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Impacts of Agroclimatic Variability on Maize Production in the Setsoto Municipality in the Free State Province, South Africa

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Abstract: The majority of people in South Africa eat maize, which is grown as a rain-fed crop in the summer rainfall areas of the country, as their staple food. The country is usually food secure except in drought years, which are expected to increase in severity and frequency. This study investigated the impacts of rainfall and minimum and maximum temperatures on maize yield in the Setsoto municipality of the Free State province of South Africa from 1985 to 2016. The variation of the agroclimatic variables, including the Palmer stress diversity index (PSDI), was investigated over the growing period (Oct–Apr) which varied across the four target stations (Clocolan, Senekal, Marquard and Ficksburg). The highest coefficients of variance (CV) recorded for the minimum and maximum temperatures and rainfall were 16.2%, 6.2% and 29% during the growing period. Non-parametric Mann Kendal and Sen's slope estimator were used for the trend analysis. The result showed significant positive trends in minimum temperature across the stations except for Clocolan where a negative trend of 0.2 to 0.12 °C year^{-1} was observed. The maximum temperature increased significantly across all the stations by 0.04–0.05 °C year^{-1} during the growing period. The temperature effects were most noticeable in the months of November and February when leaf initiation and kernel filling occur, respectively. The changes in rainfall were significant only in Ficksburg in the month of January with a value of 2.34 mm year^{-1}. Nevertheless, the rainfall showed a strong positive correlation with yield (r 0.46, p = < 0.05). The overall variation in maize production is explained by the contribution of the agroclimatic parameters; the minimum temperature (R^2 0.13–0.152), maximum temperature (R^2 0.214–0.432) and rainfall (R^2 0.17–0.473) for the growing period across the stations during the study period. The PSDI showed dry years and wet years but with most of the years recording close to normal rainfall. An increase in both the minimum and maximum temperatures over time will have a negative impact on crop yield.

Keywords: agroclimatic variability; minimum and maximum temperatures; maize yield; rainfall patterns; Setsoto municipality; climate change; Free State province

1. Introduction

There is a global consensus that climate change trends are real, and a rapidly advancing threat to millions of livelihoods, by affecting agricultural activities, food security, water resources, health, social systems and the appropriate functioning of ecosystems Barros, Field [1]. Some studies forecast that the necessary increase in food production needs to be between 70 and 210% by 2050 and 2100, to ensure global food security [2,3]. Temperature and rainfall are very important factors that affect crop production [4], mainly affecting the duration of the growing season [5]. The relationship between temperature and rainfall is very variable across the globe [6], this finding is also true for South Africa, but the model projections for the next 20–50 years show that the eastern portion of the country will receive approximately the same rainfall with the western parts becoming significantly drier [7]. The relationship between temperature and rainfall is in most cases an inverse relationship; thus, the higher the temperature the lower the rainfall [8,9]. The study by Dasgupta, Morton [10] indicated that the mean global temperature has increased by 0.5 °C per annum. This rising temperature trend suggests that there is an increase in warm indices (hot days, hottest days) and a decrease in extreme cold indices (cold days, cold nights) [9]. Studies across the world show that minimum temperatures are increasing at a faster rate than the maximum temperatures which may be as a result of global warming [11–13].

Global warming affects climate change and increases the occurrence of extreme weather events including flooding and droughts [14]. The surface air temperatures in some areas of Africa have shown a steady increase of 0.03 °C annually [15]. The South African average air temperature has increased by 1.2 °C since the 1960s and the warming rate has increased at twice the global average rate [16,17]. Thus, understanding the underlying factors that influence the climatic change of the region could improve forecasting and limit the negative impacts in the region (Richard et al., 2001).

Agricultural production is susceptible to climate change variability in the Sub-Saharan region. Higher temperatures can decrease crop yields and animal production [18]. According to Scholes et al. (2015) for each one-degree Celsius rise in temperature, there is a 5% decrease in crop yield. Temperatures raised above optimal levels create biochemical challenges for plant cells, more especially the enzymes associated with the photosynthetic pathway. The southern and northern parts of Africa are expected to be about 4 to 6 °C hotter by 2080 and the precipitation is projected to decrease by 10–20% by this period (Collier et al., 2008). Derived variables, e.g., Palmer Stress Diversity index (PDSI), are used across the globe for monitoring meteorological drought as well as agricultural drought [19,20]. The meteorological component deals with changes in rainfall, whilst the agricultural drought component indicates changes in soil moisture. In this research, the self-calibrating PDSI (Sc-PDSI) proposed by Wells [21] was used as an indicator of agricultural drought, since we are interested in the soil moisture and potential evaporation without focusing on the impact of agricultural practices, including fertilizer applications and improved seed and water conservation measures on the yield of maize [22,23].

Maize (*Zea mays* L.) is the most common staple crop grown in Sub-Saharan Africa (SSA) [24]. It is a dominant component in the diets of most households in the region. On average, a decreasing trend of 10–20% in maize yield has been projected by 2050 for the tropics as a result of climate change [25]. Maize grows better at low to medium (20–28 °C) temperatures, because that allows for maximum radiation interception and optimal growth [26].

South Africa is amongst the ten highest maize producing countries in the world [27]. It produces an average of 12 million tons per year; contributing approximately 2% of the world's maize production [28]. The Free State province alone produces over 35% of the maize in South Africa [29]. Overall, the environmental conditions and natural resources of the Free State are conducive for maize production, but there are concerns of looming agro-climatological hazards which may have a detrimental effect on production [30]. This is supported by Smale and Jayne [31] who found that the output of maize production varies yearly in South Africa mostly due to climate variability. Since only 1% of the cultivated area uses irrigation for maize production [32], there is a particularly high reliance on rainfall and thus vulnerability to changing rainfall patterns and amounts.

This study investigated the impacts of agroclimatic variability on maize production in the district of the Setsoto Municipality in the Free State province of South Africa from 1985 to 2016. Droughts and extreme events are becoming more frequent and the drought characteristics are not well understood, at this particular local scale. Temperature and rainfall patterns are usually presented over an annual cycle but this study focusses on this important region, at the time scale of the growing season, October to April. The spatial variability in the temperature and rainfall trends is high which could negatively impact the maize yields for this area which are relatively low when compared with other maize growing locations. This district may be very close to the threshold where maize can no longer be grown, and this will have a major impact on rural poverty and unemployment. Currently, all stations studied were suitable for maize production, but the interaction of increasing temperatures with evapotranspiration into the future will make some areas in the Free State province less suitable for maize production [33,34].

2. Materials and Methods

2.1. Study Area

The Setsoto Municipality is under the administrative district of Thabo Mofutsanyane in the Free State province (Figure 1). The seasonal rainfall usually starts in October and ends in April with more than 80% of the rainfall occurring from October to March [35,36]. The soil type is shallow, loamy soil with moderate water holding capacity [37]. Soil degradation and overgrazing are prominent environmental problems which have not received adequate research attention [38].

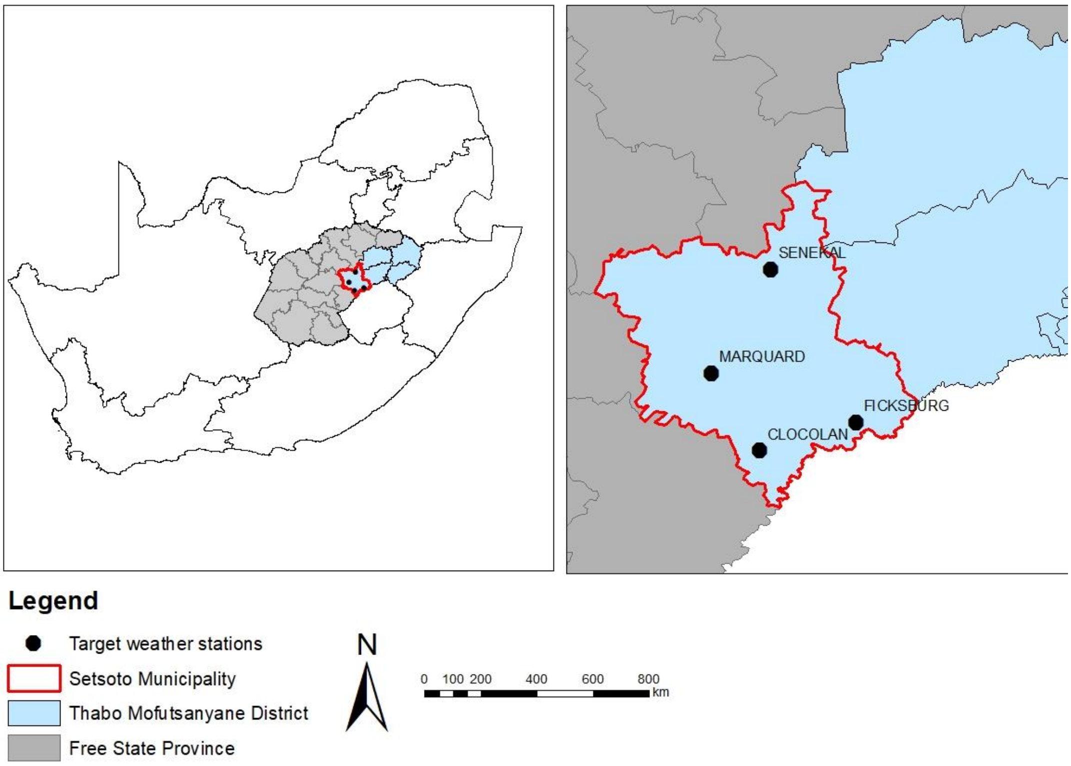

Figure 1. Map of the Free State province of South Africa showing the locations of the study area, the Setsoto Municipality and the target weather stations.

The availability of weather stations and completeness of data played important roles in the selection of the target stations within the municipality. This study targeted the weather stations in Clocolan, Marquard, Senekal and Ficksburg based on their spatial location and availability of data. There were five other stations nearby that were used for infilling missing data, these were selected based on the availability of data and proximity to the target stations (Table 1).

Table 1. List of weather stations used for this study with their longitudes, latitudes, elevation, duration of data availability and their data type. R denotes rainfall and T denotes both the minimum and maximum temperatures.

	Weather Stations	Latitude	Longitude	Elevation (m)	Data Type	Data Period (Years)
1	Senekal-AGR	−28.32200	27.6200	1433	R	40
2	Ficksburg	−28.82700	27.9040	1628	R&T	32
3	Marquard	−28.66500	27.4250	1497	R&T	40
4	Clocolan	−28.92108	27.5840	1602	R&T	36
5	Senekal-Driepan	−28.38900	27.5865	1587	R&T	31
6	Paul Roux	−28.29900	27.9480	1569	R	39
8	Lambertianin	−28.8200	27.5820	1646	R	32
7	Uintjieshoek	−28.5830	27.5200	1600	R	31

The average rainfall of Thabo Mofutsanyana is 600 mm per annum [39]. The province has the highest number of farming units in South Africa, with large areas of fertile and arable lands resulting in a significant proportion of the nation's agricultural production [40].

2.2. Data and Data Management

The daily maximum and minimum temperatures and the daily rainfall data of the study area for the period from 1985–2016 were obtained from the Agricultural Research Council (ARC) meteorological database and the South African Weather Service (SAWS). In this study, an agricultural year is defined from July to June of the following year. This allows the presentation of the growing period from October to April of the following year as a continuous record.

Meteorological data with the smallest number of missing data values (≤5%) were selected from stations within the municipality The UK method was used for the infilling of daily T_{max} and T_{min} values because of the technique's ability to accommodate the differences in altitude and its local effects. Missing rainfall data were estimated using the modified Inverse Distance Weighting method (IDWm), which allows for the influence of elevation on rainfall [41,42], missing rainfall, T_{min} and T_{max} values were less than 10% of the total data set, which satisfies the world meteorological organization (WMO) criteria for a robust climatic data analysis. Only stations with a complete data set having a duration of not less than 30 years were used for IDWm (Table 1).

Maize yield data (tons ha^{-1}) for the Setsoto Municipality for the period between 1985 and 2016 were obtained from the South African Department of Agriculture, Forestry and Fisheries [43] for the four areas except for Ficksberg where data were only available for 1985–2005. Most of the statistical analyses were computed using quantum XL 2016 and JASP 0.9.0.1 statistical software. Collection and availability of temperature, rainfall and yield data are very limited in South Africa due to the lack of infrastructure and compliance, this is a common problem especially in SSA. It would have been ideal if these data could have been used together with other variables e.g., measurements of evaporation and radiation but again these data are not collected by the South African Weather Service nor by the farmer's unions.

The self-calibrating PDSI (Sc-PDSI) was calculated using monthly temperature and precipitation. A detailed description of the fairly complex calculation of the Palmer index consisting of five steps is published in several journals [21,44–46]. The Sc-PDSI accounts for all the constants contained in the PDSI and includes a methodology in which the constants are calculated dynamically based upon the characteristics present at each station location. The self-calibrating nature of Sc-PDSI is developed for each station and changes based upon the climate regime of the location. It has wet and dry scales. The index was calculated for three decades as well as for the entire data set from 1985–2016. According to Palmer [44], the range of the monthly index time series is between −4 and +4. Negative (positive) PDSI values indicate dry (wet) periods, while those near-zero presume a state that is close to the average rainfall. The Palmer hydrological drought index (PHDI), is used to assess long-term moisture supply. The Sc-PDSI was calculated using a program developed by researchers in URL https://github.com/Sibada/scPDSI.

2.3. Climatic Trend Analysis

The non-parametric Mann Kendall (MK) test [47] was used to determine the significance of the climate trends, because the climatic data were not independent and normally distributed. The seasonal trends for T_{min}, T_{max} and Rainfall during the growing period with yield data were determined using a linear regression model. The free and open software package developed by the Finnish Meteorological Institute (MAKESENS) (https://en.ilmatieteenlaitos.fi/makesens) was used for the Mann Kendall (MK) test and Sen's slope estimator. The Sen's slope estimator allows for the significance of the trend to be analyzed. The MK test is robust, simple and frequently used in climate, environmental and hydrological studies [13,48–51]. The Sen's slope is a robust estimate of the underlying trend.

2.4. The Crop Yield Anomalies and Correlation with Climate Variables

The Pearson correlation coefficient which has proven to be an appropriate method for gaining insights into this type of study [52] was used to determine the relationship between maize yield and climatic variables. The data were detrended before performing linear regressions which prevents periodicity in the data. T_{min} and T_{max} anomalies and rainfall anomalies were correlated with detrended yield values to investigate the impacts of agroclimatic variables on maize production for the period of the study. Detrended yield values were used, for only the growing months (October–April), the coefficient of variance (CV) and standard deviation (SD) were calculated. The CV shows the variability of data around the mean of the population CV= μ/σ where: σ = standard deviation, μ = mean, the variability of the data is determined using CVs presented as a percentage. The standard diversion measures the dispersion of the dataset as relative to its mean. It is the square root of variance.

3. Results and Discussion

3.1. Variation in the Minimum and Maximum Temperatures during the Growing Period (October–April)

The average mean annual T_{min} of the area is presented in Table 2. The range of the average mean T_{min} was from 10.4 °C to 14.2 °C and for T_{max} was from 25.6 °C to 28.6 °C. The lowest T_{min} of 5.6 °C and the T_{max} of 10.0 °C were found in Ficksburg. The highest T_{min} and T_{max} recorded during the growing period in Clocolan were 16.4 °C and 31.2 °C, respectively. The CV of the T_{min} and T_{max} was between 5.8% to 16.0% and 3.8% to 8.3%, respectively (Table 2).

Table 2. The mean, minimum, maximum, SD and CV (%), for the minimum and maximum temperatures during the growing period (°C) in the Setsoto Municipality for the period between 1985 to 2016.

	T_{min} (°C)					T_{max} (°C)				
Stations	**Mean**	**Min**	**Max**	**SD**	**CV**	**Mean**	**Min**	**Max**	**SD**	**CV**
Marquard	11.6	10	13.4	0.7	6.2	27.1	24.7	29.5	1.1	4
Clocolan	14.2	9.9	16.4	2.1	14.9	28.6	24.1	31.2	2.4	8.3
Senekal	12.1	9.4	13.4	0.7	5.8	27.7	25.1	30.4	1.1	3.8
Ficksburg	10.4	5.6	13.9	1.7	16	11.6	10	13.4	0.7	6.2

3.2. The Growing Period Rainfall from 1985 to 2016

The average rainfall for the growing period in Setsoto ranged from 540.71 mm to 632.38 mm with CV ranging from 21 to 29% (Table 3). Ficksburg had the highest rainfall during the growing period (1154.10 mm) while Marquard had the lowest rainfall (204.1 mm). The patterns of rainfall variations of the growing period were similar between Senekal and Marquard and Clocolan and Ficksburg with only observed differences of about 3% between them. The rainfall of the growing period accounts for approximately 88% of the annual rainfall (Table 3).

Table 3. Rainfall (mm) during the growing period October–April (mean, minimum, maximum, standard deviation and coefficient of variation) in Setsoto Municipality (1985–2016).

Stations	Average Rainfall in Growing Period (mm)					Annual Rainfall (mm)				
	Mean	Min	Max	SD	CV	Mean	Min	Max	SD	CV
Marquard	540.7	204.1	969.5	158.5	29	613.4	259.1	1029.7	178.2	29
Clocolan	593.2	329.6	888.7	122.9	21	677.1	386.5	1074.9	149.4	22
Senekal	569.9	310	952	149.9	26	645	386.8	1019.2	167.4	26
Ficksburg	632.4	359.2	1154.1	151.4	24	718.1	397.6	1224.1	168.8	23

Mean annual rainfall over the Setsoto municipality ranged from 613 mm to 718 mm (Table 3). The summer months from October to April account for most of the annual rainfall in the municipality. The highest annual rainfall values observed were in Ficksburg with 1224 mm (Table 3). The lowest value ranged from 259 mm to 397 mm. Ficksburg had the highest mean annual rainfall (718.1 mm) followed by Clocolan (677.1 mm), while the lowest was recorded in Marquard (613.4 mm) followed by Senekal (645 mm) The CV of the annual rainfall was very high ranging from 34 to 45 (Table 3).

3.3. Maize Crop Production 1985—-2016

The average maize yield for Setsoto from 1985 to 2016 ranged from 1.96 tons ha^{-1} to 2.89 tons ha^{-1}. The highest maize yield achieved during this period was in 2016 with 6.18 tons ha^{-1} in Clocolan, while the lowest of 0.10 tons ha^{-1} was recorded in 1991 in Senekal (Figure 2). The maize yield CVs over this period was between 37.8% and 46.2% per annum, with a standard deviation of between 0.91 and 1.31 tons ha^{-1} across the municipality (Table 4).

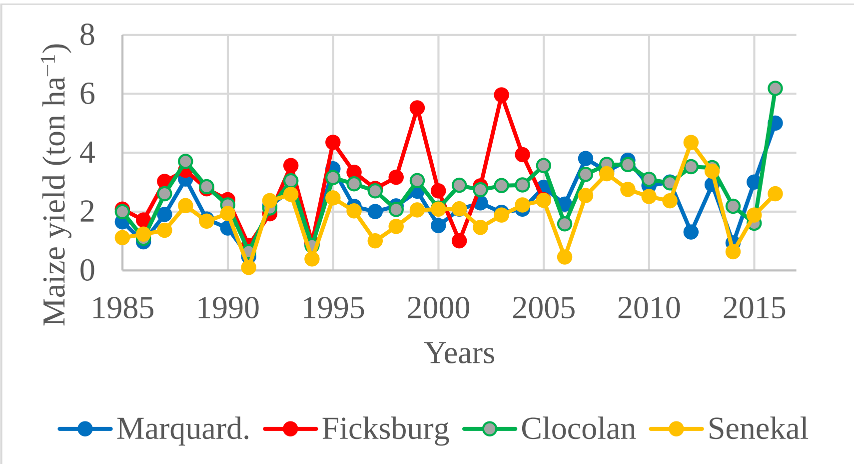

Figure 2. The annual maize yield (tons ha^{-1}) for the four stations in the Setsoto municipality from 1985 to 2016 used for this study.

Table 4. The average maize yield (tons ha^{-1}) for the four stations in Setsoto Municipality from 1985–2016 used for this study.

	Average Maize Yield (tons ha^{-1})				
Stations	Mean	Min	Max	SD	CV
Marquard	2.33	0.47	5	0.98	41.93
Clocolan	2.72	0.64	6.18	1.03	37.75
Senekal	1.96	0.1	4.34	0.91	46.19
Ficksburg	2.89	0.85	5.96	1.33	46.21

The dataset available for Ficksburg in this study was only for 20 years (1985–2005), as opposed to 32 years in the other three weather stations. Each station showed high inter-annual variation in yield. All seem to overlap at least in the first few years (1985 to 1995). The yield in Ficksburg showed the highest inter-annual variation between 1995 and 2005 (Figure 2).

3.4. Climate Trend Analysis

3.4.1. Minimum and Maximum Temperature Trends

The Clocolan monthly and the growing period minimum temperatures showed a negative trend at the 0.001 significance except in the months of November and April which showed a negative trend at a significance level of 0.05. The values of the Sen's slope were all less than zero (Table 5). In Senekal the T_{min} did not show any trend for the period of the study except for the month of January, where an increase of 0.02 °C year^{-1} was reported, compared to the increasing trend of 0.05 °C per annum shown in Ficksburg at a significance level of 0.05. In Marquard the T_{min} trend showed a positive trend for the months of October, November and December at the rates of 0.09, 0.09 and 0.06 °C increase year^{-1}, respectively during the growing period (0.01 significance level). The February, March, April and the growing period trends were negative with decreases of minimum temperatures of 0.1, 0.2, 0.25 and 0.05 °C year^{-1} (Table 5).

Table 5. Setsoto monthly growing period minimum temperature annual trends during the growing period from 1985–2016. Mann Kendall (MK) trend (Test Z) and Sen's slope estimate (Q).

Months	Marquard			Clocolan			Senekal			Ficksburg		
	Test z	**Q**	**R^2**	**Test z**	**Q**	**R^2**	**Test z**	**Q**	**R^2**	**Test z**	**Q**	**R^2**
OCT	2.72 **	0.09	0.25	−3.5 ***	−0.18	0.55	0.62	0.01	0	−0.05	0	0
NOV	2.64 **	0.09	0.25	−2.47 *	−0.15	0.35	−0.1	−0.01	0	−0.15	−0.01	0
DEC	3 **	0.06	0.36	−3.61 ***	−0.12	0.42	0.73	0.01	0.02	0.58	0.02	0
JAN	0.36	0.01	0	−3.51 ***	−0.12	0.43	1.64 *	0.02	0.1	2.3 *	0.05	0.1
FEB	−3.71 **	−0.1	0.34	−3.34 ***	−0.12	0.46	0.89	0.02	0.05	1.61	0.07	0.06
MAR	−3.91 **	−0.23	0.6	−3.57	−0.2	0.5	0.97	0.02	0.04	1.49	0.05	0.03
APR	−4.25 **	−0.25	0.61	−2.39	−0.15	0.35	−1.43	−0.04	0.06	0.84	0.03	0
GP	−3.52 **	−0.05	0.42	−3.7 ***	−0.14	0.42	1.39	0.01	0.01	1.51	0.03	0.03

NB: *** denotes significance when alpha = 0.001, ** denote significance when alpha = 0.01 and * denote significance when alpha = 0.05.

A commonly occurring pattern in climate change studies shows minimum temperatures to be increasing globally and more particularly in Sub-Saharan Africa [53]. The trends were very variable, all stations showing increases, except Clocolan which showed an overall decrease. The projected mid-altitude minimum temperature increases for subtropical Africa is 2.6 °C century^{-1} [54]. The data were very variable by the month and in Marquard, there is a significant increase in the trend of T_{min} in the months of October, November and December, likewise in January in Senekal and Ficksburg. These data are very difficult to explain. It is interesting to note that, T_{min} spatial–temporal variability is just outside the WMO 30 km radius used for justification of infilling of data. There are local factors such as vegetation cover, topography, slope and aspect of the area which affect the rainfall and temperature distribution. The IPCC (2014), states that provided the anthropogenic and greenhouse emissions remain at 2014 levels, these results fall within the projected century temperature increases of 3 °C, but only for extreme events [54].

In the months of October and November in Marquard, Senekal and Ficksburg the growing period T_{max} showed an increasing trend ranging from 0.04 to 0.10 °C year^{-1} at various levels of significance (Table 6). In Clocolan, T_{max} showed a decreasing trend in the months of March and April by 0.16 and 0.14 °C year^{-1} (0.05 significance level).

Table 6. Monthly Maximum Temperature (°C) annual trends during the growing period for the study period from 1985–2016. Mann Kendall MK Test Z denote Mann Kendall trend analysis test, and Q denotes 'the Sen's slope estimate' for the Setsoto municipality.

Months	Marquard			Clocolan			Senekal			Ficksburg		
	Test z	Q	R^2	Test z	Q	R^2	Test z	Q	R^2	Test z	Q	R^2
OCT	3.71 **	0.12	0.4	−0.68	−0.05	0.02	3.91 ***	0.12	0.38	3.02 **	0.11	0.26
NOV	1.9 +	0.08	0.11	−0.31	−0.03	0	2.38 *	0.08	0.15	2.09 *	0.1	0.14
DEC	0.76	0.04	0.04	0.13	0	0	0.44	0.02	0.03	1.52	0.06	0.12
JAN	0.26	0.01	0.01	−1.01	−0.04	0.02	−0.05	0	0.01	1.28	0.04	0.02
FEB	0.83	0.03	0.01	−1.1	−0.1	0.01	0.66	0.03	0.05	1.96 *	0.09	0.19
MAR	1.61	0.06	0.1	−2.01 *	−0.16	0.14	1.12	0.04	0.07	2.5 *	0.06	0.02
APR	1.1	0.05	0.03	−2.11 *	−0.14	0.06	0.7	0.04	0.01	−0.29	−0.01	0
GP	2.38 *	0.04	0.23	−1.23	−0.06	0.24	2.29 *	0.05	0.22	2.12 *	0.04	0.21

NB: + denote significance when alpha = 0.1, *** denote significance when alpha = 0.001, ** denote significance when alpha = 0.01 and * denote significance when alpha = 0.05.

The maximum temperatures over most of SSA are expected to increase above the global average [55]. The increasing trend of maximum temperature for Southern Africa is non-linear and its intensity is expected to increase drought and crop failure [14]. In this study, the maximum temperatures in the period between 1985 and 2016 showed an overall significant increase, during the maize growing period across the stations in the Setsoto municipality. The only months with significant decreases in T_{max} were March and April in Clocolan, while for the rest of the months either it remained unchanged or showed a significant increase (Table 6). The annual maximum temperatures increased by 0.08 °C year^{-1}, giving an increase of 2.56 °C for the entire study period of 32 years. These results also agree with the findings published by the IPCC (2014). The results also fall within the projected SSA temperature increases of 6.5 °C for the century [55–58].

3.4.2. Rainfall Trend Analysis

For all the stations used in this study only the month of January showed a positive trend of increasing rainfall in the Ficksburg station with 2.34 mm year^{-1} at a 0.05 significance level (Table 7). The rainfall trends for the study period of 32 years (from 1985 to 2016) in the Setsoto Municipality showed no significant changes. This statement applies to the seasonal distribution of the rainfall, the total amounts of rainfall and yearly distributions. The only significant data found were for the month of January in Ficksburg, where the rainfall significantly increased by 2.34 mm year^{-1} (Table 7). Rainfall in the Free State province shows high variability with the patterns, distribution, intensity and duration of rainfall varying spatially and temporally across different scales [59].

Table 7. Monthly rainfall (mm) and its annual trends during the growing period from 1985–2016 for the Setsoto municipality. MK Test Z denotes Mann Kendall trend analysis test, and Q denotes 'the Sen's slope estimate'.

Months	Marquard			Clocolan			Senekal			Ficksburg		
	Test z	Q	R^2	Test z	Q	R^2	Test z	Q	R^2	Test z	Q	R^2
OCT	−1.44	−1.09	−1.38	−1.38	−1.38	0.049	−1.36	−1.00	−1.31	−1.31	−0.88	0.014
NOV	0.63	0.69	−0.68	−0.68	−0.41	0.002	−0.05	−0.08	−0.26	−0.26	−0.39	0.039
DEC	0.00	0.00	0.97	0.97	1.12	0.031	0.19	0.33	0.65	0.65	0.52	0.039
JAN	−0.02	−0.02	1.12	1.12	1.62	0.042	1.62	2.11	2.06	2.06 *	2.34	0.179
FEB	0.73	0.60	0.44	0.44	0.43	0.011	−0.78	−0.59	−1.04	−1.04	−0.69	0.011
MAR	−0.94	−1.05	−0.99	−0.99	−0.64	0.037	−0.58	−0.56	−0.41	−0.41	−0.46	0.033
APR	−1.09	−0.74	−1.09	−1.09	−0.46	0.005	−0.10	−0.05	−0.44	−0.44	−0.45	0.134
GP	−1.36	−3.22	0.05	0.05	0.11	0.002	0.19	1.05	0.21	0.21	0.55	0.027

NB: * denote significance when alpha = 0.05.

3.5. Maize Yield Trends

Maize yield showed a positive trend in the three stations (Marquard, Clocolan and Senekal) increasing by different magnitudes. The maize yield in Marquard and Clocolan showed a positive trend increasing by 0.05- and 0.039-tons $ha^{-1}y^{-1}$, respectively. In Senekal, maize yield showed an increasing trend of 0.043 tons ha^{-1} (Table 8).

Table 8. Annual maize yield trends during the study period from 1985–2016. MK Test Z denotes the Mann Kendall trend analysis test, and Q denotes 'the Sen's slope estimate'.

	Test Z	Q	R^2
Marquard	2.76 **	0.050	0.218
Clocolan	2.45 **	0.039	0.196
Senekal	2.92 *	0.043	0.183
Ficksburg	1.27	0.054	0.119

NB: ** denote significance when alpha = 0.01 and * denote significance when alpha = 0.05.

Agroclimatic and maize yield variability in Sub-Saharan Africa (SSA) depends on the interactions between the combination of temperature, rainfall, and adaptive strategies [60]. The results from this study agree with other studies in SSA particularly with respect to temperatures and yield [61–66]. There were positive trends in all the stations for maize yield from 1985 to 2016 (Table 8). Marquard had the highest increasing trend of 0.05 tons ha^{-1} $year^{-1}$, followed by Senekal with 0.043 tons ha^{-1} $year^{-1}$ and Clocolan with 0.039 tons ha^{-1} $year^{-1}$. This general positive trend agrees with those found by [40] on a comparative analysis of maize yields for South Africa. The average maize yield for Setsoto during the period of this study was between 1.96 tons ha^{-1} to 2.89 tons ha^{-1} per year with an inter-annual variability between 38–46% (Table 4). Even though no agronomic data are available for these locations, it seems logical that some of these increases could have been accounted for by changed farming practices e.g., the addition of more inorganic fertilizers and changed maize varieties. The maize yield in the Setsoto municipality is below the free-state provincial average maize yield of 3.8 tons ha^{-1} [67] Maize production is said to be economically viable if 3.6 tons ha^{-1} is produced [40,67], the data from this study showed that maize yield is below this limit. The yield trends in this study were low and it is only marginally economical to produce maize in these areas. The contribution to GDP from farming in the Setsoto municipality is decreasing [68,69] and it has been suggested that some farms are no longer being planted with maize or alternate crops. Yield variability was high across the stations, with Senekal having the highest variability of 46.1% per year and it also recorded the lowest yield among the stations.

3.6. Maize Yield Correlation with Climatic Variables

3.6.1. De-trended Maize Yield Correlation with rainfall, T_{min} and T_{max} Anomalies

The Pearson correlation coefficient (r) and confidence interval levels of 0.05, 0.01 and 0.001 were used in this study to determine the relationship between yield and agroclimatic variables. Rainfall was positively correlated with yield during the growing period in Clocolan and with T_{max} in Senekal (r = 0.46 and 0.48 respectively) (p = 0.008 and 0.0005 respectively) (Table 9). In November, only the T_{min} in Marquard correlated with yield (r = 0.39, p < 0.027). During the month of January, the yield at this station is positively correlated with T_{min} (r = 0.37 and p = 0.038 at 0.05 confidence level).

Table 9. The correlation matrix for the monthly and growing period T_{min}, T_{max} and Rainfall variables with Maize yield in the three stations (the fourth station, Ficksburg, lacks sufficient data for analysis) of the Setsoto municipality from 1985–2016 (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$). GP denotes growing period.

		Marquard			Clocolan			Senekal		
		Pearson's *r*	***p*-Value**	**VS-MPR$^+$**	**Pearson's *r***	***p*-Value**	**VS-MPR$^+$**	**Pearson's**	***p*-Value**	**VS-MPR$^+$**
GP	T_{min}	0.03	0.87	1.00	0.12	0.52	1.00	0.02	0.90	1.00
	T_{max}	−0.18	0.33	1.01	0.12	0.51	1.00	**−0.40** *	0.02	4.43
	Rainfall	0.03	0.86	1.00	**0.46** **	0.01	8.97	0.23	0.20	1.14
OCT	T_{min}	0.07	0.69	1.00	−0.12	0.52	1.00	−0.03	0.89	1.00
	T_{max}	0.06	0.74	1.00	0.02	0.93	1.00	−0.02	0.93	1.00
	Rainfall	0.01	0.95	1.00	0.22	0.24	1.08	0.15	0.40	1.00
NOV	T_{min}	**0.42** *	0.02	5.69	0.04	0.84	1.00	0.07	0.69	1.00
	T_{max}	0.07	0.73	1.00	0.07	0.70	1.00	0.08	0.69	1.00
	Rainfall	−0.08	0.67	1.00	0.11	0.55	1.00	0.18	0.32	1.01
DEC	T_{min}	**0.42** *	0.02	5.69	0.05	0.80	1.00	−0.05	0.78	1.00
	T_{max}	0.09	0.61	1.00	0.23	0.20	1.14	−0.09	0.62	1.00
	Rainfall	−0.04	0.83	1.00	−0.18	0.33	1.01	−0.05	0.80	1.00
JAN	T_{min}	0.37	0.04	3.04	−0.22	0.23	1.10	0.25	0.16	1.24
	T_{max}	−0.35	0.05	2.38	−0.02	0.90	1.00	**−0.37** *	0.04	2.95
	Rainfall	0.05	0.77	1.00	0.22	0.23	1.09	0.25	0.17	1.22
FEB	T_{min}	−0.07	0.71	1.00	0.15	0.42	1.00	0.20	0.28	1.03
	T_{max}	**−0.51** **	0.00	19.83	0.13	0.49	1.00	**−0.42** *	0.02	5.43
	Rainfall	**0.45** *	0.01	7.64	**0.68** ***	<0.001	2118.11	0.17	0.34	1.00
MAR	T_{min}	−0.20	0.27	1.04	−0.28	0.13	1.40	0.02	0.93	1.00
	T_{max}	−0.03	0.87	1.00	−0.09	0.63	1.00	**−0.47** **	0.01	11.76
	Rainfall	−0.19	0.29	1.03	0.00	0.99	1.00	−0.12	0.51	1.00
APR	T_{min}	−0.15	0.41	1.00	−0.08	0.67	1.00	−0.20	0.27	1.04
	T_{max}	0.03	0.86	1.00	0.00	1.00	1.00	−0.17	0.36	1.00
	Rainfall	−0.16	0.38	1.00	−0.19	0.29	1.02	0.07	0.69	1.00

The minimum temperatures were correlated with maize yield only for the Marquard station in the months of November and February, this relationship was also found to be the case in studies conducted by Adisa, Botai [70]. Temperature drives the physiological and morphological development of the maize plant, with each process requiring a different minimum and maximum temperature. For instance, the study by Sanchez, Rasmussen [71] showed that leaf initiation needs a minimum of 7 °C, while shoot growth takes place above 14 °C and root growth above 13 °C. These minimum temperature conditions were not met for all cases except for the leaf initiation process in November (Table 5 above). However, in January the minimum temperature requirements for leaf initiation and shoot and root growth were met even for the late planting cultivars. Minimum temperatures, especially in November, seem to be critical for the early establishment and growth of the seedlings which ultimately influences the yield. The correlation and the regression analyses provided evidence for the significance of the minimum temperature on yield in Marquard, especially in the months of November and January. However, the November minimum temperature trend showed an increase of 0.09 °C per annum (see Table 5 above), which showed an increase of 1% in T_{min} in November increasing the yield by 0.274 tons ha^{-1} in Marquard. Climate change predictions for semi-arid regions of SSA have changed from earlier studies which gave values of 1.6 °C to recent projections of above 2.4 °C by 2050, depending on emissions and other anthropogenic activities [72]. Increasing trends in minimum temperatures are predicted for SSA, and extreme climate events, especially the frequency and severity could negatively impact yields [73].

The February T_{max} was negatively correlated with yield in Marquard and positively in Senekal (r = −0.49 and 0.657; p = 0.005 and <0.001 and 835.835, respectively) at 0.01 and 0.001 confidence levels, respectively. Similarly, the February rainfall in Marquard was positively correlated with yield (r = 0.42, p = 0.018) at 0.05 confidence level. There was also a strong correlation between them in Clocolan (r = 0.69, p < 0.001 and) in the month of February, while in March, the T_{max} in Senekal showed a positive correlation (r = 0.4512 p = 0.003) at 0.01 confidence level with yield (Table 9).

The results from this study showed that the maximum temperatures for the entire growing season were significantly correlated with maize yield only for Senekal. This was as a result of the significant correlation in the months of February and March. The stations of Clocolan and Ficksburg showed no correlation between the T_{max} and maize yield, while those in Marquard showed a significant negative correlation. The results in Marquard were also similar to other studies which showed that temperatures above 30 °C have a negative impact on maize production in southern Africa [74]. Senekal had the lowest maximum temperatures and a 1% increase of T_{max} in the months of February, March and the entire growing period (October–April) could increase the maize yield by 0.029, 0.408 and 0.536 tons ha^{-1} (Table 9). On the other hand, Marquard had the highest maximum temperatures and a 1% increase of T_{max} could decrease maize yield by 0.290 tons ha^{-1}. Lobell, Bänziger [74] showed that a 1% increase of maximum temperature above the optimal temperature for growth under drought stress could result in a maize yield decline of 1.7%. Clocolan had the highest mean T_{max} value and SD value of 28.6 °C and 2.4 °C respectively. There are several other studies that showed that high temperatures, together with soil and plant water stress lead to a decline in crop yield [75,76]. Maize yield in Marquard will be most vulnerable to water stress if the maximum temperatures continue to increase, especially at the anthesis stage, where the optimal temperature is 32 °C and the maximum tolerable T_{max} is 36 °C [58]. Muchow (1990) showed that temperatures outside the range of 13–32 °C decrease the yield by shortening the period of the kernel filling. These conditions also apply in Marquard with high February maximum temperatures which prevailed when kernel filling would have taken place if planting took place in November.

3.6.2. Maize Yield Relationship with Rainfall, Minimum and Maximum Temperature Anomalies

The monthly minimum, and maximum temperatures, as well as the rainfall that showed a significant correlation with maize yield (see Table 9 above) were subjected to regression analysis. The yield was the dependent variable while monthly T_{min}, T_{max} and rainfall were the independent variables used across the different stations of the Setsoto Municipality. The influence of the T_{min} on maize yield during the months of November and January in Marquard were significant ($p < 0.00027$ and $p < 0.038$, respectively) (Table 10). The T_{max} during the month of February showed a significant negative impact on maize yield when regression analysis was conducted ($p < 0.005$, $R^2 = 0.23$) whilst for the same month, rainfall showed a positive impact on the maize yield in Marquard. An increase of one unit of rainfall in (mm) can increase the yield by 0.0921 tons ha^{-1} (Table 10).

Table 10. A summary of regression results between detrended maize yield and the climatic (T_{min}, T_{max} and Rainfall) anomalies. Note: p = p-value at 0.05.

Months	Marquard			Clocolan			Senekal		
	Intercept	p	R^2	Intercept	p	R^2	Intercept	p	R^2
Nov T_{min}	0.274	0.0027	0.152	Nil	Nil	Nil	Nil	Nil	Nil
Jan T_{min}	0.572	0.038	0.135	Nil	Nil	Nil	Nil	Nil	Nil
Feb T_{max}	−0.290	0.005	0.238	Nil	Nil	Nil	0.0290	0.000	0.432
Mar T_{max}	Nil	Nil	Nil	Nil	Nil	Nil	0.408	0.003	0.262
GP T_{max}	Nil	Nil	Nil	Nil	Nil	Nil	0.005	0.008	0.214
GP Rainfall	Nil	Nil	Nil	0.005	0.008	0.214	Nil	Nil	Nil
Feb Rainfall	0.0094	0.018	0.174	0.015	0.000	0.472	Nil	Nil	Nil
GP	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil

In Senekal, maximum temperatures in the months of February, March as well as the entire growing period (October–April) had a significantly positive impact on the maize yield ($p < 0.05$) (Table 10). In February, for every increase in degree Celsius of T_{max} above the base temperature led to an increase of the yield by 0.3459 tons ha^{-1} year^{-1}, while an increase in T_{max} in March and the whole season of the growing period (October–April) led to an increase of maize yield by 0.367 and 0.592 tons ha^{-1} respectively in Senekal (Table 10).

The effect of rainfall during the growing period and the month of February in Clocolan, showed a significant and positive relationship with the maize yield ($p < 0.05$) ($R^2 = 0.214$ and 0.472, respectively). An increase in rainfall by a unit (mm), increased the yield from 0.1028 to 0.1179 tons ha^{-1} year^{-1} (Table 10).

3.6.3. Self-Calibrating Palmer Drought Stress Index

The average Self-calibrating Palmer Drought Severity index (ScPDSI) values for the growing period October–April are shown in Table 11. The first decade (1885–1994) had normal rainfall in Ficksburg, with a dry period in Clocolan and a wet period in Marquad and Senekal. The second decade showed three of the stations having a dry period and in the third decade, again three stations showed a dry period, with an extremely dry period being measured in Marquad. These decadal data support the maize yield data shown in Figure 2 with the first decade having the least variable maize yield.

Table 11. The average Self calibrating Palmer Drought Severity index (Sc_PDSI) values.

Period	Index	Stations			
		Marquard	Ficksburg	Clocolan	Senekal
1985–1994	Sc-PDSI	1.170776	0.097271	−1.52128	1.924278
1995–2004	Sc-PDSI	1.959666	−0.61539	−0.31812	−2.03299
2005–2016	Sc-PDSI	−3.02268	−1.11227	2.235037	−0.10628

Rainfall is a key driver of yield [77]. The amount of rainfall in the month of February was particularly strongly correlated (with $r = 0.69$) with yield in Clocolan and Marquard, adding further support to earlier evidence that the rainfall and temperatures in February have a strong influence on yield. The rainfall received in Clocolan had the lowest variability (CV 21%) when compared with the other stations (CVs up to 49%). Clocolan receives an average rainfall of 593 mm, which was similar to the 500 mm rainfall reported by for the eastern part of the Free State province. The CV associated with the total rainfall of 21–49% across the four stations was high and if either the total rainfall decreases, or variability increases then the risk of crop failure will increase. The results in this study support the findings of [78] who identified November as critical for the start of the growing season in Senekal. Maize planted later than November becomes susceptible to the frost from May onwards before the crops reach maturity [36] and expose the crop to increased rainfall variability. Maize planted in early November, will allow for maximum tasseling and grain-filling in February, which is the most sensitive period for water stress, even more, sensitive than the early establishment stages [79]. This study showed that a 1% increase in the rainfall amount in February and the overall growing period can increase the yield by 0.015- and 0.005-tons ha^{-1} respectively (Table 4). In most African countries agricultural production depends solely on rainfall pattern, distribution and duration [80,81]. This study confirmed the research by who indicated that high variability of rainfall threatens rain-fed agriculture in South Africa. These findings are similar to other previous work showing declining rainfall patterns in southern Africa.

4. Conclusions

The T_{min} and T_{max} trends showed variation across the weather stations used in this study. For instance, the T_{min} in Clocolan, showed a declining trend throughout the growing period between October and April, while in Marquard the minimum temperature increased between October and December. The maximum temperature was consistently increasing in all the stations except for Clocolan, where a decline was only reported for the month of March. The November and February trends are important for maize production that involves planting (leaf initiations, leaf and root growth) and development (tasseling and grain filling) of maize, respectively. The entire growing period (October–April) minimum and maximum temperatures for the period from 1985 to 2016, varied across the four different stations of the Setsoto municipality. The increasing minimum and maximum temperatures in all the stations of this study showed that: (1) where the minimum temperature is currently too low for optimal growth, an increase in these temperatures will increase yield and (2) the overall increase in both the minimum and maximum temperatures over time can negatively impact yield, but the magnitude of the effect is dependent on when exactly the increases are taking place during the growing season. November and February have been highlighted as specific times at which the crop is most at risk.

The changes in rainfall were significant only in Ficksburg in the month of January with a value of 2.34 mm $year^{-1}$ Nevertheless, the rainfall showed a strong positive correlation with yield (r 0.46, $p \leq 0.05$). This study indicates that the rainfall variability is increasing in parts of the study area, which could be attributed to several global and regional rainfall phenomena. There were some periods where it did appear that the yield was below average, similarly, there were periods from 2006–2012, where the yield was above the average maize yield per hectare (2.42 tons ha^{-1}). There are some concerns, especially in the Senekal area, that it will be no longer economically viable for maize production. Yield is not just a product of climatic variables, but also a combination of other agronomic factors. The average rate of increase of yield in the Setsoto Municipality is 0.044 tons ha^{-1} per annum across the stations.

The strongest positive correlation (46–68%) with yield and rainfall was during the growing period in Clocolan. The changes in minimum temperature are having two different effects on the yield in the area where: if it is colder, the yield will be negatively impacted; if it is getting warmer, where the minimum temperature has previously limited yield, the yield will be positively impacted. Increasing maximum temperatures still shows no negative impacts on maize yield except for a single month of February in Marquard. Palmer drought stress indices should be explored further to help support more accurate forecasting. This study serves as an important baseline of the impacts of agroclimatic variables on maize yield at this local scale which is a key area of production. Farmers cannot make rapid decisions about farming practices, where to plant or whether to sell the land. This study contributes to raising awareness about the risk of ongoing maize production in this area.

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