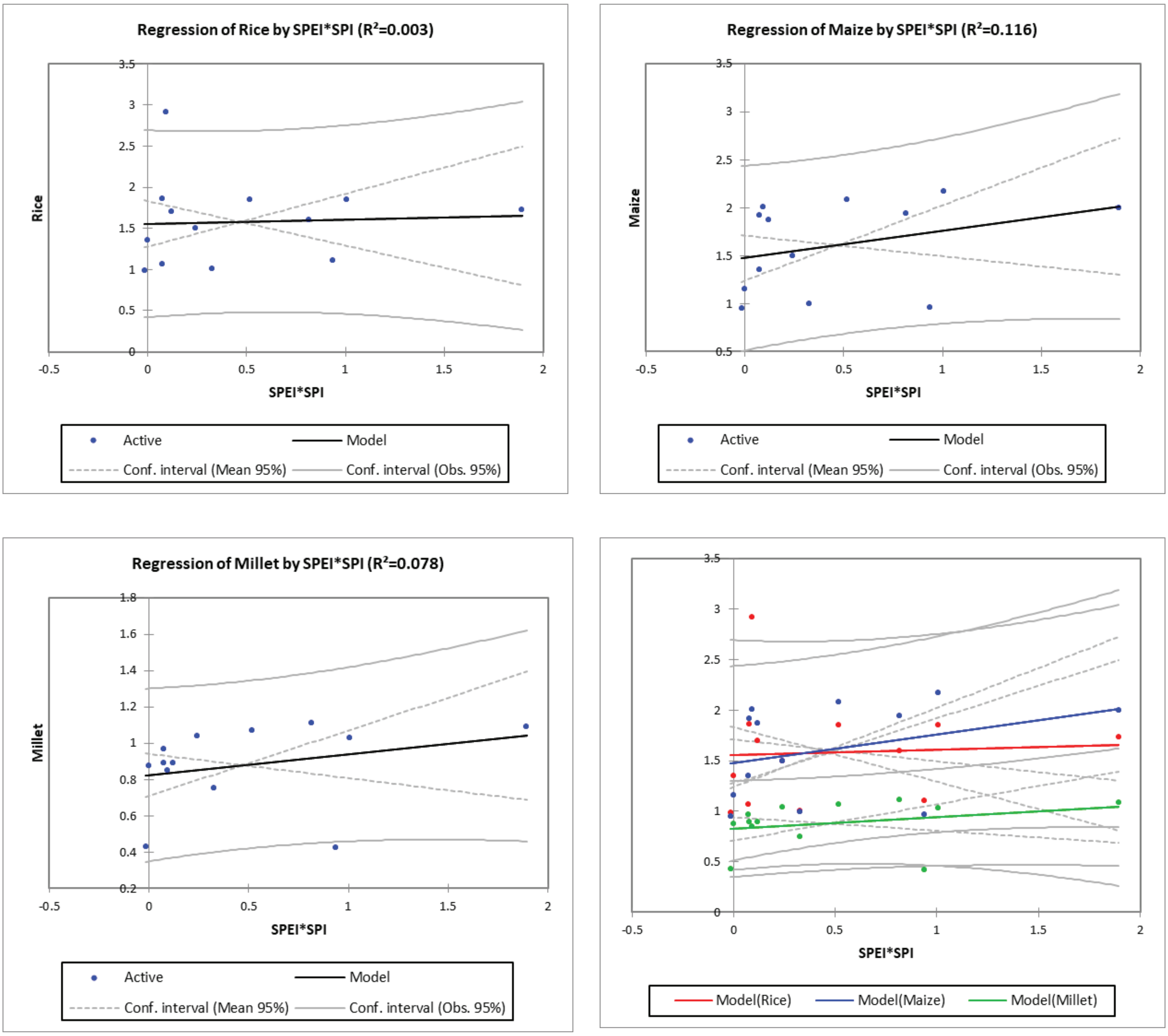


Figure 7: Linear relationship between drought indices and crop yield in Kastina

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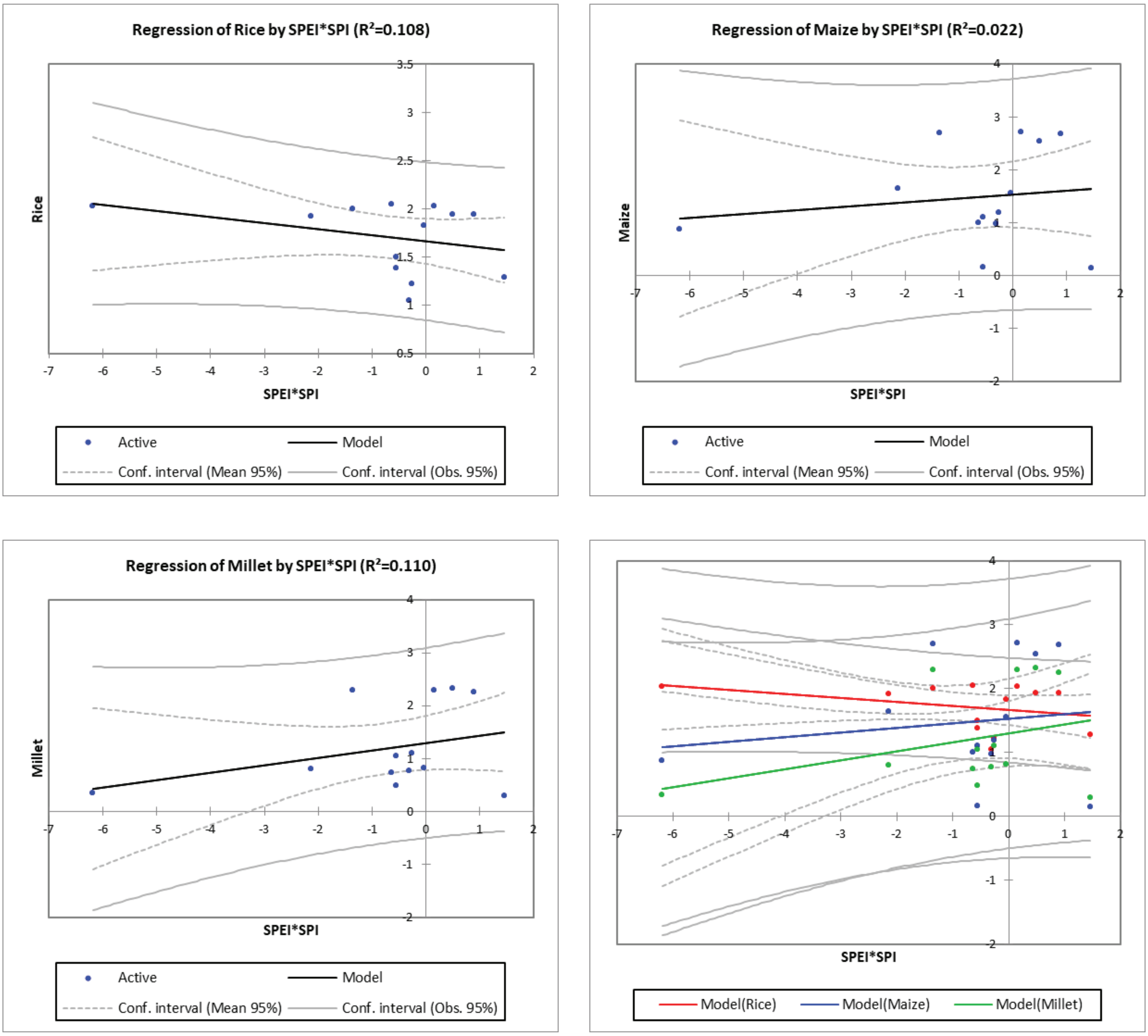


Figure 8: linear relationship between drought indices and crop yield in Sokoto

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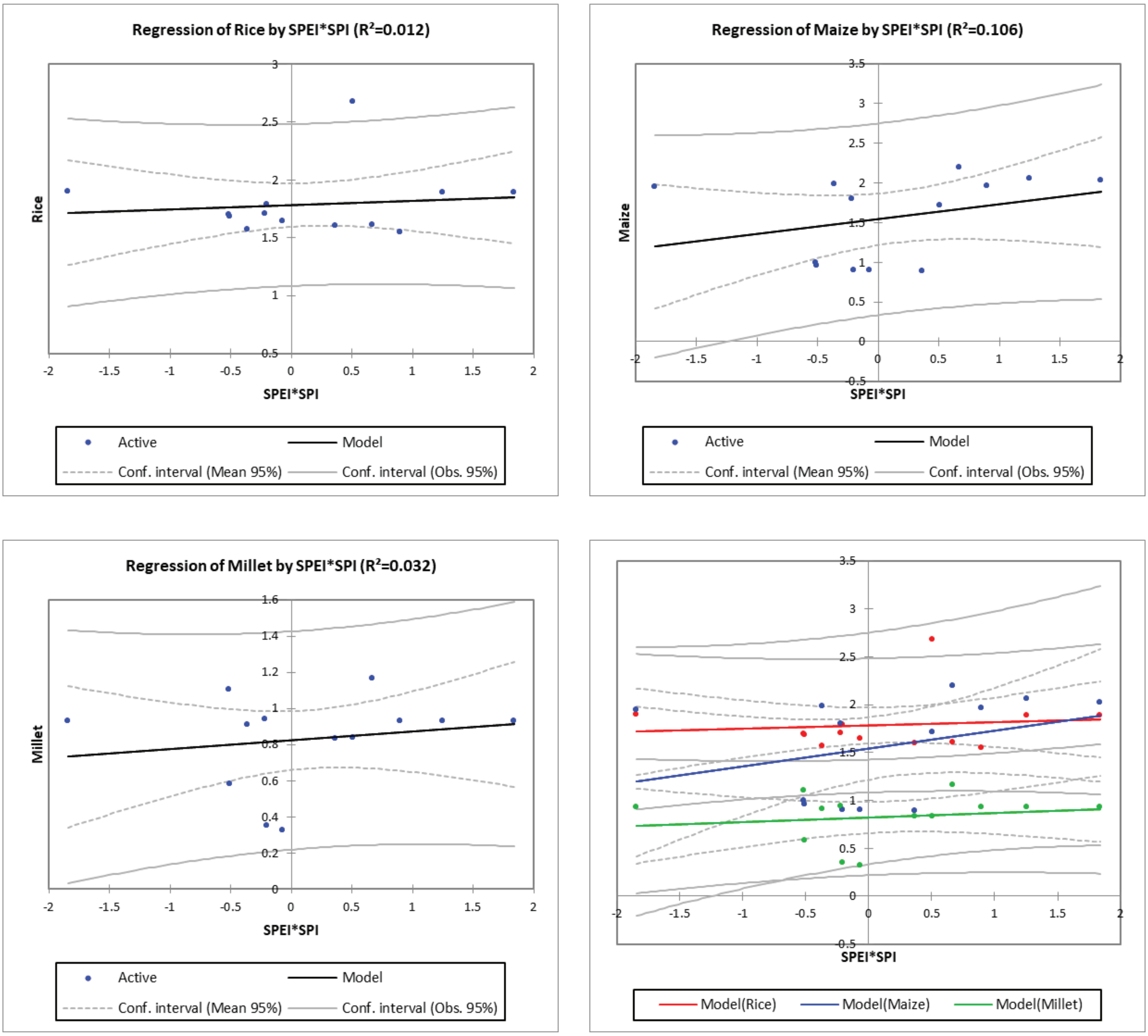


Figure 9: Relationship between drought indices and crop yield in Kebbi

## 4. Conclusion

The study demonstrates the relationship between meteorological droughts and the yield of rice, maize, and millet in Northwestern Nigeria. This was performed by analyzing drought characteristics using SPI and SPEI indices and correlating them with crop yield. The drought indices presented herein allow the estimation of the frequency of occurrence of the different drought severity classes. It was revealed that correlations between drought indices and crop yield showed both negative and positive relationships. The impact of drought indices on crop yields varied significantly by state and crop. The SPEI appeared to be significant and contributed to the increase in the yields of all selected crops compared with SPI.

It has been found that the SPEI could provide a useful tool for predicting crop yield at an earlier stage in the crop calendar than the SPI. Using the June-September major growing period of the study area. The results of this research enhance our understanding of the impacts of drought indices on crops cultivated during the growing season. Examination of the regression functions of SPI and SPEI for rice, maize, and millet revealed that SPEI accounted for more variation. It can be concluded that a combination of temperature and rainfall plays a significant role in crop yields in the study area.

## References:

Abdourahamane, Z. S., & Acar, R. (2018). Analysis of meteorological drought variability in Niger and its connection with climate indices. *Hydrological Sciences Journal*, *63*(8), 1203–1218. https://doi.org/10.1080/02626667.2018.1489542

AbdulKadir, A., Usman, M. T., Shaba, A. H., & S Saidu. (2013). An appraisal of the of eco-climatic characteristics in Northern Nigeria. *African Journal of Environmental Science and Technology*, *7*(8), 748–757. https://doi.org/10.5897/ajest12.161

Abdulrahim, M., Ifabiyi, I., & Ismaila, A. (2013). Time series analyses of mean monthly rainfall for drought management in Sokoto, Nigeria. *Ethiopian Journal of Environmental Studies and Management*, *6*(5). https://doi.org/10.4314/ejesm.v6i5.3

Adamu, I., & Umar, A. (2019). Occurrences of Droughts in the Semi-Arid and Sub-Humid Areas of Northwestern Nigeria and Their Implications for Rural Livelihoods. *International Conference on Water and Resources and Arid Environments (ICWRAE 8)*, *8*, 1–11. https://icwrae.org/papers/2018/AridEvironments/1.pdf

Adepoju, A. A., Adenuga, G. O., & Ogundunmade, T. P. (2022). Regression Analysis and Spatial Distribution of Drought Indices on Maize Production in the Northern Part of Nigeria. *Research & Reviews: Journal of Statistics and Mathematical Sciences*, *9*, 1–12.

Alamgir, M., Shahid, S., Hazarika, M. K., Nashrrullah, S., Harun, S. B., & Shamsudin, S. (2015). Analysis of Meteorological Drought Pattern During Different Climatic and Cropping Seasons in Bangladesh. *JAWRA Journal of the American Water Resources Association*, *51*(3), 794–806. https://doi.org/10.1111/jawr.12276

Ayoade, J. O. (1993). *Introduction to Climatology for the Tropics* (Reprint). Spectrum Books Limited.

Barideh, R., & Nasimi, F. (2025). A novel approach to estimating drought-Induced damage in rainfed wheat cultivation using modified drought indices. *Theoretical and Applied Climatology*, *156*(10). https://doi.org/10.1007/s00704-025-05772-w

Belal, A.-A., El-Ramady, H. R., Mohamed, E. S., & Saleh, A. M. (2012). Drought risk assessment using remote sensing and GIS techniques. *Arabian Journal of Geosciences*, *7*(1), 35–53. https://doi.org/10.1007/s12517-012-0707-2

Bezdan, A., & Bezdan, J. (2019). Comparison of the performance of SPI, STI and SPEI for agricultural drought monitoring in Vojvodina region. *EGU General Assembly Conference Abstracts*, 8516. https://ui.adsabs.harvard.edu/abs/2019EGUGA..21.8516B/abstract

Bhattacharyya, B., Biswas, R., & Chiphang, D. Y. (2021). Linear regression model to study the effects of weather variables on crop yield in Manipur State. *International Journal of Agricultural and Statistical Sciences* , *17*(1), 317–320.

Chunming, P. (2010). *Integration of Remote Sensing and Meteorological Data for Drought Monitoring* [Master's thesis].

Dalezios, N. R., Gobin, A., Maria, A., & Saeid Eslamian. (2017). *Agricultural Drought Indices: Combining Crop, Climate, and Soil Factors*. ResearchGate; unknown. https://www.researchgate.net/publication/320689949_Agricultural_Drought_Indices_Combining_Crop_Climate_and_Soil_Factors

Das, J., Poonia, V., Jha, S., & Goyal, M. K. (2020). Understanding the climate change impact on crop yield over Eastern Himalayan Region: ascertaining GCM and scenario uncertainty. *Theoretical and Applied Climatology*, *142*(1-2), 467–482. https://doi.org/10.1007/s00704-020-03332-y

Diani, K., Kacimi, I., Zemzami, M., Tabyaoui, H., & Haghighi, A. T. (2019). Evaluation of meteorological drought using the Standardized Precipitation Index (SPI) in the High Ziz River basin, Morocco. *Limnological Review*, *19*(3), 125–135. https://doi.org/10.2478/limre-2019-0011

Elagib, N. A. (2013). Meteorological drought and crop yield in Sub-Saharan Sudan. *International Journal of Water Resources and Arid Environments*, *3*(3), 164–171.

http://dx.doi.org/10.21622/MACI.2026.03.1.1731


Gadedjisso-Tossou, A., Adjegan, K. I., & Kablan, A. K. M. (2021). Rainfall and Temperature Trend Analysis by Mann–Kendall Test and Significance for Rainfed Cereal Yields in Northern Togo. *Sci*, *3*(1), 17. https://doi.org/10.3390/sci3010017

Gebremicheal, A., Quraishi, S., & Mamo, G. (2014). Analysis of Seasonal Rainfall Variability for Agricultural Water Resource Management in Southern Region, Ethiopia. *Journal of Natural Science Research*, *4*(11), 56–80.

Guenang, G. M., & Kamga, F. M. (2014). Computation of the Standardized Precipitation Index (SPI) and Its Use to Assess Drought Occurrences in Cameroon over Recent Decades. *Journal of Applied Meteorology and Climatology*, *53*(10), 2310–2324. https://doi.org/10.1175/jamc-d-14-0032.1

Hamal, K., Sharma, S., Khadka, N., Haile, G. G., Joshi, B. B., Xu, T., & Dawadi, B. (2020). Assessment of drought impacts on crop yields across Nepal during 1987–2017. *Meteorological Applications*, *27*(5), 1–18. https://doi.org/10.1002/met.1950

Hatfield, J. L., & Prueger, J. H. (2015). Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes*, *10*(Part A), 4–10. https://doi.org/10.1016/j.wace.2015.08.001

Leng, G., Huang, M., Voisin, N., Zhang, X., Asrar, G., & Leung, L. R. (2016). Emergence of new hydrologic regimes of surface water resources in the conterminous United States under future warming. *Environmental Research Letters*, *11*(11), 114003–114003. https://doi.org/10.1088/1748-9326/11/11/114003

Li, H., Li, Y., Huang, G., & Sun, J. (2021). Probabilistic assessment of crop yield loss to drought time-scales in Xinjiang, China. *International Journal of Climatology*, *41*(8), 4077–4094. https://doi.org/10.1002/joc.7059

Liliane, T. N., & Charles, M. S. (2020). Factors Affecting Yield of Crops. *Agronomy - Climate Change & Food Security*, 1–16. https://doi.org/10.5772/intechopen.90672

Mahmood, R., Jia, S., & Zhu, W. (2019). Analysis of climate variability, trends, and prediction in the most active parts of the Lake Chad basin, Africa. *Scientific Reports*, *9*(1). https://doi.org/10.1038/s41598-019-42811-9

Mishra, A. K., & Singh, V. P. (2010). A review of drought concepts. *Journal of Hydrology*, *391*(1-2), 202–216. https://doi.org/10.1016/j.jhydrol.2010.07.012

Miyamoto, B. C. B., & Hackmann, C. L. (2025). Effects of drought on crop yields and agricultural revenue in Southern Brazil. *Discover Agriculture*, *3*(1). https://doi.org/10.1007/s44279-025-00425-y

Nagarajan, R. (2009). Drought Indices. *Drought Assessment*, *10*(3), 160–204. https://doi.org/10.1007/978-90-481-2500-5_5

Narasimhan, B., & Srinivasan, R. (2005). Development and evaluation of Soil Moisture Deficit Index (SMDI) and Evapotranspiration Deficit Index (ETDI) for agricultural drought monitoring. *Agricultural and Forest Meteorology*, *133*(1-4), 69–88. https://doi.org/10.1016/j.agrformet.2005.07.012

National Agricultural Extension and Research Liaison Services (NAERLS). (2021). *National Report of Wet Season Agricultural Performance in Nigeria 2021* . Federal Ministry of Agriculture and Rural Development (FMARD); Ahmadu Bello University, Zaria. https://naerls.gov.ng/

Ndamani , F., & Watanabe, T. (2015). Influences of rainfall on crop production and suggestions for adaptation. *International Journal of Agricultural Sciences*, *5*(1), 367–374.

Ng, J. L., Huang, Y. F., Chong, A. H., Lee, J. C., Abdulkareem, M., Nur, Mirzaei, M., & Ahmed, A. N. (2023). Comparative assessment of drought indices for evaluating drought patterns in Peninsular Malaysia. *Journal of Water and Climate Change*, *14*(11), 4183–4197. https://doi.org/10.2166/wcc.2023.546

Okoduwa, A. K., & Mokhtarisabet, S. (2025). Spatiotemporal analysis of drought in the Sahelian region of northeastern Nigeria, sub-Saharan Africa. *Theoretical and Applied Climatology*, *156*(6). https://doi.org/10.1007/s00704-025-05542-8

Olanrewaju, O. M., & Shitu, M. U. (2021). A Comparison of Exponential Smoothening and ARIMA Modelling of the Infertility Rate among Women in Zaria Metropolis. *International Journal of Research and Innovation in Applied Science*, *06*(10). https://doi.org/10.51584/ijrias.2021.61005

Pérez-Sánchez, J., & Senent-Aparicio, J. (2017). Analysis of meteorological droughts and dry spells in semiarid regions: a comparative analysis of probability distribution functions in the Segura Basin (SE Spain). *Theoretical and Applied Climatology*, *133*(3-4), 1061–1074. https://doi.org/10.1007/s00704-017-2239-x

Qaisrani, Z. N., Nuthammachot, N., Techato, K., & Asadullah. (2021). Drought monitoring based on Standardized Precipitation Index and Standardized Precipitation Evapotranspiration Index in the arid zone of Balochistan province, Pakistan. *Arabian Journal of Geosciences*, *14*(1). https://doi.org/10.1007/s12517-020-06302-w

Raha, S., & Gayen, S. K. (2020). Simulation of meteorological drought using exponential smoothing models: a study on Bankura District, West Bengal, India. *SN Applied Sciences*, *2*(5). https://doi.org/10.1007/s42452-020-2730-3

Salack, S., Sarr, B., Sangare, S., Ly, M., Sanda, I., & Kunstmann, H. (2015). Crop-climate ensemble scenarios to improve risk assessment and resilience in the semi-arid regions of West Africa. *Climate Research*, *65*, 107–121. https://doi.org/10.3354/cr01282

Shiru, M., Shahid, S., Alias, N., & Chung, E.-S. (2018). Trend Analysis of Droughts during Crop Growing Seasons of Nigeria. *Sustainability*, *10*(3), 871. https://doi.org/10.3390/su10030871

Svoboda, M., & Fuchs, B. A. (2017). Drought and Water Crises. In *CRC Press eBooks*. World Meteorological Organization. Informa. https://doi.org/10.1201/b22009

Tadić, L., Dadić, T., & Bosak, M. (2015). Comparison of different drought assessment methods in continental Croatia. *Građevinar*, *67*(1), 11–22.

Tarhule, A., & Lamb, P. J. (2003). Climate Research and Seasonal Forecasting for West Africans: Perceptions, Dissemination, and Use? *Bulletin of the American Meteorological Society*, *84*(12), 1741–1760. https://doi.org/10.1175/bams-84-12-1741

Tigkas, D., Vangelis, H., & Tsakiris, G. (2018). Drought characterisation based on an agriculture-oriented standardised precipitation index. *Theoretical and Applied Climatology*, *135*(3-4), 1435–1447. https://doi.org/10.1007/s00704-018-2451-3

Tigkas, D., Vangelis, H., & Tsakiris, G. (2020). Implementing Crop Evapotranspiration in RDI for Farm-Level Drought Evaluation and Adaptation under Climate Change Conditions. *Water Resources Management*, *34*(14), 4329–4343. https://doi.org/10.1007/s11269-020-02593-6

Tigkas, H., & Vangelis, G. T. (2015). The Drought Indices Calculator (DrinC). In R. Maia, A. G. de Brito, A. S. Teixeira, J. T. Valente, & J. P. Pêgo (Eds.), *Water Resources Management* (pp. 211–216).

Turco, M., Llasat, M. C., von Hardenberg, J., & Provenzale, A. (2012). Impact of climate variability on summer fires in a Mediterranean environment (northeastern Iberian Peninsula). *Climatic Change*, *116*(3-4), 665–678. https://doi.org/10.1007/s10584-012-0505-6

Umar, A. T., & Ismaila, A. (2017). Analysis of Monthly Rainfall Variations: Further Evidence Of Climate Change In Sokoto State, Nigeria (1926-2015). *Ethiopian Journal of Environmental Studies & Management*, *4*(6), 9–15.

Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. *Journal of Climate*, *23*(7), 1696–1718. https://doi.org/10.1175/2009jcli2909.1

Vogt , J. V., & Gordon, M. (2021). *Special report on drought 2021*. United Nations Office for Disaster Risk Reduction (UNDRR; formerly UNISDR).

WHO. (2012). *Standardized Precipitation Index User Guide*. Chair, Publications Board World Meteorological Organization (WMO) 7 bis, avenue de la Paix P.O. Box 2300 CH-1211 Geneva 2, Switzerland, ISBN 978-92-63-11091-6. https://www.droughtmanagement.info/literature/WMO_standardized_precipitation_index_user_guide_en_2012.pdf

Wichitarapongsakun, P., Sarin, C., Klomjek, P., & Chuenchooklin, S. (2016). Rainfall prediction and meteorological drought analysis in the Sakae Krang River basin of Thailand. *Agriculture and Natural Resources*, *50*(6), 490–498. https://doi.org/10.1016/j.anres.2016.05.003

Wilhite, D. A., & Glantz, M. (2019). Understanding the Drought Phenomenon: The Role of Definitions. *Drought Mitigation Center Faculty Publications*, 11–27. https://doi.org/10.4324/9780429301735-2

Zhu, Y., Wang, W., Singh, V. P., & Liu, Y. (2016). Combined use of meteorological drought indices at multi-time scales for improving hydrological drought detection. *Science of the Total Environment*, *571*, 1058–1068. https://doi.org/10.1016/j.scitotenv.2016.07.096

http://dx.doi.org/10.21622/MACI.2026.03.1.1939





# Enhancing Adaptation and Mitigation Measures to Impacts of Climate Change on Natural Resources in Pwaga Village, Mpwapwa District, Dodoma Region, Tanzania

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## Abstract:

*Climate change poses significant threats to human livelihoods, with rural farming communities being among the most vulnerable due to their reliance on agriculture and natural resources. The severity of these impacts largely depends on farmers' awareness and their capacity to adopt appropriate adaptation strategies. Notably, extreme temperatures and rainfall brought on by climate change have disproportionately affected Tanzania's rural areas, posing hazards to their ability to live, work, and feed their populations. Although Tanzanian rural populations rely heavily on natural resources, the effects of climate change on these resources are poorly documented in these locations. The objective of this study was to assess the impacts of climate change on natural resources and develop the enhancement measures for better adaptation and mitigation in Pwaga village, Mpwapwa District, Dodoma Region, Tanzania. Data were collected through document review, physical observations, interviews, and focus group discussions. The study revealed that there is a significant climatic shift and its consequential impacts on natural resources over the past years. Climate change has increased competition for natural resources due to limited access, availability, and affordability. Hence, the study recommends the increasing use of renewable energy sources, intensification of awareness programs, afforestation, agroforestry, installation of rainwater harvesting systems, and proper waste management.*

**Keywords:** Drought, Rainfall, Resilience, Temperature.

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## 1. Introduction

Climate change is a pressing global challenge that transcends borders and affects diverse regions in unique ways (Yeh *et al.*, 2020; Adaptation Without Borders, 2021). Over the past decade, the climate has undergone significant transformations due to human activities such as burning fossil fuels and deforestation (Abbass et al., 2022). Also, industrial processes and agricultural intensifications have been among the factors and this is due to an increased concentration of greenhouse gases such as carbon dioxide ($CO_2$), Methane ($CH_4$), and Nitrous oxide ($NO_2$) and the fluorinated greenhouse gases such as perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), sulfur hexafluoride ($SF_6$), and Nitrogen trifluoride ($NF_3$) (Ritchie *et al.*, 2023; New York State DEC, 2023).

According to the World Health Organization (2023), climate-related challenges include prolonged droughts, erratic rainfall, an increase in the frequency and intensity of extreme weather events, and wildfires. These challenges contribute to food insecurity, loss of biodiversity, increased vulnerability to diseases, natural resource degradation, income inequality, malnutrition, and compounding injustices (Mirzabaev *et al.*, 2022; O'Neill *et al.*, 2022) as they affect resources that our livelihood depends on, such as water, energy, transportation, wildlife, agro ecosystem, and human health. Additionally, the heightened frequency and intensity of extreme weather events further contribute to the vulnerability of conflicts within communities, damaging infrastructure, and displacing populations (IMF, 2023).

Climate change has profound implications for food security across Africa, with impacts varying across regions and socio-economic settings (Bedeke *et al.*, 2023). In sub-Saharan Africa, shifting rainfall patterns often lead to droughts or floods, both of which threaten agricultural production and contribute to widespread food insecurity. Prolonged droughts in East Africa, for example, have been associated with reduced crop yields and livestock losses, while rising temperatures across the Sahel intensify water scarcity, soil degradation, and heat stress on crops and animals (Yeboah, 2024).

Extreme weather events, such as cyclones, further compound these challenges, particularly in coastal regions where storms can wipe out crops, infrastructure, and livelihoods, as seen with Cyclone Idai in 2019, which devastated Mozambique, Zimbabwe, and Malawi (Charrua *et al.*, 2021). The vulnerability is greatest among smallholder farmers who depend on rain-fed agriculture and lack access to resources, technology, and financial support needed for adaptation. In contrast, large-scale commercial farms are relatively more resilient, as they often have the means to invest in irrigation, insurance, and other adaptive measures to mitigate climate-related risks (Yeboah, 2024).

In Mpwapwa District, located in the Dodoma Region, central part of Tanzania, climate change has manifested in several ways, thus impacting the area's environmental and weather patterns (Myeya, 2021). Erratic rainfall, water scarcity, and prolonged drought have become more prevalent, posing substantial challenges to the agricultural sector, which is a vital component of the Dodoma rural economy (Gillo et al., 2017). Farmers face difficulties in crop cultivation due to changing precipitation patterns that disrupt traditional planting and harvesting seasons. This leads to increasing pests, diseases, food costs, and malnutrition, impacting millions of smallholder farmers who depend on rain-fed agriculture (Hussein et al., 2024). The scarcity of water resources also hampers livestock management, affecting the pastoralist way of life prevalent in the village. This is because major rivers have become increasingly unpredictable (Palmer et al., 2023; Opere et al., 2019). Overall, this situation is intensified by the community's high dependence on irrigation- and rainfall-fed agriculture, which is alarming and underscores the need for adaptation measures crucial for sustaining livelihoods and ensuring food security in the locality.

The Pwaga village faces increased economic stress as the changing climate disrupts traditional income sources, making it challenging for residents to adapt (O'Neill et al., 2022). Addressing the impacts of climate change in the village's ecology requires a multifaceted approach that combines sustainable agricultural practices, water management strategies, and community resilience initiatives (IFAD, 2017). Since fewer studies have been conducted on this aspect in Tanzania, this study intends to assess the climate change adaptation and mitigation measures on Pwaga village ecology and to provide enhancement measures to address the problem of climate change.

## 2. Methods

### 2.1. Case study selection

Pwaga village is found within Lumuma ward in Mpwapwa District, being one of the seven districts of the Dodoma Region in Tanzania. According to the 2022 census, Lumuma ward had a population of 4,339 people, of whom 2,138 were male, and 2,201 were female. The village is bordered by Itende to the north, Kitati to the east, Mgoma to the south, and Kidenge to the west (Figure 1).

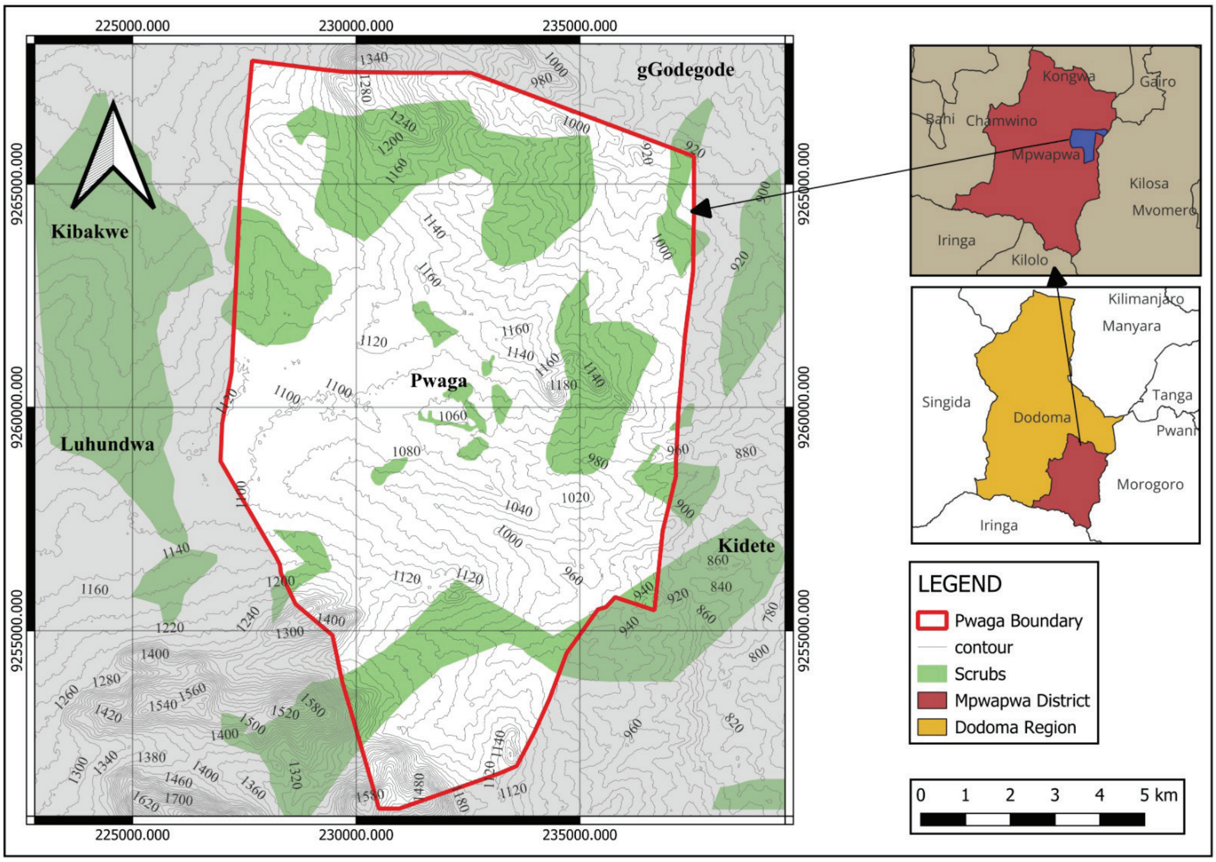


Figure 1: Pwaga village-Case study area

Due to its geographical position, and accelerating changes in climate, the village is characterized by i) Semi-arid area with prolonged dry seasons ii) Reduced availability, accessibility, and affordability of natural resources useful to human daily life activities such as water, forests which are affected by climate changes iii) Potential impacts due to existing climatic conditions inclined with natural resources present in the area. These key features contributed to the study's interest in exploring further how the population in this village adapts to and mitigates climate change impacts

### 2.2. Data collection and analysis methods

The study was conducted from March 2024 to August 2025. Both primary and secondary data were collected in this study. The primary data were collected using interviews, questionnaires, and physical observation; the secondary data were collected through document review. A total of 50 respondents were randomly sampled and were administered a questionnaire. Based on the willingness to participate in the study, the most knowledgeable person in the household was preferred for the interview. The respondents were selected to cover the whole village, in which 49% were male, and 51% were female. The dominant education status was primary level. Also, 55% of the respondents were elderly, while 45% were youth. The study used meteorological data collected from the Tanzania Meteorological Agency (TMA). The data were the maximum and minimum monthly temperature and rainfall data from 1993 to 2024. This study used a remote sensing satellite, Worldview, to assess the spatial and temporal variation of vegetation cover in the village from 2013 to 2024. Each vegetation cover was digitized to get polygons. The areas were automatically generated by the ArcGIS 10.3.1 software. Also, the study used the Checklist, Semi-Automatic Plugin, ArcGIS, and the Mann-Kendall test as tools for data analysis. To assess statistical significance, the Mann-Kendall test was used to examine trends in the recorded annual precipitation at Pwaga village in Mpwapwa District.

# 3. Results and Discussion

## 3.1. Rainfall and temperature trends for the past 30 years

### *3.1.1. Rainfall trends*

The annual total rainfall trends that were recorded for the past 30 years (1993 to 2024) are presented in Figure 2. The analysis demonstrates that annual total rainfall data for the Mpwapwa District have a significant variability. In addition to increasing tendencies in certain years, rainfall patterns have also indicated diminishing trends in other years. The fluctuations are similar to the worldwide occurrences of warm and cold episodes.

According to a study conducted by Myeya (2021) in the districts of Bahi and Mpwapwa in the Dodoma region, rainfall data analysis using the Mann-Kendall test revealed insignificant decreasing trends ($p = 0.532$ and $p = 0.473$) for the two stations for the 1961–2013 period. With a slope of 1.673 mm $y^{-1}$, the rainfall decline for Mpwapwa station indicates a 2.5% decrease in variance over the study period, while the decline for Bahi station indicates a 3.7% decrease in variance between 1961 and 2013.

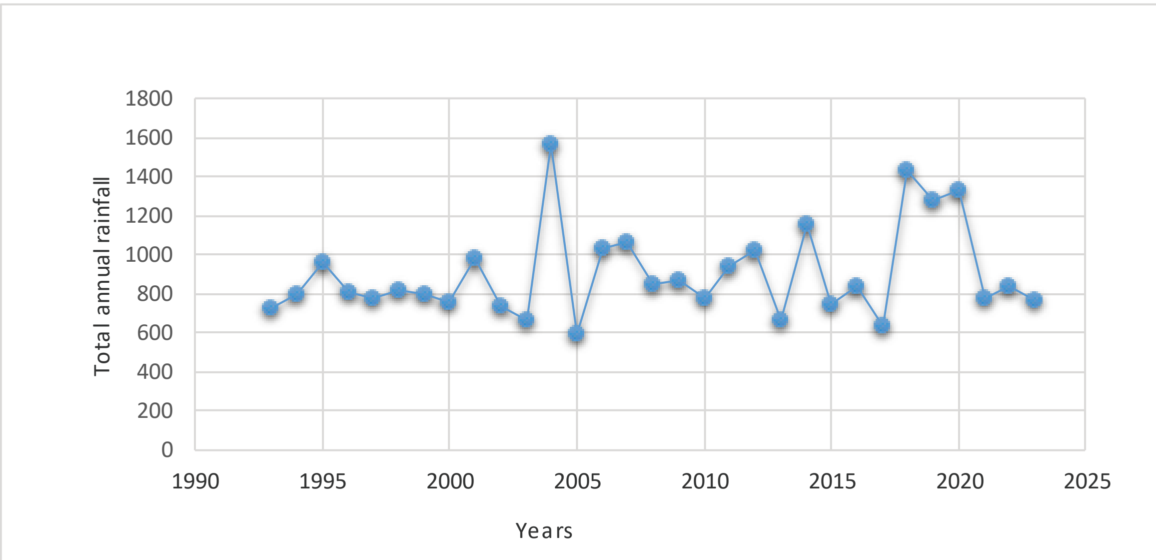


Figure 2: Temporal distribution of total annual rainfall (1993-2023)

### *3.1.2. Temperature trends*

Temperature measurements were recorded and analyzed into two categories: the mean annual minimum temperature (to represent the average lowest temperature readings recorded in each month) and the mean annual maximum temperature (to represent the average highest temperature readings recorded in each month) for the past years.

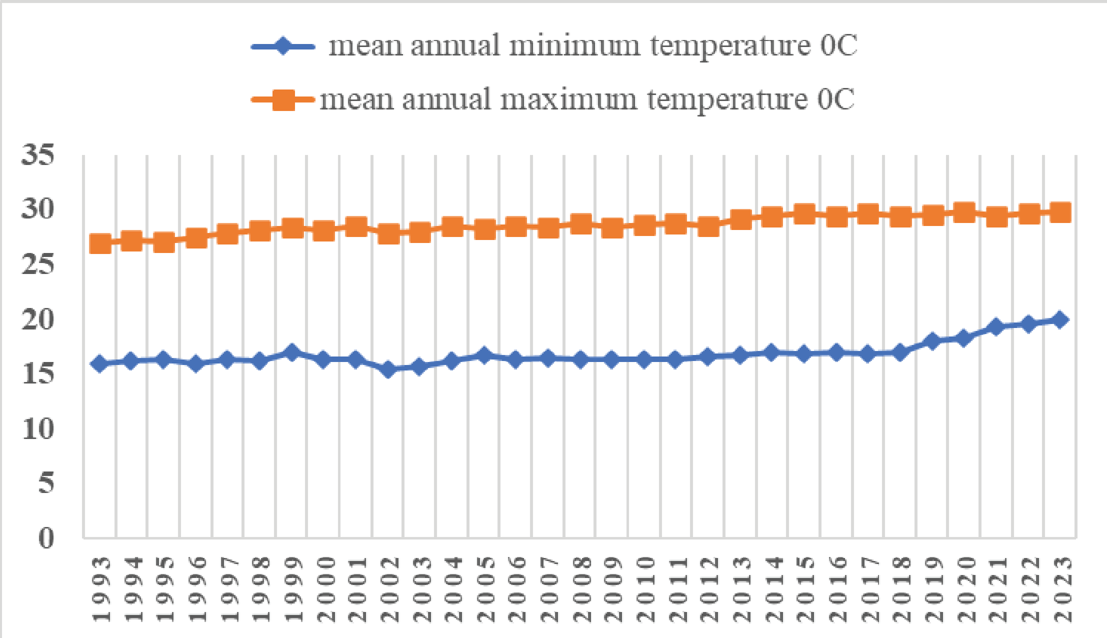


Figure 3: Temporal distribution of mean annual maximum and minimum temperatures

Also, analysis using the Mann-Kendall test reveals an increase in both the mean annual minimum and mean annual maximum temperatures. Both p-values for the mean annual minimum and maximum temperatures (P=4.24E-3 and P=8.23E-3) respectively are less than the 0.05 significance level, indicating a statistically significant increasing trend in temperature. Study done by Myeya (2021) in Bahi and Mpwapwa Districts reported that, the increased values for both the mean annual minimum and maximum temperature with the fitted linear trends in the minimum temperature ($T_{min}$) and maximum temperature ($T_{max}$) are statistically significant at the 0.05 level of significance (p=0.000, p=0.001) respectively. Based on these results, it was noted that over the past 53 years (1961- 2013), the minimum temperature in the Dodoma region has increased more rapidly than the maximum temperature. This had an implication on the increase in hot days as compared to cold ones.

On Climate change awareness, 20% of respondents were aware of climate change and its effects, while 54% of the respondents had moderate knowledge of climate change, and 26% responded with minimal knowledge of climate change and its effects on the environment. This is caused by a lack of education, traditional beliefs, and practices overshadowing scientific explanations, making it harder to change the behaviors and attitudes of some of the villagers toward climate change. Therefore, climate education is crucial for enabling informed decision-making and fostering sustainable development (UNESCO, 2017).

## 3.2. Climate change impacts on natural resources

The insignificant decrease in rainfall trends and increase in temperature in the region have impacted the natural resources in terms of availability, accessibility, and affordability. This has been discussed depending on the degree to which the village is susceptible to or unable to cope with the impacts of climate change.

### *3.2.1. Water usage*

The dominant water source in the village is a borehole that depends on rainfall to recharge, which brings about a great challenge of less water availability in the village. Most of the villagers, about 74% uses less than 20 L/person/day of water, 22% uses 20 L/person/day to 40 L/person/day, and 4% uses more than 40 L/person/day for household activities. These results show that most people use less water than the World Health Organization (WHO) recommendations, which is a minimum of 50 L/person/day. This indicates an increased risk of waterborne diseases and other health issues to vulnerable groups such as children, women, the elderly, and those with pre-existing health conditions. The situation may be worse in the

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future due to the decreasing trend of rainfall and increasing temperature in the area, leading to water shortage.

Residents of Pwaga village have been subjected to traveling a long distance of about 5 km to 9 km during the rainy season and the prolonged dry season, respectively, to fetch water from the river using power tillers and bicycles to carry the gallons and barrels. The river is a permanent one connected with the Wami Ruvu basin, thus supplying water annually. Villagers spend a lot of time fetching water, which indicates time and productivity loss since the substantial time spent on water collection reduces time available for education, work, and other productive activities. The United Nations Development Program (UNDP) states that “inequitable access to water resources exacerbates social and economic inequalities within communities” (UNDP, 2016).

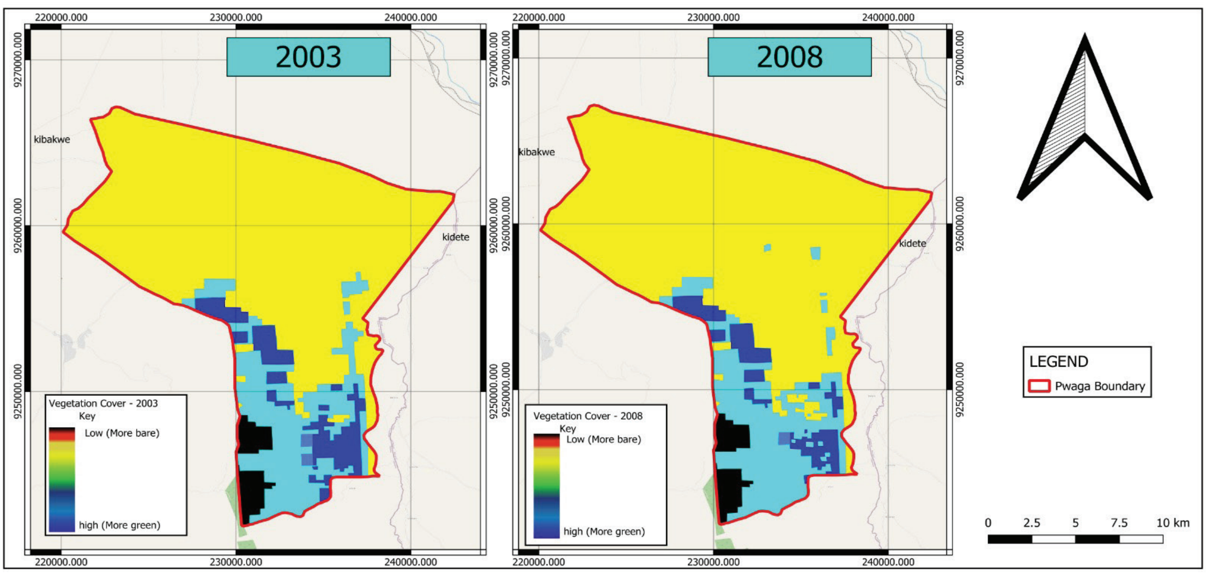
There has been an increase in the cost of buying resources, especially clean water, due to difficulty in accessibility and availability. This brings about a burden in households since it subjects poor families to reduced spending on other essential needs such as food, healthcare, and education. Also, as water becomes expensive, households have reduced their consumption, compromising hygiene and sanitation practices. A report from the United Nations Environment Program (2013) highlights that companies face increased operational costs due to rising water charges caused by scarcity. Also, the World Health Organization reported that access to affordable water is crucial for maintaining public health, and rising costs can lead to negative outcomes, specifically on health concerns (WHO, 2023), and the Sustainable Development Goals (SDGs), specifically SDG 6.1, aim to ensure universal and equitable access to safe and affordable drinking water for all by 2030.

### *3.2.2. Vegetation cover changes*

For the past 30 years, 16% of the Pwaga village land cover (square kilometers) was vegetation. The geospatial analysis for the past 20 years over a range of five years shows a decrease in vegetation cover, causing barren land. The trend is similar to rainfall characteristics in the area. However, these changes are influenced by non-climatic factors, such as deforestation, and climatic factors, such as extreme weather events, such as prolonged drought conditions that suppress the forest growth. Table 1 shows the percentage change of vegetation cover from 2003 to 2023 within Pwaga village, associated with community reliance on fuelwood and charcoal as the primary fuel source for domestic activities, as well as increased temperature and erratic rainfalls that are suppressing forest or vegetation growth. Different maps are presented in Figure 4 showing the change of vegetation coverage from 2003 to 2023 as summarized in Table 1.

Table 1: Land cover change from 2003 to 2023

| Year | Total area km$^2$ | Reduced % |
|---|---|---|
| 2003 - 2008 | 11 | 3.4 |
| 2008 - 2013 | 11 | 5.2 |
| 2013 - 2018 | 11 | 7.4 |
| 2018 - 2023 | 11 | 16 |



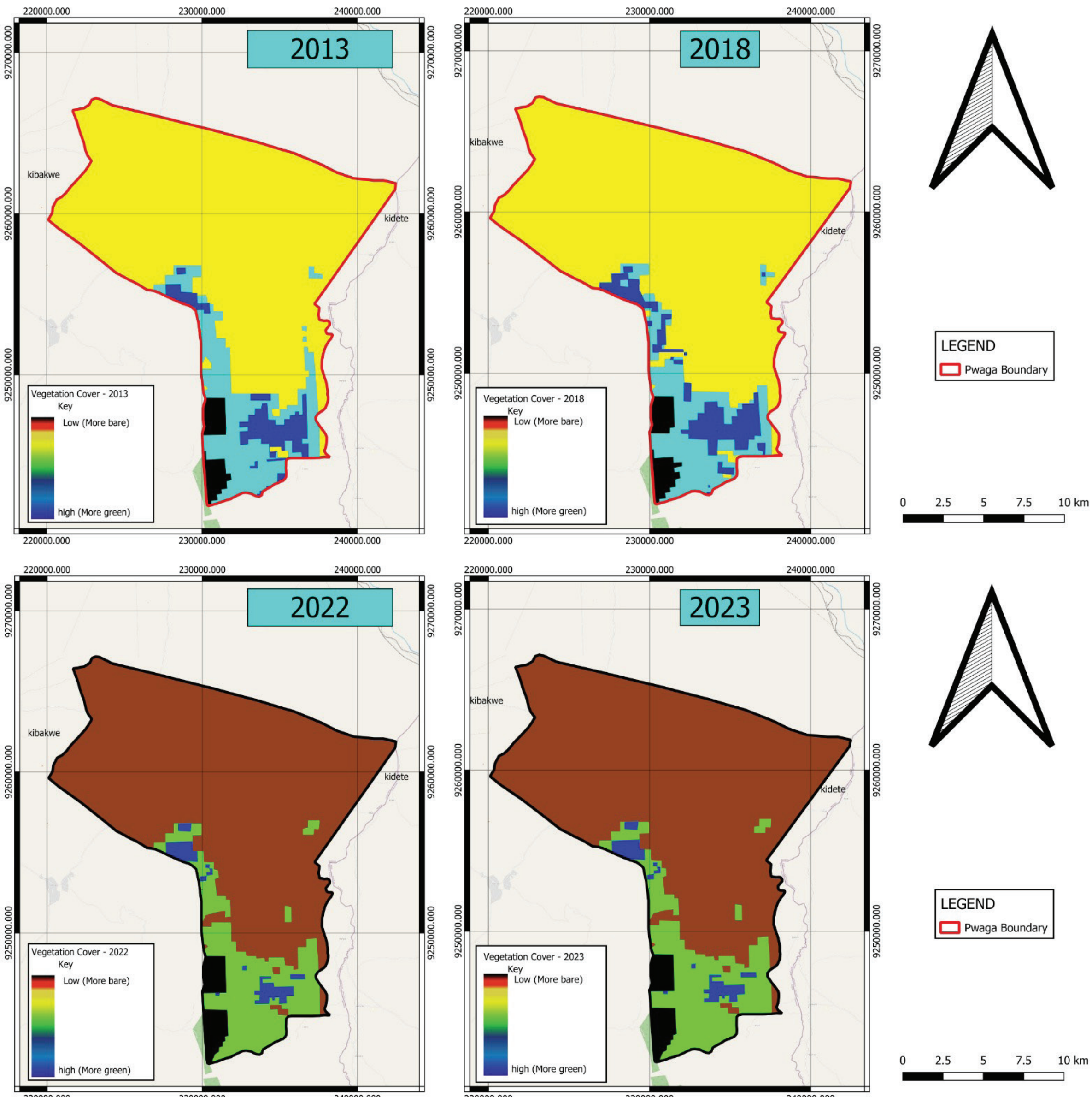



Figure 4: Maps of Pwaga village indicating land cover changes from 2003 to 2023

## 3.3. Non-climatic factors

According to the household questionnaire, about 88% of Pwaga village residents use wood and charcoal as their primary source of fuel, and only 12% uses liquefied natural gas as their source of fuel for different household activities. Higher usage of wood and charcoal as a source of fuel indicates that there is a high rate of deforestation, which indicates increased vulnerability to climate change impacts. It has been revealed that deforestation for fuel wood collection is a significant driver of forest loss, particularly in developing countries (United Nations Forum on Forests, 2019; Sintayehu, 2025). In effect, the rainfall formation through evapotranspiration and cooling is compromised, exposing people to low rainfall and high ambient temperature.

On the other hand, the land use changes in the area were another factor for the decline of natural resources. The dominant economic activities taking place within the village are small-scale industries (carpentry), agriculture, which involves growing drought-resistant crop varieties such as millet, maize, oilseed crop (sunflower), and groundnuts, together with livestock keeping. The increase in population from the past to the present year has resulted in an increase in demand for agricultural land for growing these crops, where by villagers have been clearing or cutting down trees for obtaining agricultural land, also fuelwood and charcoal as their primary energy sources, in which all these non-climatic factors have contributed in land use changes from past to present year as well.

## 3.4. Conflicts on natural resources usage

According to the interviews done among 50 residents in Pwaga village on conflict engagement on natural resources, it was found that 30% of the villagers have never experienced conflicts on natural resources usage, while 70% have at least experienced some conflicts. These conflicts were between farmers and livestock keepers on pasture, also on water usage in different water sources such as Lumuma river, Itende river, and Waturuki boreholes. These conflicts have hindered economic development. It is revealed that borehole water conflicts centered on resource control inequities, with water as a strategic resource causing tensions, particularly among marginalized groups (Mwea & Henry, 2021).

## 3.5. Adaptation & mitigation measures

### *3.5.1. Adaptation measures*

Regarding the water management system, 16% of the respondents installed rainwater harvesting systems while 84% lacks the system to collect rainwater. The failure of installing rainwater harvesting systems is also associated with the level of their economy, since the actual condition of their houses that are built with no iron sheet (covered with dry grasses) or the installed iron sheet is covered with stones as the holding material, indicating the presence of low-income household earners. Most of the villagers opt to use the Waturuki borehole, while others opt to move to the Itende River and the Lumuma River to access water due to the queue at the borehole.

The analysis shows that the effort in afforestation is not fully realized due to land use pressure associated with competing needs for agricultural land, which has led to difficulties in setting aside areas for afforestation or reforestation. Likewise, farmers have adopted drought-resistant crop varieties such as sunflower, millet, and maize, which are more resilient to dry conditions. According to the Dodoma Agricultural Office (2023), the adoption rate of drought-resistant crops has increased by 40% over the past 10 years**.** Despite growing drought-resistant crops, the agricultural yield has still been affected negatively due to increasing changes in the climatic conditions of the area. Similarly, the Dodoma Agricultural office reported that over the past 4 years, the yield of millet, maize, and sunflower has been reduced for 20% due to erratic rainfall.

### *3.5.2. Mitigation measures*

Among 50 respondents, only 26% of the respondents utilize renewable energy, and 74% do not utilize any kind of renewable energy despite having feedstocks from agricultural waste and livestock keeping that can be used in generating bioenergy. This indicates the limited adoption of renewable energy sources within the village, since the community relies heavily on potentially environmentally damaging energy sources. Increasing the use of renewable energy significantly enhances energy security and reduces environmental impacts like emission of Greenhouse gases, which contribute to climate change (IRENA, 2021).

Regarding waste management practices, all respondents showed a lack of proper knowledge and practices of waste disposal, which contribute to environmental pollution. Villagers lack adequate awareness of practices such as recycling, composting, and proper waste segregation. Thus, they end up practicing improper disposal of waste, such as open burning and open dumping of waste, which contribute to the emission of greenhouse gases. According to Li et al. (2022), waste management practices significantly influence greenhouse gas emissions and climate change mitigation efforts.

## 3.6. Enhancement measures

Addressing the impacts of climate change requires a comprehensive approach that enhances local capacities in water management, agriculture, energy, afforestation, and waste management. This study provides strategic enhancement measures supported by data and successful case studies, aiming to build resilience and sustainability in Pwaga village, ensuring the village's long-term viability in the face of existing climate change.

The enhancement measures are twofold. The enhancement measures for adaptation measures are: i) Increased water resources management by constructing more boreholes and introducing roof-based systems with gutters and storage tanks for harvesting rainwater. ii) employing climate resilient agricultural practices by growing additional drought-resistant crop varieties and improved irrigation iii) practicing the afforestation and agroforestry iv) promoting the public-private partnership wherever possible and applicable. The enhancement measures for mitigation measures include i) Expansion of renewable energy use by installation of Solar energy and biogas systems, ii) Improving waste management practices by practicing composting. iii) Raising climate change awareness by conducting regular educational/ awareness programs, workshops, and community meetings. iv) Sustainable Agricultural practices by encouraging practices like crop rotation, organic farming, and the use of natural fertilizers made from compost.

## 4. Conclusion and Recommendation

The study aimed at assessing the impacts of climate change on natural resources and developing the enhancement measures for better adaptation and mitigation in Pwaga village, Mpwapwa District, Dodoma Region, Tanzania. The study found that because of restricted access, availability, and affordability, climate change has increased the competition for natural resources, particularly water, firewood as an energy source, and waste management. There are a number of adaptation and mitigation strategies in place, but they are not yet meeting the demands. To enhance adaptation and mitigation measures against the impacts of climate change on natural resources in Pwaga Village, Mpwapwa District, the government of Tanzania, in collaboration with local authorities, should prioritize integrated resource management that combines sustainable groundwater use, afforestation, and soil conservation practices. Policies should encourage the adoption of renewable energy technologies such as solar and biogas to reduce pressure on forest resources, while promoting climate-smart agriculture to ensure food security and resilience of rural livelihoods. Furthermore, strengthening community-based awareness programs, capacity building, and the establishment of local climate action committees will foster inclusive participation in decision-making and ensure long-term sustainability of natural resources in the face of changing climatic conditions.

## References:

Abbass, K., Qasim, M. Z., Song, H., Murshed, M., Mahmood, H., & Younis, I. (2022). A review of the global climate change impacts, adaptation, and sustainable mitigation measures. *Environmental Science and Pollution Research*, *29*(1), 42539–42559. Springer. https://doi.org/10.1007/s11356-022-19718-6

Adaptation Without Borders. (2021). *Transboundary climate risks: An overview*. Adaptation without Borders. https://adaptationwithoutborders.org/

B. Yeh, K., M. Fair, J., Smith, W., Martinez Torres, T., Lucas, J., Monagin, C., Winegar, R., & Fletcher, J. (2020). Assessing Climate Change Impact on Ecosystems and Infectious Disease: Important Roles for Genomic Sequencing and a One Health Perspective. *Tropical Medicine and Infectious Disease*, *5*(2), 90. https://doi.org/10.3390/tropicalmed5020090

Bedeke, S. B. (2022). Climate change vulnerability and adaptation of crop producers in sub-Saharan Africa: a review on concepts, approaches and methods. *Environment, Development and Sustainability*, *25*(2), 1017–1051. https://doi.org/10.1007/s10668-022-02118-8

Charrua, A. B., Padmanaban, R., Cabral, P., Bandeira, S., & Romeiras, M. M. (2021). Impacts of the Tropical Cyclone Idai in Mozambique: A Multi-Temporal Landsat Satellite Imagery Analysis. *Remote Sensing*, *13*(2), 201. https://doi.org/10.3390/rs13020201

Dodoma Agricultural Office. (2023). *Dodoma region agricultural report 2023*. https://www.nbs.go.tz/nbs/takwimu/Agriculture/DODOMA%20REGION%20REPORT.pdf

Gillo, I. O., Mkomage, J., & Mayaya, H. (2017). Farmers' Awareness on Climate Change and Adaptation Practices in Mpwapwa District, Dodoma-Tanzania. *International Journal of Humanities & Social Studies*, *5*(7). https://internationaljournalcorner.com/index.php/theijhss/article/view/125727

Hussein, J., Bilotto, F., Mbui, D., Omondi, P., Harrison, M. T., Crane, T. A., & Sircely, J. (2024). Exploring smallholder farm resilience to climate change: intended and actual adaptation. *Deleted Journal*, *14*. https://doi.org/10.3389/past.2024.13424

International Monetary Fund. (2023). *Climate Challenges in Fragile and Conflict-Affected States*. IMF. https://www.imf.org/en/Publications/staff-climate-notes/Issues/2023/08/24/Climate-Challenges-in-Fragile-and-Conflict-Affected-States-537797

International Renewable Energy Agency (IRENA). (2021). *WORLD ENERGY TRANSITIONS OUTLOOK 1.5°C PATHWAY*. https://www.connaissancedesenergies.org/sites/connaissancedesenergies.org/files/pdf-pt-vue/IRENA_World_Energy_Transitions_Outlook_2021_1.pdf

Li, Y., Zhang, S., & Liu, C. (2022). Research on Greenhouse Gas Emission Characteristics and Emission Mitigation Potential of Municipal Solid Waste Treatment in Beijing. *Sustainability*, *14*(14), 8398. https://doi.org/10.3390/su14148398

Mirzabaev, A., Bezner Kerr, R., Hasegawa, T., Pradhan, P., Wreford, A., Cristina Tirado von der Pahlen, M., & Gurney-Smith, H. (2023). Severe climate change risks to food security and nutrition. *Climate Risk Management*, *39*(100473), 100473. https://doi.org/10.1016/j.crm.2022.100473

Mwea, C., & Henry, L. (2019). *Gender dynamics and water conflicts in community boreholes in Turkana County (Working paper, Pathways to Resilience in the Karamoja Cluster: A regional conference on recent research and policy options*. https://karamojaresilience.org/wp-content/uploads/2021/07/14ec3c_ccb9c0a1f46145669a89eb775f91b663.pdf

Myeya, H. E. (2021, May). *Recent Temperature and Rainfall Characteristics in Dodoma Region, Central Tanzania (1961 – 2013)*. Udsm.ac.tz; University of Ghana. https://repository.udsm.ac.tz/items/60837be2-3cc0-4d87-af0b-82ad06405a58

O'Neill, B. C., Aalst, M. van , Ibrahim, Z., Berrang-Ford, L., Bhadwal, S., Buhaug, H., Diaz, D., Frieler, K., Garschagen, M., Magnan, A.-S., Midgley, G., Mirzabaev, A., Thomas, A., & Warren, R. (2022). Key Risks across Sectors and Regions. In H.-O. Pörtner, D. C. Roberts, M. Tignor, M. Tignor, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama (Eds.), *Climate Change 2022: Impacts, Adaptation, and Vulnerability (IPCC AR6 Working Group II)*. IPCC Cambridge University Pres. https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/

Opere, A., Omwoyo, A., Purity Mueni, & Arango, M. (2019). Impact of Climate Change on Water Resources in Eastern Africa. In C. Ondieki & J. Kitheka (Eds.), *Hydrology and Water Resources Management in Arid, Semi-Arid, and Tropical Regions* (pp. 199–227). IGI Global Scientific Publishing. https://doi.org/10.4018/978-1-7998-0163-4.ch010

Palmer, P. I., Wainwright, C. M., Dong, B., Maidment, R. I., Wheeler, K. G., Gedney, N., Hickman, J. E., Madani, N., Folwell, S. S., Abdo, G., Allan, R. P., Black, E. C. L., Feng, L., Gudoshava, M., Haines, K., Huntingford, C., Kilavi, M., Lunt, M. F., Shaaban, A., & Turner, A. G. (2023). Drivers and impacts of Eastern African rainfall variability. *Nature Reviews Earth & Environment*, *4*(4), 254–270. https://doi.org/10.1038/s43017-023-00397-x

Ritchie, H., Rosado, P., & Roser, M. (2023). $CO_2$ and Greenhouse Gas Emissions. *Our World in Data*. Our World in Data. https://ourworldindata.org/co2-and-greenhouse-gas-emissions

United Nations Development Programme. (2016). *Human development report 2016: Human development for everyone*. Hdr.undp.org. http://hdr.undp.org/en/2016-report

United Nations Educational, Scientific, and Cultural Organization. (2017). UNESCO Moving Forward the 2030 Agenda for Sustainable Development. In *Unesco.org*. https://unesdoc.unesco.org/ark:/48223/pf0000247785

United Nations Environment Programme (UNEP). (2013). *Climate change, water shortages, biodiversity loss, will have growing impacts on global business: UN report*. GEO-5 for Business: Impacts of a Changing Environment on the Corporate Sector. https://smartnordicexchange.com/images/GEO5_for_Business.pdf

United Nations Forum on Forests. (2019). *Background analytical study: Forests and climate change (UNFF14-BkgdStudy-SDG13)*. United Nations. https://www.un.org/esa/forests/wp-content/uploads/2019/03/UNFF14-BkgdStudy-SDG13-March2019.pdf

World Health Organization. (2023, October 12). *Climate Change*. World Health Organization. https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health

Yeboah, A. (2024). *Assessing Climate Change Impacts on Food Security in Africa: Regional Variations and Socio-Economic Perspectives*. Sunyani Technical University. https://mpra.ub.uni-muenchen.de/120918/1/MPRA_paper_120918.pdf

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# Assessing RegCM4 Simulations of the Diurnal Temperature Range over Egypt: Sensitivity to Soil Moisture Initialization and Land-Surface Parameterization

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## Abstract:

*This study investigates the impact of soil moisture initialization and land-surface parameterization on Egypt's diurnal temperature range (DTR) using the regional climate model RegCM4. Four 40-year simulations were conducted for the period 1979–2018, representing different combinations of soil moisture datasets and hydrological schemes. Soil moisture was initialized using two products: the ESA Climate Change Initiative (ESA) satellite dataset and the Century (CEN) reanalysis dataset. In addition, two hydrological schemes were applied: TOPMODEL (TOP) and the Variable Infiltration Capacity model (VIC). All simulations were evaluated against the high-resolution TerraClimate dataset and in situ station observations.*

*The results indicate that daily maximum temperature (TMX) is largely insensitive to both soil moisture initialization and parameterization schemes, whereas daily minimum temperature (TMN) and DTR exhibit strong sensitivity. Simulations initialized with the ESA dataset generally produce warmer TMN values than those initialized with the CEN dataset, with biases ranging from 2–4°C along the Mediterranean coast and 2–6°C across much of Egypt. A similar sensitivity is observed between the TOP and VIC hydrological schemes. Overall, the CEN–TOP configuration provides the most accurate simulation of DTR across all seasons.*

*Comparison with station observations reveals that DTR biases vary by location, with both overestimation and underestimation depending on the station. Application of a linear scaling (LS) bias-correction method significantly reduces these biases. These findings suggest that accurate simulation of Egypt's DTR can be achieved when RegCM4 is initialized with the CEN soil moisture dataset, coupled with the TOP hydrological scheme, and corrected using LS.*

**Keywords:** DTR, Soil moisture initialization, Soil moisture parameterization, RegCM4, Linear-scaling.

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## 1. Introduction

Climate change significantly affects atmospheric variables such as temperature and precipitation, including their extremes (IPCC, 2021). Daily maximum and minimum air temperatures are key indicators of climate variability and change, reflecting both natural variability and anthropogenic influences (Ritchie and Roser, 2019). The diurnal temperature range (DTR), defined as the difference between daily maximum and minimum temperatures, is a widely used metric for detecting climate change signals due to its sensitivity to variations in the surface energy balance (Braganza et al., 2004; Ongoma et al., 2020). In meteorological terms, hot days are typically defined as days when temperatures exceed a specified high-percentile threshold (e.g., the 90th or 95th percentile), while heat wave (HW) days refer to periods of consecutive hot days (usually lasting at least 3–5 days). In contrast, typical summer days represent climatological average conditions without extreme temperature anomalies.

DTR plays an important role across multiple sectors, including human health, agriculture, ecosystems, and energy demand (Davis et al., 2020; Huang et al., 2020; Adekanmbi et al., 2022; Bravo et al., 2020). Its variability is controlled by several factors, including cloud cover, land use, aerosols, and land–atmosphere interactions, particularly soil moisture (Dai et al., 1999; Ren et al., 2014; Schultz et al., 2017). Observational studies have shown that increased cloudiness and soil moisture tend to reduce DTR by suppressing daytime heating and enhancing nighttime temperatures (Stone and Weaver, 2003; Wang et al., 2014). In contrast, drier conditions enhance sensible heating and increase DTR through reduced evapotranspiration (Panwar et al., 2020).

Modeling studies further highlight the complex role of land–atmosphere processes in shaping DTR variability. For example, vegetation dynamics, aerosols, and radiative forcing have been shown to modulate DTR differently across regions and climate regimes (Jeong et al., 2011; Katavoutas et al., 2023; Roesch et al., 2025). Despite these advances, uncertainties remain regarding the representation of soil moisture processes in regional climate models and their impact on temperature extremes.

In the context of Egypt, previous modeling studies using RegCM4 have demonstrated that soil moisture initialization significantly affects simulated temperature fields. For instance, initializing the model with soil moisture data improves the representation of soil and near-surface air temperatures compared to bare soil conditions (Anwar, 2023; Anwar and Mostafa, 2023). However, the combined effects of soil moisture initialization and parameterization on DTR have not been comprehensively investigated. This study aims to quantify the impact of soil moisture initialization and parameterization on the DTR over Egypt using RegCM4. Specifically, it evaluates how these factors influence daily TMX and TMN, and examines the effectiveness of linear scaling (LS) bias correction in improving the representation of the DTR annual cycle. This work represents the first systematic assessment of soil moisture–DTR interactions in Egypt using RegCM4, providing a reference for future regional modeling studies and climate adaptation planning.

## 2. Materials and Methods

### 2.1. Study area

Egypt is located in the North Africa and Middle East (MENA) region, bordered by the Mediterranean Sea to the north, the Red Sea to the east, and Libya to the west, and the Sinai Peninsula to the northeast, extending between latitudes 22°N–32°N and longitudes 24°E–37°E. The country covers approximately 1,000,000 km² and exhibits diverse topography, ranging from the Western Desert, lying around 133 m below mean sea level, to elevated terrain in the Sinai Peninsula, including Mount Catherine at 2,642 m above sea level. The Nile Valley and Delta are the primary population centers.

Climatically, Egypt is classified as a hot desert (BWh) according to the Köppen system (El-Kenawy et al., 2010; Hamed et al., 2022a, b), with pronounced spatial and temporal variability. Based on annual rainfall, six climatic regions are commonly recognized:

1. **Mediterranean Coast:** ~200 mm/year, mainly from cyclonic activity.
2. **Nile Delta:** ~25 mm/year, largely dependent on irrigation.
3. **Central Egypt:** ~10 mm/year.
4. **Upper Egypt:** minimal rainfall, dependent on Nile water.

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5. **Red Sea Coast:** infrequent but intense rainfall events cause flash floods.

6. **Sinai Mountains:** >100 mm/year due to orographic effects, supporting small-scale agriculture.

Egypt experiences two main seasons: a hot, dry period from May to October, and a cooler season from November to April, when precipitation can reach up to 200 mm in northern regions but drops below 20 mm in southern areas. Regionally, annual air temperature variability can be summarized as:

1. **Mediterranean Coast:** winter 13–21 °C, summer 24–32 °C.

2. **Nile Valley and Delta:** winter 14–20 °C, summer up to 40 °C.

3. **Western and Eastern Deserts:** winter 8–18 °C, summer >45 °C.

4. **Southern Egypt:** summer >40 °C, mild winters with cold nights (Hamed et al., 2022a).

The arid climate, combined with this spatial heterogeneity, makes Egypt highly sensitive to climate change impacts, including increased frequency and intensity of heatwaves, extended drought periods, and water scarcity, with significant implications for agriculture and public health (Nashwan et al., 2020).

## 2.2. RegCM model description and experiment design

This study investigates the sensitivity of Egypt's DTR to soil moisture initialization and land-surface parameterization using the Regional Climate Model version 4 (RegCM4; Giorgi et al., 2012). Simulations were dynamically downscaled using the ERA-Interim reanalysis (EIN15; Dee et al., 2011) at a horizontal resolution of 25 km, which provides the initial and lateral boundary conditions. Although higher-resolution products such as ERA5 are available, ERA-Interim was selected due to its extensive validation in regional climate modeling studies, including RegCM4 applications over North Africa, ensuring consistency with previous work. In addition, the multi-decadal simulations and multiple sensitivity experiments conducted in this study impose considerable computational and data storage demands, for which ERA-Interim provides a practical balance between resolution and efficiency. Furthermore, ERA-Interim offers sufficiently reliable large-scale atmospheric forcing for assessing the relative sensitivity of DTR to soil moisture initialization and parameterization.

The Egyptian domain spans 24–38°E and 22–34°N, with 60 grid points applied in both zonal and meridional directions to minimize lateral boundary buffer effects (Figure 1; Anwar and Olusegun, 2024). The model is configured in hydrostatic mode (Grell et al., 1994a,b) with 18 terrain-following sigma levels, the Emanuel cumulus scheme (Emanuel and Zivkovic-Rothman, 1999) using a tuned precipitation efficiency parameter (omtrain = 0.777), the UW planetary boundary layer scheme (Grenier and Bretherton, 2001), and the RRTM radiation scheme (Kiehl et al., 1996). The simulation period extends from 1979 to 2018, with the first two years treated as spin-up to stabilize soil moisture and energy fluxes (Steiner et al., 2009), while analyses focus on 1981–2018.

Soil moisture was initialized using two independent datasets: the ESA Climate Change Initiative (ESACCI; Dorigo et al., 2017; Gruber et al., 2019) satellite product (0.25° resolution) and the Century (CEN) global reanalysis dataset from NOAA (Slivinski et al., 2019; 1° resolution). To evaluate soil hydrology effects, two CLM45 (Community Land Model v4.5; Oleson et al., 2013) schemes were applied: TOPMODEL (TOP; Niu et al., 2005) and the Variable Infiltration Capacity model (VIC; Liang et al., 1994, 1996a, b, 2003). These schemes differ in their representation of soil moisture dynamics and runoff generation, allowing a clear separation of soil moisture initialization versus parameterization effects on DTR. The four 40-year experiments are grouped as follows: (i) soil moisture parameterization experiments using CEN initialization with TOP and VIC schemes, and (ii) soil moisture initialization experiments using the TOP scheme with ESA and CEN datasets.

The CLM45 model simulates key biogeophysical and hydrological processes governing land–atmosphere interactions, including radiation fluxes, sensible and latent heat fluxes, soil heat transfer, and runoff generation. Key soil hydrology parameters follow the standard CLM45 implementation and were tuned to ensure physically consistent differences between TOP and VIC schemes. Sensitivity experiments showed that omtrain = 0.777 produces a meaningful distinction between the two schemes, whereas omtrain = 0.999 suppresses these differences (Anwar et al., 2019).

Surface and atmospheric variables analyzed include soil moisture (SM, in mm), radiation fluxes (RSDS, RSNS, RLDS, RLNS, in W m$^{-2}$), ground temperature (TS, in °C), sensible heat flux (SHF, in W m$^{-2}$), and near-surface relative humidity (RH, in %). RSDS and RSNS stand for the global and net incident solar radiation, while RLDS and RLNS stand for the global and net incident longwave radiation. Daily maximum (TMX, in °C) and minimum (TMN, in °C) air temperatures were used to compute DTR (DTR = TMX - TMN, in °C). While other meteorological factors (e.g., cloud cover, wind speed, and atmospheric moisture) also influence DTR, this study focuses on soil moisture–driven changes, which are implicitly represented within the RegCM4 physics and associated fluxes.

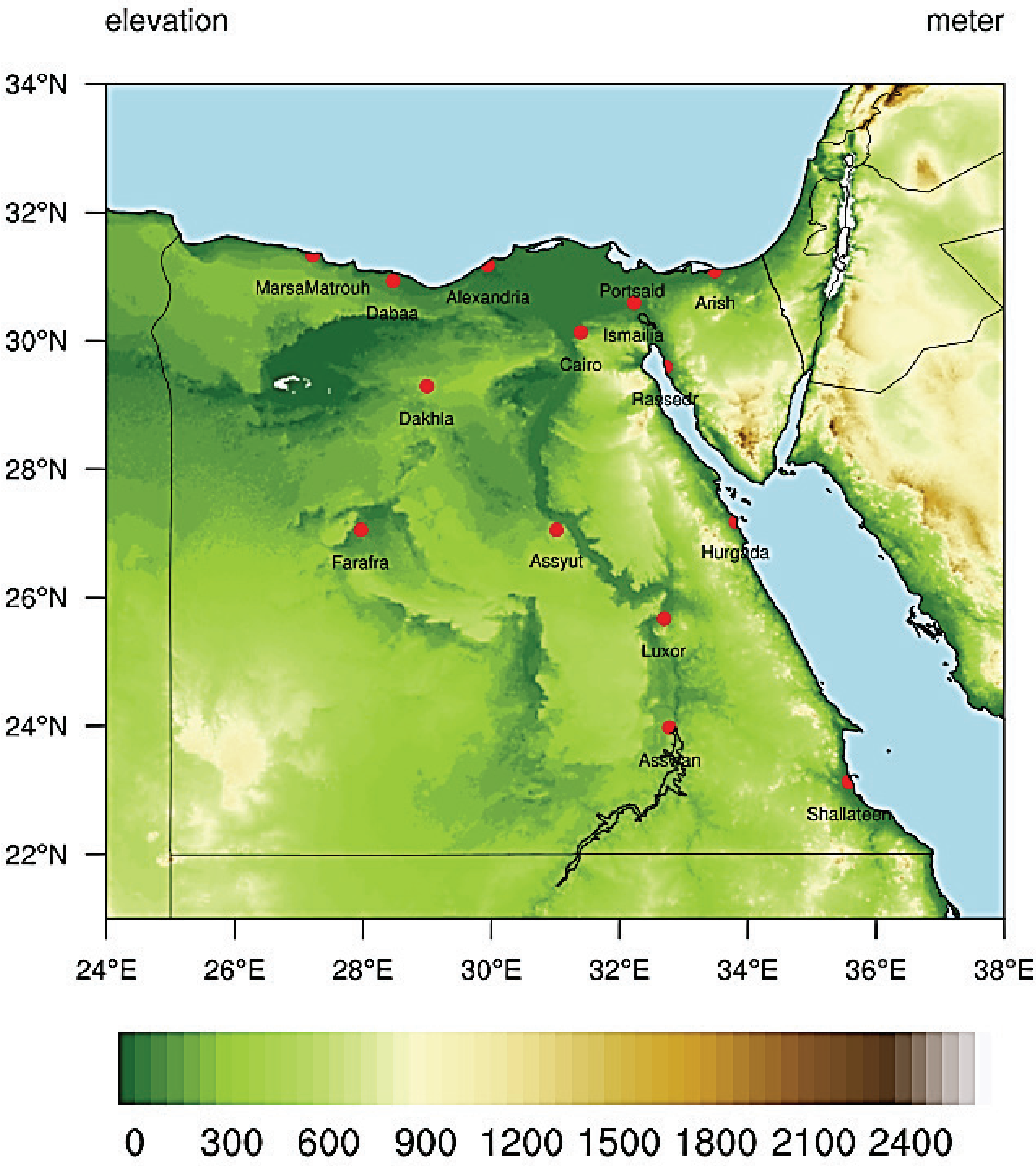


Figure 1: Topography of Egypt (elevation above mean sea level) and locations of the 15 meteorological stations used for evaluating RegCM4 simulations of diurnal temperature range (DTR). Station records span 1981–2018 and represent diverse climatic and geographic regions. Red dots indicate station locations; note that Ismailia does not have complete data, which is why only 14 dots appear on the map.

Table 1: RegCM4 configuration and experimental design adopted to assess the effects of soil moisture initialization and parameterization

| | |
|---|---|
| **Model domain** | 24 to 38°E and from 22 – 34°N, res. = 25 km; clat = 27, clon = 30 and iy = jx = 60 |
| **Map projection** | Rotated Mercator |
| **Vertical coordinate** | Terrain-following sigma coordinate; Total: 18 sigma levels |
| **Cumulus parameterization** | Emanuel scheme (with precipitation efficiency; omtrain = 0.777) over land and Ocean |
| **Land surface model** | Community Land Model version 4.5 (CLM45) |
| **Radiation parameterization** | RRTM radiation scheme (with default parameters) |
| **PBL parameterization** | UW boundary layer scheme (with default parameters) |
| **Lateral boundary condition** | ERA-Interim Reanalysis 1.5° x 1.5° |
| **Sea surface temperature (SST) boundary condition** | ERA-Interim Reanalysis 1.5° x 1.5° |
| **Soil moisture initialization** | ESACCI satellite product (ESA) and Century reanalysis (CEN) |
| **Soil moisture parameterization** | TOP and VIC soil moisture schemes of the CLM45 land surface model |

## 2.3. Observational dataset

To evaluate the simulated DTR, two observational datasets were used. First, the high-resolution TerraClimate dataset (TERRA) was employed to evaluate DTR at each grid point, as it integrates multiple reanalysis and observational products. TERRA combines climatological information from WorldClim with temporally varying data from coarser-resolution products, including the Climate Research Unit Time Series version 4.0 (CRU TS4.0; Harris et al., 2020) and the Japanese 55-year Reanalysis (JRA-55; Kobayashi et al., 2016). By interpolating CRU anomalies onto the WorldClim climatology, TERRA provides long-term, high-resolution (~4 km) data, including temperature-based metrics and derived hydro-climatic variables such as reference evapotranspiration ($ET_o$), soil moisture, runoff, and the Palmer Drought Severity Index. For the evaluation of RegCM4 outputs, TERRA was bilinearly interpolated onto the model's curvilinear grid, and the statistical significance of biases was examined using a Student's t-test at $\alpha = 0.05$.

Second, observational data on daily TMX and TMN were collected from 15 meteorological stations distributed across Egypt, representing diverse climatic and geographic regions (Figure 1; Table 2). Station records span 1981–2018, consistent with the RegCM4 simulations. All data underwent rigorous quality control, including checks for missing values, outliers, and inconsistencies, and were cross-validated with neighboring stations and the TERRA dataset to ensure reliability. These high-quality station observations provide a robust benchmark for evaluating model performance at the local scale.

Table 2: The table shows station coordinates, World Meteorological Organization (WMO) ID, and elevation above mean sea level (in meters)

| Station | WMO Code | Longitude (°E) | Latitude (°N) | Elevation (m) |
|---|---|---|---|---|
| Marsa-Matrouh | 62306 | 27.22 | 31.33 | 25 |
| Dabaa | 62309 | 28.47 | 30.93 | 17 |
| Alexandria | 62318 | 29.95 | 31.18 | -2.626 |
| Port Said | 62332 | 32.20 | 31.28 | 0.8 |
| Arish | 62337 | 33.49 | 31.09 | 30.57 |
| Cairo | 62366 | 31.40 | 30.13 | 64.12 |
| Assyut | 62393 | 31.02 | 27.05 | 226 |
| Luxor | 62405 | 32.70 | 25.67 | 83.64 |
| Asswan | 62414 | 32.78 | 23.97 | 192.53 |
| Farafra | 62423 | 27.97 | 27.05 | 77.79 |
| Dakhla | 62432 | 29.00 | 25.29 | 107.26 |
| Ismailia | 62440 | 32.23 | 30.59 | 10.14 |
| Ras Sedr | 62455 | 32.72 | 29.59 | 3.26 |
| Hurgada | 62463 | 33.82 | 27.18 | 7.79 |
| Shallateen | 62476 | 35.58 | 23.13 | 19.44 |

The DTR was calculated by taking TMX and subtracting TMN from it. The ideal configuration (of the initialized/parameterized soil moisture) will be evaluated against the OBS climatological annual pattern. Ultimately, the improved value of the linear scaling (LS) bias-correction method is attained by integrating the seasonal mean into every season of the simulation as follows:

$$RCMnew_i = RCM_i + (OBS_{seasonal} - RCM_{seasonal}) \quad (1),$$

where $i$ represents the season (winter, spring, summer, and autumn), $RCM_i$ denotes the uncorrected output from RegCM4, and $RCMnew_i$ indicates the bias-adjusted output from RegCM4. $OBS_{seasonal}$ represents the seasonal mean of the OBS, while $RCM_{seasonal}$ denotes the seasonal mean of the RegCM4. To analyze the additional benefit of the LS, the Taylor diagram (Taylor 2001) was utilized. Essentially, the Taylor diagram requires three statistical measures: Standard deviation ratio (STD), Mean bias (MB), and Spatial correlation coefficient (CORR). The Taylor diagram provides a quantitative summary for comparing two or more model configurations across multiple locations within a single figure. It allows assessment of model performance by displaying key statistical metrics, including the correlation coefficient (CORR, ranging from -1 to 1, where -1 indicates a perfect negative correlation and 1 indicates a perfect positive correlation), mean bias (MB, expressed in absolute terms or as a percentage), and standard deviation (STD, ranging from 0 to 1.65), which reflects the consistency of model variance relative to observations.

## 3. Results and Discussion

The influence of soil moisture initialization and parameterization on maximum temperature (TMX), minimum temperature (TMN), and DTR was assessed using a diagnostic analysis (Figures 2 and S1–S5). Soil moisture at 10 cm depth was examined first, followed by related radiative and thermal variables to understand their effects on temperature responses. Seasonal climatologies of TMX and TMN were analyzed for each experiment to identify which temperature component is most sensitive to soil moisture configuration and to determine the setup that minimizes DTR bias relative to the TERRA dataset. The analysis was performed for the four climatological seasons: spring (MAM), summer (JJA), autumn (SON), and winter (DJF).

The observed sensitivity of DTR to soil moisture initialization and parameterization aligns with general physical principles documented in global studies. Drier soils in the CEN-TOP configuration enhanced daytime sensible heating, resulting in increased DTR, while wetter conditions promoted latent heat flux, which cooled the surface and reduced nighttime warming, consistent with findings by Dai et al. (1999) and Panwar et al. (2020). Although these mechanisms have not been directly investigated in Egypt, they provide a robust framework for interpreting our results.

### 3.1. Influence on the TMX/TMN

Figure 2 presents the simulated soil moisture (SM) for the TOP and VIC experiments (Figures 2a and 2b) along with the significant differences between VIC and TOP (Figure 2c). Statistical significance at each grid point was assessed using a Student's t-test with $\alpha = 0.05$. Overall, VIC (Figure 2b) produces higher soil moisture than TOP (Figure 2a) across Egypt. Quantitatively, this difference ranges from 7.5 to 17.5 mm, reaching nearly 30 mm in the Nile Delta region (26–34°E, 28–34°N; Figure 2c). A similar pattern is observed when comparing the ESA and CEN initializations: ESA (Figure 2e) exhibits greater soil moisture than CEN (Figure 2d), with the ESA–TOP difference closely resembling the VIC–TOP difference (Figure 2f). Analysis of radiative fluxes indicates that soil moisture initialization has little effect on incoming shortwave radiation (RSDS, W m²; Figures S1 a–c), net surface solar radiation (RSNS, W $m^{-2}$; Figures S1 d–f), or incoming longwave radiation (RLDS, W $m^{-2}$; Figures S1g–i). However, differences are evident in net downward longwave radiation (RLNS, W $m^{-2}$), with VIC exhibiting 6–10 W $m^{-2}$ higher RLNS than TOP (Figure S1 l). As a result, surface temperature (TS, °C) is 1–3°C warmer under VIC compared to TOP (Figure S2 c). In neither contrast, neither sensible heat flux (SHF, W $m^{-2}$) nor 2 m relative humidity (RH, %) show significant differences between the TOP and VIC simulations (Figures S2 f, i).

Figure S3 demonstrates that RegCM4 accurately reproduces the spatial patterns of maximum temperature (TMX, °C) relative to TERRA across all seasons (Figures S3 a–c, g–i, m–o, and s–u). Both TOP and VIC simulations exhibit a persistent cold bias in TMX across seasons, which is particularly pronounced during summer (JJA) and winter (DJF) (Figures S2j, k, and v, w). Notably, no significant differences are observed between the two simulations in any season. This behavior can be attributed to the minimal influence of the TOP/VIC soil moisture schemes on net surface solar radiation (RSNS) and sensible heat flux (SHF), which limits their effect on TMX despite differences in surface temperature (TS). Seasonally, the cold bias in spring

(MAM) ranges between 1 and 4°C (Figures S3 d, e). In summer (JJA), a warm bias of 1–4°C occurs along the Mediterranean and Red Sea coasts, whereas a cold bias of 2–6°C dominates much of Egypt, particularly within 24–28°E and 22–26°N. During winter (DJF), a widespread cold bias of 1–5°C is observed throughout the country (Figures S3 v, w).

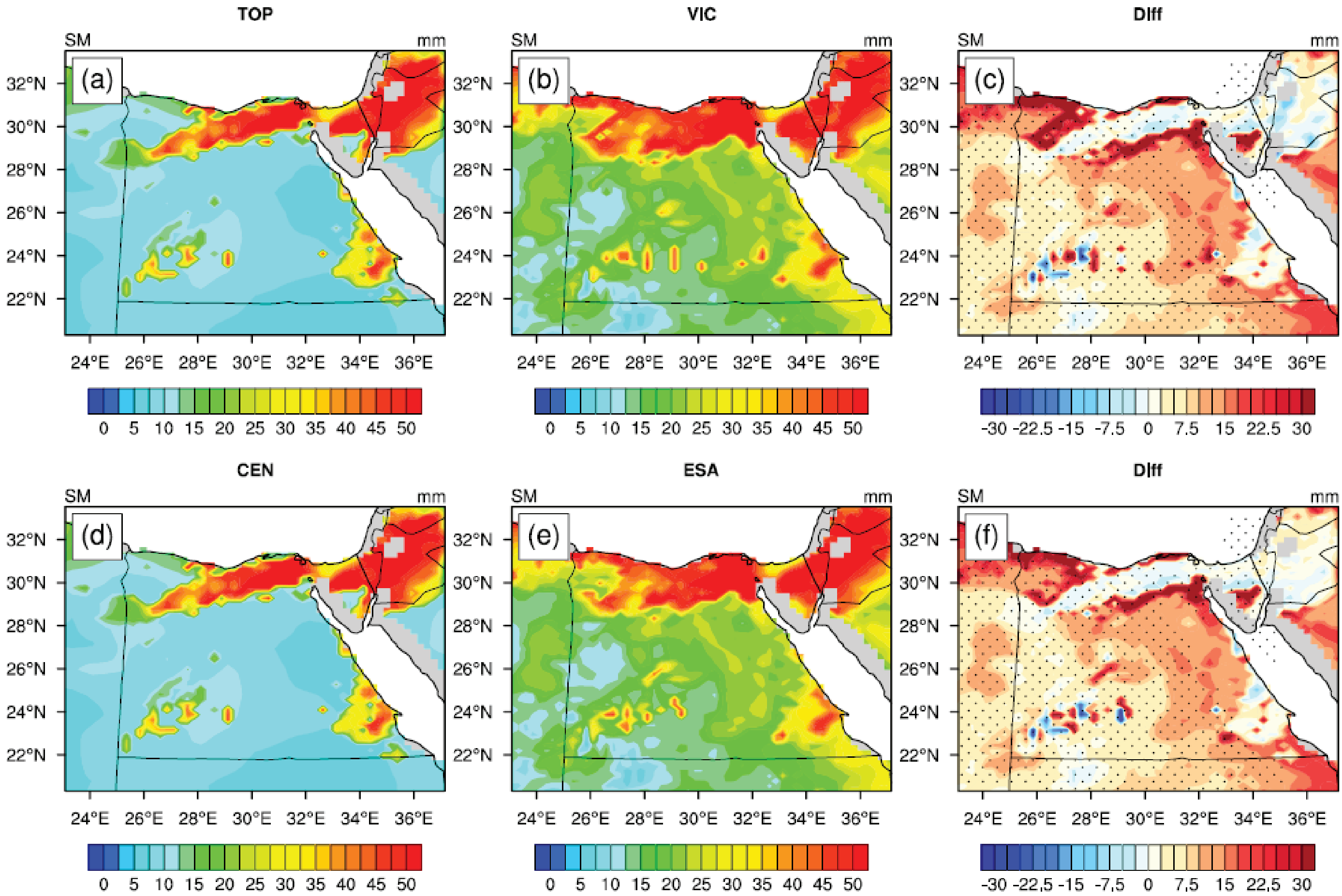


Figure 2: Soil moisture of depth 10 cm (SM; mm).
*The first row* (a-c) shows the two simulations: TOP and VIC, and their significant difference.
*The second row* shows the two simulations: ESA and CEN, and their significant difference during the period 1981 - 2018.
Note that the significant difference was calculated using a Student's t-test with $\alpha$=0.05

In contrast to TMX, notable differences between the TOP and VIC simulations are evident for minimum temperature (TMN, °C; Figure 3). For example, during the MAM season, the TOP simulation exhibits a warm bias of 1–3.5°C, primarily in the region between 28–32°E and 28–30°N, while other areas show a cold bias of 1–1.5°C, reaching up to 2°C in some locations (Figure 3d). In comparison, VIC generally produces a warm bias across Egypt, ranging from 1 to 5.5°C, with localized values reaching up to 6°C (Figure 3e). Overall, VIC is 2–5°C warmer than TOP during MAM (Figure 3e). A similar pattern is observed in the other seasons—JJA (Figures 3 j–l), SON (Figures 3 p–r), and DJF (Figures 3v–x)—with the smallest TMN bias occurring during DJF relative to the other seasons. This behavior can be explained by the influence of the soil moisture scheme on net downward longwave radiation (RLNS), surface temperature (TS), and ultimately TMN, with differences arising from the contrasting soil moisture dynamics in the TOP and VIC schemes.

Concerning soil moisture initialization, the ESA dataset produces higher soil moisture than CEN, with differences ranging from 7.5 to 22.5 mm and reaching up to 30 mm in the Nile Delta region (Figure 2d–f). Figure S4 presents the radiative analysis for the ESA and CEN simulations. The results indicate that switching between ESA and CEN has minimal impact on incoming shortwave radiation (RSDS; Figures S4a–c), net surface solar radiation (RSNS; Figures S4d–f), or incoming longwave radiation (RLDS; Figures S4g–i). Net downward longwave radiation (RLNS), however, is influenced by soil moisture initialization, with ESA exceeding CEN by 5–11 W m$^{-2}$ (Figures S4j–l). Thermally, surface temperature (TS) is higher in ESA than CEN by 1–3°C (Figure S5c). No substantial differences are observed between the two simulations for sensible heat flux (SHF) or 2 m relative humidity (RH) (Figures S5d–f and g–i). Notably, TMX remains largely unaffected by the choice of soil moisture dataset. For TMN, ESA generally produces slightly higher values than CEN, with warm and cold biases similar to those observed in the parameterized soil moisture experiments, consistent with the results reported by Anwar (2024).

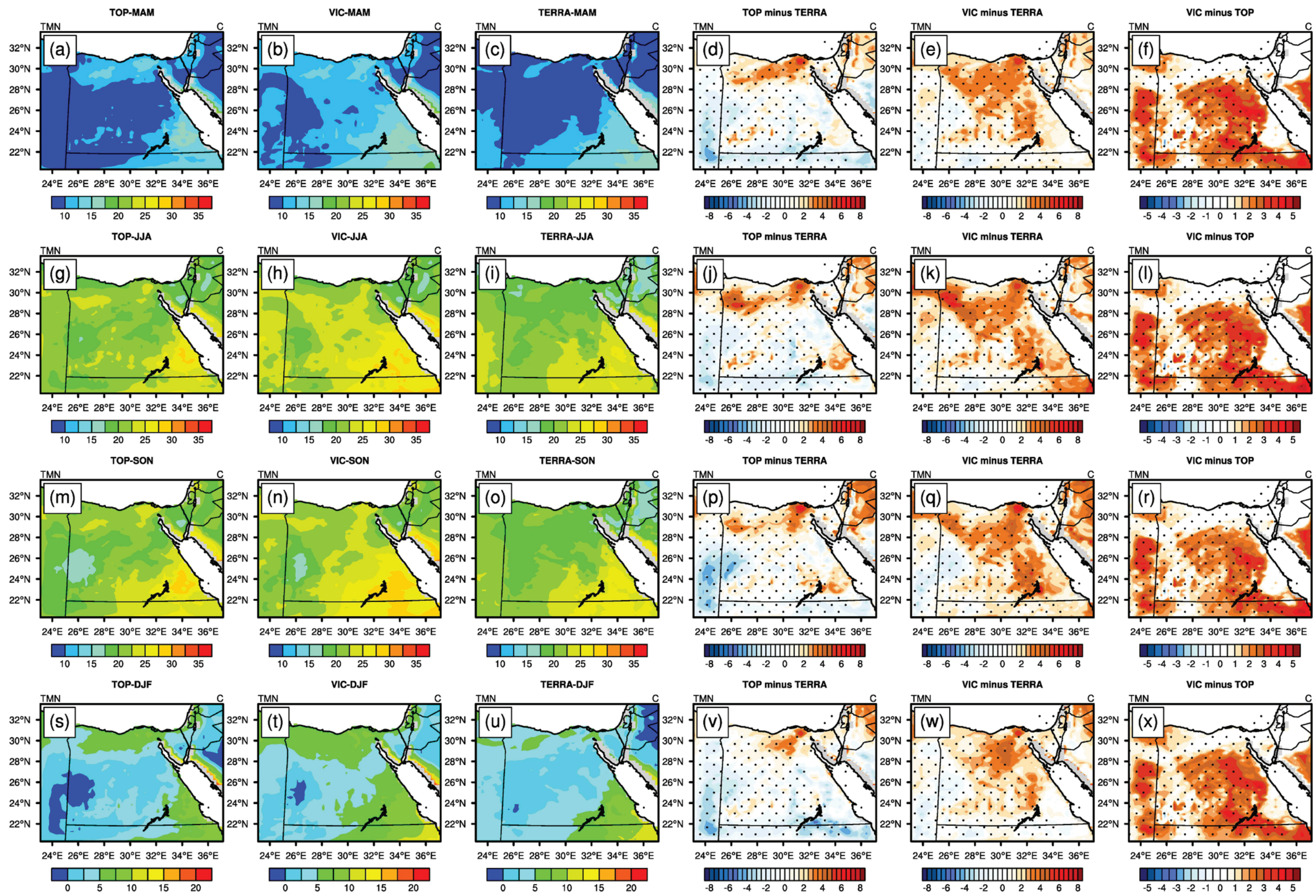


Figure 3: Seasonal climatology of 2-m minimum air temperature (TMN, °C) simulated by the TOP/VIC scheme for spring (MAM), summer (JJA), autumn (SON), and winter (DJF) over the period 1981–2018. Observations from the TERRA reanalysis product were interpolated onto the RegCM4 curvilinear grid for comparison. Statistically significant differences between simulations and reanalysis were assessed using a Student's t-test at $\alpha$ = 0.05. Panels are arranged in chronological order from spring to winter, left to right.

## 3.2. Influence on the DTR

### *3.2.1. Seasonal climatology*

This section examines the impact of soil moisture initialization and parameterization on the diurnal temperature range (DTR, °C) through their influence on daily maximum (TMX) and minimum (TMN) temperatures. Figure 4 illustrates the seasonal DTR patterns simulated using the TOP and VIC schemes. The results indicate that RegCM4 effectively captures the spatial distribution of DTR relative to the TerraClimateZ (TERRA) dataset across all seasons. Nonetheless, both simulations exhibit a consistent cold bias over Egypt. Overall, the TOP scheme demonstrates better agreement with TERRA than VIC in all seasons. During the MAM season, the TOP simulation exhibited a cold bias of 1–4°C in regions including 22–24°N, 28–30°E, and 28–30°N, 28–30°E (Figure 4d). In contrast, VIC showed a more pronounced cold bias across Egypt, ranging from 2 to 7°C (Figure 4e), making VIC 1–5°C cooler than TOP overall (Figure 4f). A similar pattern was observed in JJA, with TOP maintaining

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a comparable cold bias to MAM (Figure 4j), while VIC continued to display a 2–7°C cold bias across the country, reaching nearly 8°C in some locations (Figure 4k).

During SON, the spatial pattern shifted: TOP's cold bias was mainly confined to 28–30°E, 28–30°N, whereas a warm bias of 3–4°C appeared along the Red Sea coastline (Figure 4p). VIC, however, exhibited a cold bias ranging from 1.5 to 5.5°C, which was slightly less severe than in JJA (Figure 4q). In DJF, TOP showed a cold bias of 1–4.5°C in certain regions (Figure 4v), while VIC maintained a 2–6°C cold bias, reaching up to 7°C in some areas, and was generally 2–5°C cooler than TOP (Figure 4w–x). For soil moisture initialization, the ESA and CEN simulations (Figure S6) produced TMX and TMN patterns similar to those seen in the TOP and VIC experiments. Based on the results of the diagnostic analyses of TMX, TMN, and DTR (Figures 2 and S1–S5), the CEN-TOP configuration (hereafter RCM) was selected as the most suitable physical setup for accurately simulating DTR. Subsequent analysis evaluated the RCM's ability to reproduce the DTR annual cycle relative to in-situ observations. The added value of the LS bias-correction method was also assessed using mean bias (MB) as a statistical metric.

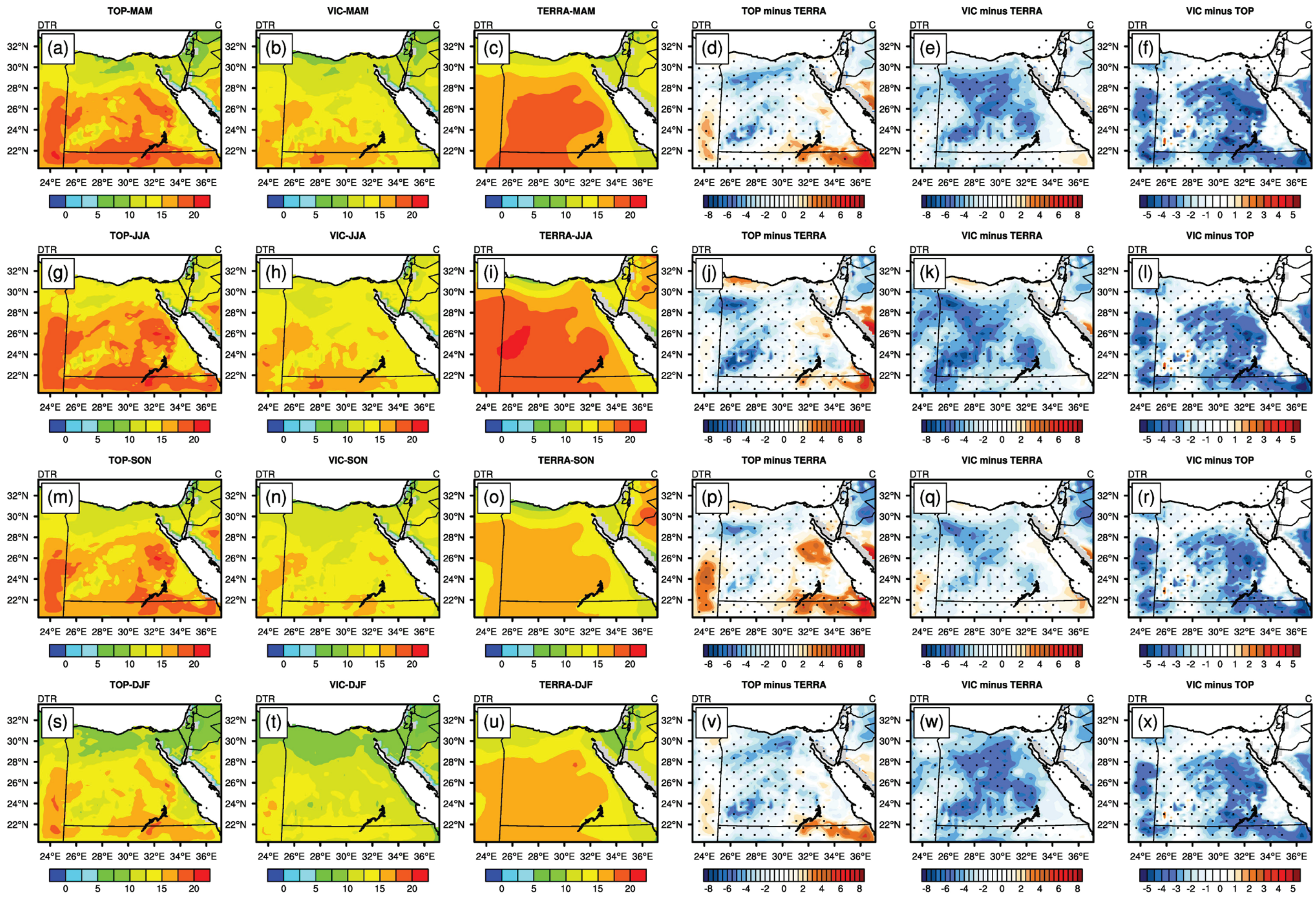


Figure 4: Seasonal climatology of diurnal temperature range (DTR, °C) simulated by the TOP/VIC scheme for spring (MAM), summer (JJA), autumn (SON), and winter (DJF) over the period 1981–2018. TERRA reanalysis data were interpolated onto the RegCM4 curvilinear grid for comparison. Statistically significant differences between simulations and reanalysis were calculated using a Student's t-test at $\alpha$ = 0.05. Panels are arranged from spring to winter, left to right

### *3.2.2. Annual cycle*

The ability of the RCM to Z reproduce the annual cycle of DTR was evaluated at 15 stations using in-situ observations (OBS), both before and after applying the LS bias-correction method. The site-specific biases in TMN and DTR reflect the critical role of soil moisture in modulating surface energy balance and land–atmosphere interactions. Variations in soil moisture influence the partitioning of net radiation into latent and sensible heat fluxes: drier soils limit evapotranspiration,

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enhancing sensible heating and increasing daytime temperatures, while wetter soils promote latent heat flux, cooling the surface and affecting nighttime conditions. Soil moisture also impacts ground heat storage and longwave radiation loss, further shaping nighttime temperatures and DTR. Consequently, the magnitude and seasonal timing of TMN and DTR biases at each site can be interpreted in terms of these soil moisture–driven processes, providing a mechanistic basis for understanding the spatial and temporal patterns observed in the model simulations.

- **Alexandria:** Observations show DTR peaks in February, March, November, and December, with minima in July and August, coinciding with the highest relative humidity. Before LS correction, the RCM systematically overestimated DTR (MB = 3.05°C), failing to capture the summer minimum. The overestimation arises from the model underrepresenting soil moisture in summer, limiting latent heat flux and enhancing daytime sensible heating. After LS correction, the RCMnew substantially improved agreement with OBS, reducing MB to 0.01°C, increasing CORR from -0.01 to 0.89, and raising STD from 0.73 to 0.97.

- **Arish:** The observed DTR exhibits two peaks (April & November) and a minimum in August. The uncorrected RCM underestimated DTR in August (MB = -2.1°C), likely due to excessive soil moisture limiting sensible heating during daytime. After LS correction, MB decreased to 0.07°C, CORR improved from 0.21 to 0.62, and STD decreased from 1.55 to 0.95, indicating improved representation of seasonal soil moisture impacts on DTR.

- **Asswan and Assyut:** Observations show DTR peaks in April and September (Asswan) and April and September (Assyut), with minima in July. The uncorrected RCM slightly underestimated DTR (MB = -2.4°C for Asswan, -3.43°C for Assyut). This underestimation is linked to the overestimation of soil moisture during dry periods, which reduces sensible heating. Following LS correction, MB improved to 0.01°C (Asswan) and -0.01°C (Assyut), while CORR and STD remained stable, confirming that soil moisture adjustments effectively corrected the seasonal biases.

- **Cairo:** The RCM slightly overestimated DTR (MB = 0.775°C) before LS correction. After correction, MB decreased to 0.03°C, CORR increased from 0.94 to 0.98, and STD decreased from 1.08 to 0.94. The improvement reflects better representation of surface energy partitioning, with adjusted soil moisture reducing excessive daytime heating and nighttime cooling errors.

- **Dabaa:** The uncorrected RCM underestimated the March peak and overestimated July DTR (MB = 6.38°C). The LS correction reduced MB to 0.22°C and increased CORR from 0.55 to 0.84. The initial bias was driven by the misrepresentation of soil moisture controlling latent and sensible heat fluxes during dry summer months.

- **Dakhla and Farafra:** Both stations showed significant underestimation of DTR in the uncorrected RCM (MB = -5.46°C and -5.7°C), reflecting excessive soil moisture and suppressed daytime heating. LS correction reduced MB to -0.01°C, increased CORR (Dakhla: 0.88 → 0.97), and improved STD (Dakhla: 0.85 → 1; Farafra: 0.66 → 0.95), demonstrating effective correction of soil moisture–related biases.

- **Hurgada:** The uncorrected RCM showed erratic DTR, sometimes inverting the observed annual cycle (MB = -7.83°C, CORR = -0.33). LS correction adjusted soil moisture representation, improving MB to -0.03°C, CORR to 0.72, and STD to 1.01, indicating stronger control of daytime heating and nighttime cooling by soil moisture.

- **Ismailia:** Observed DTR shows two peaks (May, July) and minima (October, December). The RCM slightly underestimated DTR (MB = -2.42°C). LS correction reduced MB to 0.07°C, while STD improved from 1.33 to 0.9, reflecting better soil moisture–driven energy flux partitioning.

- **Luxor:** The uncorrected RCM underestimated DTR (MB = -7.2°C), due to excessive soil moisture limiting sensible heat flux. LS correction improved MB to 0.02°C, CORR from 0.48 to 0.9, and STD from 0.56 to 0.93, capturing both the seasonal cycle and magnitude of DTR.

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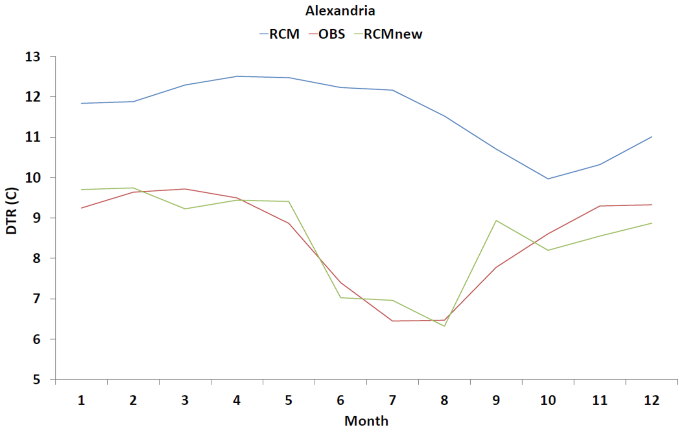
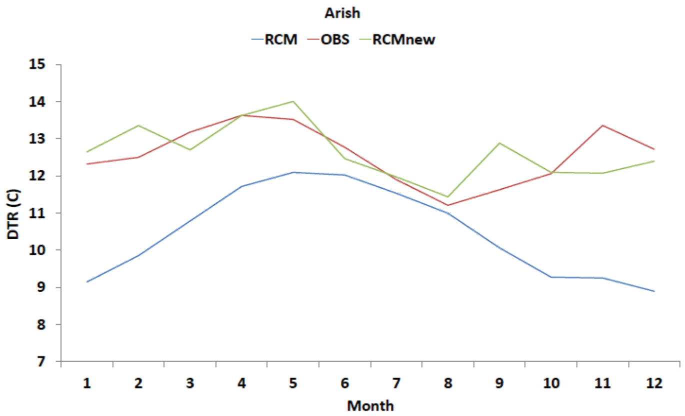
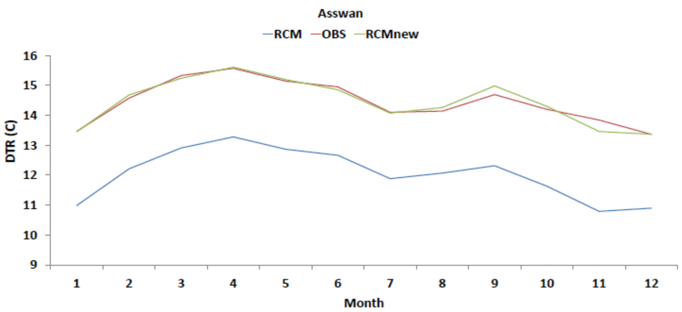
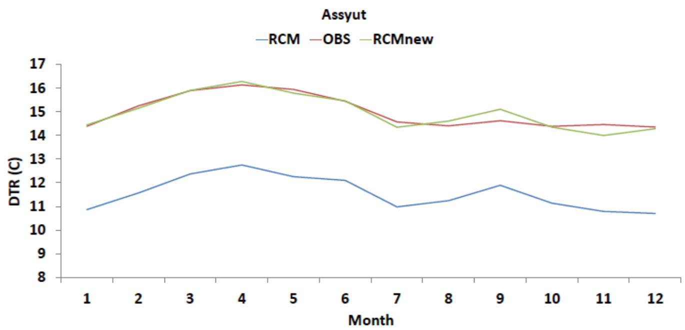
- **Port Said, Ras Sedr, Shallateen:** These stations exhibited varying initial biases (MB = -4.12°C to -8.29°C). LS correction reduced MB to near-zero values (-0.002°C to -0.01°C) and improved CORR and STD across stations.

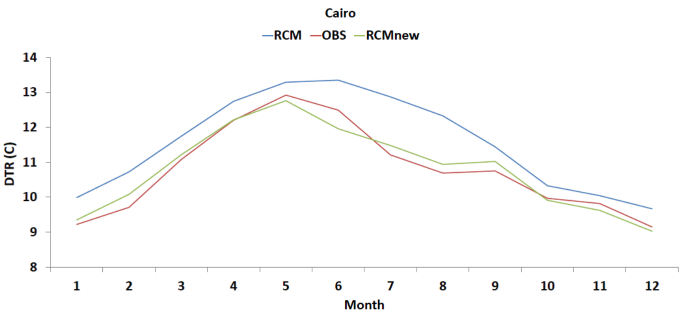
The adjustments highlight the importance of accurate soil moisture initialization and parameterization in controlling surface fluxes and DTR representation.

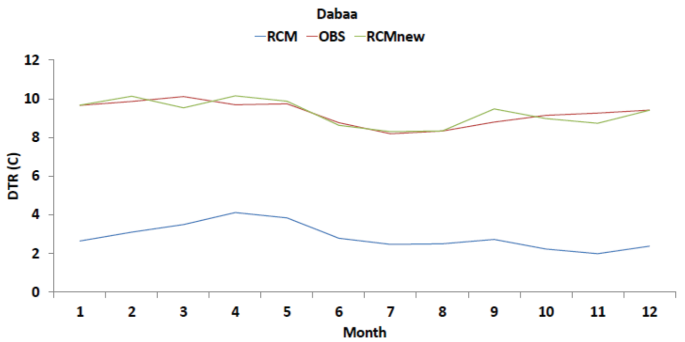


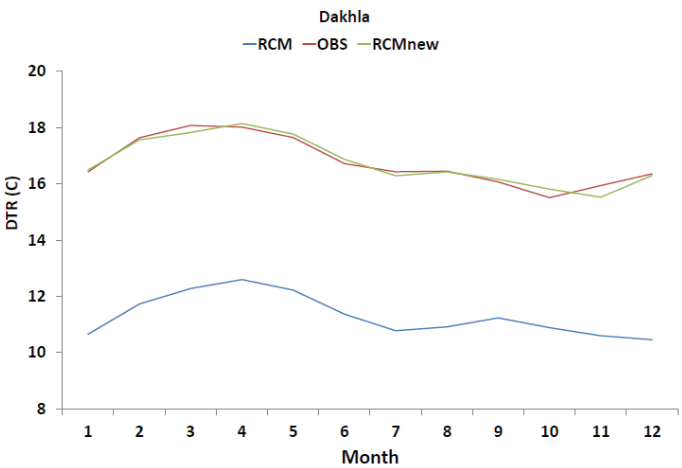



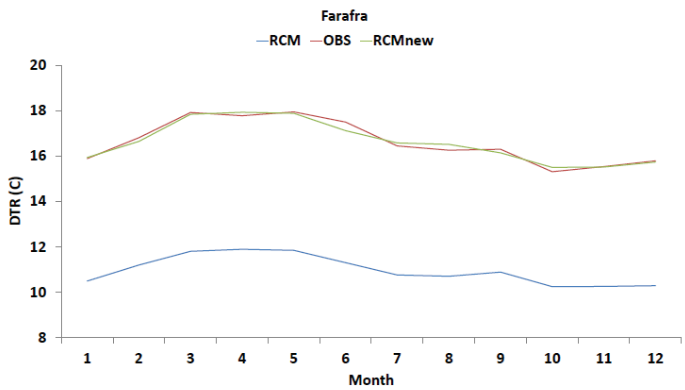



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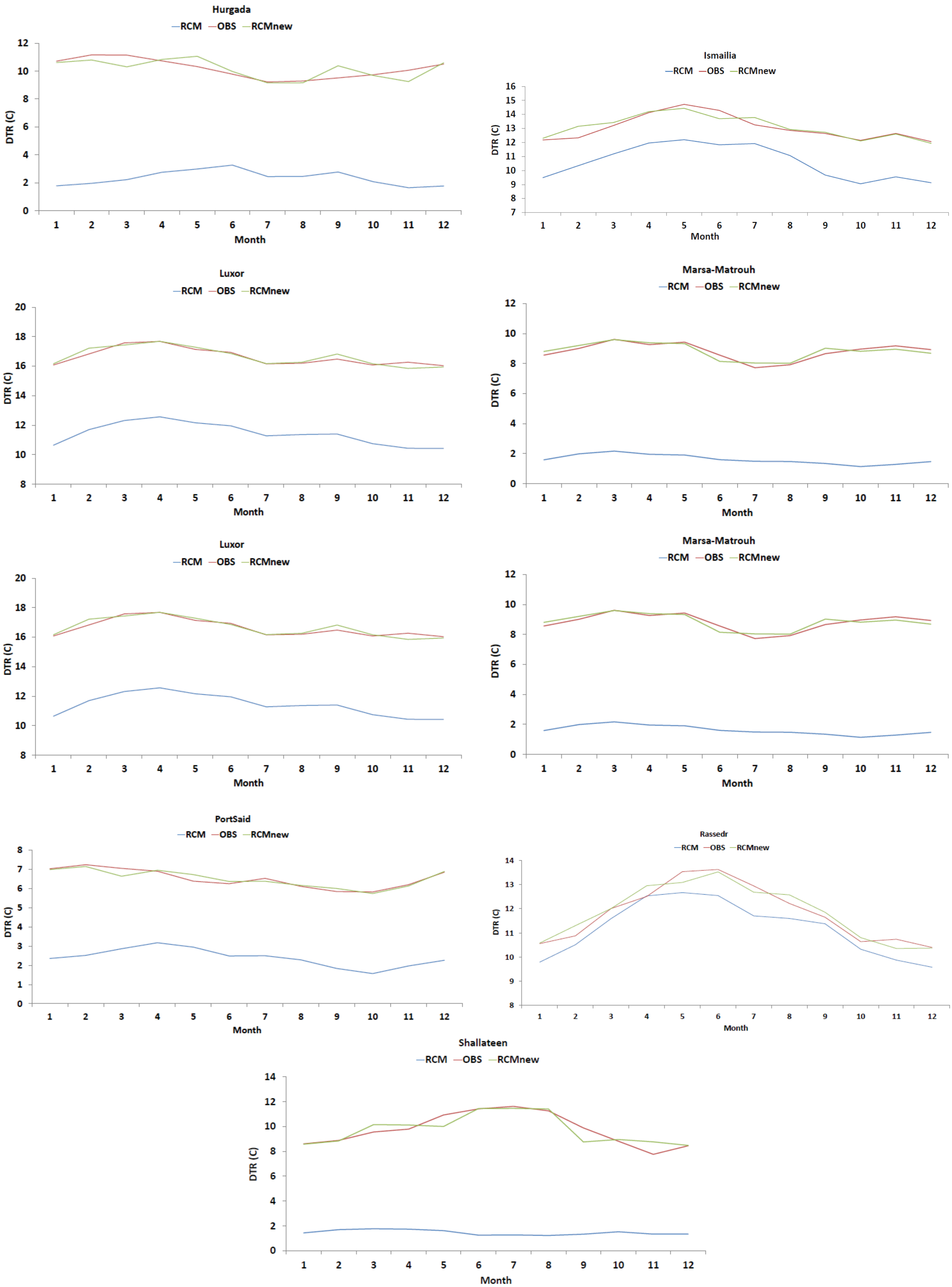


Figure 5: Diurnal temperature range (DTR; °C) annual cycle climatology during the validation period 2001 - 2010. RCM (in blue) refers to the raw data of DTR, RCMnew (in green) is the bias-corrected DTR, and OBS (in red) is the in-situ observation. RCM refers to the CEN-TOP configuration

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The biases in TMN and DTR discussed above can be directly linked to soil moisture–driven processes, where variations in latent and sensible heat fluxes, as well as land–atmosphere coupling, modulate the diurnal cycle. The quantitative performance of RCM and RCMnew for all 15 sites is summarized in Figure 6 using a Taylor diagram, which provides a consolidated assessment of CORR, STD, and overall agreement with observations. The results consistently demonstrate that the LS bias-correction method substantially improves model performance across all stations, particularly in reducing MB and enhancing correlation with observed DTR. To further facilitate comparison across stations, a summary of key statistical metrics (MB, CORR, and STD) has been added in Table 3.

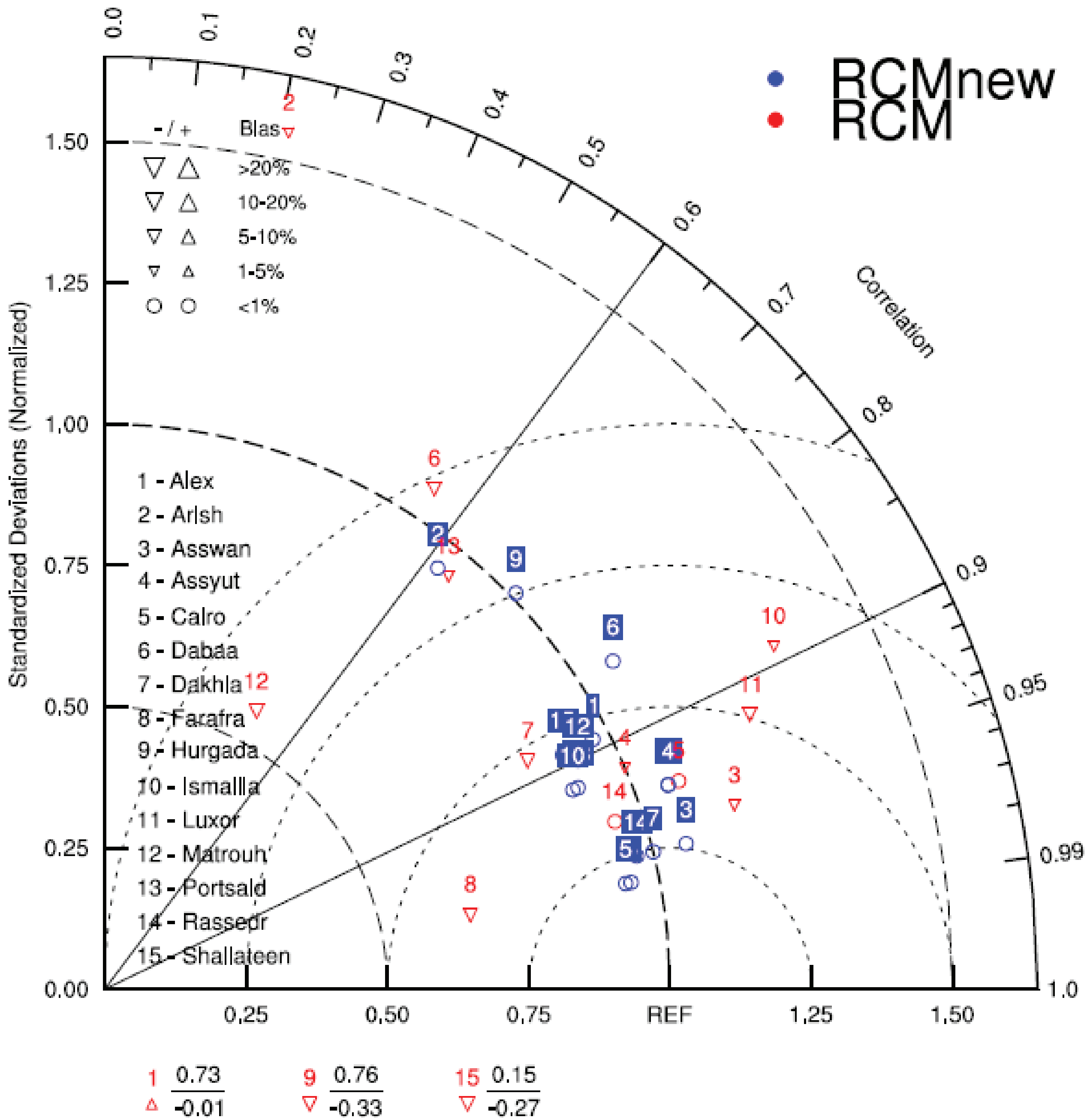


Figure 6: The Taylor diagram explores the performance of the RCM/RCMnew (concerning the OBS) for the 15 locations before and after using the LS method in the period 2001 - 2010

Table 3: Statistical performance of the regional climate model (RCM) and the bias-corrected model (RCMnew) in reproducing the annual cycle of diurnal temperature range (DTR) at 15 stations. Metrics include mean bias (MB; °C), correlation coefficient (CORR), and standard deviation (STD; °C). Missing values (—) indicate cases where the metric was not explicitly reported in the analysis

| Station | MB (RCM) °C | MB (RCMnew) °C | CORR (RCM) | CORR (RCMnew) | STD (RCM) | STD (RCMnew) |
|---|---|---|---|---|---|---|
| Alexandria | 3.05 | 0.01 | -0.01 | 0.89 | 0.73 | 0.97 |
| Arish | -2.10 | 0.07 | 0.21 | 0.62 | 1.55 | 0.95 |
| Aswan | -2.40 | 0.01 | — | — | — | — |
| Assyut | -3.43 | -0.01 | — | — | — | — |
| Cairo | 0.78 | 0.03 | 0.94 | 0.98 | 1.08 | 0.94 |
| Dabaa | 6.38 | 0.22 | 0.55 | 0.84 | — | — |
| Dakhla | -5.46 | -0.01 | 0.88 | 0.97 | 0.85 | 1.00 |
| Farafra | -5.70 | -0.01 | — | — | 0.66 | 0.95 |
| Hurghada | -7.83 | -0.03 | -0.33 | 0.72 | 0.76 | 1.01 |
| Ismailia | -2.42 | 0.07 | — | — | 1.33 | 0.90 |
| Luxor | -7.20 | 0.02 | 0.48 | 0.90 | 0.56 | 0.93 |
| Port Said | -4.12 | -0.01 | 0.64 | 0.92 | — | — |
| Ras Sedr | -0.63 | 0.03 | — | — | 0.95 | 0.97 |
| Shallateen | -8.29 | -0.002 | -0.27 | 0.89 | 0.15 | 0.91 |

To summarize the results, four 40-year simulations were conducted, representing different combinations of soil moisture datasets and hydrological schemes on the DTR across Egypt. All simulations were downscaled to a 25 km horizontal grid using the ERA-Interim reanalysis at 1.5° (EIN15). The first two simulations focused on soil moisture initialization, while the latter two examined soil moisture parameterization. Model results were evaluated against the high-resolution global TerraClimate (TERRA) dataset at each grid point, and the DTR annual cycle was assessed relative to in-situ observations (OBS).

The main findings can be summarized as follows:

1. TMX was largely unaffected by either soil moisture initialization or hydrological schemes, as neither RSNS nor SHF showed substantial changes.

2. TMN was strongly influenced in both scenarios due to variations in SM and RLNS.

3. Configuring RegCM4 with the TOP scheme and initializing with the CEN reanalysis product effectively reduced TMN and DTR biases relative to TERRA.

4. The ability of the RCM to reproduce the DTR annual cycle relative to OBS varied depending on station location.

5. The LS bias-correction method successfully reduced MB at all stations and generally improved CORR and STD. With LS applied, the RCMnew accurately captured the observed DTR yearly cycle.

The sensitivity of TMN and DTR to soil moisture can be explained by its key role in regulating the surface energy balance and land–atmosphere interactions. Variations in soil moisture influence the partitioning of net radiation into latent and sensible heat fluxes. Under drier conditions, limited soil moisture reduces evapotranspiration, enhancing sensible heating and increasing near-surface air temperatures, particularly during daytime, which contributes to an elevated DTR. In contrast, wetter soils promote latent heat flux and evaporative cooling, reducing daytime temperatures and moderating nighttime conditions. Soil moisture also affects soil heat storage and near-surface atmospheric humidity, influencing RLNS and thereby shaping TMN. Through these processes, the interaction between soil moisture, surface fluxes, and boundary layer dynamics explains the spatial and seasonal variations in DTR biases observed across Egypt.

It should be noted that the analysis does not include the most recent years (post-2018), during which accelerated warming has been reported. While the primary findings regarding DTR sensitivity to soil moisture are expected to remain robust, future work could extend the simulations using updated datasets to assess potential impacts of recent climate trends. Although other meteorological drivers—including cloud cover, wind speed, and atmospheric moisture—also influence DTR by affecting daytime heating and nighttime cooling, these factors are implicitly represented in the model simulations. Therefore, the attribution of DTR variability presented here should be interpreted primarily in terms of soil moisture effects within the modeling framework.

## 4. Conclusion and Future recommendations

The present study employed the Regional Climate Model version 4 (RegCM4) to assess the impact of soil moisture initialization and parameterization on the DTR across Egypt, using high-resolution observational datasets and in situ measurements for evaluation. The key findings are:

1. The CEN-TOP configuration consistently exhibited the lowest bias in simulated DTR relative to the TERRA dataset, highlighting its suitability for regional applications.

2. Application of the linear scaling (LS) bias-correction method effectively reduced mean bias (MB) while improving correlation (CORR) and standard deviation (STD) at all stations, demonstrating its capability to enhance DTR simulations.

These results provide the first systematic assessment of soil moisture–DTR interactions in Egypt and offer a framework for improving regional climate simulations. To further enhance DTR representation, future studies should consider:

1. Incorporating high-resolution geographic data into the static datasets used by RegCM.

2. Employing a convective-permitting setup within the latest RegCM version (RegCM5) to better capture local geographic influences on surface climate.

3. Exploring parameterization uncertainty using alternative regional climate models, such as WRF (Skamarock et al., 2019), ICON (Hohenegger et al., 2023), and REMO (Pietikäinen et al., 2018), and comparing LS with other bias-correction methods, including power transformation (PT), distribution mapping (DM), and quantile mapping (QM), to assess their relative strengths and limitations.

Overall, the study demonstrates that accurate DTR simulations in Egypt require careful consideration of soil moisture initialization and parameterization, combined with appropriate bias-correction techniques, providing a valuable reference for future climate modeling and adaptation planning.

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## References:

Adekanmbi, A. A., & Sizmur, T. (2022). Importance of Diurnal Temperature Range (DTR) for predicting the temperature sensitivity of soil respiration. *Frontiers in Soil Science*, *2*. https://doi.org/10.3389/fsoil.2022.969077

Anwar, S. A. Simulating Daily Soil Temperature in Egypt Using a High-Resolution Regional Climate Model: Sensitivity to Soil Moisture and Temperature Initial Conditions. *Eng. Proc. 2023*, 56, 106. https://doi.org/10.3390/ASEC2023-15368

Anwar, S. A. (2024). On the Sensitivity of the Potential Evapotranspiration of Egypt to Different Initial Conditions of the Soil Moisture Using a High-resolution Regional Climate Model. *Journal of Biomedical Research & Environmental Sciences*, *5*(5), 501–514. https://doi.org/10.37871/jbres1920

Anwar, S. A., A.S. Zakey, S.M. Robaa, & Abdel, M. (2018). The influence of two land-surface hydrology schemes on the regional climate of Africa using the RegCM4 model. *Theoretical and Applied Climatology*, *136*(3-4), 1535–1548. https://doi.org/10.1007/s00704-018-2556-8

Anwar, S. A., & Mostafa, S. M. Assessment of the Sensitivity of Daily Maximum and Minimum Air Temperatures of Egypt to Soil Moisture Status and Land Surface Parameterization Using RegCM4. *Eng. Proc. 2023*, 56, 115. https://doi.org/10.3390/ASEC2023-15353

Anwar, S. A., & Olusegun, C. F. (2024). Simulating the Potential Evapotranspiration of Egypt Using the RegCM4: Sensitivity to the Land Surface and Boundary Layer Parameterizations. *Hydrology*, *11*(8), 121. https://doi.org/10.3390/hydrology11080121

Braganza, K., Karoly, D. J., & Arblaster, J. M. (2004). Diurnal temperature range as an index of global climate change during the twentieth century. *Geophysical Research Letters*, *31*(13), n/a-n/a. https://doi.org/10.1029/2004gl019998

Bravo Dias, J., Soares, P. M. M., & Carrilho da Graça, G. (2020). The shape of days to come: Effects of climate change on low energy buildings. *Building and Environment*, *181*, 107125. https://doi.org/10.1016/j.buildenv.2020.107125

Dai, A., Trenberth, K. E., & Karl, T. R. (1999). Effects of Clouds, Soil Moisture, Precipitation, and Water Vapor on Diurnal Temperature Range. *Journal of Climate*, *12*(8), 2451–2473. https://doi.org/10.1175/1520-0442(1999)012%3C2451:eocsmp%3E2.0.co;2

Davis, R. E., Hondula, D. M., & Sharif, H. (2019). Examining the diurnal temperature range enigma: why is human health related to the daily change in temperature? *International Journal of Biometeorology*, *64*(3), 397–407. https://doi.org/10.1007/s00484-019-01825-8

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., … Haimberger, L. (2011). The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, *137*(656), 553–597. https://doi.org/10.1002/qj.828

Dorigo, W., Wagner, W., Albergel, C., Albrecht, F., Balsamo, G., Brocca, L., … Mistelbauer, T. (2017). ESA CCI Soil Moisture for improved Earth system understanding: State-of-the art and future directions. *Remote Sensing of Environment*, *203*, 185–215. https://doi.org/10.1016/j.rse.2017.07.001

El Kenawy, A., López-Moreno, J., M.Vicente-Serrano, S., & Morsi, F. (2010). Climatological modeling of monthly air temperature and precipitation in Egypt through GIS techniques. *Climate Research*, *42*(2), 161–176. https://doi.org/10.3354/cr00871

Emanuel, K. A., & Živković-Rothman, M. (1999). Development and Evaluation of a Convection Scheme for Use in Climate Models. *Journal of the Atmospheric Sciences*, *56*(11), 1766–1782. https://doi.org/10.1175/1520-0469(1999)056%3C1766:DAEOAC%3E2.0.CO;2

Giorgi, F., Coppola, E., Solmon, F., Mariotti, L., Sylla, M., Bi, X., ... Sloan, L. (2012). RegCM4: model description and preliminary tests over multiple CORDEX domains. *Climate Research*, *52*, 7–29. https://doi.org/10.3354/cr01018

Grell, G. A. ,. (1994). Description of the Penn State/NCAR Mesoscale Model Version 4 (MM4). *NCAR Tech. Note TN-282+STR, NCAR, Boulder, CO*.

Grell, G. A., Dudhia, J., & Stauffer, D. (1994). A description of the fifth-generation Penn State/NCAR Mesoscale Model (MM5). *NCAR Tech. Note TN-282+STR, NCAR, Boulder, CO*. https://doi.org/10.5065/D60Z716B

Grenier, H., & Bretherton, C. S. (2001). A Moist PBL Parameterization for Large-Scale Models and Its Application to Subtropical Cloud-Topped Marine Boundary Layers. *Monthly Weather Review* , *129*(3), 357–377.

Gruber, A., Scanlon, T., van der Schalie, R., Wagner, W., & Dorigo, W. (2019). Evolution of the ESA CCI Soil Moisture climate data records and their underlying merging methodology. *Earth System Science Data*, *11*(2), 717–739. https://doi.org/10.5194/essd-11-717-2019

Güttler, I., Branković, Č., O'Brien, T. A., Coppola, E., Grisogono, B., & Giorgi, F. (2013). Sensitivity of the regional climate model RegCM4.2 to planetary boundary layer parameterisation. *Climate Dynamics*, *43*(7-8), 1753–1772. https://doi.org/10.1007/s00382-013-2003-6

Hamed, M. M., Nashwan, M. S., & Shahid, S. (2021). Intercomparison of historical simulation and future projections of rainfall and temperature by CMIP5 and CMIP6 GCMs over Egypt. *International Journal of Climatology*. https://doi.org/10.1002/joc.7468

Hamed, M. M., Nashwan, M. S., Shiru, M. S., & Shahid, S. (2022). Comparison between CMIP5 and CMIP6 Models over MENA Region Using Historical Simulations and Future Projections. *Sustainability*, *14*(16), 10375. https://doi.org/10.3390/su141610375

Harris, I., Osborn, T. J., Jones, P., & Lister, D. (2020). Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Scientific Data*, *7*(1). https://doi.org/10.1038/s41597-020-0453-3

Hohenegger, C., Korn, P., Leonidas Linardakis, Redler, R., Schnur, R., Panagiotis Adamidis, ... Giorgetta, M. (2023). ICON-Sapphire: simulating the components of the Earth system and their interactions at kilometer and subkilometer scales. *Geoscientific Model Development*, *16*(2), 779–811. https://doi.org/10.5194/gmd-16-779-2023

Huang, Y., Jiang, N., Shen, M., & Guo, L. (2020). Effect of preseason diurnal temperature range on the start of vegetation growing season in the Northern Hemisphere. *Ecological Indicators*, *112*, 106161–106161. https://doi.org/10.1016/j.ecolind.2020.106161

Intergovernmental Panel on Climate Change (IPCC). (2021). Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Retrieved from IPCC website: https://www.ipcc.ch/report/ar6/wg1/

Jeong, S.-J., Ho, C.-H., Park, T.-W., Kim, J., & Levis, S. (2010). Impact of vegetation feedback on the temperature and its diurnal range over the Northern Hemisphere during summer in a 2 × CO2 climate. *Climate Dynamics*, *37*(3-4), 821–833. https://doi.org/10.1007/s00382-010-0827-x

Kiehl, J. T., Hack, J. J., Bonan, G. B., Boville, B. A., & Rasch, P. J. (1996, January 1). Description of the NCAR community climate model (CCM3). NCAR Tech. Note NCAR/TN-420+STR.

Kobayashi, C., & Iwasaki, T. (2016). Brewer-Dobson circulation diagnosed from JRA-55. *Journal of Geophysical Research: Atmospheres*, *121*(4), 1493–1510. https://doi.org/10.1002/2015jd023476

Liang, X. (2003). A new parameterization for surface and groundwater interactions and its impact on water budgets with the variable infiltration capacity (VIC) land surface model. *Journal of Geophysical Research*, *108*(D16). https://doi.org/10.1029/2002jd003090

Liang, X., Lettenmaier, D. P., & Wood, E. F. (1996). One-dimensional statistical dynamic representation of subgrid spatial variability of precipitation in the two-layer variable infiltration capacity model. *Journal of Geophysical Research: Atmospheres*, *101*(D16), 21403–21422. https://doi.org/10.1029/96jd01448

Liang, X., Lettenmaier, D. P., Wood, E. F., & Burges, S. J. (1994). A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *Journal of Geophysical Research*, *99*(D7), 14415. https://doi.org/10.1029/94jd00483

Liang, X., Wood, E. F., & Lettenmaier, D. P. (1996). Surface soil moisture parameterization of the VIC-2L model: Evaluation and modification. *Global and Planetary Change*, *13*(1-4), 195–206. https://doi.org/10.1016/0921-8181(95)00046-1

Mlawer, E. J., Taubman, S. J., Brown, P. D., Iacono, M. J., & Clough, S. A. (1997). Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. *Journal of Geophysical Research: Atmospheres*, *102*(D14), 16663–16682. https://doi.org/10.1029/97jd00237

Nashwan, M. S., Shahid, S., & Chung, E.-S. (2020). High-Resolution Climate Projections for a Densely Populated Mediterranean Region. *Sustainability*, *12*(9), 3684. https://doi.org/10.3390/su12093684

Niu, G.-Y., Yang, Z.-L., Dickinson, R. E., & Gulden, L. E. (2005). A simple TOPMODEL-based runoff parameterization (SIMTOP) for use in global climate models. *Journal of Geophysical Research*, *110*(D21). https://doi.org/10.1029/2005jd006111

Oleson, K. W., Niu, G.-Y. ., Yang, Z.-L. ., Lawrence, D. M., Thornton, P. E., Lawrence, P. J., ... Qian, T. (2008). Improvements to the Community Land Model and their impact on the hydrological cycle. *Journal of Geophysical Research: Biogeosciences*, *113*(G1), n/a-n/a. https://doi.org/10.1029/2007jg000563

Oleson, K., Lawrence, M., Bonan, B., Drewniak, B., Huang, M., Koven, D., ... Lipscomb, W. (2013). Technical description of version 4.5 of the Community Land Model (CLM). *N2t.net*. https://doi.org/10.5065/D6RR1W7M

Ongoma, V., Rahman, M. A., Ayugi, B., Nisha, F., Galvin, S., Shilenje, Z. W., & Ogwang, B. A. (2020). Variability of diurnal temperature range over Pacific Island countries, a case study of Fiji. *Meteorology and Atmospheric Physics*, *133*(1), 85–95. https://doi.org/10.1007/s00703-020-00743-4

Pal, J. S., Giorgi, F., Bi, X., Elguindi, N., Solmon, F., Gao, X., ... Steiner, A. L. (2007). Regional Climate Modeling for the Developing World: The ICTP RegCM3 and RegCNET. *Bulletin of the American Meteorological Society*, *88*(9), 1395–1410. https://doi.org/10.1175/BAMS-88-9-1395

Panwar, A., Renner, M., & Kleidon, A. (2020). Imprints of evaporative conditions and vegetation type in diurnal temperature variations. *Hydrology and Earth System Sciences*, *24*(10), 4923–4942. https://doi.org/10.5194/hess-24-4923-2020

Pietikäinen, J.-P., Markkanen, T., Sieck, K., Jacob, D., Korhonen, J., Räisänen, P., ... Kaurola, J. (2018). The regional climate model REMO (v2015) coupled with the 1-D freshwater lake model FLake (v1): Fenno-Scandinavian climate and lakes. *Geoscientific Model Development*, *11*(4), 1321–1342. https://doi.org/10.5194/gmd-11-1321-2018

Ren, G., & Zhou, Y. (2014). Urbanization Effect on Trends of Extreme Temperature Indices of National Stations over Mainland China, 1961–2008. *Journal of Climate*, *27*(6), 2340–2360. https://doi.org/10.1175/jcli-d-13-00393.1

Ritchie, H., Rosado, P., & Roser, M. (2023). $CO_2$ and Greenhouse Gas Emissions. *Our World in Data*. Our World in Data. Retrieved from https://ourworldindata.org/co2-and-greenhouse-gas-emissions

Schultz, N. M., Lawrence, P. J., & Lee, X. (2017). Global satellite data highlights the diurnal asymmetry of the surface temperature response to deforestation. *Journal of Geophysical Research: Biogeosciences*, *122*(4), 903–917. https://doi.org/10.1002/2016jg003653

Shen, X., Liu, B., & Lu, X. (2017). Effects of land use/land cover on diurnal temperature range in the temperate grassland region of China. *Science of the Total Environment*, *575*, 1211–1218. https://doi.org/10.1016/j.scitotenv.2016.09.187

Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Liu, Z., Berner, J., ... Huang, X.-Y. (2019). Description of the Advanced Research WRF Version 4. *NCAR Technical Notes NCAR/TN-556+STR*.

Slivinski, L. C., Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Giese, B. S., McColl, C., ... Domínguez-Castro, F. (2019). Towards a more reliable historical reanalysis: Improvements for version 3 of the Twentieth Century Reanalysis system. *Quarterly Journal of the Royal Meteorological Society*, *145*(724), 2876–2908. https://doi.org/10.1002/qj.3598

Steiner, A. L., Pal, J. S., Rauscher, S. A., Bell, J. L., Diffenbaugh, N. S., Boone, A., ... Giorgi, F. (2009). Land surface coupling in regional climate simulations of the West African monsoon. *Climate Dynamics*, *33*(6), 869–892. https://doi.org/10.1007/s00382-009-0543-6

Stone, D., & Weaver, A. (2003). Factors contributing to diurnal temperature range trends in twentieth and twenty-first century simulations of the CCCma coupled model. *Climate Dynamics*, *20*(5), 435–445. https://doi.org/10.1007/s00382-002-0288-y

Taylor, K. E. (2001). Summarizing multiple aspects of model performance in a single diagram. *Journal of Geophysical Research: Atmospheres*, *106*(D7), 7183–7192. https://doi.org/10.1029/2000jd900719

Wang, F., Zhang, C., Peng, Y., & Zhou, H. (2013). Diurnal temperature range variation and its causes in a semiarid region from 1957 to 2006. *International Journal of Climatology*, *34*(2), 343–354. https://doi.org/10.1002/joc.3690

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# A Literature Review on Decarbonization Pathways and Operational Strategies for Sustainable Shipping

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## Abstract:

*International shipping represents 2% to 3% of worldwide greenhouse gas (GHG) emissions. It is being regulated more to meet international climate strategies. The International Maritime Organization (IMO) 2023 Revised Strategy targets net-zero GHG emissions for international shipping by 2050. Meeting this target will require operational, fuel type, and policy changes.*

*This study focuses on measures to operationalize decarbonization and on strategies for greater sustainability in shipping. The operational measures, alternative fuels, and policy approaches are examined through a systematic literature review of peer-reviewed literature (most current is 2025), compliant with PRISMA 2020, from 2015 to 2025. The literature describes operational efficiency, the role of Digitalization and coordination between ships and ports, the life cycle, or 'well-to-wake', of alternative marine fuels, and current and developing policies and regulations.*

*Operational measures will yield positive results and demonstrate the benefits of subsequent approaches, but will not achieve full or deep decarbonization. Long-lasting, or permanent, solutions will be economically unachievable without the use of zero- or near-zero-carbon fuels. The alternative to economically unachievable permanent solutions is the use of Ammonia, Methanol, hydrogen, and synthetic fuels, but their lifecycle impact must be addressed. The review also recognizes the value of market-based measures.*

*The policy recommendations, operational measures, and fuel-type changes should include the integrated lifecycle approaches. This study will serve to define future research on operational measures and strategies for the essential sustainability of shipping.*

**Keywords:** Maritime decarbonization, Sustainable shipping, Operational efficiency, Alternative marine fuels, IMO GHG strategy.

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## 1. Introduction

Maritime shipping facilitates 80% of international trading and connects global producers to consumers (Tadros et al., 2023). Although the sector of the economy is comparatively more energy efficient, it is responsible for only 2–3% of global greenhouse gas (GHG) emissions; it is still a sector with a relative lack of efficiency and is faced with the unique and difficult challenge of ensuring future economic development while tackling climate change (Bullock et al., 2024). In July 2023, the International Maritime Organization (IMO) adopted a revised version of its 2018 Strategy on the Reduction of GHG Emissions from Ships and set the following targets for the sector: achieve net-zero GHG emissions by 2050; reduce total annual GHG emissions from the sector by a minimum of 20–30% in 2030 and 70–80% in 2040, both with 2008 as the base year; and have 5–10% of the shipped energy compose of zero, or near-zero GHG fuel by 2030 (IMO 2025a; IMO 2025b) To achieve this, the IMO in cooperation with international institutions such as the International Energy Agency (IEA), the World Bank, and the European Commission is establishing a 'basket' of midterm measures that is the combination of targeted fuel a goal-based marine fuel standard and economic incentives to drive decarbonization (Lloyd's Register 2025), Table 1 illustrates these aspects and targets.

Table 1: Summary of key maritime shipping aspects and IMO climate strategy

| Aspect | Details |
|---|---|
| Global Trade Contribution | More than 80% of world merchandise by volume |
| GHG Emissions Contribution | Approximately 2–3% of global greenhouse gas emissions |
| Challenges | Sustaining economic growth while meeting climate objectives |
| IMO Revised Strategy Adoption Date | Adopted in July 2023; establishes net-zero GHG emissions by 2050, interim reduction checkpoints for 2030 and 2040, a shift to lifecycle accounting, and the development of fuel GHG intensity standards and market-based measures |
| Target Year for Net-Zero GHG Emissions | By or around 2050 |
| GHG Emissions Reduction Target by 2030 | At least 20–30% compared to 2008 |
| GHG Emissions Reduction Target by 2040 | 70–80% compared to 2008 |
| Zero or Near-Zero GHG Fuels Target by 2030 | 5–10% of shipping energy |
| Mid-Term Measures Development | A goal-based marine fuel standard combined with an economic mechanism |

Though there is evidence supporting the proposed case, the industry is advised that it is likely to fail to meet net-zero targets without the rapid adoption of zero-carbon energy, supportive infrastructure, and effective governance. Recent studies indicate that shipping is likely to meet the 2030 carbon-intensity target but is not projected to reach net-zero by 2050 unless additional measures and faster fuel transitions are implemented (Laskar et al., 2025). Likewise, the analysis of climate policy concludes that the IMO's "strive" targets – 30% by 2030 and 80% by 2040 (considered the bare minimum to be on a 1.5 °C pathway) – demand the immediate implementation of all available efficiency measures on the existing vessels (Bullock et al., 2024). To prevent emissions leaking throughout the supply chain, the IMO published the Guidelines on Lifecycle GHG Intensity of Marine Fuels, which provide, for mitigation purposes, well-to-wake accounting on a full lifecycle basis (IMO, 2024).

The broad range of possible pathways proposed to achieve decarbonization, considering policy and regulatory frameworks, includes alternative fuels, energy efficiency (EE) upgrades and operational efficiency, onboard carbon capture, and digitalized ship–port coordination (Robalo-Cabrera et al., 2025). Lifecycle assessment studies have shown that, while there are operational measures that are capable of providing immediate mitigation potential and are low in capital costs, there are also deep operational measures, such as speed and routing, and port call management, that can be capitalized on within the current operational fleet (Degiuli et al., 2024; Kanchiralla et al., 2024; Y. Wang et al., 2025). Still, literature demonstrates fuel, infrastructure, safety, and cost tradeoffs in order to achieve operational scalability. Thus, without the varying integrations of all proposed operational mitigation measures, which add to the complexity of achieving decarbonization within the proposed pathways, there are limited opportunities to achieve decarbonization (Ezeh et al., 2024; Kondratenko et al., 2025). To achieve deep decarbonization, operational measures focused on immediate results should be combined with fuel switching and sufficient policy and market frameworks.

While there have been many reviews on decluttering the literature on maritime decarbonization, these reviews have become siloed, especially those focusing on alternative fuels and propulsion technologies, operational efficiency measures, and regulatory instruments. This siloed approach will make it difficult for policymakers and industry actors to assess the intersection of operational strategies, fuel transitions, and market-based measures for a certain vessel type and time frame. It is also important to note that a number of recent reviews were conducted prior to the adoption of IMO's 2023 revised GHG Strategy and the shift to lifecycle (well-to-wake) accounting (e.g., Tadros et al., 2023; Zanobetti et al., 2023). This creates a time lag in upstream evidence synthesis and is likely to be detrimental to the current regulatory landscape. Closing this gap would require a synthesis that is integrated with an up-to-date assessment and simultaneously reviews the best estimates of technological viability, operational efficiencies, and public policy iteratively.

### 1.1. Aim and contribution

This study's objective is to depict in more detail the part operational measures, alternative fuels, and policy tools will play, where they impose constraints, and how they will interact with one another in the holistic lifecycle approaches needed to meet the IMO targets for greenhouse gas containment in the literature concerning the pathways and operational strategies for the sustainable shipping niche.

This research focuses on the following aspects in the literature on the decarbonization of shipping:

1. The operational efficiency measures, alternative fuel pathways, and policies and regulations related to the decarbonization of shipping, as well as the considerable peer-reviewed literature on this topic.

2. The operational measures for progressing to the next level of decarbonization and their value as short-term mitigation measures.

3. The alternative fuel pathways, with a well-to-wake analysis of lifecycle emissions, and how they should guide policy and investment decisions.

4. The findings are actionable, practical recommendations concerning policy relevant to the maritime sector with decarbonization targets set by the IMO to guide primary future research.

The study is organized in the following manner. Methodological approaches are outlined in Section 2, along with the PRISMA-based systematic review. Section 3 provides findings from the literature review concerning operational measures, alternative fuels, and policy frameworks. Finally, Section 4 analyzes the findings and their significance for maritime stakeholders. This section also concludes the study by offering recommendations for future research and industry practice.

## 2. Methodology

The study employs a systematic literature review (SLR) compliant with PRISMA 2020 (Page et al., 2021). In addition, it examines the available literature on decarbonization pathways and operational strategies for green shipping and analyzes the key themes, trends, and gaps.

### 2.1. Literature review

Between January 2015 and April 2025, a systematic review of the databases was conducted to identify the latest peer-reviewed publications on the decarbonization of the maritime sector available up to 2025. Purposeful search queries were designed to construct comprehensive meta-analyses on the operational dimensions of decarbonization, including Decarbonization and Sustainable Shipping in Policy and Technical analyses. To ensure all possible high-quality, peer-reviewed publications were identified and included from the fields of maritime research, engineering, energy systems, and policy research, the Web of Science, Scopus, and ScienceDirect databases were searched. To maximize accuracy and minimize duplication across the various dimensions of the review, the proposed search strategy was structured to comprise three interrelated analytical and conceptual frameworks using Boolean search techniques, as follows:

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- **Scope Block. (The Sector):** Focuses on the description of the particular industry (e.g., shipping, maritime, vessel).

- **Goal Block. (The Problem):** Focuses on the main goal of the study (e.g., emissions decrease, decarbonization).

- **Measures Block. (The Solutions):** Focuses on a variety of technical, operational, and regulatory measures that could be employed.

The initial search query was built as follows: (Scope Block) AND (Goal Block) AND (Measures Block). Within the Measures Block, specific terms included key substitutable fuels (Ammonia, Methanol, hydrogen, LNG, biofuel), operational efficiency, and Digitalization (energy efficiency, voyage optimization, Artificial Intelligence (AI)). policy instruments (IMO strategy, Carbon Intensity Indicator (CII), Energy Efficiency Existing Ship Index (EEXI), policy).

The combined database search yielded an initial set of 737 records. These records were further explored through citation snowballing and forward searching before moving on to the formal screening and selection phases.

## 2.2. Screening and selection process

As guided by PRISMA (Page et al., 2021), literature selection followed a methodical, stepwise approach. The complete trail of studies from initial search to final inclusion decision is shown in the PRISMA diagram (Figure 1). This ensured that the final evidence base was selected in a transparent and reproducible manner.

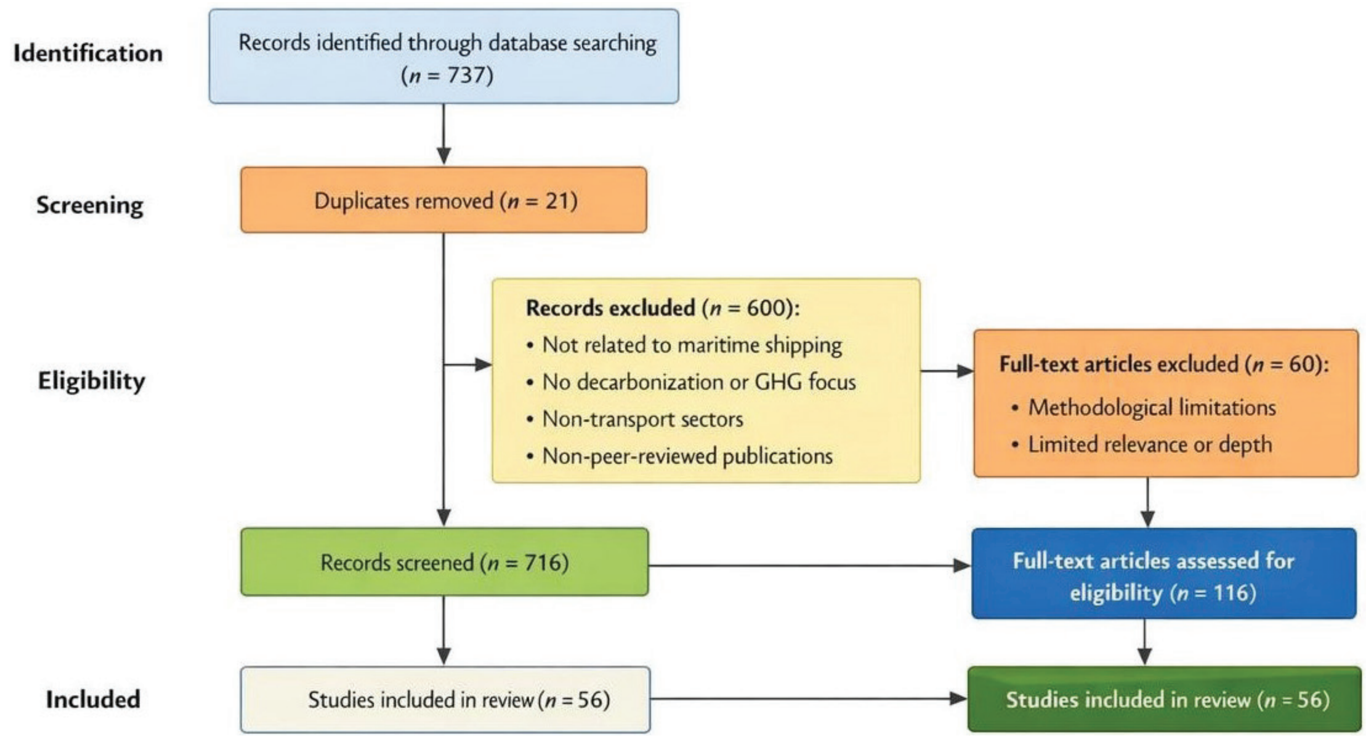


Figure 1: Flow diagram of the research selection process, Source: author

The first stage of the screening process started after the collection of 737 documents. A master spreadsheet was generated, and the documents began their systematic review. Automated and manual duplication checks were conducted using DOI and title filters, followed by manual checks, resulting in the removal of 21 duplicate records, leaving 716 documents for the first screening round. These documents were first screened by title and abstract to determine whether they were aligned with the review's focus on decarbonization pathways and operational strategies for sustainable shipping. 600 documents were removed in this screening round for various reasons that aligned with the custom exclusion criteria, leaving 116 documents for the next screening phase. These documents were fully screened for relevance and theme before a more in-depth scope of review was applied.

During the title and abstract screening phase, studies were excluded according to the predetermined eligibility criteria. Articles were excluded if they were not specifically about international maritime shipping, did not mention decarbonization or reduction of greenhouse gases, were about non-maritime transport sectors, or were unpublished or non-peer-reviewed. From the first screening stage, 600 records were excluded. 116 studies were advanced to full-text review. All of these documents were fully retrieved, and the full text was reviewed against the review's more detailed inclusion and exclusion criteria.

These documents were assessed for:

- Relevance and depth with a more insightful, thorough analysis of the decarbonization associated pathways (fuels/technology) or operational, policies, and strategies that were directly geared to international deep-sea shipping.
- **Methodological quality:** The study's quality must meet the requirements set by the quality evaluation checklist criteria (Section 2.4).
- **Data contribution:** The study has to provide new empirical evidence or analytical information of quality and depth, which has positive implications for the understanding of the sector's sustainable transition as regards diverse robust quantitative modeling.

Following the assessment results, the database removed 60 articles. The predominant rationale concerning the removal was due to the articles lacking primary empirical data, articles of low quality in terms of methodology, and articles lacking sufficient description of the processes of the transition in international shipping (these reasons are explained in the PRISMA flow diagram, Figure 1). Only these 56 articles, which are deemed to have met all the inclusion criteria, are the ones that make up the Final Evidence Base for this systematic review. At this point, the inclusion and exclusion decisions for each article have been made independently, based on the eligibility and quality criteria, and consistency checks have been conducted to address selection bias in the Final Evidence Base.

## 2.3. Data extraction and synthesis

After completing the final stage of selection, a standard protocol for data extraction was developed and consistently applied across the 56 samples included in the review. This stage aimed at obtaining a homogeneous set of relevant information for data synthesis and analysis.

The data below were extracted for each of the studies:

- **Complete reference:** Name(s) of Author(s), Year of Publication, Journal, and DOI.
- **Research design:** Determination of the type of research conducted as a Lifecycle Assessment (LCA), technical modeling, case study, survey, or economic analysis.
- **Research topic:** The specific decarbonization pathway, or the operational strategy, was studied.
- **Summary of the findings:** Principal conclusions of the study, including the relevant findings and policy recommendations.

Primarily, the articles underwent systematic coding through the mechanization of Thematic Tagging. This process, inductively, assigned tags based on the articles' emphases. The subsequent tags were then aggregated and organized into broader categories, which comprise the results of this review: Digitalization/AI, Policy/Regulation, Alternative Fuels, and Port Operations. The painstaking nature of this thematic classification, which was demonstrated by the counts in the Tag Summary, enables the integrated synthesis of knowledge gaps, convergence, and the possible fragmented trends in the reviewed literature. This is exactly the objective of this review. For the sake of the thematic tagging's analytical quality, the primary analytical focus was differentiated from the secondary or enabling themes. Only if the theme was the leading analytical focus, research question, methodological focus, or the main contribution of the paper was it coded to be primary. Themes like Digitalization, data analytics, or monitoring systems were often taken as enabling or cross-cutting themes. They were embedded within the primary

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focus of the studies, which were mostly about fuels, operational efficiency, and policy. Therefore, while digital technologies are seen in high frequency throughout the literature, it does not entail that the same level of analytical focus was given to them in each case. This was done in order to avoid the overrepresentation of transversal themes, which in turn would affect the interpretative reliability of the thematic synthesis, which in this case was to be.

### 2.4. Quality assessment and risk of bias

To provide the highest level of trust and confidence in the final findings, a quality assessment of the 56 included studies was conducted. Due to the heterogeneity of the literature, including technical modeling, LCA, and case studies, the studies were evaluated using the Bespoke Quality Checklist, based on systematic review quality evaluation standards (Page et al., 2021) and quality criteria. These criteria were: the purpose of the study was clearly stated, appropriate methods were used, the data source was reliable, and the conclusions drawn were trustworthy. Some studies did not meet these criteria, which led to the exclusion of 60 studies during the full-text review. Of these, 24 studies were excluded for insufficient methodological rigor, 18 for limited relevance to international maritime shipping decarbonization, and 18 for insufficient analysis or lack of substantial contribution. Thus, ensured that the findings of the thematic synthesis were drawn from accurate and reliable arguments.

## 3. Discussion and Review of findings

### 3.1. Policy and regulatory framework for maritime decarbonization

All decarbonization strategies that the maritime sector can pursue must work within the context of the policy and regulatory framework. Which of the international regulations, marketbased measures, and fuelintensity standards apply will determine compliance, dictate investment, and drive operational and technological change. Therefore, this subsection addresses the regulatory and economic instruments applicable to maritime decarbonization before discussing operational measures and alternative fuel solutions.

This chapter presents the summaries from the 31 studies on Policy and Economics (Sun et al., 2026; W. Wang et al., 2025; Zeng et al., 2025). Among the research components, this one is most critical to addressing market failures that impede the transition and are associated with the costs of both conventional and zero-emission fuels and the insufficient level of investment in new technologies. The operational and technological measures, coupled with the existence of global frameworks, are, according to the literature, the only solutions to the problem of the high price of carbon (Carral et al., 2020; Ng et al., 2022).

#### *3.1.1. Policy instruments: Driving the market signal*

Studies examining Carbon Pricing Mechanisms, such as a global Carbon Levy or Emission Trading Schemes (ETS), are numerous (Fadiga et al., 2024; Kondratenko et al., 2025; Zincir, 2025). There exists an academic consensus regarding the efficacy of Market-Based Measures (MBMs) in closing the cost parity gap and steering industry focus and investments (Chen et al., 2024; Ng et al., 2022; W. Wang et al., 2025). There is no disputing that a high carbon price of over $100/ton of CO2-equivalent is required to alter the cost differential between HFO and provide a financially viable alternative for the production of green hydrogen/Ammonia. (Robalo-Cabrera et al., 2025; Tadros et al., 2023; Zeng et al., 2025). The breadth of coverage for such mechanisms is important to avoid carbon leakage and a competitive gap (e.g., the EU ETS) (Carral et al., 2020; W. Wang et al., 2025).

There have been several studies analyzing the Fuel EU Maritime Initiative along with the carbon pricing framework (Kondratenko et al., 2025; Li & Tang, 2024; Ng et al., 2022). These studies show that these regulations that require a decreasing average GHG intensity of the energy consumed on board are essential in providing a demand signal for clean fuels, addressing the chicken-and-egg dilemma of the ship investment for the production of fuel (Ezeh et al., 2024; Soltani Motlagh et al., 2023; Xiao et al., 2025). The studies suggest that the optimal approach to hastening the decarbonization of the industry is to simultaneously implement fuel regulations (Non-MBM) and carbon pricing (MBM) measures (Carral et al., 2020; Chen et al., 2024; Sun et al., 2026). Among the studies, market-based measures are in the lead as the principal enabling factor, while fuel regulations are the essential supportive factor that mitigates investment risk and demand volatility.

The output of the IMO Marine Environment Protection Committee (MEPC) 83 meeting advanced the implementation of the new GHG strategy of the organization, within the current regulatory framework. MEPC 83 advanced the Annual GHG Fuel Intensity (GFI) target, which sets an increasingly stringent GHG fuel lifecycle GHG emissions cap on the use of maritime fuels. MEPC 83 shifted to a target-based approach to fuel GHG emissions. This approach directly targets the fuel used and energy sources, regulating the extent to which lifecycle fuel GHG emissions are mitigated. MEPC 83 proposed mechanisms on top of other integrated market measures to offer both an economic and regulatory framework to scale performance targets focused on the use of low and no-cost carbon alternatives (IMO, MEPC83).

### *3.1.2. Economic challenges and investment*

Within the literature, there is a consensus that the greatest investment barrier that comes with the process of decarbonization is the substantial long-term Capital Expenditure (CAPEX) needed for the construction of new vessels, as well as the new shore-side infrastructure that will be needed as well (Bolat, 2026; Ng et al., 2022; W. Wang et al., 2025; Zeng et al., 2025). Studies demonstrate the need for innovative financial models, particularly public-private alliances and Green Shipping Funds, to alleviate the risks of financing new technologies (ammonia engines and hydrogen bunkering) (Tadros et al., 2023; Vakili et al., 2023). Under investment risk, there is the possibility of deserting the assets where the vessels that are procured today (i.e., LNG carriers) will be at a high risk of being economically unfit in the course of over two decades due to increased enforcement of policies that are geared towards the environment, highlighting the need for policies to address the issue to protect and encourage investment (Bolat, 2026; Dong et al., 2025).

It is clear that there is growing concern regarding the appropriate allocation of the proceeds from (MBMs). (Liu et al., 2024; Vakili et al., 2023; Y. Wang et al., 2025; Zincir, 2025), discuss how the literature provides compelling justification for the proceeds (for example, from a carbon tax) to be retained within the maritime industry and directed towards the financing and establishment of the production of zero-emission fuels, as opposed to the unrestricted disposal of the funds into a country's general revenue account. For a variety of reasons (Carral et al., 2020; Chen et al., 2024; Ng et al., 2022), this approach is essential for ensuring that the industry is able to innovate, reduce the economic impacts on poorer countries, and increase the speed at which technologies necessary for the transition can be made available.

In combination with legislative actions, financial institutions influence the course of maritime decarbonization, especially through their lending and investing activities, the most recent of which are the Poseidon Principles. These Principles are the first voluntary framework adopted by leading banks in the shipping industry to align their maritime finance portfolios with the decarbonization objectives of the International Maritime Organization. By stipulating that borrowers must have, at a minimum, certain vessel-level emissions-performance and climate alignment scores, the Poseidon Principles introduce a positive financial risk that works in conjunction with other regulations and market mechanisms. This serves to motivate shipowners to consider emissions performance in their decisions with respect to renewing and operating their fleets; in addition, it improves the transparency and accountability of maritime finance. Thus, the Poseidon Principles demonstrate how financial governance in the private sector, in combination with regulations, can stimulate the faster realization of low-carbon pathways in shipping. In this sense, the Poseidon Principles reinforce the policy recommendations presented in Section 4.2 by aligning financial decision-making with regulatory decarbonization objectives (Poseidon Principles, 2023).

As per Section 2.2, this section examines the guided systematic synthesis of all 56 articles. As per the most recent findings received from (IMO, 2023; Laskar et al., 2025), the global shipping industry is now optimized towards achieving net-zero GHG emission by 2050, which further solidifies the academic output towards the 3 key, and inter-related, themes of operational efficiency, technical fuel pathway, and regulation (W. Wang et al., 2025) For the purpose of systematic synthesis, this section examines the findings that were organized regarding the data extraction themed tags per Section 2.3 and provide a summary of the concentration of evidence and the remaining evidence areas that were systematic and objective. The analysis first examines the concentration of evidence per thematic distribution (3.1) and proceeds towards the findings on the most dominant approaches towards decarbonization for the remaining evidence areas. Throughout the research, the analysis and findings for operational efficiency, technical fuel pathway, and regulation are based on cycle time, either the short (more operational) or the long (more structural), to determine the decarbonization closure, whether shallow or deep. For IMO's 2050 net-zero goal, the closure to be achieved here would be based on the operational measures and those with deep decarbonization, for the remaining based on the long cycle time. This will enhance the removal of the temporal ambiguity affecting compliance and cost optimization.

The following analysis is oriented towards understanding not only which policies are effective, but rather when and under what circumstances these policies lead to the greatest change.

## 3.2. Overview of thematic distribution

The thematic coding process revealed an uneven distribution of research focus across the three primary branches of maritime decarbonization studies. Table 2, thematic distribution and frequency of decarbonization research focus (56 Included Studies). This table presents the main thematic tags inductively attached to the 56 articles included in the final synthesis. The number indicates how many studies had the particular tag as a primary research focus. The fields of interest are subdivided into Operational, Technical, or Regulatory. Given that papers cover many themes, the total number of tags exceeds the number of studies included.

Table 2: Thematic distribution and frequency of decarbonization research focus (Based on 56 included studies)

| Rank | Thematic Tag | Count of Studies | Focus Area |
|---|---|---|---|
| 1 | Digitalization / AI / Machine Learning (ML) | 55 | Operational |
| 2 | Ports & shore power | 44 | Operational |
| 3 | Alternative fuels (general) | 41 | Technical |
| 4 | Policy/IMO/CII/EEXI | 31 | Regulatory |
| 5 | Hydrogen | 10 | Technical (Specific Fuel) |
| 6 | LNG | 9 | Technical (Specific Fuel) |
| 7 | Operational measures | 9 | Operational |
| 8 | Lifecycle assessment (LCA) | 8 | Technical/Method |

There is significant interest in the area of Operational Strategies (Digitalization and Ports), which has the most publications, in stark contrast to the relative interest in the technical fuel pathways (Bolat, 2026; Wang et al., 2025). Digitalization is present in most of the studies reviewed, albeit usually as an enabling or crosscutting theme and not as the main focus of analysis, which accounts for the high incidence.

## 3.3. Synthesis of operational strategies

The research gap confirms that the scholarly community has operational strategies as the most popular research topic driven by Digitalization (55 papers) and Ports (44 papers). This rush is a testament that the industry is desperate for solutions that have minimal capital investments but are significantly impactful given the immediate requirements posed by the CII and EEXI (Robalo-Cabrera et al., 2025).

### *3.3.1. Ship-level optimization and digitalization*

Vessel-level optimization clearly supports the claim that digital and AI technologies are the most efficient and effective means of improving energy efficiency (EE) across the fleet (Kondratenko et al., 2025; Xiao et al., 2025; Zeng et al., 2025). This research supports the United Nations sustainable development goals SDG 7 (Affordable and clean energy. The analysis identifies three strategies used to manage the immediate emissions reduction:

- **Passage plan optimization and slow steaming:** Rapid speed reductions (slow steaming) have been quantitatively proven as the most effective short-term operational measure that can be implemented at the fleet level and have an immediate impact on GHG emissions reduction (Dong et al., 2025;

Soltani Motlagh et al., 2023). In this measure, the ships are also provided with advanced weather routing and tracking systems to optimize the fuel and emissions efficiency across the weather and sea state, as the systems are adapted to the fuel-efficient and optimum cruise speeds (Dong et al., 2025; Soltani Motlagh et al., 2023; W. Wang et al., 2025). Other digital models have also been used to optimize the operational variables of trim and ballast for the complete hull-form resistance (Carral et al., 2020).

- **Predictive performance monitoring:** The contributions of the synthesized literature on Predictive Performance Monitoring, focusing on Machine Learning (ML) and Artificial Intelligence (AI), are designed to achieve real-time prediction and optimization of vessel operational performance and fuel consumption (Chen et al., 2024). The models provide operational emissions prediction with sufficient accuracy needed to compute and implement changes for real-time operational compliance in the EEXI and the CII regulatory compliance.

- **Efficiency without propulsion & retrofitting:** In addition to primary propulsion, there is also a focus in literature on optimizing the energy use through the incorporation of upgraded Waste Heat Recovery (WHR) systems and the improved power control of ancillary devices (Dong et al., 2025; Vakili et al., 2025). Moreover, there is further corroboration on the potential of Wind-Assisted Propulsion (WAP) technologies as a first-tier retrofitting solution for current vessels (Kondratenko et al., 2025; Li & Tang, 2024).

Altogether, the literature posits operational optimization, especially speed control enabled by digital instruments, as the most effective temporary mitigation measure for the current fleet, and simultaneously outlines the measure's drawback as solely efficiency-focused, rather than aiming for a total zero-emissions solution.

### *3.3.2.Port call optimization and the land-sea interface*

The extent of research on decarbonization of maritime transport clearly demonstrates recognition of the challenge posed by the incorporation of maritime operations into global supply chains (Çağlayan & Aymelek, 2024; Elkafas & Seddiek, 2024; Fadiga et al., 2024; Parvasi et al., 2025). The port is the critical point of integration where ship operational tactics interface with onshore energy and logistics systems, and is therefore the focus of complex optimization problems that span the land and sea legs of the extended supply chain (Elhussieny, 2025; Liu et al., 2024; Qi et al., 2025). The literature reviewed suggests that the port is more than a point of cargo transfer; it is the primary node of a system that achieves substantial efficiency gains through Just-In-Time (JIT) planning and a complete shift to zero-emission operational technologies, supplemented by Shore Power and future port bunkering. Therefore, the focus on the land-sea interface is motivated by the need to streamline the movement of ships, energy, and data to achieve a reduction of emissions at berth and during the approach phase, and hence result in an overall reduction of the carbon footprint of the voyage.

- **Just-In-Time (JIT) Arrival:** JIT Arrival strategies (W. Wang et al., 2025), as the predominant research stream at the port interface, focus on the optimization of the ship-queuing process. Researchers show through various sophisticated optimization techniques that the JIT method is a feasible improvement over the extremely inefficient First Come, First Served (FCFS) method as a result of a tremendous reduction in anchorages waiting time and their emissions (Dong et al., 2025; Parvasi et al., 2025). Case studies show operational compliance in terms of attaining a reduction of 32.8% to 45% of $CO_2$ emissions during the approach and waiting intervals, which confirms JIT to be instantly operationalized (Sun et al., 2026).

- **Shore power supply (HVSC) and decarbonizing berthing:** The use of High Voltage Shore Connection (HVSC) "cold ironing" is confirmed to be a crucial component to attain zero-emission berthing (Elkafas & Seddiek, 2024; Fadiga et al., 2024; Liu et al., 2024). However, techno-economic studies emphasize that the environmental benefit must be based on the port electricity supply being genuinely renewable, thus avoiding the full cycle of Tank-to-Wake (TTW) emissions being landed on a fossil fuel source, as this is critical.

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### 3.4. Technical pathways and fuel adoption: The systemic transition challenge

This section presents conclusions on the basis of a systematic, structured comparison of the studies on alternative marine fuels in the final evidence base. The authors of the reviewed studies were asked to clarify their position on a number of recurring analytical dimensions, including energy density, storage and handling requirements, safety, technological maturity, compatibility with existing infrastructure, and lifecycle greenhouse gas emissions (Ezeh et al., 2024; Kondratenko et al., 2025; W. Wang et al., 2025). The authors demonstrated how the dimensions influenced the type of vessel, the operational profile, and the trade route, which allowed the authors to identify the areas of convergence and divergence in the reviewed literature (Robalo-Cabrera et al., 2025; Sarbanha et al., 2023). This type of analysis justifies the widely reported conclusion in recent reviews that there is, and likely will be, no single alternative fuel pathway that can be applied to the entire global shipping fleet.

No single alternative fuel pathway can be seen as a structural transition, rather than a transitional change, to be able to fully replace conventional marine fuels for all vessel types, trading routes, and operational patterns. The other key area of focus is the zero-emission shipping fuels-related transition to alternative fuels and the needed infrastructure, which is considered to be the most long-term and expensive component of decarbonization of shipping (Bolat, 2026; W. Wang et al., 2025; Wei et al., 2026). This area of research comprises 41 works about Alternative Fuels (General) and another 19 about specific zero- and low-carbon carriers. The category of “Alternative Fuels (General)” encompasses those works that likely belong to the general systems perspective of alternative maritime fuels as opposed to a fuel systems approach or a fuel-technology approach focusing on a single fuel. These works analyze several of the leading candidate marine fuels (see Ammonia, Methanol, hydrogen, biofuels, synthetic fuels (e-fuels), liquefied natural gas (LNG)) and seek to identify, understand, and explain, to what extent the various fuels have advantages, disadvantages, and tradeoffs associated with each fuel within different types of vessels, operational profiles, and transition time frames. Hence, the body of literature has cross-cutting considerations on energy density, storage, handling, safety, infrastructure, and other constraints, along with scalability, cost, and life cycle greenhouse gas emissions, thereby justifying a strategic assessment to optimize fuel selection rather than a fuel-centric approach.

The large number of works produced in this field reflects the industry’s recognition that operational efficiencies alone will not drive the transition needed to meet net-zero targets by 2050. The research responds to the growing body of review work on the high level of technical and rival competitiveness in the diverse fuel offerings (Ammonia, Methanol, hydrogen) and the unavoidable compromises in energy content, safety, and the essential clarity required in determining an accurate lifecycle environmental impact (Ezeh et al., 2024; Ismail et al., 2025; Kondratenko et al., 2025; Sarbanha et al., 2023; Zincir, 2025).

#### *3.4.1. Technical viability of alternative fuels*

The literature analysis supports the premise that the future mix of fuels will be complex and heterogeneous, with no ‘silver bullet’ alternative to Heavy Fuel Oil (HFO) being capable of supplanting all the HFO uses across the global fleet (Ezeh et al., 2024; Kondratenko et al., 2025; W. Wang et al., 2025). This is an inevitable consequence of a technical requirement. Different types of vessels have different priorities and tradeoffs. For example, large, long-distance container vessels have a necessity for high energy density (fuels that are Ammonia or Methanol), whereas short-sea ferries and coastal vessels have a lower energy density (batteries or hydrogen) as they have shorter cycles for refueling (Sarbanha et al., 2023; Soltani Motlagh et al., 2023). The technical tradeoffs around fuel storage volume and the safety measures required, the engine retrofitting, and the complexity of safety measures required fuel the need for a complex multi-fuel system to be developed and diversifies the system of tradeoffs to be developed in a segmented transition pathway (Bolat, 2026; Çağlayan & Aymelek, 2024; Li & Tang, 2024).

Among the papers regarding hydrogen (10) and its derivative, Ammonia (7), the most popular debate is the specific storage, handling, and safety intricacies related to high risk (Chen et al., 2024; Kondratenko et al., 2025; Sarbanha et al., 2023; Soltani Motlagh et al., 2023; W. Wang et al., 2025). The studies emphasize that the required cryogenic ( -253 C) storage for liquid hydrogen is challenging as it has relatively low volumetric energy density and thus, involves a complex redesign and a reduction of storage capacity (Li & Tang, 2024). While Ammonia has relatively high storage density, its toxicity and high corrosion rate (the required inhibition, as well as extensive crew training, serve as a ventilation system's barrier) are noted as some of the most significant obstacles for deploying Ammonia at scale(Bolat, 2026; Kondratenko et al., 2025). Because hydrogen storage poses significant technical challenges, Ammonia is validated repeatedly as a promising long-term carrier for especially deep-sea routes.

One of those areas is research on Methanol (6 papers) and Biofuels/e-fuels. Among them, Methanol is relatively more mature and possesses lower barriers to adoption. Methanol has been studied more on account of supply chain maturity, lower risks of combustion, and more versatile and straightforward engine retrofitting, as opposed to the more complicated hydrogen and ammonia storage cryo- or pressurized (Ezeh et al., 2024; Li & Tang, 2024; W. Wang et al., 2025). However, the literature on sustainable Biofuels and synthetic fuels (e-fuels) virtually unanimously expresses concerns with the feedstock sustainability and global scalability (Soltani Motlagh et al., 2023; W. Wang et al., 2025). Analyses show that the projected total global supply of sustainable biomass feedstock is likely to be insufficient to meet the demands needed to decarbonize the entire global fleet, and there will be resource competition with other sectors, especially aviation and road transport (Ezeh et al., 2024; Robalo-Cabrera et al., 2025).

On the other hand, the research on Liquefied Natural Gas (LNG) (9 papers) has been mainly focused on the role that LNG plays as a necessary transition fuel. Although LNG allows for a considerable drop in local air contaminants such as SOx, NOx, and particulate matter, multiple techno-economic and environmental assessments have raised serious questions about its expected function in attaining net-zero objectives on account of its capacity for methane slip (methane in its unburnt for, a very harmful GHG) (Liu et al., 2024; W. Wang et al., 2025). Studies argue that the net climate impact of LNG, if any, is case-specific to the kind of engine technology in use (e.g., high-pressure versus low-pressure injection) and, most importantly, is negative when the fuel is obtained from systems that have no oversight of upstream methane leakage (Fadiga et al., 2024).

### *3.4.2. Environmental accounting: The Well-to-Wake (WTW) imperative*

Across all 41 fuel papers and particularly 8 Lifecycle Assessment (LCA) focused papers, the predominant and overarching finding/service is the scientific necessity and soon-to-be universal acceptance of the Well-to-Wake (WTW) accounting methodology (Chen et al., 2024; W. Wang et al., 2025; Y. Wang et al., 2025). WTW methodology is the primary, and possibly the most important, analytical output of technical research, as it serves as the most authoritative scientific bulwark against which the long-term climate viability of a fuel can be assessed (Fadiga et al., 2024). In the absence of WTW, the risks associated with the substitution of emissions, termed "emissions leakage" in the literature, are left unchecked (Kondratenko et al., 2025; Li & Tang, 2024; Sun et al., 2026).

Numerous primary documents in the LCA literature indicate that the (TTW) approach, which focuses solely on the emissions released from the ship's fuel nozzle, is the current and historically prevailing regulatory standard. Regulatory standards that allow only TTW calculations are TTW vs. WTW the biggest policy fault line in the literature, as they incentivize the use of 'clean' ship-level fuels that have carbon-intensive production, processing, or transport (Ezeh et al., 2024; Vakili et al., 2023; W. Wang et al., 2025). Research indicates that the TTW approach to regulation 'locks' the industry into suboptimal solutions and that it is critical to move to a full lifecycle approach to regulation in order to satisfy the IMO's net-zero goals.

The requirement can be fulfilled by thoroughly conducting Emissions Transfers as well as Full Scope analysis. WTW accounting requires Well-to-Tank (WTT) emissions of all greenhouse gases emitted while the fuel is being extracted, refined, and transported (Fadiga et al., 2024; Wang et al., 2025). Literature has shown that a fuel such as fossil (LNG) that is TTW compliant can have a total WTW footprint equal to, or worse than, a conventional HFO if upstream methane leakage and production energy sources are poorly mitigated (Liu et al., 2024; Sarbanha et al., 2023; Sun et al., 2026). This evidence directly contradicts policy approaches that assume effective decarbonization can be achieved through fuel switching based solely on local TTW performance.

Across individual fuel pathways, the literature consistently shows that (TTW) accounting on its own is insufficient to guide long-term decarbonization, highlighting the need for comprehensive (WTW) assessment frameworks.

Table 3 summarizes the well-to-wake environmental outcomes for alternative marine fuel pathways as reported in the reviewed literature.

Table 3: Summary of well-to-wake (WTW) environmental outcomes reported in the reviewed literature for alternative marine fuel pathways

| Fuel pathway | Reported WTW emissions performance | Key environmental considerations highlighted | Main insights from the reviewed studies | Representative studies |
|---|---|---|---|---|
| Hydrogen | Reported WTW emissions vary significantly depending on the production pathway | High upstream energy demand and dependence on electricity carbon intensity | Studies emphasize that the environmental performance of hydrogen is strongly contingent on lowcarbon or renewable production pathways | Sarbanha et al., 2023; Wang et al., 2025 |
| Ammonia | Potential for low WTW emissions when produced from green hydrogen | Energyintensive production processes and safetyrelated considerations | The literature frequently identifies Ammonia as a viable longterm option under WTW accounting, subject to production pathway and safety constraints | Kondratenko et al., 2025; Ezeh et al., 2024 |
| Methanol | WTW emissions outcomes depend on feedstock and production route | Risks of limited lifecycle benefits when derived from fossil sources | Reviewed studies highlight that Methanol offers meaningful WTW reductions primarily when produced from renewable or lowcarbon feedstocks | Ismail et al., 2025; Wang et al., 2025 |
| Biofuels | WTW emissions show high variability across fuel types and feedstocks | Feedstock sustainability and scalability limitations | The literature suggests that biofuels may provide shortterm mitigation potential, although longterm scalability remains uncertain | Ezeh et al., 2024; Sarbanha et al., 2023 |
| (LNG) | WTW emissions reductions are often lower than expected | Methane slip during combustion and upstream leakage | Multiple studies indicate that methane emissions can offset TTW benefits, raising concerns regarding LNG's longterm role under WTW frameworks | Liu et al., 2024; Wang et al., 2025 |

## 4. Conclusion and Future research

This segment aims to provide a summary of the research findings and articulate the primary findings to regulators, industry stakeholders, and infrastructure developers. Provided findings are summary findings, not restatements of the studies, but drawn from the consolidated evidence in Section 3, placing the findings in the context of the wider implications of the IMO decarbonization framework. This particular part of the research outlines the major gaps in the existing research and identifies the urgent need for further research.

### 4.1. Overarching conclusion and review of Findings

In the context of maritime shipping, decarbonization refers not only to the reduction of greenhouse gas emissions from vessel operations but also to a systemic transition involving changes in energy carriers, operational practices, infrastructure, regulatory frameworks, and investment decision-making across the maritime sector.

The purpose of the analysis was to understand academic writings published in recent years relating to the framework of the decarbonization of shipping industries and the operational decisions on the industries to achieve the target of the International Maritime Organization to attain net-zero GHG emissions by the year 2050. The operational efficiency studies found that it is possible to improve and achieve cost-effective emission reductions at a faster pace with the prevailing fleet in the shipping industry. However, operational efficiency improvements will be key to achieving deep long-term decarbonization of the shipping industry.

The literature demonstrates that decarbonization of the shipping industry is the first in a series of systemic transition challenges to be addressed. The industry must move beyond a focus on incremental technological improvements. It is clear that speed and routing operational efficiencies found in the use of weather optimization and digital support systems for operational decision-making will help the industry achieve emission mitigation and operational compliance. However, with the use of zero and near-zero-carbon fuels, the industry will be able to remove the cap on emissions reduction and improve the decarbonization safety and support of global resources, which at present are lacking.

In conclusion, the review demonstrates that meeting the IMO's interim and long-term targets calls for 'commitment and combination'. This means that in the absence of any one of the three prerequisites, operational optimization, fuel transition pathways with binding regulations that consider the cost of carbon, meeting the targets will be unachievable. Within the operational context of the measures being examined, operational measures act as demand-reduction levers, fuel transition is the determined emissions ceiling, and the regulations control transformation at all levels of the system.

## 4.2. Definitive outcomes and practical recommendations

These changes have direct implications for both shipping companies and ports. Shipowners face strategic decisions regarding fleet renewal, retrofitting, fuel choice, and compliance costs, while ports are increasingly required to invest in energy infrastructure, shore power, digital coordination, and alternative fuel bunkering systems. As such, decarbonization affects not only vessel operations but the broader maritime logistics and port ecosystem. The findings detailed in section 3 of the review support the following recommendations for effective and plausible decarbonization of the maritime industry.

**Recommendation 1: Mandatory adoption of Well-to-Wake accounting**

WTW accounting must be the single metric that regulatory bodies, such as the IMO and regional authorities, must implement as a statutory requirement for carbon price and fuel standards compliance. This requirement is on par with the policy analyses and fuel lifecycle assessments synthesized in Section 3, which demonstrates that tank-to-wake accounting neglects and even misinterprets the climate impacts of alternative fuels. This could lead to perverse policy designs that encourage options with little or negative net emissions reductions, and even climate impact mitigation, on a system-wide level. WTW is the appropriate accounting methodology that confirms that the selection of fuels, investments, and operational strategies is directed to true, sustained, and long-term decarbonization, as opposed to mere superficial compliance.

**Recommendation 2: Implementation of mandatory market-based measures**

Mandatory market-based measures are needed, including government-coordinated carbon pricing, to offset the enduring cost difference between conventional marine fuels and zero-carbon fuels. Evidence suggests that carbon priced over USD 100 per tonne of $CO_2$-equivalent will potentially make fuel selections more affordable and accelerate the fleet transition. Such measures should aim to reduce market inefficiencies and are complemented by transparent revenue retention mechanisms that aid in developmental research. Furthermore, the tradeoff impacts on the most vulnerable transport sectors are integrated into infrastructure development. The lack of imposition of market-based measures on the shipping industry will make the voluntary uptake of low-carbon fuels impractical. This will jeopardize the IMO's decarbonization framework.

Policy interventions can accelerate the effectiveness of marketbased measures by providinglongtermregulatorycertainty,harmonized international enforcement, and targeted recycling of revenues toward zeroemission fuel production and supporting infrastructure. In particular, predictable and internationally coordinated carbon pricing signals can reduce investment risk and facilitate earlier adoption of alternative fuels by shipping companies. Coordination between global and regional policy instruments is also critical to avoid market fragmentation and carbon leakage.

**Recommendation 3: Strategic investment in fuel and port infrastructure**

It is recommended that the government and authorities at the ports consider triaging and target their near-term liquid fuel infrastructure investments (2025-2035) towards the creation and implementation of scalable, bunkering and fuel supply, and zero-emission (Ammonia and methanol) fuel supply infrastructure, as well as shore-side electricity infrastructure at key global maritime centers. This recommendation is based on the synthesized evidence that infrastructure is critical and that investments in infrastructure that have already been delayed are likely to 'trap' the sector in intermediate investments of low potential viable transitional infrastructure. Ports, energy suppliers, and shipping companies should focus on adapting their respective infrastructures to the technological renewal of the fleets and the new policies to be signed and implemented.

Given the situation at the ports, the potential to construct bunkering infrastructure for alternative fuels is an important consideration for the adoption of fully and near-zero-carbon fuels. The first major, scalable investments in bunkering for ammonia and methanol fuels at hub and gateway ports will reduce the uncertainty in decision-making for shipowners and therefore support coordinated fleet transition. With this in mind, strategic planning and collaboration among ports, energy providers, and regulators are of utmost importance to prevent stranded assets, promote effective regional interoperability, and ensure safe and efficient alternatives to traditional marine fuels.

## 4.3. Limitations and avenues for future research

The peer-reviewed literature constrains this review of existing literature, the diversity of methods in existing literature, and the fast pace of change in technologies and regulations in the field of maritime decarbonization.

This review has been conducted meticulously, yet several gaps in the existing literature, which have been reviewed, have had a significant impact and are important for future research. This includes the clear absence of well-to-wake data that is standardized and transparent, and relevant to emerging fuel pathways, particularly upstream electricity sourcing and fuel production pathways, as well as across different regions. The most crucial gap to be closed is for comprehensive analysis, regulation evaluation, and the most efficient and effective regulation.

Prioritized areas of study include the systemic interrelationships of fuel, infrastructure, and regulation systems at a fleet and trade-route level, and not at an individual vessel level, as well as the safety, operational, and human factors of the use of Ammonia and other alternative fuels, which require more profound interdisciplinary studies.

Additionally, the effect of the interactions between the Global Market-based Instruments and the regional regulations, their interplay, and the resulting impact on competitiveness, modal shift, and trade, requires additional research focus and is fundamental to achieving the right level of regulation, investment, and safety to support the decarbonization of the maritime sector.

A more systems-based approach to the shipping industry and the broader maritime cluster as interdependent networks of ships, ports, energy, regulation, and finance is warranted. There is a need to focus more on fleet-level pathway transitions, the concurrent development of ports and other infrastructure, alternative fuel supply chains, the interrelations, and co-impacts between global and regional policy instruments. Finally, real-world longitudinal studies of outcomes, investment, and operational performance are necessary to provide the empirical evidence to reduce the unknowns related to the maritime decarbonization transition.

## References:


Bolat, F. (2025). Time series modeling of greenhouse gas emissions: A case study for a chemical tanker ship. *Maritime Technology and Research*, *8*(1), 278949. https://doi.org/10.33175/mtr.2026.278949

Bullock, S., Mason, J., & Larkin, A. (2023). Are the IMO's new targets for international shipping compatible with the Paris Climate Agreement? *Climate Policy*, *24*(7), 963–968. https://doi.org/10.1080/14693062.2023.2293081

Çağlayan, Ö., & Aymelek, M. (2024). An Integrated Multi-Criteria Decision Support Model for Sustainable Ship Queuing Policy Application via Vessel Traffic Service (VTS). *Sustainability*, *16*(11), 4615–4615. https://doi.org/10.3390/su16114615

Carral, L., Fernández-Garrido, C., Vega, A., & Sabonge, R. (2019). Importance of the Panama canal in the reduction of CO2 emissions from maritime transport. *International Journal of Sustainable Transportation*, *14*(11), 819–832. https://doi.org/10.1080/15568318.2019.1632994

Chen, Z. S., Siu, J., & Xiao, Z. (2024). Prediction of harbour vessel emissions based on machine learning approach. *Transportation Research Part D Transport and Environment*, *131*, 104214–104214. https://doi.org/10.1016/j.trd.2024.104214

Degiuli, N., Martić, I., & Grlj, C. G. (2024). Slow Steaming as a Sustainable Measure for Low-Carbon Maritime Transport. *Sustainability*, *16*(24), 11169–11169. https://doi.org/10.3390/su162411169

Dong, T., Alamoush, A., Schönborn, A., Ghaforian Masodzadeh, P., Park, C., Park, H.-S., Vakili, S., Bilgili, L., Ballini, F., & Ölcer, A. I. (2025). Roadmap for the Decarbonization of Domestic Passenger Ferries in the Republic of Korea. *Sustainability*, *17*(4), 1545. https://doi.org/10.3390/su17041545

Elhussieny, M. (2025). Smart green ports: a sustainable solution for the maritime industry in a changing climate. *Multidisciplinary Adaptive Climate Insights*, *2*(1), 1. https://doi.org/10.21622/maci.2025.02.1.1162

Elkafas, A. G., & Seddiek, I. S. (2024). Application of renewable energy systems in seaports towards sustainability and decarbonization: Energy, environmental and economic assessment. *Renewable Energy*, *228*, 120690. https://doi.org/10.1016/j.renene.2024.120690

Ezeh, C. I., Richter, U. H., Seufert, J. H., & Peng, C. (2023). Operational-based decarbonization of container ports: The case of Ningbo-Zhoushan Port. *International Journal of Sustainable Transportation*, *18*(1), 34–45. https://doi.org/10.1080/15568318.2023.2197859

Fadiga, A., D.F, M., & Bigotte, J. F. (2024). Decarbonising Maritime Ports: A Systematic Review of the Literature and Insights for New Research Opportunities. *Journal of Cleaner Production*, *452*, 142209–142209. https://doi.org/10.1016/j.jclepro.2024.142209

IMO. (2021). *Mid- and long-term GHG reduction measures*. Imo.org. https://www.imo.org/en/OurWork/Environment/Pages/Mid--and-long-term-GHG-reduction-measures.aspx

IMO. (2023). *IMO Strategy on Reduction of GHG Emissions from Ships*. Imo.org. https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx

IMO. (2024). *IMO framework on life cycle GHG intensity of marine fuels (LCA)*. Www.imo.org. https://www.imo.org/en/OurWork/Environment/Pages/Lifecycle-GHG---carbon-intensity-guidelines.aspx

Ismail, A. M., Metwalli, M. M. A., & Alamoush, A. S. (2025). Towards Safe Maritime Decarbonization: Safety Barriers of Methanol Fuel. *Sustainability*, *17*(11), 4896. https://doi.org/10.3390/su17114896

Kanchiralla, F. M., Brynolf, S., & Mjelde, A. (2024). Role of biofuels, electro-fuels, and blue fuels for shipping: environmental and economic life cycle considerations. *Energy & Environmental Science*, *17*(17), 6393–6418. https://doi.org/10.1039/d4ee01641f

Kondratenko, A. A., Zhang, M., Tavakoli, S., Altarriba, E., & Hirdaris, S. (2025). Existing technologies and scientific advancements to decarbonize shipping by retrofitting. *Renewable and Sustainable Energy Reviews*, *212*, 115430. https://doi.org/10.1016/j.rser.2025.115430

Laskar, I. I., Dowlatabadi, H., & Giang, A. (2025). Expert Assessments of Maritime Shipping Decarbonization Pathways by 2030 and 2050. *Earth S Future*, *13*(4). https://doi.org/10.1029/2024ef005255

Li, Z., & Tang, J. (2024). Circulation-controlled wind-assisted ship propulsion: Technical innovations for future shipping industry decarbonization. *Energy Conversion and Management*, *319*, 118976–118976. https://doi.org/10.1016/j.enconman.2024.118976

Liu, J., Liao, R., Dong, F., Huang, C., Li, H., Liu, J., & Zhao, T. (2024). Low-carbon technology selection and carbon reduction potential assessment in the shipbuilding industry with dynamically changing grid emission factors. *Journal of Cleaner Production*, *441*, 140707–140707. https://doi.org/10.1016/j.jclepro.2024.140707

Lloyd's Register. (2025, April 3). *IMO Update: GHG midterm measures (ISWGGHG 19)*. Lr.org; Lloyd's Register. https://www.lr.org/en/knowledge/insights-articles/imo-update-ghg-mid-term-measures

MEPC83. (2025). *Marine Environment Protection Committee (MEPC 83), 7 to 11 April 2025*. Imo.org. https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/MEPC-83rd-session.aspx

Motlagh, H. R. S., Zadeh, S. B. I., & Garay-Rondero, C. L. (2023). Towards International Maritime Organization Carbon Targets: A Multi-Criteria Decision-Making Analysis for Sustainable Container Shipping. *Sustainability*, *15*(24), 16834–16834. https://doi.org/10.3390/su152416834

Ng, C., Li, J., Mishra, R., & Fagan, C. (2022). Abatement of GHG emissions onboard mobile offshore units. *Journal of Physics: Conference Series*, *2311*(1), 012036. https://doi.org/10.1088/1742-6596/2311/1/012036

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., & McGuinness, L. A. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *British Medical Journal*, *372*(71). https://doi.org/10.1136/bmj.n71

Parvasi, S. P., Siu, J., & Psaraftis, H. N. (2025). Redesigning logistics systems towards sustainability: the impact of autonomous green-fueled ships. *Maritime Policy & Management*, 1–32. https://doi.org/10.1080/03088839.2025.2574673

Poseidon Principles. (2023, December 13). *Principles Overview - Poseidon Principles for Financial Institutions*. Poseidon Principles for Financial Institutions. https://www.poseidonprinciples.org/finance/principles/

Qi, Y., Wang, Y., & Huang, Y. (2025). Techno-Economic Assessment of Carbon-Neutral Ammonia Fuel for Ships from Renewable Wind Energy. *Energies*, *18*(20), 5485. https://doi.org/10.3390/en18205485

Robalo-Cabrera, I., Alcayde, A., Filgueira-Vizoso, A., Castro-Santos, L., García-Diez, A. I., & Manzano-Agugliaro, F. (2025). Shipping sector decarbonisation measures: A review. *Sustainable Energy Technologies and Assessments*, *82*, 104549–104549. https://doi.org/10.1016/j.seta.2025.104549

Sarbanha, A.-A., Larachi, F., Taghavi, S.-M., Thiboutot-Rioux, M., Boudreau, A., & Dugas, G. (2023). Mitigation of Ship Emissions: Overview of Recent Trends. *Industrial & Engineering Chemistry Research*, *62*(4), 1707–1724. https://doi.org/10.1021/acs.iecr.2c03621

Sun, R., Abouarghoub, W., Demir, E., & Potter, A. (2025). Geopolitical disruptions and maritime transitions: Environmental and economic costs of rerouting. *Transportation Research Part a Policy and Practice*, *203*, 104737–104737. https://doi.org/10.1016/j.tra.2025.104737

Tadros, M., Ventura, M., & Soares, C. G. (2023). Review of current regulations, available technologies, and future trends in the green shipping industry. *Ocean Engineering*, *280*, 114670–114670. https://doi.org/10.1016/j.oceaneng.2023.114670

Vakili, S., Schönborn, A., & Ölçer, A. I. (2023). The road to zero emission shipbuilding Industry: A systematic and transdisciplinary approach to modern multi-energy shipyards. *Energy Conversion and Management: X*, *18*, 100365–100365. https://doi.org/10.1016/j.ecmx.2023.100365

Vakili, S., White, P., & Turnock, S. (2025). Advancing a sustainable maritime future: Integrating energy efficiency and underwater radiated noise reduction strategies in commercial shipping. *Marine Pollution Bulletin*, *215*, 117835–117835. https://doi.org/10.1016/j.marpolbul.2025.117835

Wang, W., Wang, H., Pang, K.-W., Zhen, L., & Wang, S. (2025). Optimizing bunkering and sailing strategies for sustainable shipping: a decision model for reducing costs and carbon emissions. *Annals of Operations Research*, *351*(3), 2287–2305. https://doi.org/10.1007/s10479-025-06650-4

Wang, Y., Xiao, X., & Ji, Y. (2025). A Review of LCA Studies on Marine Alternative Fuels: Fuels, Methodology, Case Studies, and Recommendations. *Journal of Marine Science and Engineering*, *13*(2), 196. https://doi.org/10.3390/jmse13020196

Wei, S., Tukker, A., & Steubing, B. (2026). Decarbonizing potential of global container shipping with hydrogen-based fuels. *Energy & Environmental Science*, *19*(1), 264–283. https://doi.org/10.1039/d5ee03477a

Xiao, G., Pan, L., & Lai, F. (2025). Application, opportunities, and challenges of digital technologies in the decarbonizing shipping industry: a bibliometric analysis. *Frontiers in Marine Science*, *12*. https://doi.org/10.3389/fmars.2025.1523267

Zanobetti, F., Pio, G., Jafarzadeh, S., Ortiz, M. M., & Cozzani, V. (2023). Decarbonization of maritime transport: Sustainability assessment of alternative power systems. *Journal of Cleaner Production*, *417*, 137989–137989. https://doi.org/10.1016/j.jclepro.2023.137989

Zeng, F., Chen, A., Xu, S., Chan, H. K., & Li, Y. (2025). Digitalization in the Maritime Logistics Industry: A Systematic Literature Review of Enablers and Barriers. *Journal of Marine Science and Engineering*, *13*(4), 797–797. https://doi.org/10.3390/jmse13040797

Zincir, B. A. (2025). Transitioning to sustainable shipping: A multidimensional analysis of maritime emission strategies. *Ocean & Coastal Management*, *269*, 107823. https://doi.org/10.1016/j.ocecoaman.2025.107823

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# Spatial Community Vulnerability to Drought Disaster in Simanjiro District, Manyara Region

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## Abstract:

*Drought is the critical environmental hazard affecting livelihoods in semi-arid regions of Tanzania. Much has been documented on community-level vulnerability; however, spatial analyses of drought hotspots using long-term climate data remain scarce. The study assessed community vulnerability to drought in Simanjiro District, Manyara Region, Tanzania, using a mixed-methods approach that integrated household surveys, key informant interviews, remote sensing, and climate data analysis from 1983 to 2022. Results indicate that drought occurred in 24 out of 40 years (60%), with SPI values ranging from -0.1 to -1.2, confirming persistent moderate drought conditions. The average annual rainfall was low (40–70 mm), and the annual total rainfall declined at approximately 2.43 mm/year, while temperatures increased at rates of 0.0189°C/year (maximum) and 0.0211°C/year (minimum). Severe drought events in 2003 and 2022 resulted in livestock losses exceeding 110,000 and 92,000, respectively. Survey results revealed that 70% of respondents perceived declining rainfall, and 90% of households depend on pastoralism, increasing their vulnerability. Key drivers of vulnerability include overreliance on rain-fed systems, high livestock densities, limited access to early warning systems, and low adaptive capacity. The study concludes that drought risk in Simanjiro is both frequent and intensifying, necessitating strengthened early warning systems, expansion of irrigation infrastructure, livelihood diversification, and improved resource governance to enhance community resilience.*

**Keywords:** Drought, Vulnerability, SPI, Simanjiro, Livelihoods, Early warning.

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# 1. Introduction

Drought is a slow-onset disaster posing a serious impact on health, agriculture, economies, energy, and the environment (Aston, 2021). An estimated 55 million people are affected by drought every year, and they are the most serious hazard to livestock and crops in nearly every part of the world (UNCCD, 2022; WWF, 2019). Drought threatens people's livelihoods, increases the risk of disease and death, and causes mass migration (UNCCD, 2022; UNDRR, 2021; WHO, n.d.). Water scarcity affects 40% of the world's population, and as many as 700 million people are at risk of displacement due to drought by 2030 (World Bank, 2023).

Drought has been one of the crucial hazards that has caused significant damage to the community economically, socially, and environmentally (Aston, 2021; Thalheimer et al., 2022; UNDRR, 2021). Tanzania has been highly dependent on rain-fed agriculture, which is highly vulnerable to rainfall amounts and distribution (ILSSI, 2019; Mtwanga, 2022; Randell et al., 2022). As observed in most pastoral communities, many livestock have died due to a lack of food and water in the area. This might be since most of the communities may lack access to modern scientific information and forecasting, as well as awareness, preparedness, and capacity to manage impacts brought by drought (Wens et al., 2021). Hence, the communities become more vulnerable to drought and are greatly impacted whenever it occurs.

Simanjiro District is dominated by pastoralist communities that depend on rainfall and natural resources to provide pasture and water for their livestock (Cosmas et al., 2022; Nkedianye et al., 2020). This leaves communities highly vulnerable to the impacts of drought disasters because recent climate change has increased rainfall variability in the region. In 2022, drought killed 92,000 livestock in Simanjiro District, Manyara Region, Tanzania. It was further stated that such significant impacts result from a high illiteracy rate, inadequate mitigation measures, and a lack of a preparedness plan, which puts the community at high risk of drought disasters (Juma, 2022). Therefore, the study aimed to assess the extent of vulnerability and risk the community faces to drought and to propose better mitigation measures to the community to reduce the severity of drought impacts.

# 2. Methodology

## 2.1. Case study selection and sampling

Simanjiro District is one of the six districts of the Manyara Region in Tanzania. It is bordered by Arusha Region to the north, Kilimanjaro Region to the north-east, Tanga Region to the south-east, Kiteto District to the south, and Babati District to the west (Figure 1). This study was conducted in other semi-arid regions of Tanzania, such as Dodoma and Shinyanga. However, Manyara is less studied. Hence, the choice of the case study. Furthermore, the study was conducted in other districts in Manyara Region. However, Simanjiro District was the best representative of other districts due to a higher Standardized Precipitation Index (SPI) value than any other district in the region. The district comprises 15 wards, with Ngorika, Naisinyai, and Liborsoit having the highest risk of drought disasters due to the lowest average monthly rainfall over the past 40 years. Therefore, with frequent drought disaster events within the district, the growing population is put at high risk of food insecurity, malnutrition, death of livestock, and diseases.

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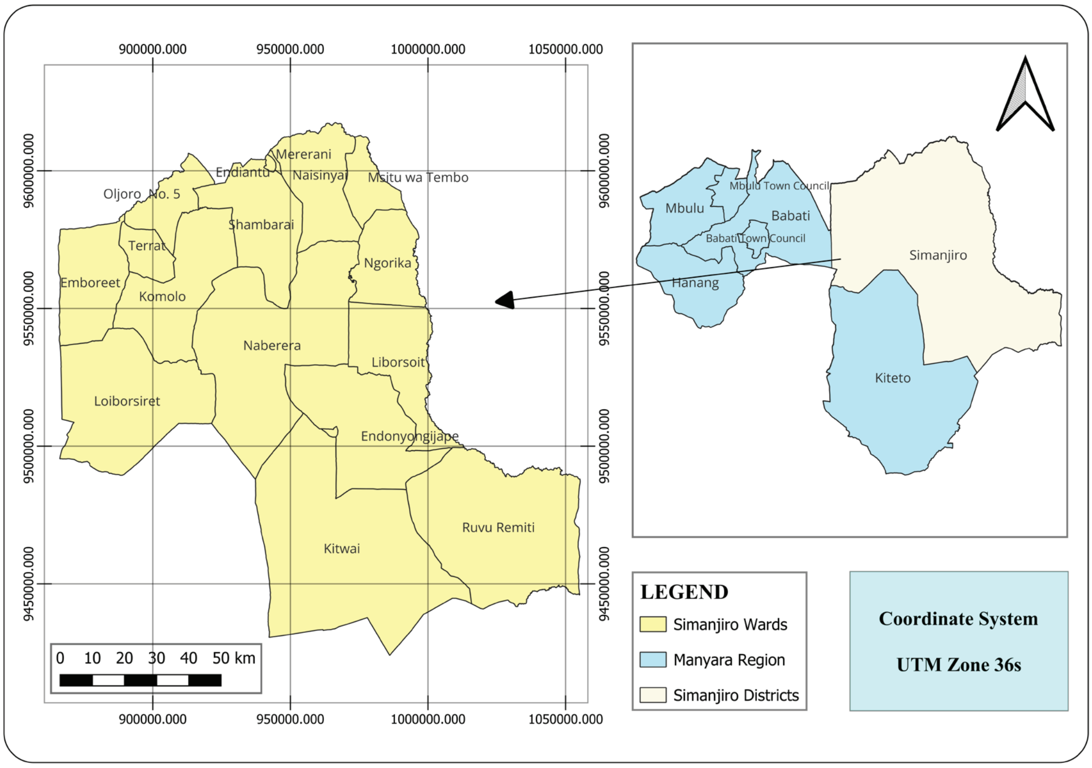


Figure 1: Map of Manyara Region, where Simanjiro District is found

## 2.2. Sampling procedure

The selection of survey locations and respondents in Simanjiro District was guided by the distribution and intensity of key socio-economic activities, as well as geographical representation across wards. A total of 100 households were purposively selected from three wards, namely Ngorika, Naisinyai, and Loiborsoit. The households were chosen to represent areas with varying levels of exposure to drought-related impacts. In addition, respondents were required to have resided in the study area for at least 30 years to ensure they possessed adequate experience and knowledge of long-term drought trends.

Fifteen (15) key informants from relevant district departments at the district and ward levels were purposively selected. These departments were identified based on their roles and availability of records related to drought impacts, including effects on biodiversity, crop production, livestock populations, environmental conditions, water resources, and social development. The departments and officials involved in the study included the Agriculture and Irrigation Department, Environmental Department, Water Supply Authority (RUWASA), as well as local government officials such as Ward Executive Officers (WEOs) and Village Executive Officers (VEOs).

## 2.3. Data collection and analysis methods

A mixed-methods design was applied. Data collection involved physical observation, structured interviews, remote sensing techniques, questionnaires, and document review. A questionnaire was administered to 100 households. The households were purposively selected to cover the case study wards, in which 48% were male, and 52% were female. The dominant education level was primary. Also, 46% of the respondents were elders, while 54% were youth. 15 semi-structured interviews with government officials (WEOs, agricultural officers, Rural Urban Water Supply Authority) and elders were conducted to document impacts and coping strategies. Data analysis was conducted using ANOVA to determine statistical differences in climate change. Software used was MS Excel, SPSS, and ArcGIS. Climate datasets (monthly precipitation and temperature) covering 1983–2022 were obtained from CHIRPS, NASA Data Access Viewer, and Climate Engine.

## 2.4. Determination of the Standardized Precipitation Index (SPI)

To determine drought severity, the standardized precipitation index (SPI) was used to assess precipitation probability over different time scales. The SPI was computed for different time scales, providing early warning of drought and helping assess drought severity. Palmer Drought Severity Index (PDSI), Drought Severity Index (DSI), Standardized Precipitation Evapotranspiration Index (SPEI), and Reconnaissance Drought Index (RDI) were thought to be used in this study; however, the Standard Precipitation Index (SPI) was found to be better due to minimal data requirement, simplicity in analyzing drought severity, multi-timescale flexibility, and sensitivity to short-term changes. The SPI was used to measure precipitation deficits over a range of periods, which may indicate how drought affects the availability of various water resources (McKee et al. 1995; Straitony, 2026).

The time scales used for SPI computation are SPI-3, SPI-6, SPI-12, and SPI-24. In the context of Simanjiro District, where livelihoods are highly dependent on rain-fed agriculture and livestock, the SPI was computed at a 6-month time scale (SPI-6), as this scale captures seasonal rainfall variability and is closely associated with agricultural drought. Given that the study focuses on impacts such as crop failure, livestock losses, and water scarcity, SPI-6 provides a balanced representation of drought conditions influencing both farming and pastoral systems in Simanjiro District. Values of the SPI for a given precipitation are calculated from the equation:

$$SPI = \frac{f(p) - \bar{u}}{d} \quad (1)$$

Where: SPI – standardized precipitation index; f(P) – transformed sum of precipitation; ū – mean value of the normalized precipitation sequence; d – standard deviation of the normalized precipitation sequence.

The study adopted the Standardized Precipitation Index (SPI) classification developed by McKee et al. (1995). SPI values were categorized as follows: ≥ 2.00 (extremely wet), 1.50 to 1.99 (very wet), 1.00 to 1.49 (moderately wet), 0.00 to 0.99 (mildly wet), 0.00 to -0.99 (mild drought), -1.00 to -1.49 (moderate drought), -1.50 to -1.99 (severe drought), and ≤ -2.00 (extreme drought).

## 2.5. Analysis of exposure, sensitivity, and adaptive capacity

The study adopted the IPCC Vulnerability Framework, which encompasses the analysis of exposure, sensitivity, and adaptive capacity to drought hazards to determine the Extent of Potential Impact (EPI) and the existing adaptive capacity. The EPI was determined as follows;

EPI = Exposure X Sensitivity (2)

For both sensitivity and exposure, numerical values were assigned as indicated below.

Highly exposed = 3, Medium exposure = 2, Less exposed = 1

Highly sensitive = 3, Medium sensitivity = 2, less sensitive = 1

The adaptive capacity of the community was assessed based on risk knowledge, institutional arrangements/governance, access and availability of resources, social cohesion and connectedness, and the economic opportunities and financial resources.

The participants in the focus group discussion brainstormed and reached a consensus on a numerical value to assign to adaptive capacity (1, 2, or 3 on a 1-3 scale, and vice versa) for each category element exposed to drought hazard. To determine the level of vulnerability (defenselessness), the vulnerability score was calculated using the following formula;

$$\text{Vulnerability score} = \frac{HSS\ X\ EPI}{AC} \quad (3)$$

Whereby

HSS = Hazard Severity Score
EPI = Extent of Potential Impact
AC = Adaptive Capacity

# 3. Results and Discussion

## 3.1. Rainfall trends

Simanjiro District is characterized by a bimodal rainfall pattern, with a short rainy season from November to December (ND) and a long rainy season from March to May (MAM). The MAM season receives the highest rainfall, with average monthly amounts ranging from 50 mm to 170 mm. However, total annual rainfall has been decreasing by

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approximately 2.246 mm per year over the past 40 years. In contrast, rainfall during the October to December (OND) season ranges from 15 mm to 180 mm, with a slight increasing trend of about 0.28 mm per year. The dry season, which spans from June to September, receives the least rainfall, with monthly averages ranging between 3 mm and 15 mm.

The rainfall data revealed that Simanjiro District receives an average annual rainfall of 40-70mm/year. The total annual rainfall trend was found to decrease at rate of 2.433mm/year while other arid areas such as Kahama town in Shinyanga region decrease at the rate of 0.053mm/year Thus, the average annual rainfall in Simanjiro seemed to be low with high decreasing rate of annual rainfall trends compared to other arid regions since an average annual rainfall ranging 50 to 120 mm/year for other arid and semi-arid regions in Tanzania (Mdee, 2022; Sawe et al., 2018), This was also revealed by the responses from questionnaires that shows 70% of people reported that rainfall was decreasing and 30% responded that rainfall is low.

It was observed that most wards in Simanjiro District have experienced average annual rainfall ranging between 30 and 80 mm over the past 40 years, with the majority receiving less than 75 mm. Ngorika, Shambarari, Naberera, and parts of Naisinyai Ward recorded the lowest average rainfall, ranging from 55 to 65 mm, compared to other wards within the district (Figure 2).

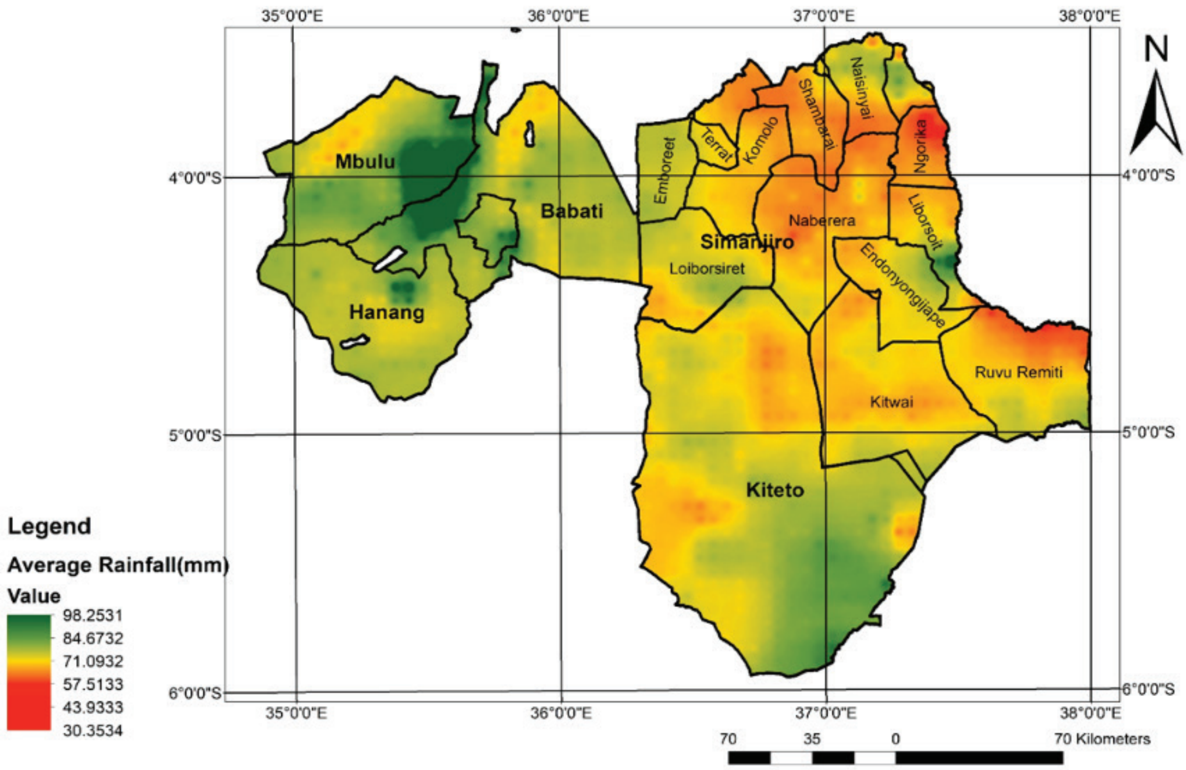


Figure 2: Monthly average rainfall spatial distribution in Simanjiro Ward (1983–2022)

The annual average maximum and minimum temperatures in Simanjiro District show an increasing trend of 0.0189°C/year and 0.0211°C/year, respectively. Consequently, the average monthly maximum temperature rises to about 34°C during February and March (Figure 3). In addition, the number of months receiving average maximum temperatures above 30°C has been increasing over the past 40 years. This trend may be attributed to global climatic change as well as local human activities within the district, such as deforestation and overgrazing (Abera et al., 2024; Kunte & Bhat, 2024; Sawe et al., 2018). Overall, the findings indicate that rising temperatures, combined with declining annual rainfall, are key drivers of agricultural drought in Simanjiro District (Kew et al., 2019; Pal et al., 2023).

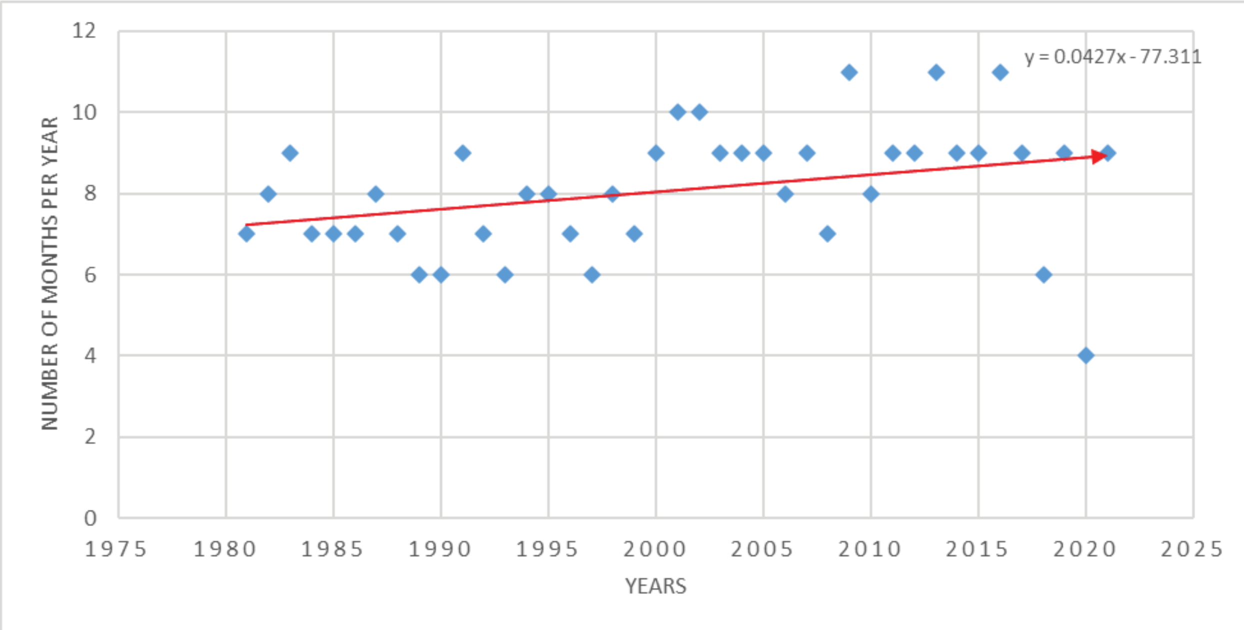


Figure 3: Number of months in a year receiving average maximum temperature greater than 30°C at Simanjiro (1983-2022)

## 3.2. Drought trends

The SPI index revealed that 24 of the 40 years have experienced drought disasters. The years 2000, 2003, 2017, and 2022 had the lowest SPI index values. The Ward Executive Officers (WEOs) provided further information to substantiate evidence of the occurrence of a drought disaster in the district, reporting that 2003 and 2022 were years when severe drought events occurred, resulting in losses of more than 110,000 and 92,000 livestock, respectively. The study showed that people's perception of drought years was defined as eight years of drought events associated with food and water shortages and crop production losses in Simanjiro District from 2007 to 2014.

The Standardized Precipitation Index (SPI) analysis revealed that 24 out of 40 years experienced drought conditions. The years 2000, 2003, 2017, and 2022 recorded the lowest SPI values, indicating severe drought events. Information provided by Ward Executive Officers (WEOs) further corroborated the occurrence of droughts in the district. Specifically, 2003 and 2022 were identified as years of extreme drought, resulting in the loss of more than 110,000 and 92,000 livestock, respectively. Additionally, the study found that community perceptions aligned with the SPI results, identifying eight drought years between 2007 and 2014. These years were associated with significant impacts, including food shortages, water scarcity, and reduced crop production across Simanjiro District. The difference between the number of droughts identified by SPI (16 drought years) and communities' perceptions (8 drought years) is that SPI captures meteorological drought (rainfall deficit), whereas people respond mainly to impact-based drought—when crops fail, water sources dry up, or livestock die. Thus, the 16 years may include moderate droughts, while the 8 years represent high-impact events.

The spatial distribution of the Standardized Precipitation Index (SPI) (Figure 4) shows that most wards in Simanjiro District experience drought conditions. However, Ngorika, Naisinyai, and Liborsoit wards were identified as experiencing more severe drought conditions over the past 40 years compared to other wards in the district. This implies that, although the entire district is generally classified as arid, Ngorika, Naisinyai, and Liborsoit represent the most arid areas within Simanjiro District.

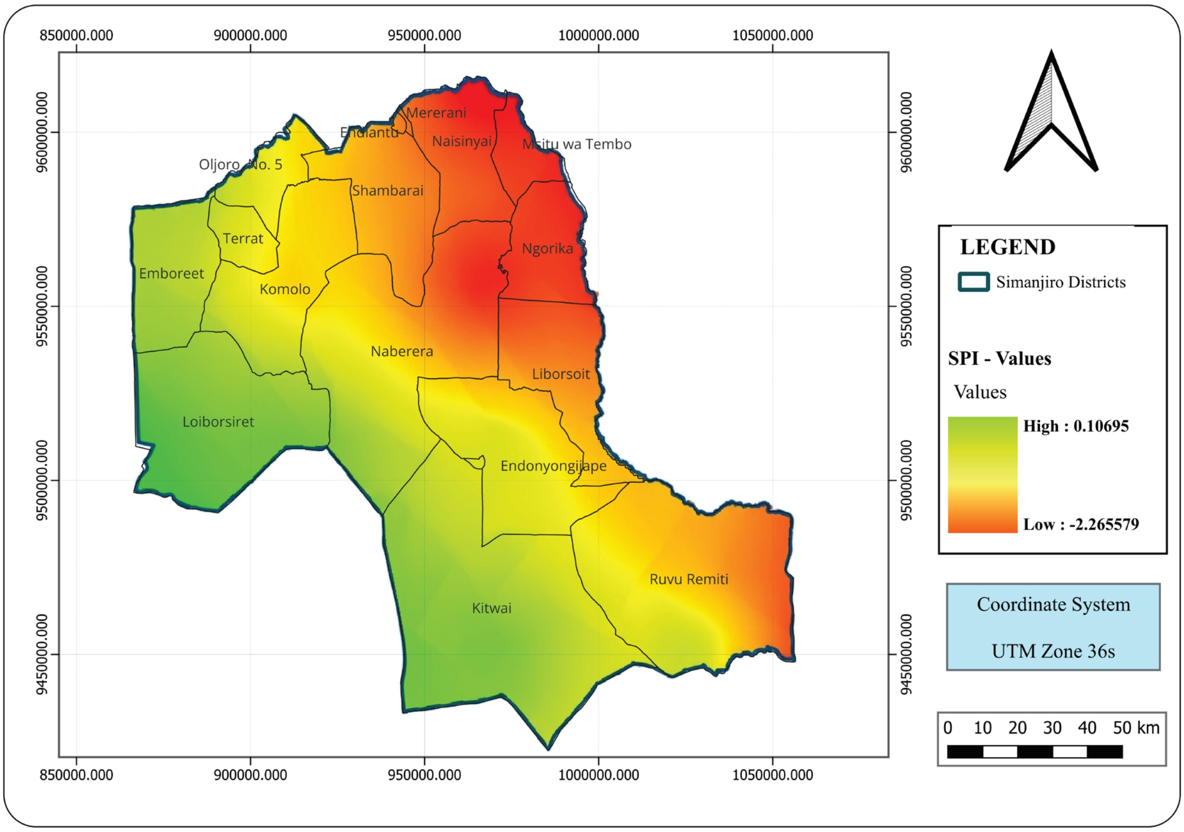


Figure 4: SPI spatial distribution in Simanjiro District

### *3.2.1. Environmental, social, and economic impacts of drought*

The findings revealed that the environment has been affected by drought, which in turn affects the community and ultimately influences the economy of the wards and the district at large (CIWA & SADRI, 2021; Lombe et al., 2024; Musungu et al, 2024). This shows that the effects of drought are interconnected in a chain-like sequence. The direct impacts of drought in the study area were observed on water resources, shrubs, and grassland. Regarding water resources, drought causes a decline in water levels in the Pangani River, which supports a large percentage of the ecosystem components, such as livestock, crops, wild animals, fish, and Birds. During the drought period, most of the fish in the Nyumba ya Mungu dam migrate to other parts of the Pangani Basin, causing a food crisis in the ecosystem. This is because during drought, river and dam temperatures increase by almost 27%, and dissolved oxygen decreases by 17%, which in turn causes competition for oxygen and drives fish species away (Graham et al., 2024). Regarding shrubs and grassland, drought has led to the overgrowth of invasive plant species, pasture drying, and loss of soil fertility. Indirect impacts of drought on the ecosystem involved competition for resources, such that migration becomes a serious issue in the district.

Studies show that drought has been directly and indirectly affecting people's social lives. Where food becomes scarce and expensive, resulting in food insecurity (Gbadegesin et al., 2024; Lombe et al., 2024; Wudil et al., 2022). This is revealed in the study where 90% of the community in Ngorika, Naisinyai, and Liborsoit ward are pastoralists; they highly face the problem of food insecurity since they don't conduct farming, and during this period their economy also declines, meaning that they also don't have enough money to purchase food. This is supported by WEO of Naisinyai Village, who reported that "*We can't even cook food for children anymore at school due to the expensive prices of food during the drought period*".

The district has been affected in various ways, including low crop yields due to rainfall scarcity, trespassing by wild animals on farms in search of water and food, and increased cultivation costs resulting from persistent pests and diseases during drought periods. Interviews with agricultural officers in the respective wards revealed that drought is the major setback hindering agricultural production in both the wards and the district as a whole. Regarding livestock keeping, drought has had severe impacts, including livestock deaths due to inadequate pasture and water, a decline in pastoralists' income, conflicts between pastoralists and farmers, and increased migration in search of grazing land and water. It was reported that drought disasters led to the loss of approximately 92,000 livestock in the district, subsequently pushing many pastoralists into unexpected poverty. This was further exacerbated by a sharp decline in livestock prices, where the price of a bull dropped from TSh 600,000 to TSh 50,000. These findings are consistent with reports from Ethiopia, which indicate that drought leads to significant reductions in livestock holdings and milk production by 8.4% and 25.8%, respectively (Abebe & Alem, 2025).

### *3.2.2.Relationship between SPI temporal distribution and drought impacts*

The SPI and people's perceptions of drought years revealed that the most frequent drought events occurred from 1999 to 2010. The year 2003 experienced the most extreme drought among the years in Simanjiro, with an SPI of -1.8 (5). Furthermore, 2022 was the most recent year to experience a drought. Figure 5 presents the years of extreme drought events and the level of impacts on food shortage, water shortage, and loss of crop production based on people's perception. The allocated number represents the severity of drought, where 4=Extreme, 3=Less extreme, 2=Normal extreme, and 1=No drought effect.

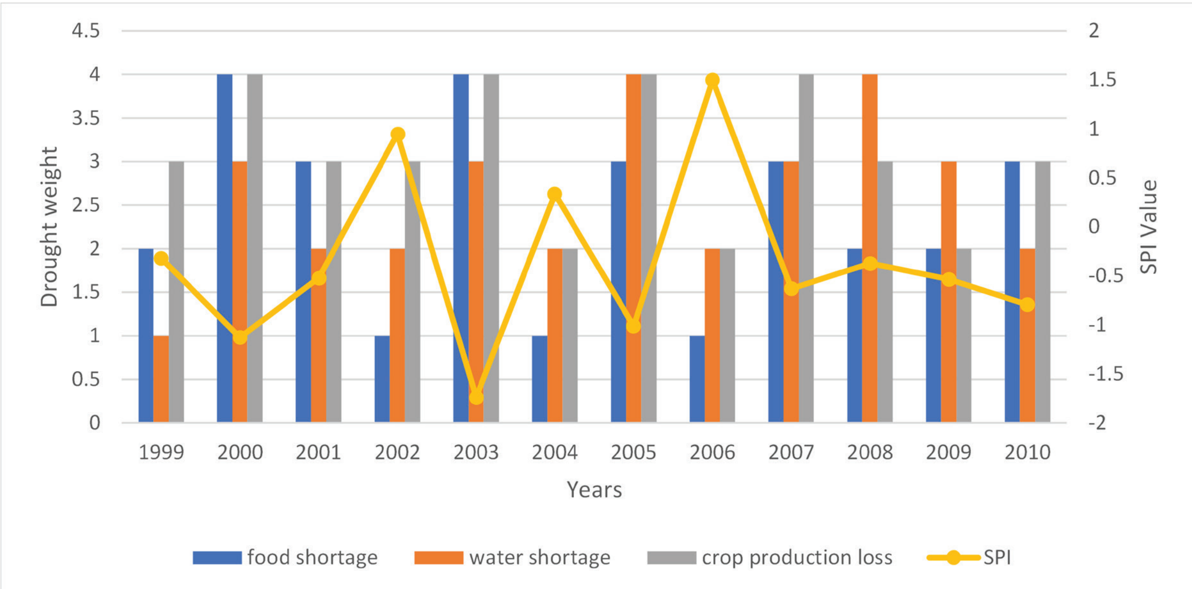


Figure 5: Weight of drought impacts during years of extreme drought from 1983 to 2022

### *3.2.3.Spatial drought risk vulnerability*

Simanjiro District has been experiencing more drought events over the past 40 years than other districts in the region, with SPI values ranging from -0.1 to -1.2. Within Simanjiro District, three (3) wards were selected as a sample space to represent the district as a whole. Through SPI distribution within the district, wards with the lowest SPI values (Ngorika, Naisinyai, and Liborsoit) were selected as the case study for this study. Figure 6 shows the distribution of SPI values within the district.

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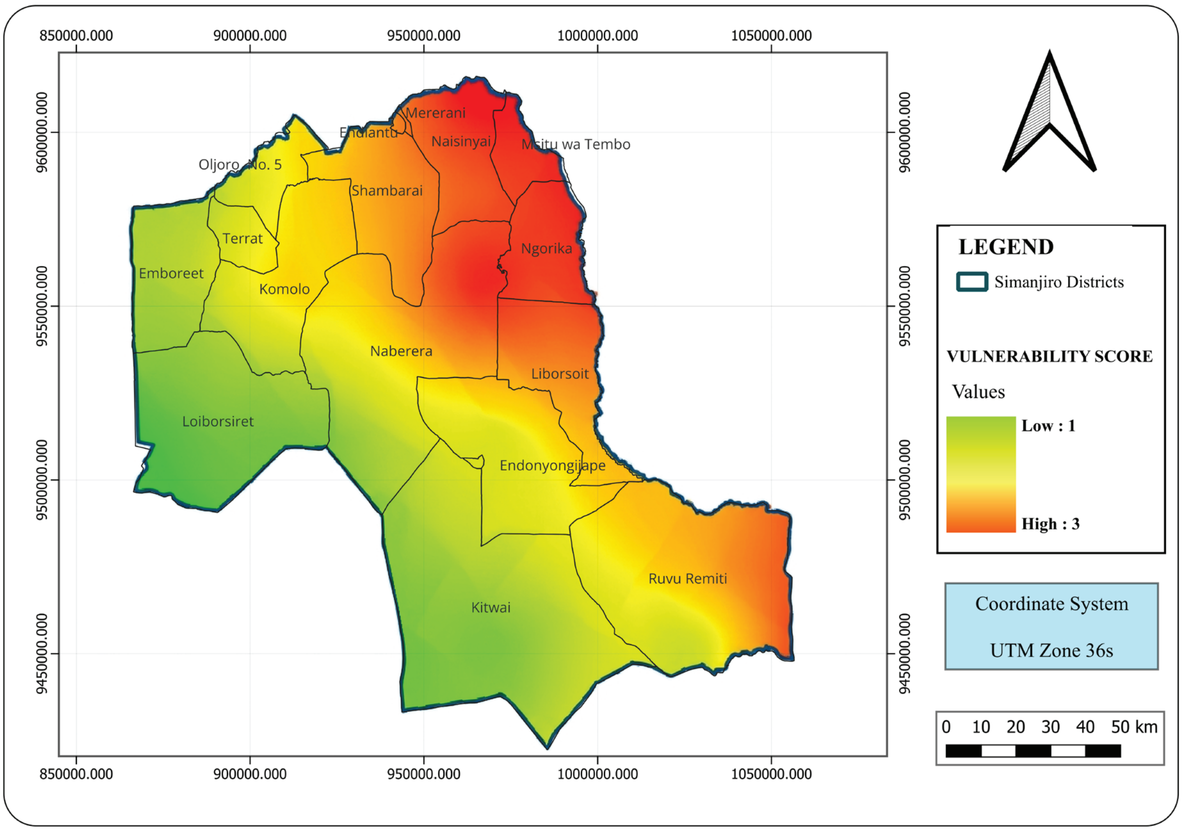


Figure 6: Spatial drought vulnerability distribution in Simanjiro District

Agriculture and livestock keeping are the most vulnerable economic sectors to drought disasters, which in turn affect livelihoods. Despite their importance to the Simanjiro community, there are several reasons that increase susceptibility to drought disasters in each of the mentioned economic sectors. The factors resulting in high susceptibility of the agriculture sector to drought disaster risk include:

1. Over dependency of rain-fed agricultural system;
2. Geographic location (i.e., Naisinyai, Ngorika, and Liborsoit wards are located at lower altitudes;
3. Lack of sufficient technology;
4. Lack of accurate early warning systems;
5. Lack of enough capital.

At the same time, factors that contribute to the high vulnerability of livestock (The pastoralism sector) include an excessive number of livestock and over-dependence on nature. Also, the factors contributing to vulnerability of people's livelihood to drought disaster include:

1. High illiteracy rate;
2. Over-dependence on vulnerable economic sectors for survival;
3. Lack of food reserves.

### *3.2.4. Existing adaptation measures on drought disaster risk*

There are several adaptation measures that have been established in Simanjiro in response to drought-related disaster risk. These adaptation measures have been established to reduce the magnitude of impacts; for example, in the agricultural sector, hybrid crop seeds have been used, education has been provided, and irrigation schemes have been implemented. In livestock keeping, there has been pasture management through plot reservation for grazing during drought disasters, and cattle troughs (a total of six were constructed in different villages in Naisinyai ward to provide water for livestock). Regarding the livelihood sector, adaptation measures include installing a water distribution point (i.e., the main water source is the Pangani Basin and the Nyumba ya Mungu dam). In the environmental sector, the adaptation measure used was afforestation.

## 4. Conclusion and Recommendation

This study assessed spatial community vulnerability to drought in Simanjiro District using climate data and socio-economic analysis. The findings indicate that drought is a frequent hazard, occurring in 24 out of 40 years, with severe events in 2003 and 2022 causing major livestock losses and livelihood disruptions. Declining rainfall and rising temperatures further intensify drought conditions, increasing stress on ecosystems and pastoral systems. A mismatch was observed between SPI-based drought detection and community perceptions, with local populations primarily recognizing high-impact drought events. This highlights the need to integrate scientific analysis with local knowledge in drought assessment. Agriculture and pastoralism were identified as the most vulnerable sectors due to overdependence on rainfall, high livestock numbers, and limited adaptive capacity. Although some coping strategies exist, they remain inadequate. Strengthening early warning systems, improving water and irrigation infrastructure, and promoting livelihood diversification are essential to enhance resilience to drought.

## References:

Abebe, M. B., & Alem, Y. (2025). Drought, livestock holding and milk production: A difference-in-differences analysis. *European Review of Agricultural Economics*, *52*(2), 240–272. https://doi.org/10.1093/erae/jbaf014

Abera, T. A., Heiskanen, J., Maeda, E. E., Muhammed, M. A., Bhandari, N., Vakkari, V., Hailu, B. T., Petri, Hemp, A., Zyl, van, & Zeuss, D. (2024). Deforestation amplifies climate change effects on warming and cloud level rise in African montane forests. *Nature Communications*, *15*(1). https://doi.org/10.1038/s41467-024-51324-7

Bureau for Agricultural Consultancy and Advisory Services (BACAS), & Sokoine University of Agriculture (SUA). (2019). Feed the Future Innovation Lab for Sustainable Intensification. *ILSSI — Tanzania Research Design (Feed the Future). Texas A&M University*.

Cooperation in International Waters in Africa (CIWA) & Sustainable Development in Rural Areas (SADRI). (2021). *Drought Resilience Profiles | Tanzania*. https://www.ciwaprogram.org/wp-content/uploads/SADRI_Drought_Resilience_Profile_Tanzania.pdf

Cosmas, E., Ngowi, E., Ng'winamila, K., & Muhanga, M. (2022). Factors influencing transient poverty among Maasai pastoralists households in semi-arid areas of Simanjiro district, Tanzania. *The Sub-Saharan Journal of Social Sciences and Humanities (SSJSSH)*. https://www.suaire.sua.ac.tz/bitstreams/a8a28ec5-9441-4592-8f8b-82d58678ed53/download

Gbadegesin, T., Andrée, B. P. J., & Braimoh, A. (2024). *Climate Shocks and Their Effects on Food Security, Prices, and Agricultural Wages in Afghanistan*. Washington, DC: World Bank. https://doi.org/10.1596/1813-9450-10999

Graham, D. J., Bierkens, M. F. P., & T.H, M. (2024). Impacts of droughts and heatwaves on river water quality worldwide. *Journal of Hydrology*, *629*, 130590–130590. https://doi.org/10.1016/j.jhydrol.2023.130590

Jackson, S., Claude, G. M., & Godfrey, F. K. (2018). The impacts of climate change and variability on crop farming systems in Semi-Arid Central Tanzania: The case of Manyoni District in Singida Region. *African Journal of Environmental Science and Technology*, *12*(9), 323–334. https://doi.org/10.5897/ajest2018.2481

http://dx.doi.org/10.21622/MACI.2026.03.1.2046

John, O. (2022). Evaluation of Rainfall Extreme Characteristics in Dodoma Urban, A Central Part of Tanzania. *International Journal of Environment and Geoinformatics*, *9*(3), 166–177. https://doi.org/10.30897/ijegeo.1000458

Juma, M. (2022, March 28). *Drought kills 92,000 livestock in Simanjiro*. The Citizen. https://www.thecitizen.co.tz/tanzania/news/national/drought-kills-92-000-livestock-in-simanjiro-3763406

Kew, S. F., Philip, S. Y., Hauser, M., Hobbins, M., Wanders, N., van Oldenborgh, G. J., van der Wiel, K., Veldkamp, T. I. E., Kimutai, J., Funk, C., & Otto, F. E. L. (2021). Impact of precipitation and increasing temperatures on drought trends in eastern Africa. *Earth System Dynamics*, *12*(1), 17–35. https://doi.org/10.5194/esd-12-17-2021

Kunte, G., & Bhat, V. (2024). Deforestation, Climate Change and the Sustainability of Agriculture: A Review. *Journal of Resources and Ecology*, *15*(1), 140–150. https://doi.org/10.5814/j.issn.1674-764x.2024.01.012

Lombe, P., Carvalho, E., & Rosa-Santos, P. (2024). Drought Dynamics in Sub-Saharan Africa: Impacts and Adaptation Strategies. *Sustainability*, *16*(22), 9902. https://doi.org/10.3390/su16229902

Mtwanga, J., Haule, T., & Fundisha, E. (2022). Sustainability of Adaptation Strategies in Rainfed Agriculture to Climate Change and Variability in Nyang'oro Ward in Iringa District, Tanzania. *JOURNAL of the GEOGRAPHICAL ASSOCIATION of TANZANIA*, *42*(1), 129–144. https://doi.org/10.56279/jgat.v42i1.221

Musungu, A. L., Kubik, Z., & Matin Qaim. (2024). Drought shocks and labour reallocation in rural Africa: evidence from Ethiopia. *European Review of Agricultural Economics*, *51*(4), 1045–1068. https://doi.org/10.1093/erae/jbae020

Nkedianye, D. K., Ogutu, J. O., Said, M. Y., Kifugo, S. C., de Leeuw, J., Van Gardingen, P., & Reid, R. S. (2020). Comparative social demography, livelihood diversification and land tenure among the Maasai of Kenya and Tanzania. *Pastoralism*, *10*(1). https://doi.org/10.1186/s13570-020-00165-2

Pal, S. C., Chatterjee, U., Chakrabortty, R., Roy, P., Chowdhuri, I., Saha, A., Towfiqul Islam, A. R. Md., Alam, E., & Islam, M. K. (2023). Anthropogenic drivers induced desertification under changing climate: Issues, policy interventions, and the way forward. *Progress in Disaster Science*, *20*, 100303. https://doi.org/10.1016/j.pdisas.2023.100303

Straitony, D., Kiunsi, R. B., & Nicholaus Mwageni. (2026). Dynamics of Meteorological Drought and Coping Strategies: A Case of Misima Ward in Handeni District, Tanzania: Dynamics of Meteorological Drought and Coping Strategies. *Journal of Business, Socioeconomics and Development*, *1*(1), 43–61. https://doi.org/10.1007/978-3030-22759-3_183-1

Thalheimer, L., Choquette-Levy, N., & Garip, F. (2022). Compound impacts from droughts and structural vulnerability on human mobility. *IScience*, *25*(12), 105491. https://doi.org/10.1016/j.isci.2022.105491

United Nations Convention to Combat Desertification. (2022). *Drought in Numbers DROUGHT IN NUMBERS 2022 -restoration for readiness and resilience*. https://www.unccd.int/sites/default/files/2022-05/Drought%20in%20Numbers.pdf

United Nations Office for Disaster Risk Reduction UNDRR. (2021). *Global Assessment Report GAR Special Report on Drought 2021*. Www.undrr.org. https://www.undrr.org/publication/gar-special-report-drought-2021

Wens, M. L. K., Mwangi, M. N., van Loon, A. F., & Aerts, J. C. J. H. (2021). Complexities of drought adaptive behaviour: Linking theory to data on smallholder farmer adaptation decisions. *International Journal of Disaster Risk Reduction*, *63*, 102435. https://doi.org/10.1016/j.ijdrr.2021.102435

World Bank Group. (2023, November 15). *Going with a better flow: Improving policy and delivering results at scale in global water*. World Bank; World Bank Group. https://www.worldbank.org/en/news/feature/2023/11/16/going-with-a-better-flow-improving-policy-and-delivering-results-at-scale-in-global-water

Wudil, A. H., Usman, M., Rosak-Szyrocka, J., Pilař, L., & Boye, M. (2022). Reversing Years for Global Food Security: A Review of the Food Security Situation in Sub-Saharan Africa (SSA). *International Journal of Environmental Research and Public Health*, *19*(22), 14836. https://doi.org/10.3390/ijerph192214836

WWF. (2019). *Worsening drought risk impacts 55 million people every year, says WWF report*. Panda.org. https://wwf.panda.org/wwf_news/?352050%2FWorsening-drought-risk-impacts-55-million-people-every-year-says-WWF-report=

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