Analysis of agro-climatic parameters and their influence on maize production in South Africa

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Abstract

This study analysed the variability of the agro-climatic parameters that impact maize production across different seasons in South Africa. To achieve this, four agro-climatic variables (precipitation, potential evapotranspiration, minimum and maximum temperatures) were considered for the period spanning 1986 – 2015, covering the North West, Free State, Mpumalanga and KwaZulu-Natal (KZN) provinces. Results illustrate that there is a negative trend in precipitation for North West and Free State provinces and positive trend in maximum temperature for all the provinces over the study period. Further more, the result showed that among other agro-climatic parameters, minimum temperature had the most influence on maize production in North West, potential evapotranspiration (combination of the agro-climatic parameters), minimum and maximum temperature influenced maize production in KwaZulu-Natal while maximum temperature influenced maize production in Mpumalanga and Free State. In general, the agro-climatic parameters were found to contribute 7.79 %, 21.85 %, 32.52 % and 44.39 % to variation in maize production during the study period in North West, Free State, Mpumalanga and KwaZulu-Natal respectively. The variation in maize production amongst the provinces under investigation could most likely attributed to the variation in the size of the cultivated land among other factors including soil type and land tenure system. There were also difference in yield per hectare between the provinces; KwaZulu-Natal and Mpumalanga being located in the humid subtropical areas of South Africa had the highest yield per hectare 5.61 tons and 4.99 tons respectively while Free State and North West which are in the semi-arid region had the lowest yield per hectare 3.86 tons and 3.03 tons respectively. Understanding the nature and interaction of the dominant agro-climatic parameters discussed in the present study as well as their impact on maize production will help farmers and agricultural policy makers to understand how climate change exerts its influence on maize production within the study area so as to better adapt to the major climate element that either increases or decreases maize production in their respective provinces.

Keywords: Maize, production, yield, multivariate regression, climate variables

1. Introduction

Change in climate has substantial impacts on human health, hydropower, food security, water resources and so on, at local and global scale (Magadza. 2000). Climatic parameters such as solar radiation, air humidity, precipitation, temperature, and wind speed, often determine the global distribution and productivity of crops and livestock (Ajadi et al. 2011). Hence, climate change and variability is foreseen to have direct and indirect effects on the existing agricultural production systems potentially threatening local, regional and/or global food security (Ajadi et al. 2011), depending on the spatial scale of the change. The trend and level of impact due to climate change and/or variability is region dependent (FAO 2013). In areas, where rainfall is the limiting factor for production, an increase in rainfall amount and distribution with little or no change in rainfall intensity and atmospheric temperature may increase crop yield. While excessive increase in rainfall intensity beyond the soil's infiltration rate may lead to runoff losses and erosion (Hawkins 1981) further negatively affecting agricultural production due to loss of the top fertile soil (Wenbin et al. 2015). Similarly, an increase in temporal rainfall amount beyond the soil's capacity to retain water in the active root zone may lead to excessive nitrate leaching beyond the reach of the plant roots (Tesfamariam et al. 2015). Such excessive nitrate leaching beyond the crop root system leads to nitrogen deficiency (reduced crop production) and the leached nitrate may cause ground water contamination (Suresh et al. 2017). In contrast, a reduction in the amount and distribution of rainfall during the sensitive growth stages of crops has detrimental effects on crop yield (Tesfamariam et al. 2010). Similar to rain, a change in atmospheric temperature has its own impact on crop yield. For instance, an increase in temperature from 30 ^{o}C to $\geq$ 35 ^{o}C during the reproductive stage in most photoperiod sensitive crops will adversely affect the pollen viability, fertilization and consequently grain formation, hence lending to a decrease in productivity (Hatfield et al, 2008; 2011).

The impacts of climate change on crop production can no-longer be ignored as they have already become key areas of scientific concern (Yinhong et al. 2009). Such impacts are becoming increasingly significant in the arid and semi-arid areas, particularly in Africa, which comprises of 66 % of the total land area, and harbouring approximately 200 million people (Molua et al. 2010). South Africa is a semi-arid country with about two-third of its land area receiving a mean annual rainfall of less than 500 mm (Durand 2006). More than a million people in South Africa are directly dependent on agriculture for their livelihood. Rainfall variability and high temperatures are currently the most significant elements of climate change in South Africa that are expected to have a severe impact on agriculture (Durand 2006, Botai et al. 2016). For instance, climate projection studies have indicated that the frequency of droughts is likely to increase spontaneously with a higher spatial variability in rainfall, consequently resulting in a negative effect on farm production (IPCC 2007). Studies by Erasmus et al. (2000) on modelling future climate change in the Western Cape alluded that future climate change may lead to lower precipitation, implying that less water will be available for agriculture in the province and consequently leading to a negative effect on the farm economy. With an increase in mean temperature by 0.13 ^{o}C between 1960 and 2003 (Kruger and Shongwe 2004), an expected further increase of 1.2 ^{o}C in 2020, 2.4 ^{o}C in 2050 also 4.2 ^{o}C by the year 2080 and a projected rainfall decrease of about 5-10 percent in the next 50 years (Hewitson 1999; Durand 2006), South Africa is expected to have food insecurity soonest.

Previous studies on the potential impact of climate change on field crop production in southern Africa indicated that different crops respond differently to the envisaged change in climate. (Schulze et al. 1993; Chipanshi et al. 2003; Fischer et al. 2005; Thornton et al. 2011). Schulze et al. (1993), developed an analysis tool to simulate primary productivity and crop yields under different climatic conditions in southern Africa. The results reported an overall increase in potential maize production that corresponds to an increased carbon dioxide and temperature conditions. Du Toit et al. (2001) assessed the vulnerability of maize production to climate change in South Africa and found that maize production in the country is characterized by high variations in crop yield that manifest from changes in seasonal precipitation. Gbetibouo and Hassan (2005) used a Ricardian model to assess the impacts of climate change on seven field crops (maize, wheat, sorghum, sugarcane, groundnut, sunflower and soybean) in South Africa. The authors reported that the production of field crops was sensitive to marginal changes in temperature than to changes in precipitation, whereby an increase in temperature positively affects the net revenue whereas a reduction in rainfall negatively affect the net revenue. Similar studies by Deressa et al. (2005) alluded that climate change has significant nonlinear impacts on the net revenue of sugarcane production in South Africa, with higher sensitivity to increasing temperature than precipitation.

Maize is one of the rain-fed summer field crops grown in South Africa with a 3 % annual increase in demand (Durand 2006). In particular, maize production covers 58 % of the cropping area in southern Africa (Schulze et al. 1993), with South Africa producing 50 % of this main staple crop in the Southern African Development Community (SADC) region (Molua and Lambi 2006), hence making the country the major source of food in the region (FAO 2010). In addition, maize plays a crucial role in red-meat production by contributing up to 50 % of feedlot diet (Department of Agriculture, Forestry and Fisheries, 2015). Contributing about R9.4 billion per annum to the economy, it is conclusively acknowledged that maize production plays an essential role on the South African economy in general and food security in particular. However, most (approximately 60 %) of the maize is produced in the drier region of South Africa (Molua and Lambi 2006). The limiting factor to maize production in South Africa is water availability, whereby approximately 60 % of this scarce resource are used for irrigation (James 2009). In particular, climate variability has a significant impact on maize production emanating from seasonal rainfall and temperature which are responsible for the shifting of the seasons. Such effects pose a potential threat to small scale farmers in South Africa as they are likely to face challenges of crop failures and reduced maize productivity which may consequently lead to hunger, malnutrition and spread of diseases (Wisdom et al. 2008; Jill et al. 2013).

Generally, on-going climate change impacts will indisputably hamper agricultural output and contribution of the agricultural sector to South African's Gross Domestic Production (GDP) and food security, and therefore potentially destabilizing not only the country but eventually the whole SADC region. This implies that, climate change influences on maize production in South Africa can no-longer be underestimated, given the ultimate consequences of such impacts. Despite numerous research studies on the impact of climate change on crop production in South Africa, most of these studies were models based (such as crop processing models, statistical models and econometric models). These models fail to determine the dominant weather variable(s) contributing to the change observed on maize production under different climate conditions. The aim of this study is to characterize the spatio-temporal agro-climatic patterns across the four South Africa maize producing provinces and to determine the most dominant climatic parameter influencing maize production in each of the provinces.

Acknowledging that most of the climate variables are beyond the control of the farmers, this study seeks to contribute towards achieving proper climate adaptation practices by farmers, in a bid to minimize the adverse effects of climate change on maize production. To the best of our knowledge, this study is unique and rarely reported in the literature considering the study regions, the set of parameters selected and the analysis methodology adopted.

2. Study Area

The study area covers Free State (FS), North West (NW), Mpumalanga (MP) and KwaZulu-Natal (KZN) provinces of South Africa, see Fig 1. The study area is located in the north-eastern part of South Africa between 22^{o}E to 33^{o}E and -32^{o}S to -24^{o}S longitude and latitude, respectively. The four selected provinces are the largest producers of maize in the country, accounting for approximately 83% of the total production. The four regions can be further divided into the dry west and the wet east, whereby approximately 60 % of the maize produced is from the dry western areas the rest comes from the eastern areas. The Free State and North West provinces are the highest maize producers, contributing more than 60% of the total maize production in South Africa, followed by Mpumalanga (~24 %) and KZN (less than 5 %). South Africa's climate conditions range from Mediterranean in the south-western corner of South Africa to temperate in the interior plateau and subtropical in the northeast, with small area in the northwest exhibiting a desert climate. According to Koppen climate classification (Kottek et al. 2006), shown in Table 1, climate conditions within the selected study region range between cold, temperate and subtropical conditions. Rainfall exhibit seasonal distribution, with all the four selected provinces receiving summer rainfall. In particular, the North West and Free State provinces receive total annual rainfall of less than 500 mm whereas Mpumalanga and KZN receive between 500 mm and 800 mm. The annual mean maximum temperature for the four provinces is 25 ^{o}C, while the annual mean potential evapotranspiration is 3.7 mm/day.

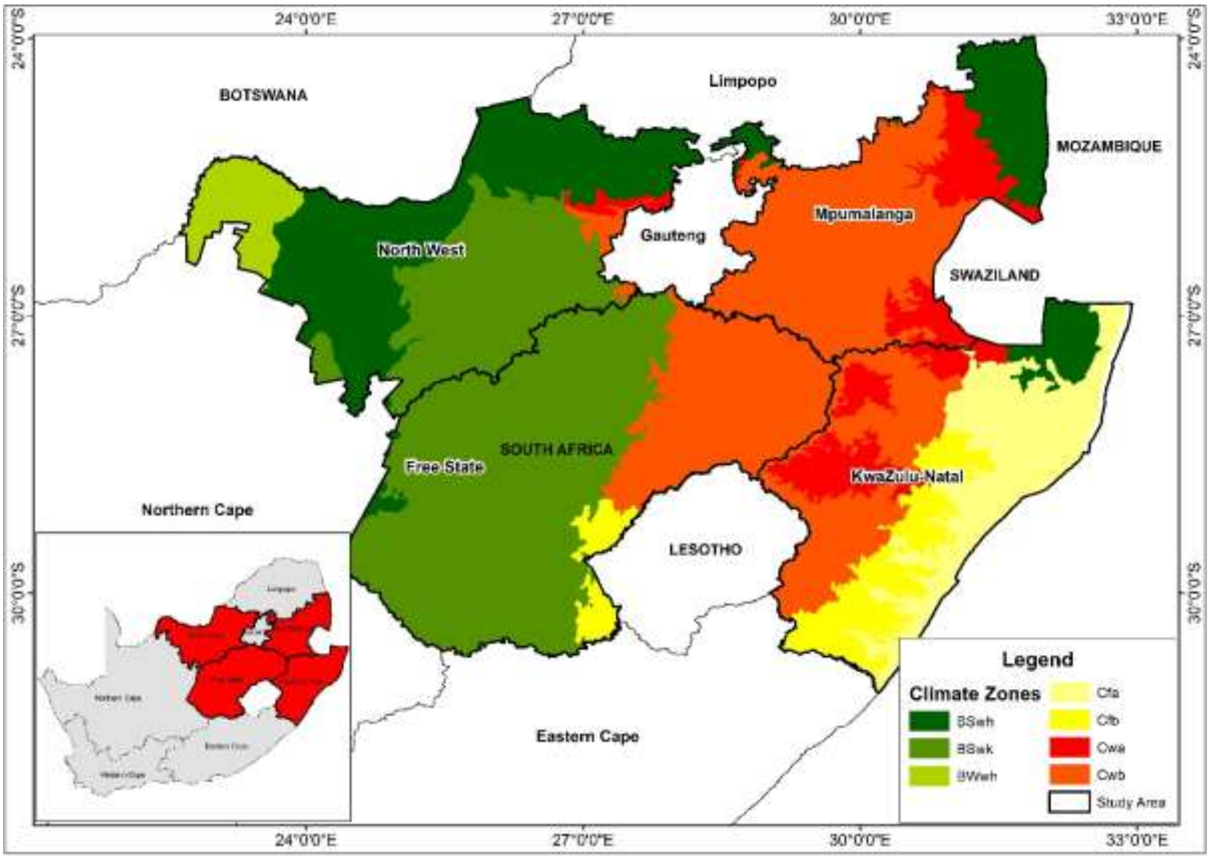

Fig 1: *Map of seven Southern African countries with inset showing the provinces division.*

Table 1: *South African Koppen Climate Classification (Interpretation of Fig 1 legend) (Kottek et al. 2006). North West (NW), Mpumalanga (MP), KwaZulu-Natal (KZN) and Free State (FS)*

Provinces	**Description of the climate/ codes**	**Annual Precipitation (mm)**	**Annual Temperature °C**	
			Summer	**Winter**
NW	Largely Semi-arid *(BSwh, BSwk, Cwa & Cwb)*	250 - 500	17 - 31	3 - 21
MP	Largely Humid Subtropical *(BSwh, Cwa, & Cwb)*	500 - 850	12 - 29	1 - 23
KZN	Largely Humid Subtropical *(BSwh, Cfa, Cfb, Cwa, & Cwb)*	500 - 850	21 - 28	11 - 23
FS	Largely Semi-arid *(BSwk, Cfb, & Cwb)*	250 - 650	13 - 31	-2 - 16

3. Data and Method

3.1 Data Sets

3.1.1 Climate data

This study analysed the latest updated gridded climate dataset, the Climate Research Unit Time-Series 3.24.01 (CRU TS 3.24.01) for the period spanning 1986 – 2015. The CRU TS climate data are derived from monthly observations from more than 4000 meteorological stations distributed across the world's land areas. The gridded CRU TS 3.24.01 product is freely available for science community on http://www.cru.uea.ac.uk or http://badc.nerc.ac.uk/data/cru. For more information on the construction of the CRU TS 3.24.01 product, the reader is referred to Harris et al. (2014). The climate variables included in the CRU TS 3.24.01 are the mean temperature, diurnal temperature range, precipitation, wet-day frequency, vapour pressure, and cloud cover. These climate variables were further used to arithmetically derive the monthly maximum and minimum temperature. For the purpose of this study, only four variables were analysed for the period spanning 1986 – 2015. These variables are precipitation (PRE), potential evapotranspiration (PET) (note* PET was calculated based on the Penman-Monteith formula (Howard Penman and John Monteith) using gridded daily mean temperature (TMP), monthly average daily minimum temperature (TMN), monthly average daily maximum temperature (TMX), vapour pressure (VAP) and cloud cover (CLD)) and monthly average daily maximum and minimum temperature, (TMX) and (TMN), respectively.

3.1.2. Maize data

Maize production data sets in tonnes (here after tons) for each selected province spanning from 1986 to 2015 were obtained from the Abstract of Agricultural Statistics compiled by the Department of Agriculture, Forestry and Fisheries of South Africa. This abstract document contains important information on *inter alia*, field crops, horticulture, livestock, vital indicators and the contribution of primary agriculture to the South African economy. The analysed data are available on the department's website, www.daff.gov.za. Additionally, total land area hectare (here after ha) cultivated for maize production in the provinces is only available from 2002 to 2015 and was acquired from Grain South Africa. Hence, total yield/ha was calculated (Production data in tons divide by Land cultivated in ha for 2002 to 2015).

3.2 Methodology

3.2.1 Spatial-temporal characteristics of agro-climatic parameters

In this study, agro-climatic parameters, e.g. PRE, PET, TMX and TMN were analysed to understand the inherent spatio-temporal characteristics of each parameter. The statistical properties of the computed data series (that is PRE, PET, TMX, TMN, maize production and the average yield per hectare) were described based on the mean, standard deviation, and coefficient of variation as a measure of variability. This is presented in tabular format and boxplot.

3.2.2 Trends

The processing of these agro-climatic parameters were performed by converting the monthly time series of climatic parameters into annual and seasonal data series across the four selected provinces. The monthly, annual and seasonal time series data were analysed to assess the trends of the agro-climatic parameters during 1986 – 2015. To compute the trends, the regional kendall test (rkt) package in R software was used, which helps to calculate the Mann-Kendall (MK) as well as the Seasonal and Regional Kendall Tests for trend (SKT and RKT) also the Theil-Sen's slope. The three tests (MK, SKT and RKT) are usually used to test for monotonic trends (that is consistent increase or decrease trend over the years) in a time series data based on the kendall rank correlation. The RKT and SKT are intra-block tests in which test statistics are computed for each month or season (SKT) otherwise for each year (RKT) all combined in a single test (Marchetto et al. 2013). The two sided *p*-value from the result of this analysis is used to ascertain the significant difference in the monthly, seasonal and annual agro-climatic parameters as well as annual maize production. From the output we were able to determine which climatic parameter or maize production is statistically significant ($p \leq 0.05$). In this method, the null hypothesis (H_0), (rejected when $p \leq 0.05$), is that there is no trend in the population from which the dataset is drawn. The alternative hypothesis (H_1) is that there is a trend in the population.

3.2.3 Seasonal variation

In order to understand the impact of each agro-climatic parameter on maize production across different seasons, multiple coefficient of determination (r^2) analysis was used. The r^2 is a statistic that explains the amount of variance accounted for, in the relationship between two (or more) variables. Thus, given a paired of variables (X_i, Y_i), a linear model given in Equation (1) can be used to explain the relationship between the two variables,

$$Y = \beta_0 + \beta_1 X + e \qquad \text{Eq. 1}$$

where *e* is a mean zero error. The parameters of the linear model can be estimated using the least squares method and the estimated model can be denoted as per Equation (2),

$$\hat{Y} = \boldsymbol{\beta}_0 + \boldsymbol{\beta}_1 X \qquad \text{Eq. (2)}$$

The sum of squared errors or residuals (SSE) and the total sum of squares (SST) in the *Y* are derived from Equation (3) and Equation (4), respectively

$$SSE = \sum_{i=1}^{n} Y_i^2 - \boldsymbol{\beta}_0 \sum_{i=1}^{n} Y_i - \boldsymbol{\beta}_1 \sum_{i=1}^{n} X_i Y_i \qquad \text{Eq. (3)}$$

and

$$SST = \sum_{i=1}^{n} Y_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} Y_i\right)^2 \quad \text{Eq. (4)}$$

The coefficient of multiple determination is given by Equation (5)

$$r^2 = \frac{SST - SSE}{SST} \quad \text{Eq. (5)}$$

Equation (5) can also be expressed as a function of the sample cross-covariance as follows,

$$r^2 = \frac{{S_{xy}}^2}{S_{xx}S_{yy}} = \frac{(\overline{XY} - \bar{X}\bar{Y})^2}{(\overline{X^2} - \bar{X}^2)(\overline{Y^2} - \bar{Y}^2)} \quad \text{Eq. (6)}$$

where $SSE = nS_{yy} - n\frac{{S_{xy}}^2}{Sxx}$ and $SST = nS_{yy}$

Equation (6) corresponds to the square of the Pearson product moment correlation coefficient,

$$r = \frac{S_{xy}}{\sqrt{S_{xx}}\sqrt{S_{yy}}} = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{X})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})\sum_{i=1}^{n}(Y_i - \bar{Y})}} \quad \text{Eq. (7)}$$

In this contribution, using the multiple coefficient of determination analysis given in Equation (6), we wish to characterize to which extent the agro-climatic variables (here represented by variable X) affect maize production in the four of the selected provinces in the same season. For this purpose, the selected seasons were December and January (DJ, also considered as the early phase), December, January and February (DJF, the middle phase), February and March (FM, the late phase) and November, December, January, February and March (NDJFM).

3.2.4 Multivariate analysis

Multivariate linear regression analysis of climatic variables (PRE, PET, TMN and TMX) and crop yield anomalies were calculated with the objective to describe the dependence of the maize production on the predictor variables (here selected as the agro-climatic variables). In particular, the multivariate regression analysis performed in this study can be explained by a linear model given in Equation (8).

$$\Delta Y = \varepsilon + (\alpha \times \Delta PRE) + (\beta \times \Delta PET) + (\gamma \times \Delta TMN) + (\delta \times \Delta TMX) \quad \text{Eq. (8)}$$

where ΔY corresponds to the observed change in the yield as a result of precipitation, potential evapotranspiration and temperature (minimum and maximum) in the season as maize growth. In addition, ε is a constant and α, β, γ and δ are coefficients of the precipitation, potential evapotranspiration, minimum temperature and maximum temperature during the season, respectively. Furthermore, ΔPRE, ΔPET, ΔTMN and ΔTMX are the observed changes in precipitation potential evapotranspiration, minimum and maximum temperatures of the seasons, respectively, during 1986 – 2015.

4. Results

4.1 Spatial-temporal characteristics

Table 2 provides a descriptive statistics of the mean value of maize production annually in tons (1986-2015), land area in ha (2002-2015), annual maize yield/ha (2002 to 2015) and the seasonal mean value (NDJFM) of selected agro-climatic parameters for four South African provinces spanning from 1986 to 2015. The maize production for Free State was the highest of all the four provinces with a mean production of about 3,365,400 tons (1986-2015) and a mean of about 4,002,357 tons (2002-2015) from an area of about 1,036,000 ha. The annual average of maize yield for Free State province was 3.86 tons/ha (2002-2015). The province received an annual mean precipitation of 81.01 mm/month; mean potential evapotranspiration of 5.12 mm/day; and the minimum temperature and maximum temperature were 13.92 ^oC and 28.63 ^oC, respectively for NDJFM. North West had the second largest mean maize production of about 2,399,570 tons/annum (1986-2015) and about 2,241,357 tons/annum (2002-2015) on a land area of about 748,000 ha. The annual maize yield for North West was an average of 3.03 tons/ha (2002-2015). Between 1986 and 2015, North West province received an annual mean precipitation amount of 74.84 mm/month; mean potential evapotranspiration of 5.25 mm/day; minimum temperature and maximum temperature of 16.36 ^oC and 30.72 ^oC respectively during NDJFM. In Mpumalanga province, the annual mean maize production was about 2,104,730 tons (1986-2015) and 2,400,857 tons (2002-2015) on mean land area of about 484,000 ha. The province has an annual average of maize yield of 4.99 tons/ha making it the second largest province in maize yield/ha. During the whole period under investigation, Mpumalanga recorded an annual mean precipitation of about 130.42 mm/month; potential evapotranspiration of 3.81 mm/day; minimum temperature of about 14.02 ^oC and maximum temperature of 25.25 ^oC during the NDJFM months. KwaZulu-Natal recorded the lowest mean maize production of about 380,800 tons (1986-2015) and 463,429 tons (2002-2015) with an average land area of 82,000 ha (2002-2015). The province has the highest maize yield with an average of 5.61 tons/ha. For the period understudy, KZN received a mean annual precipitation of 124.37 mm/month; potential evapotranspiration of 3.88 mm/day; minimum temperature of 15.88 ^oC and maximum temperature of 26.74 ^oC.

Considering the variation in maize production and the agro-climatic parameters from the mean values in table 2 (variance) and Fig 3 (box plot), maize in Free state had the highest level of variation with a variance of 1,476,903, followed by North West (715,721.7), Mpumalanga (283,016.8) and KwaZulu-Natal (10,408.8) recorded the lowest variation. Likewise, there is great difference in the maize yield value across the provinces (Fig 2).

Agro-climatically, high variation in precipitation is noticed in Mpumalanga (864.89) when compared to the other three provinces (Table 2 and Fig 2). For potential evapotranspiration, North West and Free State experienced almost the same high level of variation (0.07 and 0.06 respectively) within the provinces compared to the other two provinces. In the case of minimum temperature and maximum temperature Free State exhibited the highest variability compared to the other provinces.

Furthermore, the precipitation values for Mpumalanga and KwaZulu-Natal were almost equal, this could be attributed to the fact that they are in the same climatic zone (Humid Subtropical). Similarly, North West and Free State provinces which have semi-arid climatic conditions exhibit same first order statistical moment. For instance, the potential evapotranspiration mean values of Mpumalanga and KwaZulu-Natal are similar and that of North West and Free State are similar as well. But minimum and maximum temperature values, the results are contrasting across the provinces.

Table 2*: Maize yield and selected agro-climatic parameters for four South Africa provinces. precipitation (PRE) mm/month; potential evapotranspiration (PET) mm/day; monthly average daily minimum temperature (TMN) ºC; monthly average daily maximum temperature (TMX) ºC (1986-2015); maize production 1000tons (1986-2015); maize yield tons/ha (2002-2015); cultivated land for maize 1000ha (2002-2015)*

Table 2a: North West				**Table 2b: Mpumalanga**			
Variable	**Mean**	**STD**	**Variance**	**Variable**	**Mean**	**STD**	**Variance**
Maize Prod	2399.57	846	715721.7	**Maize Prod**	2104.73	532	283016.8
PRE	74.84	18.93	308.32	**PRE**	130.42	29.41	864.89
PET	5.25	0.27	0.07	**PET**	3.81	0.18	0.03
TMN	16.36	0.52	0.27	**TMN**	14.02	0.42	0.18
TMX	30.72	1.05	1.10	**TMX**	25.25	0.79	0.63
Land	747.79	179.21	32116.49	**Land**	484.21	58.17	3384.18
Maize Yield	3.03	0.77	0.60	Maize **Yield**	4.99	0.95	0.91
Table 2c: KwaZulu-Natal				**Table 2d: Free State**			
Variable	**Mean**	**STD**	**Variance**	**Variable**	**Mean**	**STD**	**Variance**
Maize Prod	380.8	102	10408.8	**Maize Prod**	3365.4	1215.3	1476903
PRE	124.37	23.83	567.84	**PRE**	81.01	19.40	376.22
PET	3.88	0.17	0.03	**PET**	5.12	0.25	0.06
TMN	15.88	0.40	0.16	**TMN**	13.92	0.65	0.43
TMX	26.74	0.6	0.36	**TMX**	28.63	1.06	1.11
Land	82.48	8.45	71.36	**Land**	1035.79	200.83	40333.26
Maize Yield	5.61	0.61	0.37	Maize **Yield**	3.86	0.73	0.53

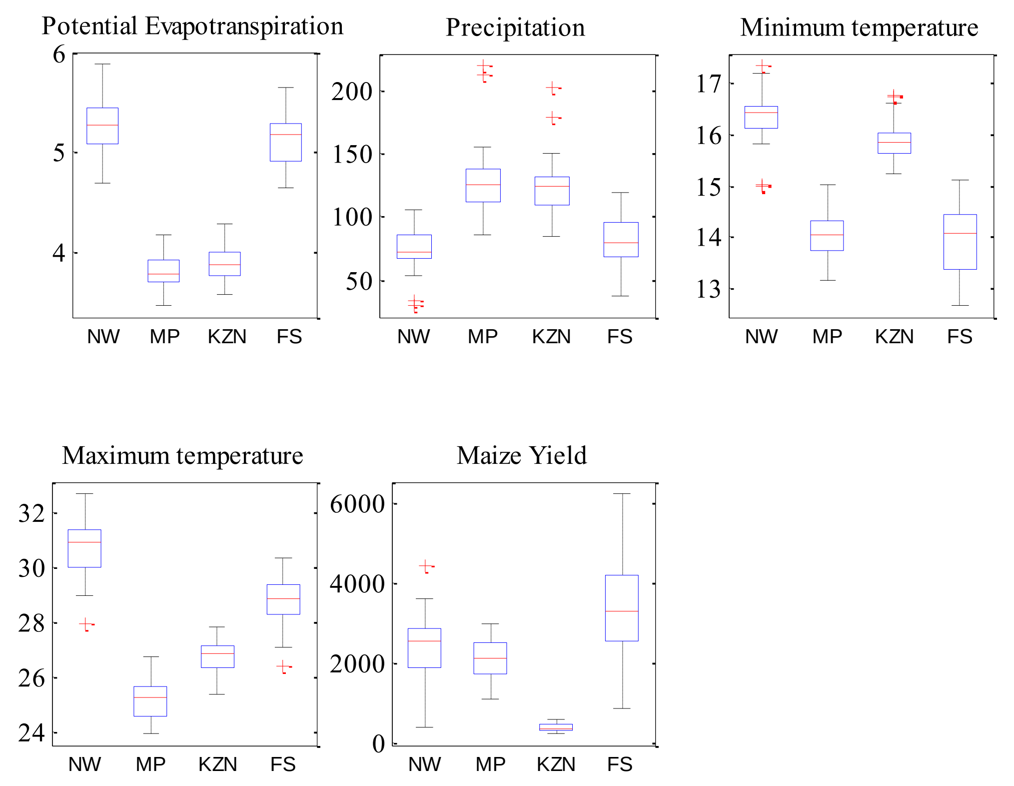

Fig 2*: Overall median properties of Potential evapotranspiration (mm/day), Precipitation (mm), Minimum temperature and Maximum temperature (°C) (1986-2015): Maize yield is compared for 2002-2015.*

Shown in Fig 3 is the variation in maize production against cultivated land for maize from 2002-2015. The figure depicts that there is a similar pattern noticed between maize production (tons) and amount of cultivated land (ha). Increase in cultivated acreage to depicts increase in production across all provinces and vice versa. This is to say that when more land is cultivated for maize production there is an increase in the maize production and when less portion of land is cultivated, production tends to reduce. There is a strong positive correlation of 0.77 and 0.84 between maize production and cultivated land for maize in Free State and KZN respectively. While a moderate positive relationship (0.55) in North West and a weak positive relationship (0.33) in Mpumalanga exist between maize production and acreage. This similar variation in production and cultivated land can be held to be the same for previous years (1986-2001) in which cultivated land data is not available at provincial level. Hence, agro-climatic parameters can be said to be comparable with production data if land is held in constant variation with production.

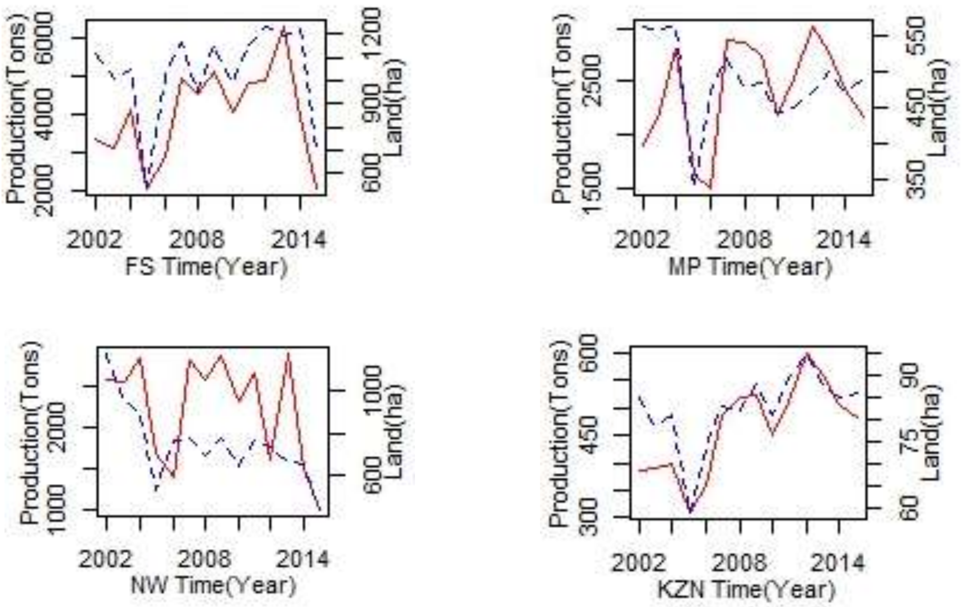

Fig 3*: Variation in maize production and acreage (Plot of time series of maize production (tons) on left Y-axis (Red line) and time series of cultivated land for maize (h) (right Y-axis) (dashed Blue line) 2002-2015).*

4.2 Trend analysis

For the 30-year study period, the monthly values (Fig 4a) shows that there is a negative trend in precipitation across the four provinces. Precipitation in North West decreased by 0.0018 mm/month, Mpumalanga by 0.012 mm/month, KwaZulu-Natal by 0.0062 mm/month and in Free State by 0.0135 mm/month. On the other hand, there is positive trend in potential evapotranspiration in all the provinces, indicating that North West's PET increased by 0.0009 mm/day, Mpumalanga and KwaZulu-Natal by 0.0004 mm/day and Free State by 0.0007 mm/day. Similarly, maximum temperature increased in North West by 0.0059 °C, Mpumalanga by 0.0032 °C, KwaZulu-Natal by 0.0029 °C and Free State by 0.0046 °C. The minimum temperature exhibited different patterns in trends among the provinces: it showed increasing trend in North West by 0.0006 °C, declining trend in Mpumalanga by 0.0004 °C and no change in KwaZulu-Natal and in Free State.

On seasonal time scales, shown in Fig 4b, the result indicates a negative trend in the precipitation received in North West and Free State (decrease of 0.35 mm/month and 0.04 mm/month respectively) while precipitation for Mpumalanga and KwaZulu-Natal (increase of 0.38 mm/month and 0.27 mm/month respectively) had a positive trend. On other hand, maximum temperature had a positive trend in all the provinces; North West increased by 0.054 °C, Mpumalanga by 0.036 °C, KwaZulu-Natal by 0.034 °C and Free State by 0.028 °C. Similarly, potential evapotranspiration had a positive trend for all the provinces where North West increased by 0.0113 mm/day, Mpumalanga by 0.004 mm/day, KwaZulu-Natal by 0.005

mm/day and Free State by 0.006 mm/day. Minimum temperature exhibited a different pattern in trends among the provinces: it showed an increase in TMN for North West, Mpumalanga and KwaZulu-Natal by 0.01 ^{o}C, 0.0009^{o}C and 0.0002 ^{o}C respectively while the minimum temperature for Free State decreased by 0.006 ^{o}C during the study period.

Furthermore, as shown in Fig 4c, the annual values of precipitation decreased in all the provinces; North West by 0.255 mm/month, Mpumalanga by 0.192 mm/month, KwaZulu-Natal by 0.235 mm/month and Free State by 0.341 mm/month. Maximum temperature increased over the years for all the provinces (North West by 0.064 ^{o}C, Mpumalanga by 0.04 ^{o}C, KwaZulu-Natal by 0.0375 ^{o}C and Free State by 0.054 ^{o}C). Potential evapotranspiration had a positive trend in all the provinces. There was an increase of about 0.01 mm/day in North West, 0.006 mm/day in Mpumalanga, 0.0053 mm/day in KwaZulu-Natal and 0.0083 mm/day in Free State. In addition, annual minimum temperature values increased in North West and Free State by 0.0067 ^{o}C and 0.01^{o}C respectively and decreased by 0.0075 ^{o}C in Mpumalanga and 0.0011^{o}C in KwaZulu-Natal.

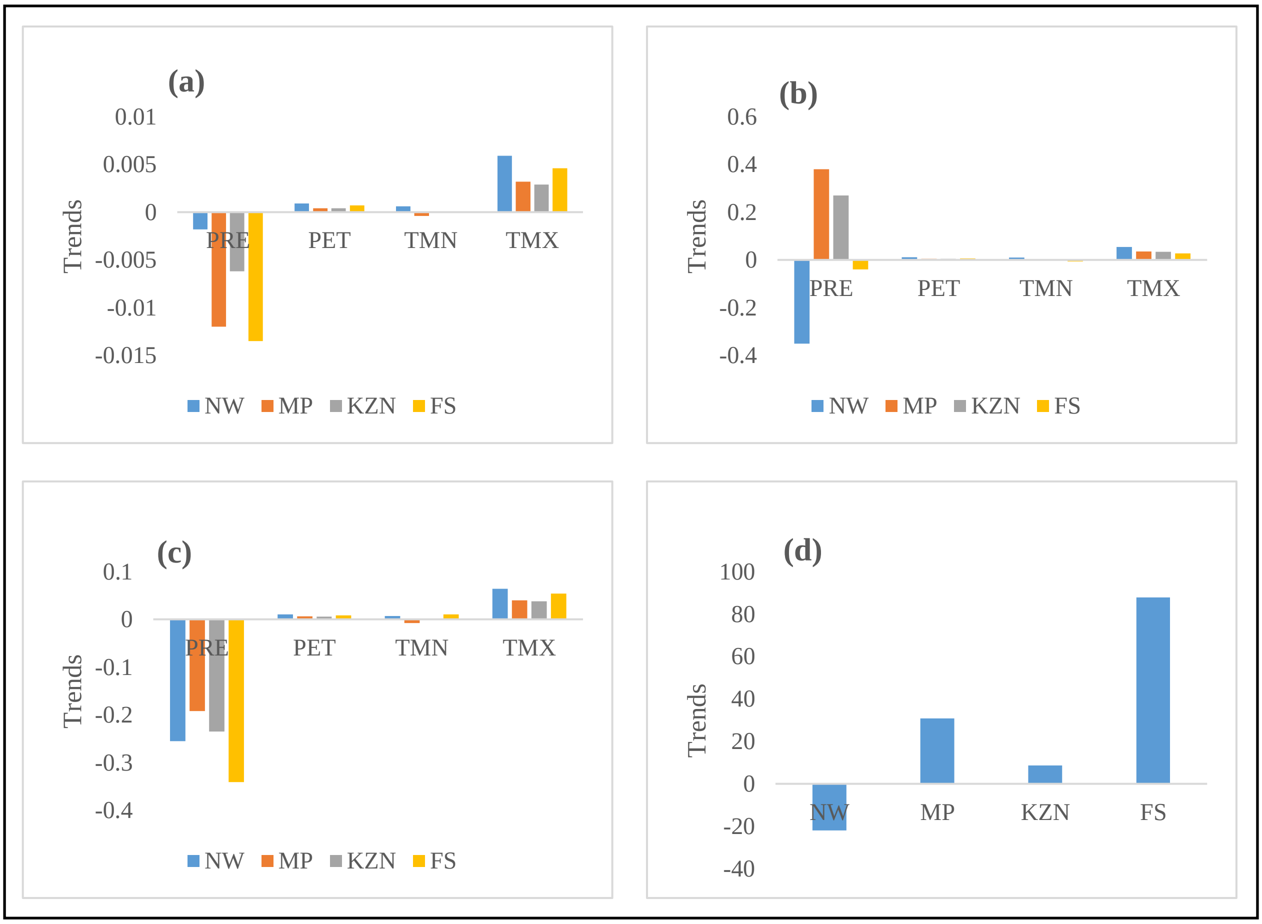

Fig 4: *Trends of Precipitation (mm/month), Potential evapotranspiration (mm/day), Minimum and Maximum Temperature (°C) (1986-2015) at (a) monthly, (b) seasonal (NDJFM), (c) annual time series and (d) annual maize production trend (tons/year).*

Moreover, the result of the analysis as shown in Fig 4d, indicates that there is a decreasing trend in annual maize production in North West by 22 tons/year. However, an increasing trend in annual maize production of about 30.87 tons/year, 8.57 tons/year and 87.88 tons/year are observed in Mpumalanga, KwaZulu-Natal and Free State respectively over the study period.

Table 3 depicts the significant level of the agro-climatic parameters across different time scale for the 30 years of study. Based on the *p*-value in Table 3, for all the agro-climatic parameters there is no significant difference in the monthly values (since all the values are greater than 0.05) except for maximum temperature which has a notable difference in the parameters for all the provinces (North West 0.003, Mpumalanga 0.013, KwaZulu-Natal 0.018 and Free State 0.034). This means that the monthly values for all the agro-climatic parameters are similar except for maximum temperature whose values differs significantly.

Table 3: *The significance of linear trends in agro-climatic parameters (Precipitation (PRE); Potential Evapotranspiration (PET); monthly average daily minimum temperature (TMN); monthly average daily maximum temperature (TMX)) across different time scales for South African provinces (North West (NW); Mpumalanga (MP); KwaZulu-Natal (KZN); Free State (FS) from 1986-2015)*

Provinces	Variables	Monthly		Seasonal (NDJFM)		Annual	
		***p*-value**	**Sign.**	***p*-value**	**Sign.**	***p*-value**	**Sign.**
NW	PRE	0.45	No	0.35	No	0.25	No
	PET	0.11	No	0.03	Yes	0.0002	Yes
	TMN	0.78	No	0.40	No	0.57	No
	TMX	0.003	Yes	0.01	Yes	0.00001	Yes
	Maize					0.37	No
MP	PRE	0.45	No	0.59	No	0.54	No
	PET	0.16	No	0.28	No	0.02	Yes
	TMN	0.80	No	0.96	No	0.32	No
	TMX	0.01	Yes	0.04	Yes	0.002	Yes
	Maize					0.005	Yes
KZN	PRE	0.78	No	0.52	No	0.41	No
	PET	0.16	No	0.17	No	0.02	Yes
	TMN	0.92	No	0.87	No	0.89	No
	TMX	0.02	Yes	0.01	Yes	0.001	Yes
	Maize					0.0001	Yes
FS	PRE	0.27	No	0.94	No	0.18	No
	PET	0.24	No	0.29	No	0.03	Yes
	TMN	0.97	No	0.63	No	0.51	No
	TMX	0.03	Yes	0.16	No	0.003	Yes
	Maize					0.0057	Yes

On the seasonal scale, maximum temperature for all the provinces exhibited significant difference (North West (0.01), Mpumalanga (0.04), and KwaZulu-Natal (0.01)) except for Free State (0.16) which had no notable difference. Potential evapotranspiration differed significantly only in North West (0.03) while the other provinces had no significant difference. Precipitation and minimum temperature in all the provinces had no notable difference during the rainy season. There was variation in the annual maize production values in all the provinces

(Mpumalanga 0.005, KwaZulu-Natal 0.0001 and Free State 0.0057) for the period of study, except North West which had no substantial difference in its maize production. This means that the maize production values are not the same for the period of study expect for North West which had similar values.

4.3 Seasonal Variability

In this section we aim to determine the relationship between maize production and climatic variables across different seasons. The results for this analysis are summarized in Table 4. As shown in Table 4, there is a strong relationship between maize production and agro-climatic parameters in North West (approximately 4 % of variance in maize production can be explained from potential evapotranspiration in the area, precipitation explains 1% while maximum temperature explains 0.72 % of the maize production) during December January (DJ) growing season.

For February March season there was strong relationship between maize production and agro-climatic parameters in Mpumalanga (approximately 17 % of potential evapotranspiration explained the variation in maize production in the area, precipitation explained 12 %, minimum temperature explained 2% and maximum temperature explained 24.7 % the variability in maize production).

Similarly in KwaZulu-Natal Potential evapotranspiration explained approximately 12 % of the variation of maize production in the province, precipitation explained 4 %, minimum temperature explained 3 % and maximum temperature explained 23 % of the variation of the maize production in the province. For Free State, potential evapotranspiration and precipitation explained approximately 9 % of the variability in maize production, minimum temperature explained 5 % and maximum temperature explained 19 % of the variability in maize production.

Table 4: *Influence of the Agro-climatic Parameters on Maize Yield across Seasons. Precipitation (PRE); Potential Evapotranspiration (PET); monthly average daily minimum temperature (TMN); monthly average daily maximum temperature (TMX); North West (NW); Mpumalanga (MP); KwaZulu-Natal (KZN); Free State (FS); December January (DJ); December January February (DJF); February March (FM); November December January February March (NDJFM)*

Variables	DJ				DJF				FM				NDJFM			
	NW %	MP %	KZN %	FS %	NW %	MP %	KZN %	FS %	NW %	MP %	KZN %	FS %	NW %	MP %	KZN %	FS %
PET	4.4	5.6	3.7	1.0	1.3	16	10.8	2.3	0.0	17.4	12.3	9	0.8	14.7	7.5	7.6
PRE	1.2	3.5	0.2	0.5	0.1	6.7	0.0	0.0	0.2	11.5	3.7	8.8	0.5	8	0.0	0.7
TMN	0.2	0.5	2.8	0.2	2.2	0.5	0.7	1	11.5	1.6	3.3	5.1	5.3	0.9	0.3	0.0
TMX	0.7	13.3	14.8	2.1	0.2	20	19.5	6.5	0.0	24.7	23.2	18.6	0.0	24	22	12.2

4.4 Multivariate analysis

In this study, a multivariate regression model was used to assess the impact of climate change based on seasonal PRE, PET, TMN and TMX variables on maize production where land is held in constant variation with production. In particular, the linear relationship developed in this analysis was to determine the maize production change due to changes in the four climate variables during 1986 – 2015, using the seasonal values since maize is grown during this period in South Africa. The relationships were derived based on Equation (8). The multivariate regression analysis results are summarized in Table 5. Based on the results presented in Table 5, the model is able to describe the predisposing factors for variations in the maize production ranging from 44.39 % (0.4439) in the KwaZulu-Natal province to only 7.79 % (0.0779) in North West. Additionally, the *p*-values indicate that the influence of climate on the production of maize is significant in potential evapotranspiration (0.04), minimum temperature (0.02) and maximum temperature (0.0005) for KwaZulu-Natal as well maximum temperature for Mpumalanga (0.02) as their p values are greater than the significant level ($p \geq 0.05$).

As shown in table 5, from 1986 to 2015 an estimated decrease in maize production of about 1480.94 tons was observed for North West province when the values of PET, PRE, TMN and TMX are at their average (that is when PET is 5.25 mm/day, PRE is 74.84 mm/month, TMN is 16.36 ^{o}C and TMX is 30.72 ^{o}C (Table 2)). However, one percent increase in potential evapotranspiration (which is the combination of the other parameter) lead to a decrease of about 852.32 tons in maize production. One percent increase in precipitation (rainfall intensity) lead to decrease in maize production by 3.76 tons. Also, one percent increase in minimum temperature lead to an increase in maize production by 420.86 tons. Likewise, one percent increase in maximum temperature lead to an increase in maize production by 58.07 tons. However, the agro-climatic parameters predicted 7.79 % of the maize production.

For Mpumalanga province an estimated decreased in maize production for about 3535.36 tons was observed when the average of the four agro-climatic parameters are considered (that is when PET is 3.81 mm/day, PRE is 130.42 mm/month, TMN is 14.02 ^oC and TMX is 25.25 ^oC). One percent increase in potential evapotranspiration (combination of the other agro-climatic parameter) lead to a decrease of about 1751.44 tons of maize and also one percent increase in precipitation (rainfall intensity) lead to an increase in maize production by 0.56 tons. Furthermore, one percent increase in minimum temperature lead to a decrease of about 436.04 tons of maize and maximum temperature lead to an increase in maize production by 726.65 tons. In general, agro-climatic parameters only predicted about 32.52% of the maize production in the province (Table 5).

Maize production in KwaZulu-Natal decreased by 2317.28 tons when the average of agro-climatic parameters (PET (3.88 mm/day), PRE (124.37 mm/month), TMN (15.88 ^oC) and TMX (26.74 ^oC)) are considered (Table 5). However, there is a decrease of 395.16 tons and 115.81 tons in maize production when potential evapotranspiration (combination of the other parameters) and minimum temperature are increased by one percent respectively. On the other hand, one percent increase in precipitation and maximum temperature lead to increase of about 1.50 tons and 220.06 tons respectively in maize production. Agro-climatic parameters predicted 44.39 % of maize production in the province.

Considering the average of the four agro-climatic parameters (PET (5.12 mm/day), PRE (81.01 mm/month), TMN (13.92 ^oC), TMX (28.63 ^oC)), a decrease of about 14498.24 tons is observed in Free State (Table 5). One percent increase in potential evapotranspiration and minimum temperature lead to a decrease of about 1989.49 tons and 531.10 tons of maize production respectively. For precipitation and maximum temperature one percent increase lead to an increase of about 18.55 tons and 1185.38 tons in maize production respectively. However, the four agro-climatic parameters only predicted 21.85 % of maize production for Free State.

Overall, Table 5 depicts that, minimum temperature had the most influence on maize production for the study period in North West since it had the least p-value (0.32). Maximum temperature however had a notable influence on maize production in Mpumalanga ($p < 0.05$). For KwaZulu-Natal, potential evapotranspiration, minimum temperature and maximum temperature are the most influencing parameters. The most influential agro-climatic parameter to maize production in Free State is maximum temperature as it had the lowest *p*-value.

Table 5: *Coefficients of the model. Precipitation (PRE) in mm/month; Potential Evapotranspiration (PET) in mm/day; monthly average daily minimum temperature (TMN) in °C; monthly average daily maximum temperature (TMX) in °C; Maize tons; KwaZulu-Natal (KZN)*

Province	Crop	Constant	PET (*p*-value)	PRE (*p*-value)	TMN (*p*-value)	TMX (*p*-value)	R^2
North West	Maize	-1517.41	-852.32 (0.58)	-3.76 (0.77)	420.86 (0.32)	58.07 (0.89)	7.79
Mpumalanga	Maize	-3535.36	-1751.44 (0.17)	0.56 (0.89)	-436.04 (0.12)	726.65 (0.02)	32.52
KZN	Maize	-2317.28	-395.16 (0.04)	1.50 (0.06)	-115.81 (0.02)	220.06 (0.0005)	44.39
Free State	Maize	-14498.24	-1989 (0.40)	18.55(0.23)	-531.10 (0.19)	1185.38 (0.06)	21.85

Regression models for predicting maize yield from a new set of the four agro-climatic parameters values from equation 8 and Table 5:

*NW: Y = -1517.41 + (-3.76*PRE) + (-852.32*PET) + (420.86*TMN) + (58.07*TMX)*

*MP: Y = -3535.36 + (0.56*PRE) + (-1751.44*PET) + (-436.04*TMN) + (726.65*TMX)*

*KZN: Y = -2317.28 + (1.50*PRE) + (-395.16*PET) + (-115.81*TMN) + (220.06*TMX)*

*FS: Y = -14498.24 + (18.55*PRE) + (-1989*PET) + (-531.10*TMN) + (1185.38*TMX)*

5. Discussion

Maize is the most important grain crop grown in South Africa, despite the fact that South Africa is largely arid and semi-arid. However, the success in South Africa maize production depends on various factors, including weather and climate conditions. This study investigated the impact of PRE, PET, TMN and TMX climate variables on maize production in the North West, Free State, KwaZulu-Natal and Mpumalanga provinces, South Africa. The land cultivated for maize production during 2002-2015 was on average of about 1,036,000ha in Free State, 748,000ha in North West, 484,000ha in Mpumalanga and about 82,000ha in KwaZulu-Natal. Generally, the total provincial maize yield from KwaZulu-Natal was low, mainly due to the smaller land used for maize cultivation compared to the other provinces, most of the cultivated land in this province is under sugarcane production. Nonetheless, the maize yield per given unit land size was highest in KwaZulu-Natal due to favourable climate for maize production. On the other hand, the highest provincial maize yield was harvested from Free State due to the largest land used for the production of maize but the yield per unit area was the smallest among the provinces (Table 2).

Areas in the same climatic zone had similar agro-climatic parameters, except for maximum temperature in North West for the study period (1986-2015) which is different from that of Free State even though they are both in the same climatic zone (Table 2 and Fig 2). A noticeable disparity in the variation of the agro-climatic parameters among all the provinces is evident. For instance precipitation in Mpumalanga varies more than the other provinces, while the North West exhibits the greatest variability in potential evapotranspiration and maximum temperature. And the minimum temperature in Free State varied more than the other provinces. In case of maize production there is dissimilarity in the variation pattern within and among the provinces. The high variation in precipitation (Table 2) which happen to be the most influencing agro-climatic parameter in North West (Table 5) coupled with the high fluctuation in maximum temperature which went as high as 35 ^{o}C for some months could have contributed to the reduction in maize yield (negative trend, Fig 4d).

The recent drought that affected numerous sectors in the country is more evident across the study area, with most of these regions depicting a decrease in precipitation and an increase in potential evapotranspiration and maximum temperature (Fig 4), which is detrimental to crop production. The increase in the annual potential evapotranspiration and maximum temperature value is notable in all the provinces. The increase in the monthly potential evapotranspiration is subtle while there was significant increase in the monthly maximum temperature for all the provinces. The seasonal values showed notable increase in the potential evapotranspiration of North West and maximum temperature for all the provinces except Free State which had no significant increase in the maximum temperature.

From Table 4 the most significant season that impacts maize production differs from province to province. For instance, DJ favours maize production in North West province more than the other seasons. This could be attributed to the peak precipitation that is received during this season. This is also the planting season or germination stage when maize requires a warm and moist conditions for seedlings to emerge quickly (Jean 2003). For the other province (that is Mpumalanga, KwaZulu-Natal and Free State) however, FM months are more crucial to maize production. In order to enhance productivity farmers should regulate their planting time.

It is however important to note that aside from the agro-climatic parameters other factors which influence maize production in the provinces include land available for production, farm management decisions, government decision, topography, soil type and so on. From the time series analysis of production plotted against cultivated land (Fig 3), it can be deduced that production increases with increasing cultivated or available land and vice versa.

In North West and Free State provinces the agro-climatic parameters contribute about 7.79 % and 21.85 % respectively to maize production whereas in Mpumalanga and KwaZulu-Natal, the agro-climatic parameters contribute 32.52 % and 44.39 % of maize production. For North West, the minimum temperature has more influence on the maize production than the other agro-climatic parameters (Table 5), manipulating time of planting will help reduce the effect of minimum temperature on the maize production. In the case of Mpumalanga and Free State, maximum temperature has more influence on maize production than the other parameters. For KwaZulu-Natal (humid-subtropical) PET which is the combination of the other agro-climatic parameters, minimum temperature and maximum temperature influences maize production. The use of conservation agriculture and high yielding maize varieties will benefit the farmers to increase maize production. In Free State provinces, the maximum temperature is found to influence maize the most, and identifying drought tolerant maize varieties will improve adaptive capacity of the farmers. We can conclude that maximum and minimum temperature influences maize production positively in all the provinces. But for KwaZulu-Natal more than one agro-climatic parameter influences maize production and the other two parameter (that is PET and TMN) which significantly influence maize production in the province had a negatively influence.

6. Conclusions

Many of the previous studies on the impact of climate change on crop production in South Africa have utilized methodologies such as crop processing, statistical and econometric models. Thus far, the body of literature focusing on determining a suite of agro-climatic parameters influencing maize production has largely remained in-exhaustive. This study contributes to this vital topic through investigating the most dominant climatic variables that influence maize yield in four provinces of South Africa. It is evident from this study that in the context of global change, increase in temperature leads to higher rate of evapotranspiration. On the other hand, decrease in precipitation leads to prolonged drought conditions which impact negatively on maize production. According to the South African Weather Service, there had been approximately 8 summer-rainfall seasons which had been 80 % less than normal in South Africa between July 1960 and June 2004. To combat this, farmers in Mpumalanga and KwaZulu-Natal could practise conservation agriculture whereby mechanical disturbance of soil is reduce and suitable variety of crops are grown. Furthermore, farmers in humid-subtropical areas of KwaZulu-Natal and Mpumalanga should get involved more in maize production since these areas favour maize yield per hectare more compared to the semi-arid areas (that is Free and North West). Additionally, identification of suitable maize varieties that tolerate frost for North West and drought and heat wave for Free State can be of great help. A limitation to this study is the non-availability of data on the cultivated land size covering the same time span of other data sets. This would have helped in making a time series comparison with maize yield and agro-climatic variables. However, the land data (2002-2015) indicated that there is strong similarity between cultivated land and production. This can be taken to be true for the previous years where data was not available. Finally, further studies are recommended to investigate the influence of other non-climatic factors such as farmers' decision making process, who may or not have been informed due to access to information on climate change among other factors.

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Author Contributions

Omolola M. Adisa collected and analyzed the data and drafted the manuscript. Christina M. Botai drafted and finalized the manuscript. Joel O. Botai coordinated the group study and edited the manuscript. Abubeker Hassen, Daniel Darkey and Eyob Tesfamariam were involved in designing and discussing the study. Alex A. Adisa interpreted the analysis and edited the manuscript, while Abiodun Adeola prepared study area and edited the manuscript and Katlego P. Ncongwane edited the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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