ALBERTO DOMINGOS MACAMO

POTENTIAL PRODUCTIVITY OF MAIZE IN MOZAMBIQUE: MODELING OF CURRENT AND FUTURE SCENARIOS

Dissertation submitted to the Applied Meteorology Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Magister Scientiae*.

Adviser: Jackson Martins Rodrigues

Co-adviser: Flávio Barbosa Justino

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APPROVED: November 08, 2021.

Assent:

Alberto Domingos Macamo

Alberto Domingos Macamo
Author

Jackson Martins Rodrigues
Adviser

To my brother Leonel Domingos Macamo (in memoriam)
My wife Telma Gento Morais,
My daughters: Lucrênciay Alberto Macamo Domingos,
Adaeze Alberto Macamo Domingos and
Victória Alberto Domingos Macamo.

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God for his presence at all times in my life.

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o my brothers Leonel (in memoriam), Iolanda, Ivanilda, Cecilia, Junior, Chico, Gonsalves, and Manucha, who have always been my audience and who have always pushed me to succeed.

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To Graça for her willingness, diligence, and help.

Here are my feelings of admiration.

“Education is the most powerful weapon
you can use to change the world”.

(Nelson Mandela)

ABSTRACT

MACAMO**,** Alberto Domingos, M.Sc., Universidade Federal de Viçosa, November, 2021. **Potential Productivity of Maize in Mozambique: Modelling of Current and Future Scenarios**. Adviser: Jackson Martins Rodrigues. Co-adviser: Flávio Barbosa Justino.

Food security is seriously compromised due to climate change. Of the various existing methods of adapting to the effects of climate change on agricultural productivity, it involves knowledge of the productive potential, the possible impacts of climate change, as well as the application of technology to maximize yields. The main objective of this study was to model a maize crop productivity potential in Mozambique for the current scenario (1981–2020) and future scenarios (mean temperature increase scenario). This study used data from the ERA5 model in representation of observed data to estimate maize crop yield potential over the period 1981–2020 and in RCP4.5 and 8.5 scenarios. The results show that a reanalysis of ERA5 provides the closest maximum and minimum values to the observed data. The validation results of the maximum and minimum temperature data from the ERA5 model showed values closer to the observed data at all points. The results of the potential yield of the maize crop, simulated by the model, are close to the research field data provided by IIAM. The values of the average estimated potential productivity was 4.88 tons/ha and the average productivity of the IIAM research field was 4.71 tons/ha, thus demonstrating that the model simulates approximately the field data of search. The real productivity in the period under analysis is 0.72 tons/ha, corresponding to 85% lower than the potential productivity estimated by the model. In scenarios of RCP 4.5 and 8.5, it may cause a reduction of more than 33% in the potential yield of the maize crop. With the application of the technological effect in both scenarios, the potential productivity will be reduced, increased or no loss.

Keywords: Climate Change. Agricultural Modelling. Maize. ERA5. CMIP5

RESUMO

MACAMO, Alberto Domingos, M.Sc., Universidade Federal de Viçosa, novembro de 2021. **Produtividade Potencial de Milho em Moçambique: Modelagem de Cenários atual e Futuro**. Orientador: Jackson Martins Rodrigues. Coorientador: Flávio Barbosa Justino.

A segurança alimentar está seriamente comprometida devido às mudanças climáticas. Dos vários métodos existentes de adaptação aos efeitos das alterações climáticas na produtividade agrícola, envolve o conhecimento do potencial produtivo, os possíveis impactos das alterações climáticas, bem como a aplicação de tecnologia para maximizar os rendimentos. O objetivo principal deste estudo foi modelar um potencial de produtividade da cultura de milho em Moçambique para cenário atual (1981–2020) e cenários futuros (cenário de aumento da temperatura média). Este estudo usou dados do modelo ERA5 em representação dos dados observados para estimar o potencial de produtividade da cultura de milho no período de 1981–2020 e em cenários RCP4.5 e 8.5. Os resultados mostram que uma reanálise da ERA5 oferece os valores máximos e mínimos mais próximos dos dados observados. Os resultados de validação dos dados das temperaturas máximas e mínimas do modelo ERA5 mostraram valores mais próximos dos dados observados em todos os pontos. Os resultados da produtividade potencial da cultura de milho, simulados pelo modelo são próximos aos dados de campos de pesquisa fornecidos pelo IIAM. Os valores da média da produtividade potencial estimada foi de 4,88 t/ha e da média da produtividade do campo de pesquisa do IIAM foi de 4,71 t/ha, demonstrando assim que o modelo simula de forma aproximada os dados de campo de pesquisa. A produtividade real no período em análise é de 0,72 t/ha correspondendo 85% inferior à produtividade potencial estimada pelo modelo. Em cenário de RCP 4.5 e 8.5 poderá ocasionar uma redução de mais de 33% da produtividade potencial da cultura de milho. Com a aplicação do efeito tecnológico em ambos os cenários, a produtividade potencial terá redução, incremento ou nenhuma perda.

Palavra-Chave: Mudanças Climáticas. Modelagem Agrícola. Milho. ERA5. CMIP5

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LIST OF ACRONYMS AND ABBREVIATIONS

ECMWF	European Medium-Term Forecasts Center
ENSO	El Niño-Southern Oscillation
ERA5	Fifth Generation ECMWF atmospheric reanalysis
GDP	Gross Domestic Product
IIAM	Agricultural Research Institute of Mozambique
INAM	National Meteorology Institute
IPCC	Intergovernmental Panel on Climate Change
RCP	Representative Concentration Trajectories

SUMMARY

GENERAL INTRODUCTION

Agricultural production is directly linked to the climate and, therefore, adaptation to climate change has essential weight. There is evidence and studies worldwide on the impact of climate change on yield from culture (Challinor et al., 2014).

The African Continent is particularly vulnerable and designed to experience adverse effects of climate change, thus having several economies of various countries at risk due dependence mainly of natural resources and subsistence agriculture, (Asafu-adjaye, 2014).

The main basis of the Mozambican economy is agriculture practiced by 87.8% of the population living in rural areas. Maize is grown primarily by small farmers. Many studies have shown losses of maize culture in climate change scenarios that could lead to hunger in this country (Jones; Thornton, 2003; IAI, 2020).

Few empirical studies were made to understand the real impact of climate change on maize culture in Mozambique.

Objectives

The general objective of this study is to model the potential productivity of the maize crop in the current scenario and scenarios of average temperature increase in Mozambique.

However, this dissertation consists of an article separated by introduction, objectives, literature review, methodology, results, conclusion and references.

The dissertation using reanalysis data aims to model the potential productivity of the maize crop in Mozambique in the period 1981-2020 and in scenarios RCP4.5 e 8.5, and application of the technological effect.

POTENTIAL PRODUCTIVITY OF MAIZE IN MOZAMBIQUE: MODELLING OF CURRENT AND FUTURE SCENARIOS

Abstract

Climate change significantly compromises food security around the world, especially for small farmers in poor countries like Mozambique. The objective of this study is to estimate the potential productivity of the maize crop in the period 1981-2020 and in scenarios RCP4.5 and 8.5, as well as the application of the technological effect. To represent the observed data, the validation of reanalysis data extracted from the ERA5 model was performed. The statistical tests showed the reproduction of the reality observed in the maximum and minimum temperatures. The potential productivity values, simulated by the model, are 85% higher than the actual productivity data and close to the values of the IIAM investigation fields. For the modelling of potential yield in CMIP5 RCP4.5 and 8.5 scenarios, the results show a reduction in the potential yield of the maize crop above 33%, and with the application of the technology effect, the results show reduction, increase or no loss of the potential productivity of the maize crop for the years 2050 and 2080.

Keywords: Climate Change, Agricultural Modelling, Maize, ERA5

POTENTIAL PRODUCTIVITY OF MAIZE IN MOZAMBIQUE: MODELLING OF CURRENT AND FUTURE SCENARIOS

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1.1. INTRODUCTION

Climate change is a direct result of human action due to extensive fossil fuel burning and consequent carbon emissions into the atmosphere (Masson-Delmotte et al., 2018). The imbalance in the atmospheric conditions caused by climate change extends from waves of cold and/or heat to severe or dry storms (Rummukainen, 2012; Herring et al., 2019). Although the large world polluters are developed countries, the consequences are global, affecting different rich and poor countries (Mendelsohn; Dinar; Williams, 2006; Letta; Tol, 2019). The developing countries, in turn, have the aggravating circumstance of having precarious infrastructures to address increasingly frequent and intense extreme climatic events (Barbier; Hochard, 2018).

Many of the world's poorest countries are concentrated on the African continent. The population and economy of Africa depend heavily on agriculture without irrigation, which employs between 70 to 80% of the population and contributes an average of 30% of gross domestic product (GDP) and at least 40% of exports (Oluwatayo; Ojo, 2016). Poverty in the countryside corresponds to 90% of total poverty in the region, and approximately 80% of the poor still depend on agriculture or agricultural work for their subsistence (Mabaya; Omanga; Devries, 2013).

Future climatic scenarios point to aggravation of these adverse conditions with increasingly high temperatures with rainfall events or their equally severe absence directly impacting agricultural production (Müller et al., 2011; Kendon et al., 2019). The consequences of these phenomena are already being felt when droughts attributed to climate change cause losses of more than 20% in maize production in some Southern African countries (Malawi, Malawi, Zambia, and Zimbabwe), mainly small farmers (Nhamo et al., 2019). In these countries, based on the area, yield levels and source of feeding of families, maize culture stands out as a primary culture (Tesfaye et al., 2016).

Mozambique is a poor country that has an agriculture-based development base that has been suffering from climate instability. Although it has shown growth in gross domestic product (GDP) in recent years (Ferrão et al., 2018), poverty has further prevailed in the country, mainly in rural regions (Sitoe, 2014; Arndt et al., 2018). The production of the Mozambican primary sector (fishing, mining and agriculture) is the most important for the country's economy (Ferrão et al., 2018). Among these, agriculture stands out, having grown at a rate of 10.3% between 2000 and 2014, corresponding to almost 25% of the country's GDP (Deloitte, 2016).

Maize is Mozambique's main agricultural culture, cultivated by 80% of populations in rural areas (Sitoe, 2014; IAI, 2020). The largest production is concentrated in the center and northern parts of the country, where more than 3 million tons were produced between 2014 to 2018 (INE, 2018). Maize stands out for its economic importance and for food security, especially for the poorest families that depend on agriculture for subsistence. Therefore, increasing production and productivity is key to reducing poverty, hunger, and balancing the local economy (Mango et al., 2018).

The climate changes in progress have been affecting all regions of Mozambique significantly, intensifying the disasters associated with extreme climate events (Uamusse; Tussupova; Persson, 2020). As a consequence, increasing numbers of deaths, wounded and homeless, in addition to large losses of agricultural crops (Manjoro; Ferreira; Rosse, 2019) are recorded. Table 1 mentions some significant events that occurred between 2000 to 2019.

For future climate change scenarios, the situation tends to become even more severe. Studies such as Jones et al. (2003) point to a reduction of greater than 200 kg/ha in maize production by 2055. Another study is from Brito and Homan (2012), with projections for 2065 indicating a fall in maize production in the order of 11.0% compared to the study year, and the highest loss will be recorded in the center of the country with a reduction greater than 350 kg/ha.

Climate change will be mostly responsible for the fall in maize production, with an aggravating increase in the event of extreme events (Harrison et al., 2011; Manuel et al., 2020).

Cyclonic Events	**Year**	**Region**	**Human's losses**	**Agricultural production loss**	**Citation**
Eline e Hudah	2000	Center and South	+800	12%	(World Bank, 2000)
Dera	2001	Center	100	79.000 ha	(Matyas, 2015)
Delfina e Japhet	2003	North	47	+ 237.000 ha	(Matyas, 2015)
Favio	2007	South	10	78.000 ha	(Matyas, 2015)
Jokwe	2008	North	16	100.000 ha	(Matyas, 2015)
Funso	2012	Center	15	42.000 ha	(Zermoglio et al., 2018))
Dineo	2017	South	9	29.173 ha	(Meyiwa, 2019)
Idai e Kenneth	2019	Center e North	+600	67%	(Manjoro; Ferreira; Rosse, 2019)

Table 1. Some significant events occurred between the years 2000 to 2019

According to evidence of an increase in the global average air temperature at regional and continental scales, the IPCC (Intergovernmental Panel on Climate Change) in phase five of its project considered four new scenarios, RCP (Representative Concentration Trajectories) where RCP2. 6 (mitigation scenario, leading to a very low forcing level), RCP4.5 and RCP6.0 (two stabilization scenarios) and RCP8.5 (scenario with very high greenhouse gas derivatives) (IPCC, 2014; Junior et al., 2018). As a result, the advancement of technology development for application to the crucial sector that is agriculture should be seen by many countries as the most obvious solution. Thus, the advancement of the development of technologies applied to the agricultural sector (use of improved seeds, chemical fertilizers, pesticides, and others) is a fundamental cause of increased agricultural productivity worldwide (Ewert et al., 2005; Zhai et al., 2021). In the context of the use of improved technologies in the agricultural sector in Mozambique, the average percentage is 7.5% (use of watering systems, 9.1%, chemical fertilizers, 7.8%, pesticides, 5.5%, herbicides, 1.8% and manure, 8.8%) (IAI, 2020).

In this way, in the face of an imminent problem of food shortages in Mozambique caused by changes in atmospheric conditions, it has become important for studies that seek to understand how agricultural production will respond to these changes. There is a scarcity of studies on how future climate change will influence maize production and productivity in Mozambique in average temperature increase scenarios.

The present work presents the estimation of the potential productivity of maize culture in current and future scenarios, as well as the effect of technological advancement. For representation of the observed data, ERA5 model data was validated with data observed from the 10 surface weather stations in the study area. For maize productivity modelling for future conditions and future scenarios, the work model of Costa et al., (2009) was used.

In this way, one of the expected contributions of this work, in addition to adding a recent study, is that the study model is used as a valuable tool for planning in the agricultural sector and incrementing public policies aimed at greater reach of the productivity levels of the crop in the maize contributing to the country's economic growth.

1.2.MATERIALS AND METHODS

1.2.1. Study Area

Mozambique is located in the southern hemisphere between the parallels 10º 27 'and 26° 52' south and the meridians 30º 12 'and 40º 51' East on the southeast coast of the African continent, opposite the island of Madagascar, separating from it by the channel of Mozambique (Charles, 2012). The country is bounded on the north by Tanzania, on the northwest by Malawi and Zambia, on the west by Zimbabwe and South Africa, on the south by Swaziland, and on the east by the Indian Ocean (Charles, 2012).

Mozambique has a surface of 799,380 km^2. Of this area, 786.380 km^2 corresponds to solid ground and 13,000 km^2 is occupied by inland waters (rivers, lakes, lagoons, dams, among others) and is economically divided into three large regions (North, Center, and South) (Muchangos, 1999; Amade, 2019).

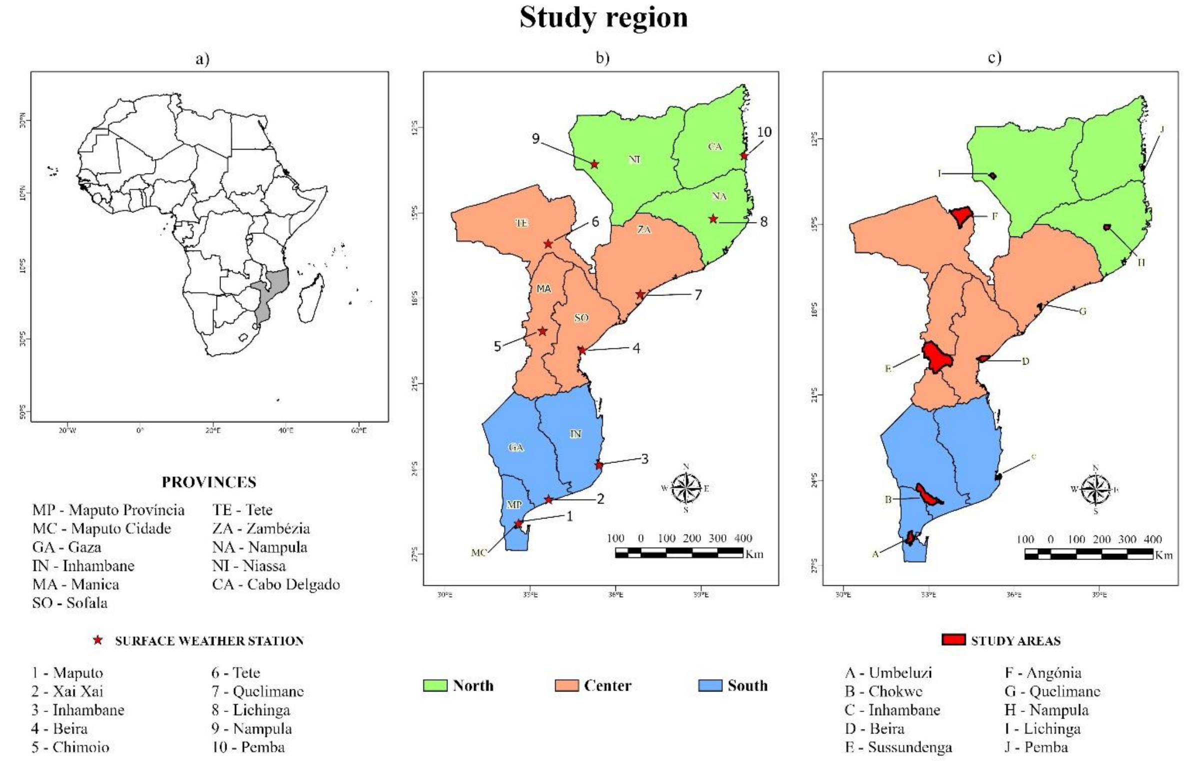


Figure 1. Identification of regions, Provinces, weather stations and localization of study area.

The climate in general is wet tropical with two distinct stations: drought (or winter) and rainy (or summer). The average annual precipitation varies between 300 and 1500 mm (Figure 2) and occurs mostly during the summer, between the months of October and April, with the month of January being the rainier (Manhique, 2008). Temperatures present regional variations due to the interference of factors such as latitude, continentality, and relief itself. In general, temperature values tend to increase towards lower latitudes (Hoguane, 2007). Annual average temperatures are distributed as follows: From 18 to 20 °C (Figure 2) in mountainous regions; from 22 to 24 °C (Figure 2) in the central and plateau regions of the North and Center, as well as in the east and west areas of the Southern Provinces; and from 24 to 26 °C (Figure 2) throughout the eastern portion of the North and Central regions and within the southern regions of the country (Micoa, 2007).

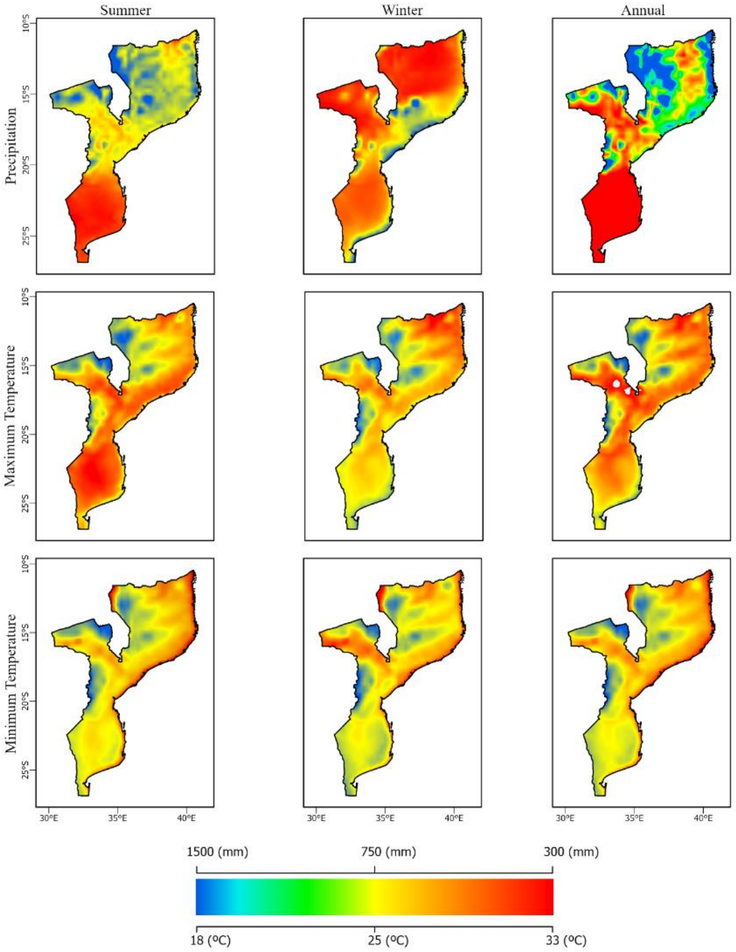


Figure 2. Seasonality (summer and winter) and the annual distribution of maximum and minimum temperatures and precipitation in Mozambique between 1990-2020. For precipitation, the annual value corresponds to the total annual mean, while the other variables are annual averages (Adapted by the author using data from ERA5).

1.2.2. Datasets

For the present study, the following data were used:

- Daily radiation data, maximum and minimum temperature from model ERA5 of 1980-2020;
- Daily observed data of maximum and minimum temperatures of 1980-2020 from 10 surface weather stations (Figure 1b) obtained at INAM (National Meteorology Institute) of Mozambique;
- The IIAM (Agricultural Research Institute of Mozambique) research field maize yield data.

1.2.3. ERA5 Models

Due to gaps in the observed data that do not allow continuous and complete temporal series analysis, the ERA5 model dataset (0,25° X 0,25° resolution) was used.

The project was developed by the European Medium-Term Forecasts Center (ECMWF) and brings together reanalysis data from a large number of climate remarks around the world. Meteorological Reanalysis can be defined as a set of grid data. These are achieved by combining acquisitions of data measured by meteorological institutes with physical models of global circulation and forecasts. The result of this interaction is a new set of high-resolution data that can describe in detail the climate of different weather variables, atmosphere, terrestrial surface and oceans (Hersbach et al., 2020).

The radiation data, maximum and minimum temperature were extracted at the grid point of the stations of Figure 1b. These stations were selected because they contain the largest amounts of data collected for the period under analysis.

1.2.4. Evaluation metrics

All statistical procedures were conducted on R platform (R Core Team, 2021) and the statistical parameters chosen are from the Hydrogof package (Zambrano-Bigiarini, 2020) which are:

The Mean Absolute Error (MAE) (Table 2 - Equation 1) measuring the magnitude of forecasting errors disregarding your direction and according to Fox, (1981) in the analysis of the simulated data capacity in reproduce reality, the calculation of the MAE is stronger and concise.

The Root Mean Square Error (RMSE) (Table 2 – Equation 2) is an absolute measure of the general error in estimates in relation to the observed values that can take positive and zero value to indicate the absence of error (Wang et al., 2011). The $RMSE \geq MAE$ and together diagnose the variation of errors in forecasts.

Assuming values ± 1, where +1 indicates a perfect positive linear correlation the Pearson correlation coefficient (r) (Table 2 - Equation 3) measures the linear relationship between two variables (Kirkwood; Sterne, 2003). For ($r \leq 0.39$) means weak positive correlations, ($r \geq 0.40$ to

0.69) means moderate positive correlations, (r≥0.70 to 0.89) means strong positive correlations and r≥0.9 means very high positive correlations (Taylor, 1990).

Willmott's concordance index (d) (Table 2 - Equation 14) with values varying between 0 (no concordance) and 1 (perfect concordance), is a standardized measure of the degree of error of the simulated data (Willmott, 1981). In the values of the Willmott Agreement Index, between 0.61 to 0.65 is average performance, 0.66 to 0.75 is good performance, 0.76 to 0.85 is very good performance and greater than 0.85 is excellent performance (Willmott et al., 1985; Martins, 2012).

Percent bias (pbias) (Table 2 - Equation 5) where zero value is ideal in indication of the accuracy of the simulated data in relation to the data observed by measuring the average tendency of predicted values are smaller or larger in relation to those observed, thereby indicating overestimation (values positive) and underestimation (negative values) (Gupta; Sorooshian; Yapo, 1999).

Table 2. Statistical parameters used in this study

	Statistical parameters	Formula
Equation 1	Mean Absolute Error	$MAE = \frac{1}{N}\sum_{i=1}^{N} \lvert S_i - O_i \rvert$
Equation 2	Root Mean Square Error	$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N} (S_i - O_i)^2}$
Equation 3	Pearson correlation coefficient	$r = \frac{\sum(S_i - \overline{S})(O_i - \overline{O})}{\sqrt{\sum(S_i - \overline{S})^2 \sum(O_i - \overline{O})^2}}$
Equation 4	Willmott's concordance indexes	$d = 1 - \frac{\sum_{i=1}^{N}(O_i - S_i)^2}{\sum_{i=1}^{N}(\lvert S_i - \overline{O}\rvert + \lvert O_i - \overline{O}\rvert)^2}$
Equation 5	Percent bias	$pbias = 100\frac{\sum_{i=1}^{N}(S_i - O_i)}{\sum_{i=1}^{N} O_i}$

1.2.5. Productivity Model

In the simulation of potential productivity solar radiation, maximum and minimum temperatures were used as input data. The used productivity model uses three sets of equations (Costa et al., 2009):

1. The first group includes meteorological variables (for example, radiation, temperature);

2. The second set of equations deals with the parametrizations of harvest physiology (eg. dry matter, photosynthesis);

3. A module to reproduce the carbon balance is also included.

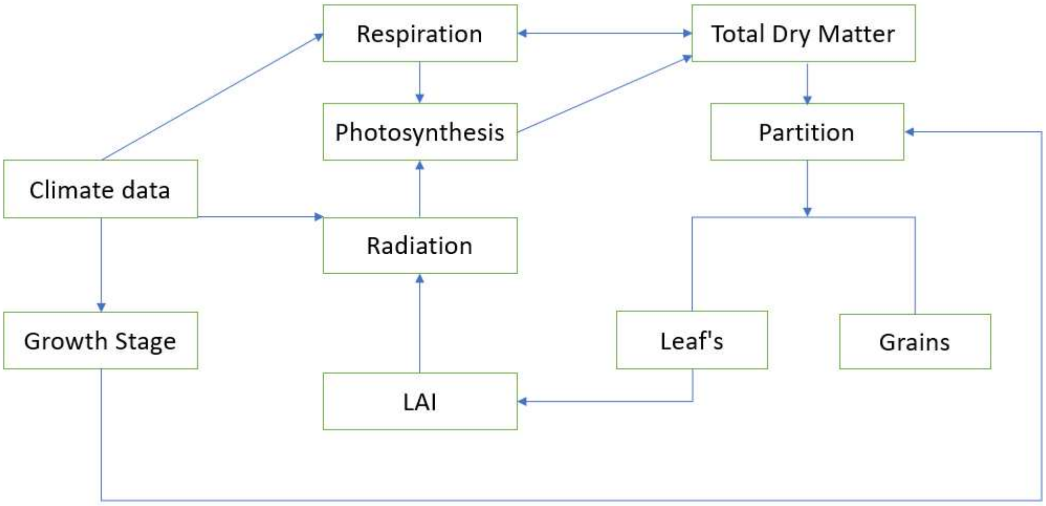


Figure 3. Model configuration, where LAI is leaf area index (source: Costa et al., 2009)

1.2.6. Future projections and effect of technological advancement

1.2.6.1.Future projections

In the simulations, climatic conditions were used, projected by the general circulation model of the atmosphere CSIRO-MK3.6.0, developed at the Commonwealth Scientific and Industrial Research Organization of Australia, for the years 2050 and 2080, considering the scenario RCP4.5 and 8.5. Then, how simulated yields for the years 2050 and 2080 were compared with the potential yield for the base year. The CSIRO-MK3.6.0 model presented better performance in simulating temperature data of the 28 CMIP5 models tested for the African continent (Zebaze et al., 2019).

The two scenarios assumed for this study are from the fifth IPCC assessment report, the optimistic scenario (RCP4.5) with the total radiative forcing is stabilized shortly after 2100 not exceeding the 4.5 W/m2 radiation level and the pessimistic scenario (RCP8.5) which is characterized by increasing greenhouse gas emissions over time (IPCC, 2014; Weber et al., 2020; Mavume et al., 2021).

1.2.6.2.Effect of technological advancement

Technological advances are directly linked to the increased productivity of agricultural crops around the world. According to Ewert et. al. (2005), measures that result in an increase in income are efficient crop management (better machinery, herbicides and pesticides, etc., and the notion of agronomy techniques on the part of farmers) and improvement (development of higher yielding cultural varieties) constitute technological development.

The formula for calculating the technological effect on potential productivity is (Costa et al., 2009):

$$PP_T = P_g + \int_{to}^{t} P_g * f_{T,PPT}$$

Where PP_T is a technological effect on potential productivity:

Pg it is genetic progress for the maize crop. According to Masuka (2017), genetic progress for maize cultivation (1.41% per year);

$f_{T,PPT}$ is a parameter representing the increase in income in potential productivity for maize culture from 0.6 to 2050 and 0.4 to 2080 (Ewert et al., 2005).

In this study, the application of the technology based on the formula will be applied to two climate change scenarios for the years 2050 and 2080.

1.3.RESULTS AND DISCUSSION

1.3.1. Performance of datasets

Figure 4 shows the amount of missing data in the observed data (MD) and the statistical comparisons of the maximum and minimum temperature data extracted from the ERA5 model with the observed data provided by INAM.

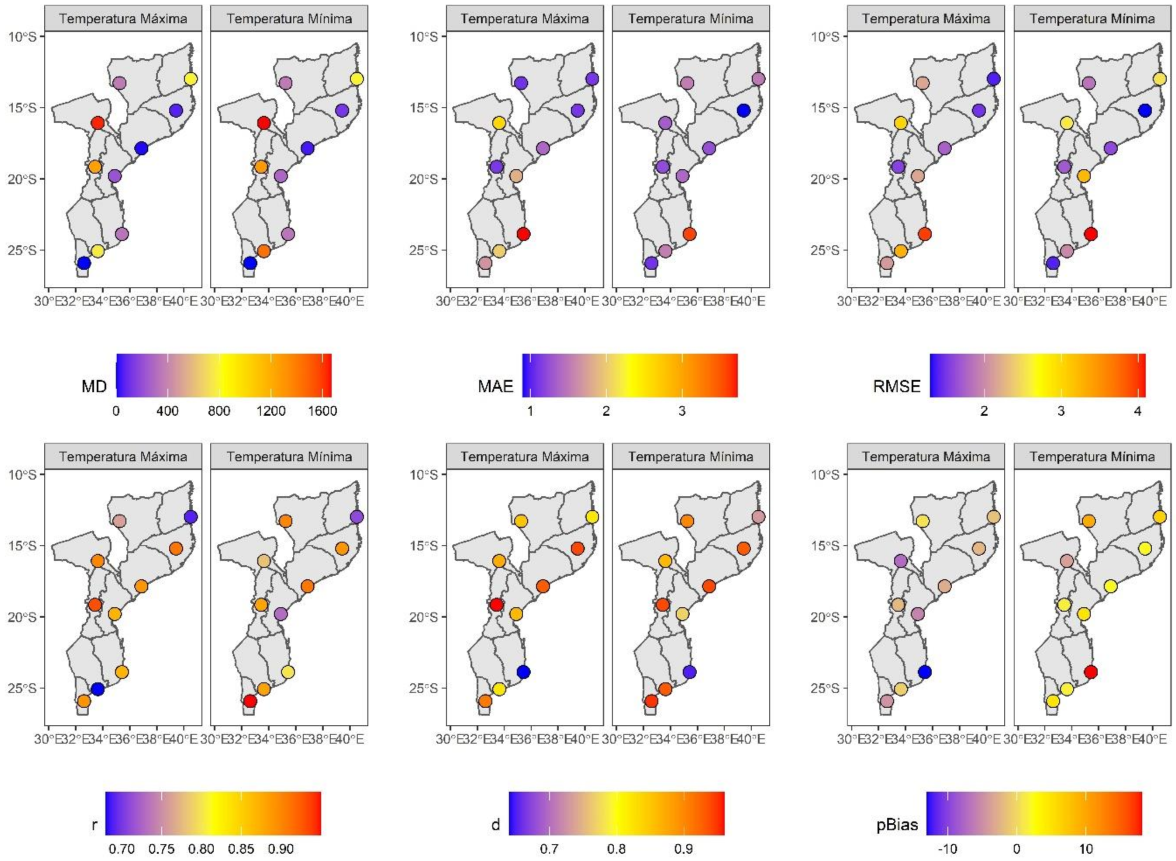


Figure 4. Statistical results of maximum and minimum temperature

Analysing the missing data in observed data (MD), the Tete station presents the highest number of missing data, followed by Chimoio, Pemba and Inhambane. The Maputo, Quelimane and Nampula station presents complete data for the period under review. In the results of the statistical tests of the figures, it is observed that the MAE and RMSE test presents higher values for the maximum and minimum temperatures in the Inhambane station, which are 3.73 and 3.58 for MAE, 3.27 and 4.09 for RMSE respectively, indicating a lower degree of adjustment in relation to the observed data. The lowest MAE value is 1.09 and 0.90 for the maximum and minimum temperatures at the Lichinga and Nampula stations and RMSE are 1.19 and 1.30 at the Pemba and Nampula stations, indicating a high degree of adjustment in relation to the observed data.

In the results, the r values for the maximum temperature vary from moderate, strong and very strong positive correlation. The stations of Xai Xai and Pemba presented lower values in relation to the others. The values were 0.68 and 0.69, respectively, thus indicating a moderate positive correlation in relation to the observed data. For the minimum temperature, the r values range from strong positive correlations to very strong positive correlations, thus demonstrating the reliability of the data. The correlation between the observed data and the ERA5 model reanalysis data is statistically significant at all 10 stations. By comparing the two parameters under analysis, it is verified that the best correlation is the minimum temperature.

Willmott's concordance index (d) values show average to excellent performance in both parameters. The average performance value is 0.64 for the maximum temperature and 0.65 for the minimum temperature, both values from the Inhambane station. This indicates a lower performance of the simulated data from this station in relation to the other stations. Willmott's concordance index showed statistically significant values for the data under study.

The Bias percentage values show that the maximum temperature tends to underestimate the observed data, except for the Lichinga station with a value of 0.8. The minimum temperature presents Bias percentage values with a tendency to overestimate the observed data with the exception of the Tete station with a value of -3.7. The Inhambane station has high values of underestimation and higher overestimation with values of -13.0 and 18.1 respectively.

In general, both parameters have acceptable values in statistical tests, and can thus be used in representation of the observed data. The results of the study by Gleixer, Demissie e Diro, (2020) that analysed the ERA5 models and ERA5-interim for simulation of the data observed (temperature and precipitation) in Africa showed that model ERA5 demonstrated higher approximation of observed data than ERA5-interim, which was one of the motivations for the choice of this model for this study.

1.3.2. Potential productivity

Figures 5, 6 and 7 show the annual variability of maize potential yield and cycle duration simulated by the model under the influence of different weather conditions for each year. All values refer to the period 1981 to 2020.

Figure 5. Potential productivity (tonnes/ha) and cycle duration (days) of maize, simulated in the trading areas in the northern region (Umbeluzi, Chokwe and Inhambane) and the representation of the years of occurrence of ENSO.

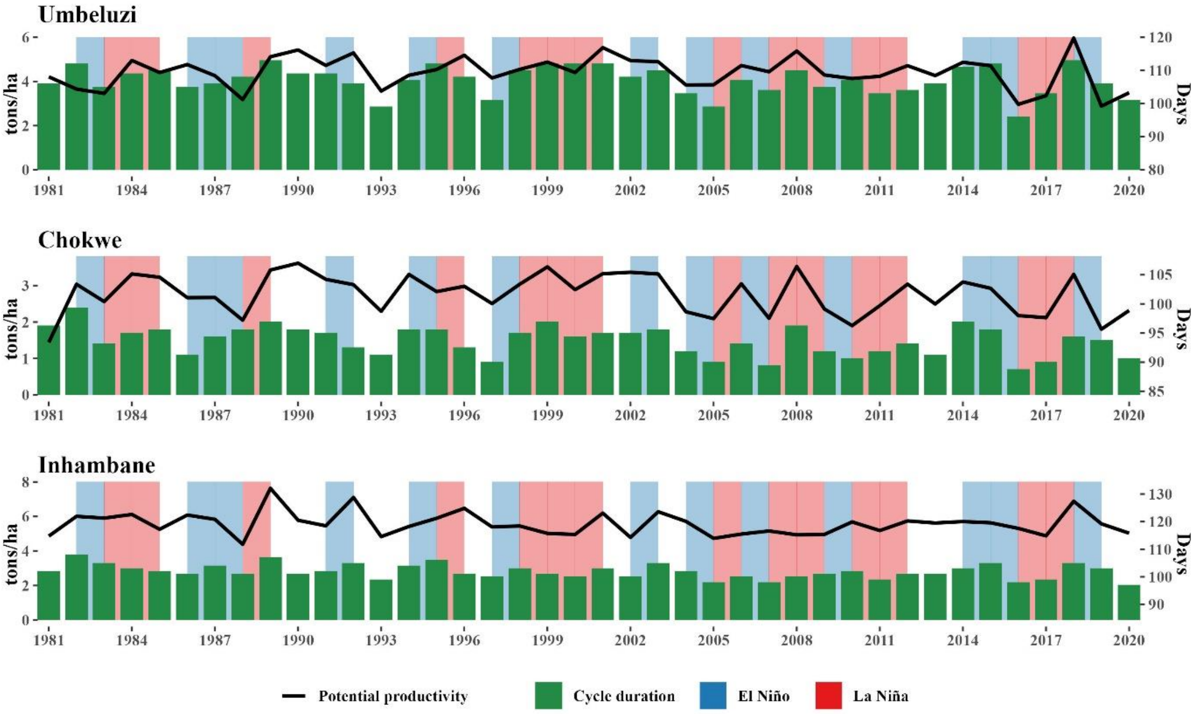


Figure 6. Potential productivity (tonnes/ha) and cycle duration (days) of maize, simulated in the trading areas in the northern region (Beira, Sussundenga, Angónia and Quelimane) and the representation of the years of occurrence of ENSO.

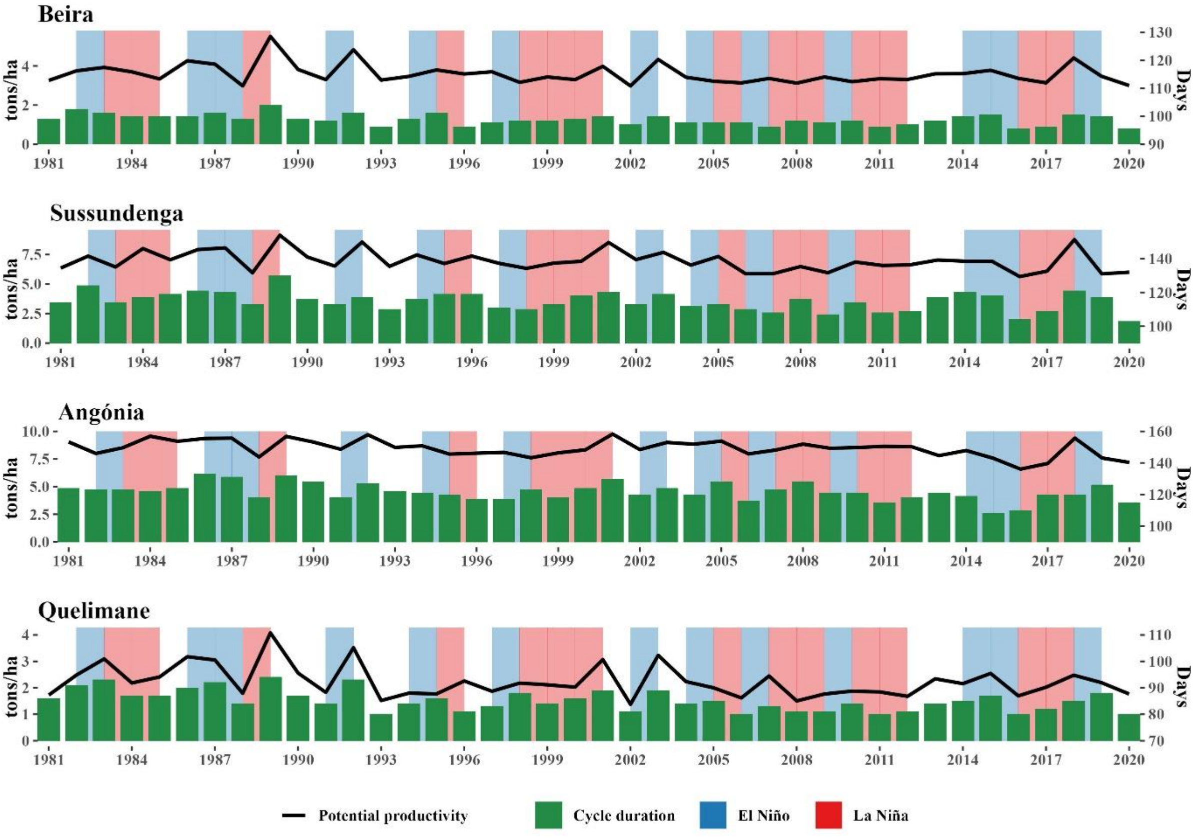
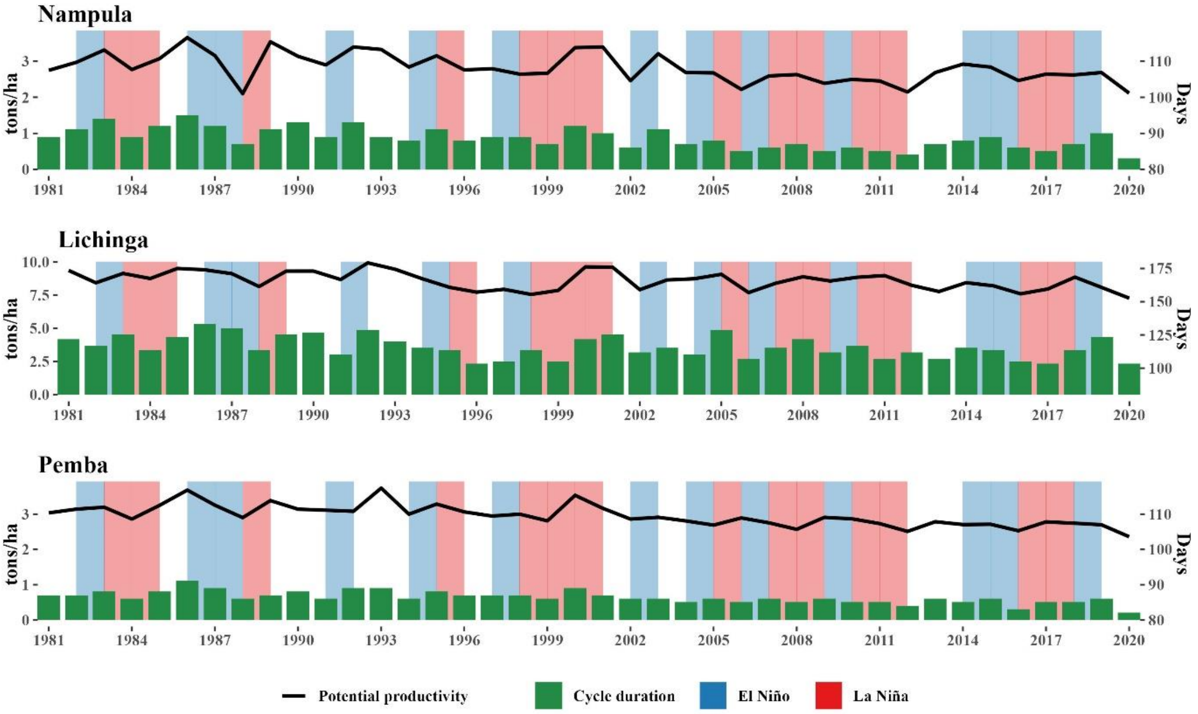


Figure 7. Potential productivity (tonnes/ha) and cycle duration (days) of maize, simulated in the trading areas in the northern region (Lichinga, Nampula and Pemba) and the representation of the years of occurrence of ENSO.



In Figure 5, the results for areas located in the southern region are plotted, which show a significant drop in potential productivity in 1988 and 1993, and high potential productivity peaks in 1989 and 2017. In the southern region, it is noted that in Inhambane it has higher potential productivity values where the expressive peak is 7.63 tons/ha in 1988 with a cycle duration of 107 days, while Chokwe has lower potential productivity values where the average in the period under analysis is 2.77 tons/ha. Comparing the results from the southern region with field survey data from IIAM (3.17, 3.88 and 5.37 tons/ha for the Umbeluzi fields and 4.34 tons/ha for the Chokwe field), it is observed that the values simulated by the model are acceptable.

In Figure 6, the results for areas located in the central region are plotted, where there is a significant drop in potential productivity in 1988 and 1993, and productivity peaks with great expressiveness in 1989 and 2018. In the central region, it is noted that in Sussundenga and Angónia they present higher potential productivity values where the expressive peak is 9.14 tons/ha in 1989 with a duration cycle of 130 days in Sussundenga and 9.76 tons/ha in 2001 with a duration cycle of 130 days in Angónia, while Beira and Quelimane have lower potential productivity values where the average in the period under analysis is 3.59 tons/ha in Beira and

2.23 tons/ha in Quelimane. Comparing the results from the central region with field survey data from IIAM (3.61 tons/ha from the slurry fields and 7.41 tons/ha from the Angónia field), it is observed that the values simulated by the model are acceptable.

In Figure 7 are plotted the results for areas located in the northern region, where there is a significant drop in potential productivity in 1988 and 2020, and productivity peaks with great expressiveness in 2000. In the northern region, it is noted that in Lichinga it has higher potential productivity values where the expressive peak is 9.92 tons/ha in 1992 with a cycle duration of 127 days, while Pemba has lower potential productivity values where the average in the period under analysis is 2.81 tons/ha. Comparing the results of the northern region with field research data from IIAM (7.77 tons/ha in the Lichinga field and 2.13 tons/ha in the Nampula field), it is observed that the values simulated by the model are acceptable.

Making a general analysis based on the results presented in figures 5, 6 and 7, it is clear that the model is able to satisfactorily reproduce the potential maize yield as a function of the oscillation in the time series due to climatic oscillations. The overall average (all areas) of maize potential yield is 4.88 tons/ha which is approximated to the overall average of the IIAM field survey data which is 4.71 tons/ha. The real yield of maize for the period under analysis is 0.72 tons/ha (Faostat, 2021). Comparing the average of the potential maize productivity with the average of the real productivity, it is observed that the potential productivity is about 85% higher than the real productivity, making it clear that the current scenario of maize cultivation is far from ideal.

Based on the results presented in figures 5, 6 and 7 it is clear that the model is able to satisfactorily simulate the potential maize yield as a function of weather fluctuations due to climatic fluctuations. Figures 5, 6 and 7 show a significant reduction in potential maize yield in all areas studied in response to ENSO conditions, such as the El Ninõ event in 1987/1988 and 2015/2016. On the other hand, there is an increase in the potential maize yield in response to ENSO conditions, as is the case of the La Ninã events in 1988/89, 2000/01 and 2017/18.

The article by Ubilava, (2019) describes that under ENSO conditions (El Niño and La Niña) they result in a decrease in maize productivity, and during the El Niño event the productivity reduction is more than 20% in affected countries. Although these conditions affect many countries, in developing countries the impact caused by ENSO is more severe due to lack of preparedness for resilience to climate shocks. In most regions in southern African countries during El Niño events there are reductions in maize productivity, while during La Niña events there are increases in maize productivity (Sazib; Mladenova; Bolten, 2020).

The El Ninõ events in Mozambique are characterized by extreme droughts affecting the demand for water for agricultural production, as is the case for the events that occurred in the 1997/1998 and 2015/16 seasons (Nicholson; Kim, 1997; Meque; Abiodun, 2015; Setimela et al., 2018). And the La Ninã events in Mozambique are associated with excessive rainfall causing flooding in some regions, such as the 1999/2000 rainy season floods that affect more southern provinces causing direct and indirect losses in the order of US$600 million (58 million dollars in the agricultural sector alone), thus causing a sharp drop in GDP from 7.5 percent to 1.6 percent between 1999 and 2000. (Nicholson; Kim, 1997; Browne, 2011; Meque; Abiodun, 2015). ENSO information is used in Mozambique for planning the agricultural season at different times of the year and is therefore of great importance for understanding climate variability.

In the 2015/2016 El Niño event considered the strongest in the last 50 years, the maximum magnitude of which is 2.3 caused a severe drought in the southern African region affecting the regional economy, including agriculture, food and nutrition security, health, water, sanitation and energy. The drought has affected more than 40 million people, with 23 million in need of emergency humanitarian support as of June 2016 (Hove; Kambanje, 2019). This event created below-normal rainfall conditions in Mozambique with greater severity in the southern region, creating a hydrological crisis unprecedented in history. This event intensified food insecurity caused by major crop failures, thus placing millions of people in need of humanitarian aid, especially in the southern region. In Mozambique, during the El Niño event of the 2015/2016 season, there was a different behaviour between the different regions, such as the North region where there were floods and the South and Center regions of the country were hit by droughts (Mahumane, 2019).

1.3.3. Future projections

The results of the simulations of potential maize crop yield in scenarios RCP4.5 and RCP8.5 in the study areas, in response to future climatic conditions for 2050 and 2080, are found in Table 3. Estimates of average variations in yield for both scenarios, daily data were used for scenarios RCP4.5 and 8.5 of CSIRO-MK3.6.0, compared to the year with the highest potential productivity in the historical series.

The table shows the estimates of the model for the years 2050 and 2080 in the scenarios RCP4.5 and RCP8.5 in tons/ha and as a percentage of the potential yield, compared to the potential yield for the base year, where it is noted that the maize crop with variations in the RCP4.5 scenario from -66 to 22% (2050) and -72 to -5% (2080) in the RCP8.5 scenario from -75 to -15% (2050) and -94 to -22% (2080).

	Year-base		**RCP4.5**		**RCP8.5**		**RCP4.5**		**RCP8.5**	
	(year)	**(ton/ha)**	**2050**	**2080**	**2050**	**2080**	**2050**	**2080**	**2050**	**2080**
Umbeluzi	2018	6.0	4.56	3.98	5.08	1.57	-24%	-33%	-15%	-74%
Chokwe	1990	3.6	4.41	3.43	1.86	1.86	22%	-5%	-49%	-49%
Inhambane	1989	7.6	3.98	3.57	3.67	2.14	-48%	-53%	-52%	-72%
Beira	1989	5.5	3.17	2.52	2.82	1.78	-42%	-54%	-49%	-68%
Sussundenga	1989	9.1	3.10	2.59	2.30	0.54	-66%	-72%	-75%	-94%
Angónia	2001	9.8	4.41	2.89	2.47	1.86	-55%	-70%	-75%	-81%
Quelimane	1989	4.1	2.48	1.97	2.44	1.54	-39%	-52%	-40%	-62%
Nampula	1986	3.7	1.63	1.11	1.53	0.80	-55%	-70%	-58%	-78%
Lichinga	1992	9.9	4.20	3.18	3.64	1.51	-58%	-68%	-63%	-85%
Pemba	1993	3.7	2.99	2.77	2.89	2.92	-20%	-26%	-23%	-22%

Table 3. Projection of annual variation in potential yield for maize crop, simulated from daily data of CSIRO-MK3.6.0 model.

Analysing Table 3, it is observed that the model results estimate a greater potential loss of maize crop yield in scenarios RCP4.5 and 8.5 for the Sussundenga area with a percentage loss above 60% which is equivalent to a loss of 6-6.51 tons/ha (RCP4.5) and loss above 70% corresponding to a drop of 6.8-8.56 tons/ha (RCP8.5). Analysing the results by region, in the 2050s and 2080s of the RCP4.5 scenario, the greatest loss of potential productivity can be seen in the central region with losses above 50% in the order of 3.83 tons/ha (2050) and 4.63 tons/ha (2080), followed by the northern region with losses above 45% and the southern region with losses above 25%. In the RCP8.5 scenario in the years 2050 and 2080, the greatest loss of potential productivity can be registered in the central region with losses above 60% in the order of 4.61 tons/ha (2050) and 5.69 tons/ha (2080), followed by the northern region with losses above 50% and the southern region with losses above 35%.

The model's results in future scenarios of average temperature increase raise an important alert on the issue of food security, with the aggravating focus that maize is the main crop grown in Mozambique and the central and northern regions are considered the main producers of this cereal. The adaptation of maize culture should take into account not only in medium climate change but also with a higher frequency and intensity of extreme events, as the example of Mozambique where there were losses of 67% crops in the passage of cyclones Idai and Kenneth in 2019 in the Central and North regions (Manjoro; Ferreira; Rosse, 2019). Several studies identified thermal stress as a major threat to maize cultivation in future scenarios in various relevant production regions, demonstrating that the variation of 1 °C at the average temperature may take 10% losses of production (Brown; Funk, 2008; Lobell et al., 2011; Gourdji et al., 2013; Kamali et al., 2018).

The study by Jones at al., (2003) on the potential impacts of climate change on maize production in Africa and Latin America in 2055 showed that for Mozambique, productivity losses in excess of 2 tonnes/ha, which corresponds to more of 18%. In the present study, the estimated results show average losses above 30%, these estimates are far above the estimate suggested by Jones at al., (2003) because this study used data from CMIP5 and not CMIP3. Another study by Brito and Homan (2012) on the impacts of climate change on agricultural productivity in Mozambique shows projections for a drop in maize crop productivity of more than 11% (2046–2065) across the country, with the worsening of the increase. loss of productivity being registered in the central zone with losses in excess of 3.50 tons / ha. In the present work, results also show higher losses in the central region with losses above 3.50 tons/ha in the RCP4.5 scenario and above 4.60 in the RCP8.5 scenario.

1.3.4. Effect of technological advancement

In Table 4 shows the projections of average percentage changes in potential yield for maize, considering the effect of technological advances according to Ewert et. al. (2005), and its effect in a CMIP5 scenario (RCP4.5 and RCP8.5). For potential productivity simulations, according to the Ewert at. al. (2005), the year of maximum potential productivity for each study area was used as the base year, as in the example (for Umbeluzi the projections of the effect until 2050 is PPT(%) = 1.41 + (1.41 x 0, 6)(2050-2018) = 28% and until 2080 is PPT (%) = 1.41 + (1.41 x 0.4) (2080-2018) = 36%), that is, with the application of technology there will be an increase in maize crop yield by 28% by 2050 and 36% by 2080 for Umbeluzi. Applying these percentages in CMIP5 scenarios (RCP4.5 and 8.5 Scenarios), we will have the results presented in Table 4.

			RCP4.5		RCP8.5	
	2050	**2080**	**2050**	**2080**	**2050**	**2080**
Umbeluzi	28%	36%	5%	3%	14%	-37%
Chokwe	52%	52%	74%	47%	4%	4%
Inhambane	53%	53%	5%	0%	1%	-19%
Beira	53%	53%	11%	-2%	4%	-15%
Sussundenga	53%	53%	-13%	-19%	-22%	-41%
Angónia	43%	46%	-12%	-24%	-32%	-35%
Quelimane	53%	53%	14%	1%	13%	-10%
Nampula	56%	54%	0%	-15%	-3%	-24%
Lichinga	50%	51%	-7%	-17%	-13%	-34%
Pemba	50%	50%	30%	25%	27%	29%

Table 4. Percentage projection of average potential yield estimates for maize in the study areas, considering the technological effect as well as the application of the technological effect in scenarios RCP4.5 and 8.5.

The results of the application of the technological effect show increases in all areas under study of the potential productivity of the maize crop, ranging from 28-56% until the year 2050 and 36-54% until the year 2080. Nampula presents for both scenarios one higher percentage of potential productivity increase with application of technology and the opposite happens with Umbeluzi. In the application of the technology effect in CMIP5 scenarios, the results show in some areas a reduction in losses, in others an increase in productivity and in others with no loss of potential productivity. In the RCP4.5 scenario the percentages range from -13 to 74% in 2050 and -24 to 47% in 2080, for the RCP8.5 scenario the percentages range from -32 to 27% in 2050 and -37 to 29% in 2080.

Several studies show that the application of technology in the agricultural sector is the solution for increasing productivity in several countries, Ewert at. al. (2005) with the application of the technological effect found increases of 140% in wheat productivity for Europe. The adoption of technologies comprehensively in the agricultural sector primarily for low-income households in Africa can significantly dampen demand for the maize crop, starting with the adoption of strong drought-resistant cultivars and appropriate agronomic management (Hansen et al., 2019; Zhai et al., 2021).

1.4.CONCLUSION

The present study evaluated the potential yield of the maize crop, simulated using reanalysis data from the ERA5 model for the period 1981-2020 and in scenarios of increasing mean temperature, as well as the application of the technology effect.

Overall, the results in the validation of the ERA5 model reanalysis data show statistically acceptable values to represent the observed data. Of the data from the 10 meteorological stations analysed in this study, the data from the meteorological station in Inhambane stands out, which underestimates the maximum temperature and overestimates the minimum temperature, with the Tete station also showing a greater absence of observed daily data.

From the simulated data of potential productivity in the analysed period, oscillations in the annual variability in all areas under study can be observed due to the empirical method in the choice of parameters, where higher temperatures are associated with low productivity. The highest potential yield estimated by the model was 9.9 tons/ha in Lichinga and the lowest was 1.4 tons/ha in Quelimane. The average potential productivity simulated by the model for all areas under study was 4.88 tons/ha, which is approximated to the average obtained in the IIAM experimental fields of 4.71 tons/ha, showing that the model can satisfactorily present values close to the experiment. Compared to the average real productivity, which is in the order of 0.72 tons/ha, it can be concluded that this is 85% below the potential productivity. In the simulation of the climate scenarios RCP4.5 and 8.5 of the CMIP5, the results show, on average, a reduction in the potential productivity of the maize crop above 30%, where Sussundenga presents greater losses. With the application of the technology effect in both scenarios, the results show that there may be, in some areas under study, a reduction in losses, an increase in productivity or no loss at all.

The present model proves to be an added-value tool for estimating the potential productivity of the maize crop in Mozambique, and can thus be used for planning public policies in the agricultural sector. This model needs to be improved in future studies, as it does not consider issues such as the impact of water and nutritional restriction, pests, diseases or the occurrence of extreme events on the potential productivity of the maize crop.

1.5.ACKNOWLEDGMENTS

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1.6.SUPPLEMENTARY MATERIAL

Study areas	Province	Latitude	Longitude	Height (m)	Source
Umbeluzi	Maputo Província	26° 60' 00" S	32° 21' 36" E	10	IIAM
Chokwe	Gaza	25° 31' 48" S	32° 58' 48" E	33	IIAM
Inhambane	Inhambane	23° 52' 12" S	35° 25' 12" E	9	INAM
Beira	Sofala	19° 48' 00" S	34° 53' 24" E	8	INAM
Sussundenga	Manica	19° 24' 36" S	33° 18' 00" E	620	IIAM
Angónia	Tete	14° 42' 36" S	34° 21' 00" E	1270	IIAM
Quelimane	Zambézia	17° 51' 00" S	36° 52' 12" E	6	INAM
Lichinga	Niassa	15° 12' 00" S	39° 25' 48" E	1364	IIAM
Nampula	Nampula	13° 16' 48" S	35° 15' 00" E	438	IIAM
Pemba	Cabo Delgado	12° 58' 48" S	40° 31' 12" E	101	INAM

Table S1. Study areas data (source: IIAM and INAM)

Weather Stations	WMO Indicative	Latitude	Longitude	Height (m)
Maputo	67341	25° 55' 12" S	32° 36' 36" E	34
Xai Xai	67324	25° 42' 00" S	32° 38' 24" E	4
Inhambane	67323	23° 52' 12" S	35° 25' 12" E	9
Beira	67297	19° 48' 00" S	34° 53' 24" E	8
Chimoio	67295	19° 09' 00" S	33° 25' 48" E	731
Tete	67261	16° 04' 48" S	33° 37' 48" E	149
Quelimane	67283	17° 51' 00" S	36° 52' 12" E	6
Lichinga	67217	15° 12' 00" S	39° 25' 48" E	1364
Nampula	67237	13° 16' 48" S	35° 15' 00" E	438
Pemba	67215	12° 58' 48" S	40° 31' 12" E	101

Table S2. Weather Stations data (source: INAM)

Entry	Experiment	Grain Weight (GW)	Anth Date	Pedigree
Umbelúzi	VCU191	5,37 ton/ha	54	SY5054
Umbelúzi	VCU192	3,88 ton/ha	83	SY5054
Umbelúzi	VCU194	3,17 ton/ha	59	SY5054
Chókwè	VCU195	4,34 ton/ha	52	SY5054
Sussundenga	VCU1910	3,61 ton/ha	67	SY5054
Nampula	VCU1911	2,13 ton/ha	57	SY5054
Angónia	VCU1912	7,41 ton/ha	63	SY5054
Lichinga	VCU1913	7,77 ton/ha	71	SY5054

Table S3. Field search data (source: IIAM)

1.7.REFERENCES

AMADE, S. **Geografia Física de Moçambique**, 2019.

ARNDT, C. et al. **Evolução da pobreza e do bem-estar em Moçambique: 1996/97-2014/15Desafios para Moçambique**. Maputo: IESE: [s.n.].

ASAFU-ADJAYE, J. The economic impacts of climate change on agriculture in Africa. **Journal of African Economies**, v. 23, n. SUPPL.2, p. Pages ii17–ii49, 2014.

BARBIER, E. B.; HOCHARD, J. P. The impacts of climate change on the poor in disadvantaged regions. **Review of Environmental Economics and Policy**, v. 12, n. 1, p. 26–47, 2018.

BRITO, R.; HOLMAN, E. Respondendo as mudanças climáticas em Moçambique. Tema 6: Agricultura. **INCG, Respondendo às mudanças climáticas em Moçambique. Fase II.**, 2012.

BROWN, M.; FUNK, C. Food security under climate change. **NASA**, 2008.

BROWNE, N. Model evaluation for seasonal forecasting over southern Africa. 2011.

CHALLINOR, A. J. et al. A meta-analysis of crop yield under climate change and adaptation. **Nature Climate Change**, v. 4, n. 4, 2014.

CHARLES, A. J. **Proposta metodológica para a Cartografia censitária de Moçambique**. [s.l.] Universidade Federal de Pernambuco, 31 jan. 2012.

COSTA, L. C. et al. Potential forcing of CO2, technology and climate changes in maize (Zea mays) and bean (Phaseolus vulgaris) yield in southeast Brazil. **Environmental Research Letters**, v. 4, n. 1, p. 10pp, 2009.

DELOITTE. **Mozambique's Economic Outlook Governance challenges holding back economic potential**. [s.l: s.n.].

EWERT, F. et al. Future scenarios of European agricultural land use: I. Estimating changes in crop productivity. **Agriculture, Ecosystems and Environment**, v. 107, n. 2–3, p. 101–116, 2005.

FAOSTAT. **FAOSTAT Statistical Database**, 2021. Disponível em:

<http://www.fao.org/faostat/>

FERRÃO, J. et al. Agriculture and Food Security in Mozambique. **Journal of Food, Nutrition and Agriculture**, v. 1, n. 1, p. 7–11, 2018.

FOX, D. G. Judging Air Quality Model Performance. **Bulletin of the American Meteorological Society**, v. 62, n. 5, p. 599–609, 1981.

GLEIXNER, S.; DEMISSIE, T.; DIRO, G. T. Did ERA5 improve temperature and precipitation reanalysis over East Africa? **Atmosphere**, v. 11, n. 9, p. 996, 2020.

GOURDJI, S. M. et al. An assessment of wheat yield sensitivity and breeding gains in hot environments. **Proceedings of the Royal Society B: Biological Sciences**, v. 280, n. 1752, 2013.

GUPTA, H. V.; SOROOSHIAN, S.; YAPO, P. O. STATUS OF AUTOMATIC CALIBRATION FOR HYDROLOGIC MODELS: COMPARISON WITH MULTILEVEL EXPERT CALIBRATION. **Journal of hydrologic engineering**, v. 4, n. 2, p. 135–143, 1999.

HANSEN, J. et al. Climate risk management and rural poverty reduction. **Agricultural Systems**, v. 172, p. 28–46, 2019.

HARRISON, L. et al. Effects of temperature changes on maize production in Mozambique. **Climate Research**, v. 46, n. 3, p. 211–222, 2011.

HERRING, S. C. et al. Introduction to explaining extreme events of 2014 from a climate perspective. **Bulletin of the American Meteorological Society**, v. 100, n. 1, 2019.

HERSBACH, H. et al. The ERA5 global reanalysis. **Quarterly Journal of the Royal Meteorological Society**, v. 146, n. 730, 2020.

HOGUANE, A. Perfil diagnóstico da zona costeira de Moçambique. **Revista de Gestão Costeira Integrada**, v. 7, n. 1, p. 69–82, 2007.

HOVE, L.; KAMBANJE, C. Lessons from the El Nino--induced 2015/16 drought in the Southern Africa region. In: **Current Directions in Water Scarcity Research**. [s.l.] Elsevier, 2019. v. 2p. 33–54.

IAI. **Inquérito Agrário Integrado**. [s.l: s.n.]. Disponível em: <https://www.fnds.gov.mz/index.php/pt/documentos/relatorios/inquerito-agrario-integrado-2020>. Acesso em: 31 jul. 2021.

INE. **Anuário Estatístico 2018 - MoçambiqueStatistical Yearbook 2018 – Mozambique**

(Instituto Nacional de Estatística, Ed.). [s.l.] Instituto Nacional de Estatística, 2018. Disponível em: <www.ine.gov.mz>.

IPCC. **Climate Change 2014 Mitigation of Climate ChangeClimate Change 2014 Mitigation of Climate Change**. [s.l: s.n.].

JONES, P. G.; THORNTON, P. K. **The potential impacts of climate change on maize production in Africa and Latin America in 2055Global Environmental Change**. [s.l: s.n.].

JUNIOR, A. D. M. et al. Thornthwaite climate classification for brazil under ipcc-ar5 climate change scenarios. **Revista Brasileira de Meteorologia**, v. 33, n. 4, p. 647–664, 2018.

KAMALI, B. et al. Drought vulnerability assessment of maize in Sub-Saharan Africa: Insights from physical and social perspectives. **Elsevier**, 2018.

KENDON, E. J. et al. Enhanced future changes in wet and dry extremes over Africa at convection-permitting scale. **Nature Communications**, v. 10, n. 1, 2019.

KIRKWOOD, B. R.; STERNE, J. A. C. **Essential Medical Statistics**. SECOND EDI ed. Australia: Blackwell Science Ltd, 2003.

LETTA, M.; TOL, R. S. J. Weather, Climate and Total Factor Productivity. **Environmental and Resource Economics**, v. 73, n. 1, 2019.

LOBELL, D. B. et al. Nonlinear heat effects on African maize as evidenced by historical yield trials. **Nature Climate Change**, v. 1, n. 1, p. 42–45, 2011.

MABAYA, E.; OMANGA, P.; DEVRIES, J. **Africa agriculture status report: Focus on staple cropsNairobi: Alliance for a Green Revolution in Africa**. [s.l: s.n.].

MAHUMANE, A. A. **A Ocorrência de Eventos Climáticos Extremos de Precipitação e a sua Relação com Fenómenos El Niño e La Niña na Cidade de Xai-Xai (1951-2017)**. [s.l.] Universidade Pedagógica de Maputo, 2019.

MANGO, N. et al. Maize value chain analysis: A case of smallholder maize production and marketing in selected areas of Malawi and Mozambique. **Cogent Business and Management**, v. 5, n. 1, p. 1–15, 1 jan. 2018.

MANHIQUE, A. J. **The South Indian Convergence Zone and relationship with rainfall variability in Mozambique**. [s.l.] University of Cape Town, 2008.

MANJORO, A.; FERREIRA, P. A.; ROSSE, M. E. G. Desafios de Moçambique Após os

Ciclones IDAI e Kenneth. **academia.edu**, p. 17, 2019.

MANUEL, L. et al. **Economic implications of climate change in Mozambique**. South Africa: [s.n.].

MARTINS, M. A. **Estimativa de produtividade das culturas do milho e do sorgo a partir de modelos agrometeorológicos em algumas localidades da região nordeste do Brasil**. [s.l.] Instituto Nacional de Pesquisas Espaciais - INPE, 2012.

MASSON-DELMOTTE, V. et al. IPCC, 2018: Summary for Policymakers. In: Global warming of 1.5 C. An IPCC Special Report on the impacts of global warming of 1.5 C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global. **World Meteorological Organization, Geneva, Tech. Rep**, 2018.

MASUKA, B. et al. Gains in maize genetic improvement in Eastern and Southern Africa: I. CIMMYT hybrid breeding pipeline. 2017.

MATYAS, C. J. Tropical cyclone formation and motion in the Mozambique Channel. **International Journal of Climatology**, v. 35, n. 3, p. 375–390, 1 mar. 2015.

MAVUME, A. F. et al. Analysis of climate change projections for mozambique under the representative concentration pathways. **Atmosphere**, v. 12, n. 5, p. 588, 2021.

MENDELSOHN, R.; DINAR, A.; WILLIAMS, L. The distributional impact of climate change on rich and poor countries. **Environment and Development Economics**, v. 11, n. 2, 2006.

MEQUE, A.; ABIODUN, B. J. Simulating the link between ENSO and summer drought in Southern Africa using regional climate models. **Climate Dynamics**, v. 44, n. 7–8, p. 1881–1900, 1 abr. 2015.

MEYIWA, S. **Numerical modelling of Tropical Cyclone Dineo and its rainfall impacts over north-eastern South Africa**. [s.l.] Faculty of Science, 2019.

MICOA. **National Adaptation Programme of Action (NAPA)**. [s.l: s.n.].

MUCHANGOS, A. DOS. Moçambique, paisagens e regiões naturais. 1999.

MÜLLER, C. et al. Climate change risks for African agriculture. **Proceedings of the National Academy of Sciences of the United States of America**, v. 108, n. 11, p. 4313–4315, 2011.

NHAMO, L. et al. **Cereal production trends under climate change: Impacts and adaptation strategies in Southern AfricaAgriculture (Switzerland)**, 2019.

NICHOLSON, S. E.; KIM, J. The relationship of the El Niño–Southern oscillation to African rainfall. **International Journal of Climatology: A Journal of the Royal Meteorological Society**, v. 17, n. 2, p. 117–135, 1997.

OLUWATAYO, I. B.; OJO, A. O. Is Africa's dependence on agriculture the cause of poverty in the continent?: An empirical review. **The Journal of Developing Areas**, v. 50, n. 1, p. 93–102, 2016.

RUMMUKAINEN, M. Changes in climate and weather extremes in the 21st century. **Wiley Interdisciplinary Reviews: Climate Change**, v. 3, n. 2, 2012.

SAZIB, N.; MLADENOVA, LLIANA E.; BOLTEN, J. D. Assessing the Impact of ENSO on Agriculture Over Africa Using Earth Observation Data. **Frontiers in Sustainable Food Systems**, v. 4, p. 188, 2020.

SETIMELA, P. et al. When the going gets tough: Performance of stress tolerant maize during the 2015/16 (El Niño) and 2016/17 (La Niña) season in southern Africa. **Agriculture, Ecosystems & Environment**, v. 268, p. 79–89, 1 dez. 2018.

SITOE, T. A. Os desafios da investigação agrária em Moçambique. **Desenvolvimento em Questão**, v. 12, n. 25, p. 81–104, 2014.

TAYLOR, R. Interpretation of the Correlation Coefficient: A Basic Review: **Journal of diagnostic medical sonography**, v. 6, n. 1, p. 35–39, 1 jul. 1990.

TEAM, R. C. **R: A language and environment for statistical computing (R Version 4.0. 3, R Foundation for Statistical Computing, Vienna, Austria, 2020)**, 2021.

TESFAYE, K. et al. Targeting drought-tolerant maize varieties in southern Africa: a geospatial crop modeling approach using big data. **International Food and Agribusiness Management Review**, v. 19, n. A, p. 18, 2016.

UAMUSSE, M. M.; TUSSUPOVA, K.; PERSSON, K. M. Climate change observations into hydropower in Mozambique. **applied sciences**, v. 10, n. 4842, p. 12, 2020.

UBILAVA, D.; ABDOLRAHIMI, M. The El Niño impact on maize yields is amplified in lower income teleconnected countries. **Environmental Research Letters**, v. 14, n. 5, p. 54008, 2019.

WANG, F. et al. Evaluation and application of a fine-resolution global data set in a semiarid mesoscale river basin with a distributed biosphere hydrological model. **Journal of Geophysical**

Research Atmospheres, v. 116, n. D21, 2011.

WANG, M. et al. Global Change Can Make Coastal Eutrophication Control in China More Difficult. **Earth's Future**, v. 8, n. 4, 2020.

WEBER, T. et al. Analysis of Compound Climate Extremes and Exposed Population in Africa Under Two Different Emission Scenarios. **Earth's Future**, v. 8, n. 9, 2020.

WILLMOTT, C. J. On the validation of models. **Physical Geography**, v. 2, n. 2, p. 184–194, 1981.

WILLMOTT, C. J. et al. Statistics for the Evaluation and Comparison of Models. **JOURNAL OF GEOPHYSICAL RESEARCH**, v. 90, n. C5, p. 8995–9005, 1985.

WORLD BANK. **A Preliminary Assessment of Damage from the Flood and Cyclone Emergency of February--March 2000**The World Bank Washington, DC, USA, , 2000.

ZAMBRANO-BIGIARINI, M. **Package "hydroGOF"**Zenodo, 2020.

ZEBAZE, S. et al. Assessment of CMIP5 multimodel mean for the historical climate of Africa. **Atmospheric Science Letters**, v. 20, n. 8, p. e926, 2019.

ZERMOGLIO, M. F. et al. **Climate change and health in Mozambique: Understanding the impacts on malaria and diarrheal disease dynamics**. Washington: [s.n.].

ZHAI, R. et al. Africa Would Need to Import More Maize in the Future Even Under 1.5°C Warming Scenario. **Earth's Future**, v. 9, n. 1, 2021.

GENERAL CONCLUSIONS

In this study, five statistical tests were given to the maximum and minimum temperature data (1980-2020) from the ERA5 model compared to observed data from 10 surface stations. The results show that the model data are the closest to the observed data. The average of the maize crop yield potential modelling for the 1981-2020 period is 4.88 tons/ha corresponding to 85% higher than the actual average yield. CMIP5 scenarios demonstrate a decrease in yield potential above 30% and with the application of the technology effect there can be a reduction, increase or no loss of the potential yield of the maize crop.

This dissertation provides an estimate of the potential maize productivity in the current and future scenario in Mozambique, the relevance of the reanalysis data and the difference between actual and potential productivity, as well as the application of the technological effect. It is expected that with this study, the model used will be one more tool to be applied to the agricultural sector in Mozambique, as well as to other sectors related to the research area.

In the preparation of this thesis, it became clear that future research work should focus on:

- Calibration of the maize productivity potential simulation model.
- Coupling in the model water restriction conditions, occurrence of extreme events, pests and diseases.