



The impact of past and current district-level climatic shifts on maize production and the implications for South African farmers

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Abstract

South Africa's climate studies generally focus on coarser provincial levels, which aid policy recommendations, but have limited application at the farm level. District level climate studies are essential for farmer participation in climate change mitigation strategies and management. Our study aimed to investigate historical climate data for trends and their influence on maize yields at the magisterial level. Six sites were selected from three major maize-producing provinces in South Africa: Mpumalanga, Northwest, and Free State. Magisterial districts in each province were selected from different Köppen-Geiger climate zones. The climate variables assessed by the Mann–Kendall trend test included maximum or minimum temperature, rainfall, number of extreme high-temperature days, rainfall onset and cessation from 1986 to 2016. The average maximum temperatures were observed to have significant upward trends in most locations, except for Schweizer-Reneke and Bethlehem. The fastest rate of change was observed at Klerksdorp (0.1 °C per 30 years of study), while the Schweizer-Reneke district was the slowest (0.05 °C per 30 years of study). No significant changes were observed in rainfall onset, cessation, or total rainfall in Schweizer-Reneke, Standerton, and Bethlehem, which are scattered across the different provinces. The other districts in each province showed significant changes in these parameters. Rainfall accounted for the significant variation in maize yields over the study period, explaining between 18 and 40% of the variation in the North West, and between 1 and 17% in the Free State. These findings highlight the importance of understanding location-specific changes at a finer scale, which can help farming communities adjust agronomic practices and adapt to local climate shifts.

Keywords Agroclimatic parameters · Climate change · Seasonal variability · Drought · Heat stress · Corn yield

1 Introduction

The agriculture sector is highly dependent on climatic conditions and is therefore more sensitive to climate change than any other resource sector (World Bank, 2014). This has led to a major increase in the number of studies focusing on the impact of future climate change on crop production in recent decades (Pathak et al. 2018; ur Rahman et al. 2018; Anderson et al. 2020; Peng et al. 2020; Mangani et al. 2023). While it is critical to study the effects of climate change on future agricultural production, it is equally important to understand how past shifts in climate have impacted agriculture and current crop yields (Lobell and Field 2007). An understanding of recent climate trends can help anticipate climate change and provide insight into the applicability of technologically-driven progress in yield improvement or maintenance in the future (Lobell and Field 2007).

There are two main methods commonly used to evaluate the potential effects of weather and future climate on

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agriculture: the statistical approach (Wang et al. 2016; Adisa et al. 2018), which is used in this study, as well as mechanistic crop models (Rurinda et al. 2015; Rahman et al. 2018). Statistical crop models that explore the empirical relationships between observed weather conditions and crop yields have been developed from data reported through field surveys or agricultural censuses (Parkes et al. 2019). Mechanistic crop models use mathematical representations of plant physiology to simulate crop growth and yield development for specified environmental conditions and management practices (Chenu 2015; Bustos-Korts et al. 2019; Muller and Martre 2019). The strength of statistical models lies in their limited reliance on field data for calibration, whereas mechanistic models can be very difficult to calibrate even when the required data is available due to their reliance on several uncertain parameters (Lobell and Burke 2010). Statistical models, however, are limited to the sites for which observed data has been collected, making them unsuitable for use in applications or sites that are not directly linked to their design. Mechanistic models are more flexible in this regard and can be derived without any real data as long as the process is described (Pasquel et al. 2022).

Several studies have focused on how historical climate trends affect crop yields over time. These studies have focused on different levels including, global (Lobell and Field 2007), regional (Lobell and Burke 2010) and local (Rowhani et al. 2011; Wang et al. 2015, 2016; Li et al. 2016; Chen and Tian 2016; Adisa et al. 2018) scales. According to Tao and Zhang (2010), the relationships between climate and crop yields are generally scale-dependent. It is thus essential to analyse these relationships at a finer spatial scale to accurately assess the effects of climate change and help develop appropriate adaptation strategies. In South Africa, it is generally more common for studies to focus on coarser spatial resolutions, often at the provincial level (for example Adisa et al. 2018; Mapfumo et al. 2020; Tshikovhi and van Wyk 2021). These studies used agroclimatic parameters for the entire province to explain the variation in yield over time. While such studies have some utility, they have limitations for farmers to implement at the farm level. This is because of the coarse spatial resolution, which provides generalities across a province, but does not explore variations in climate variables within a single province.

Maize plays a significant role in South Africa's economy and food security. It contributes approximately R9.5 billion per annum to the economy (Adisa et al. 2018). In maize production, South Africa is ranked ninth globally, whereas it is second in sub-Saharan Africa (DAFF 2016). In South Africa, maize production accounts for close to 60% of the land under crop production and nearly 70% of grain production (Akpalu et al. 2009). South Africa produces an average of approximately 10.2 million tonnes annually, with roughly 80% of this annual average being used locally as food and fodder (FAO 2012). Every year, nearly

31 000 km² of land is planted with maize, of which roughly 12% is irrigated (Hardy et al. 2011; Bradley et al. 2012). South Africa produces most of its maize (63%) in the Mpumalanga, Free State, and the Northwest provinces. As a percentage of the total maize production in South Africa, the Free State, North West, and Mpumalanga contributed 39%, 23%, and 21%, respectively (South African Grain Quality 2011).

In this study, we consider the distinctions between climatic zones within the three primary maize-producing provinces in South Africa based on the Köppen climate classification (Kottek et al. 2006). We aim to begin addressing the gap in the literature where South African district-level climate studies are underrepresented and urgently required for farmer participation in climate change mitigation strategies. Consequently, our research concentrated on the magisterial districts within the selected provinces, each representing a unique climatic zone. Our objective is to investigate historical climate trends and their influence on maize crop yields at a finer spatial resolution, in contrast to previous studies (Adisa et al. 2018; Mapfumo et al. 2020; Tshikovhi and van Wyk 2021), which often focused on a coarser provincial level. Significant differences in climate shifts were observed across districts within the same provinces, which highlights the need for district-level analyses that can better support industry stakeholders and maize production in these regions. Detailed assessments such as these are essential for helping to support the development of site-specific climate adaptation strategies based on the site's unique climate characteristics.

2 Materials and methods

2.1 Study sites

Six study sites were selected from the three main maize-producing provinces of South Africa, including Mpumalanga, Northwest, and Free State. In each province, two magisterial districts with different climate zones were selected according to the Köppen climate classification system (Fig. 1). Mpumalanga is an exception, as maize is only grown in one climate zone in this province, and the remaining area is unsuitable for production. Consequently, we chose two locations separated by a significant distance (~270 km) to improve the possibility of observing climatic variation. The magisterial districts that were selected, included Klerksdorp and Schweizer-Reneke for the Northwest Province, Lydenburg and Standerton for the Mpumalanga Province, and Bethlehem and Bloemfontein for the Free State Province. All the study sites receive summer rainfall (November to March), have diverse annual precipitation or evaporation, and variable maximum and minimum temperatures (Table S1). The altitude, latitude and longitude Global Positioning System (GPS) coordinates are also provided in Table S1.

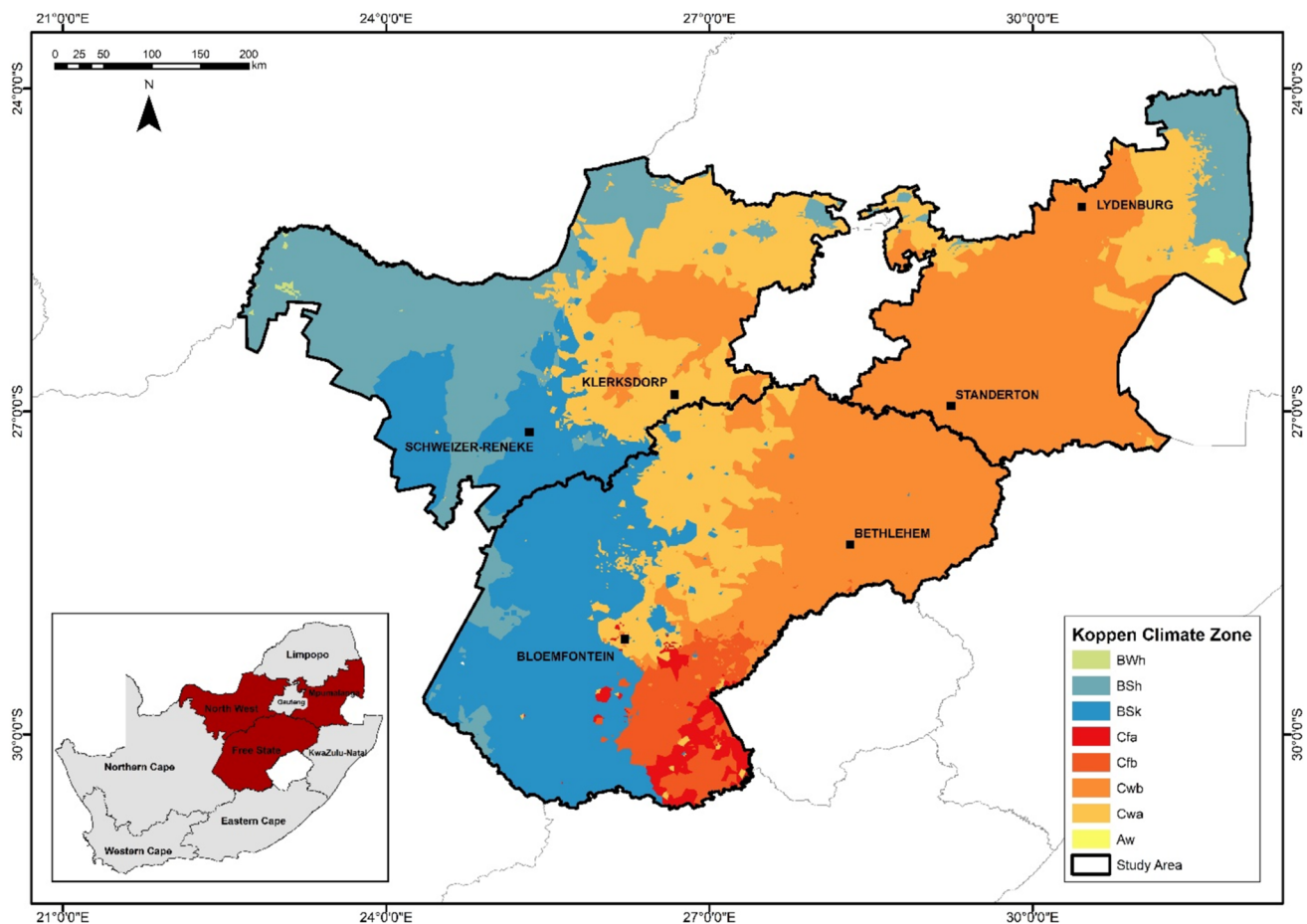


Fig. 1 Map of the study districts (Klerksdorp-Cwa, Schweizer-Reneke-Bsk, Lydenburg-Cwb, Standerton-Cwb, Bethlehem-Cwb and Bloemfontein-Cwa) in the main maize production provinces (North West, Free State and Mpumalanga) of South Africa (bottom left map inset). The descriptions of the Koppen climate zone codes (bottom right color key) on the map are as follows:- **BWh** : hot desert cli-

mate; **BSh** : hot semi-arid climate; **BSk** : cold semi-arid climate; **Cfa** : humid subtropical climates; **Cfb** : oceanic climate; **Cwa** : dry-winter humid subtropical climate; **Cwb** : dry-winter subtropical highland climate; **Aw** : tropical savanna climate with dry-winter characteristics. *Climate data*

Climate data for all six locations were collected from weather stations administered by the Agricultural Research Council - Institute of Soil, Climate, and Water (ARC-ISCW) and the South African Weather Service (SAWS) (www.weathersa.co.za). This dataset contains daily precipitation and the maximum and minimum temperatures from 1986 to 2016. Missing values at each weather station were accounted for using the following methods: (1) In the case where ARC data was incomplete, we made use of SAWS data and vice versa. We pursued this approach because we required climate data obtained from direct observations. (2) Direct substitution of values from the National Oceanic and Atmospheric Administration (NOAA) data (<https://power.larc.nasa.gov/data-access-viewer/>) was performed when ARC and SAWS data had missing values. Though SAWS and the NOAA make use of the same stations, NOAA also employs a gap-filling method including careful estimations of missing values to represent a complete data set with no gaps.

2.2 Calculations for days with extreme high temperatures, rainfall onset and cessation

The number of days with extremely high temperatures (EHT) was calculated using the maximum temperatures across the seasons at each location. Any day with a maximum temperature greater than or equal to 35 °C was considered to be an EHT day. This was averaged across the study period and rate of change decimals are explained as the amount of change over time, so an increase of 0.5 days per season indicates that over four seasons the season would have shifted in that variable by two days. The EHT variable was used, because the final grain yield of maize has been observed to be negatively influenced by high temperatures, which can suppress ovary fertilization and grain filling (Siebers et al. 2017; Lizaso et al. 2018). Additionally, the anthesis-silking interval increases with heat stress and

reduces the viability and amount of pollen produced (Lizaso et al. 2018).

To determine the rainfall patterns at different locations within the study area, we analysed daily rainfall data for 30 growing seasons spanning from 1986 to 2016. The data was converted into rainfall dekads, which are 10-day periods of rainfall. In South Africa, the summer growing season spans from November of the previous year to March of the following year. A calculation of the dekads for the entire year, from January 1st to December 31st was conducted. When rain extended into the next year, as expected because of the rainfall pattern in this region, we added the dekads to the 36 existing dekads in a year (for instance, 36 + 1 when rain occurred in the first dekad of the following year). This enables outliers to be removed when averaging dekads. Rainfall fluctuations were determined using the dekads allocations and averages. The date of rainfall onset in the study area was defined as the last day in which rainfall of 25 mm or more accumulated over the previous 10 days and at least 20 mm accumulated in the subsequent 20 days. Generally, this criterion has been widely used to determine the start of the growing season for dryland maize in the semi-arid areas of southern Africa (Tadross et al. 2005; Hachigonta et al. 2008; Moeletsi and Walker 2012). With an additional 20 mm of rainfall over the next two dekads, the crop will not only germinate, but will also be able to sustain itself through its early developmental stages. To determine the end of the rainy season, we followed the method used by Moeletsi and Walker (2012), which defines the end of the season as the last day on which the cumulative rainfall totals 25 mm or less over a 10-day period.

2.3 Crop yield data

Time-series maize yield data for specific locations were acquired from the Directorate of Statistics and Economic Analysis of the Department of Agriculture, Land Reform, and Rural Development of South Africa. The crop estimation process is carried out by the Crop Estimates Committee (CEC), under the direction of the Department of Agriculture, Land Reform, and Rural Development. The CEC is responsible for estimating both summer grains (such as maize, sunflower seed, soybeans, groundnuts, sorghum, and dry beans) and winter cereal crops (including wheat, malting barley, and canola). To generate these estimates, the CEC utilizes geographic information system (GIS) technologies combined with robust statistical methods.

In addition to these tools, the consortium conducts aerial surveys over provinces heavily involved in the production of key crops, such as maize, to improve the accuracy of the data regarding planted areas. Multiple layers of information—ranging from provincial data, Agricultural Research Council (ARC) insights, and input from the South African Grain

Information Service (SAGIS), among others—are incorporated. Extensive farmer surveys conducted by the Department of Agriculture, Land Reform, and Rural Development are also considered and used as checks and balances. All of these inputs are synthesized to provide reliable and complete estimates of crop areas and production across different districts and provinces, which are then aggregated into national estimates (Cerfonteyn 2016). The data consists of provincial production datasets and average magisterial district yields for different locations within the provinces of South Africa. For our study, we focused on the total maize yield per hectare for each study site at the district level, which was calculated from the production data for each magisterial location in tons divided by land cultivated in hectares. The time series yield data spanned 30 seasons from 1986/87 to 2016/17.

2.4 Statistical tests and analyses

Trends for all climatic variables and yield production were assessed for each of the six locations separately using the Mann–Kendall (MK) trend test (Equations S4; Supplementary file). The MK trend test is a non-parametric test used to identify trends in a series and the calculations by Alemu and Dioha (2020) were used in our study. It is also used to determine whether a time series exhibits a monotonic upward or downward trend. This method has been widely used to detect hydrological, climatological, and crop-yield series (Lobell and Asner 2003; Chmielewski et al. 2004; Tao et al. 2006). This test has two distinct advantages. Firstly, it does not require the data to follow a normal distribution because the test is non-parametric or distribution-free. Secondly, the test exhibits low sensitivity to abrupt breaks in data, even when dealing with non-homogeneous time series (Blain 2013). For these reasons, the method has been endorsed by the World Meteorological Organization (Mitchell et al. 1966). The null hypothesis is that no trend exists in the population on which the dataset is based, whereas an alternative hypothesis implies the opposite (Pohlert 2020). A null hypothesis was accepted when the *p*-value exceeded the α level of significance and rejected when the *p*-value was less than or equal to the α level of significance. In this study, the level of significance, $\alpha = 0.05$, was used for all locations and parameters. The Theil–Sen estimator was then used for calculating the magnitude or rate of change of trends in climate. It is a robust estimator that can handle outliers effectively. One of the advantages of the Theil–Sen estimator is that it does not rely on any assumptions about the distribution of errors. Instead, it is based on the median rather than the mean. The formula for the Theil–Sen estimator is provided in Equations S5 (Supplementary file).

Spatially aggregated annual maize yields at the magisterial-district level and the coefficient of determination (r^2) were used to examine the relationship between annual maize production

and agro-climatic factors. The r^2 statistic helps to quantify the extent to which independent variables, in our case, temperature (Tmin and Tmax, EHT days), total seasonal rainfall, rainfall onset, and rainfall cessation, explain the variance in the dependent variable, which in our case is the crop yield across different study sites. To mitigate the influence of long-term yield improvements resulting from factors such as improved seeds, fertilizers, pesticides, and crop management, we employed a common detrending technique involving the first differencing of time-series data for both climate variables and crop yield, as previously suggested in the literature (Lobell et al. 2005; Lobell and Field 2007; Bhatt et al. 2014). The relationship between detrended crop yields and agroclimatic parameters during the growing season was then evaluated using the coefficient of determination (Zhang 2017).

Multiple linear regression models were fitted to test the effects of the detrended agroclimatic variables (described above) on maize yield at the six different study sites. Models included changes in crop yield (Y) as the dependent variable, and maximum temperature (Tmax), minimum temperature (Tmin), extreme high temperature (EHT), rainfall (seasonal), rainfall onset (dekads) and rainfall cessation (dekads) as the independent variables. The fitted model is defined as:

$$\Delta Y = \beta_0 + (\beta_1 \times \Delta \text{Tmax}) + (\beta_2 \times \Delta \text{Tmin}) \\ + (\beta_3 \times \Delta \text{Rainfall}) + (\beta_4 \times \Delta \text{EHT}) \\ + (\beta_5 \times \Delta \text{Ro}) + (\beta_6 \times \Delta \text{Rc})$$

where ΔY , ΔTmax , ΔTmin , $\Delta \text{Rainfall}$, ΔEHT , ΔRo and ΔRc denote the change in crop yield, Tmax, Tmin, rainfall, EHT, rainfall onset and rainfall cessation, respectively. The constant β_0 denotes the intercept of the model, while the constants β_1 to β_6 denote the coefficients of independent variables. The values of the parameters β_1 to β_6 were estimated from the data using the least-squares method (Miller 2006). The coefficient of a variable indicates the impact of a one unit change in that variable on the year-to-year change in maize yield whilst keeping the other variables fixed. The significance level for all statistical tests was set at $p=0.05$. All analyses were conducted using XLSTAT software (Data Analysis and Statistical Solution for Microsoft Excel, Paris, France).

3 Results

3.1 Spatial-temporal climate characteristics and maize yield at the district level

Average rainfall onset, cessation, and quantity were assessed over 30 years at different locations. On average, rain began on the 29th dekad in Mpumalanga (Table 1) at

both locations (Standerton and Lydenburg). The onset of rains occurred a little later in the Free State with Bloemfontein and Bethlehem starting around the 30th dekad, while the North West province had the latest onset of rain with larger differences between the two districts in the province. In Schweizer-Reneke the rain onset was more than a dekad later than in Klerksdorp (Table 1). A similar analysis of the average rain cessation showed that rains ceased in similar dekads for both districts in the Free State province (13th dekad) and the North West province (~ 12th dekad). Interestingly, the timing of rainfall cessation in Mpumalanga was different between the two districts with Standerton's rain ceasing more than 2 dekads before Lydenburg (Table 1). These findings indicate that districts in the same province have rainy seasons of different lengths, with Schweizer-Reneke in the North West province and Standerton in the Mpumalanga province having shorter seasons than the other districts in their respective provinces (Table 1). Lydenburg in Mpumalanga province, which had a longer rainy season than the other district in the province, also averaged the highest rainfall (681.76 mm/season) of all sites investigated over the 30-year time frame. The lowest average rainfall was recorded for Bloemfontein (365.83 mm/season), which was closely followed by Schweizer-Reneke (387.37 mm/season) with a documented short rainy season (Table 1).

The average maximum (Tmax) and minimum (Tmin) temperatures showed that Bloemfontein had the highest mean values, followed by Schweizer-Reneke and Klerksdorp at 30 °C and 29 °C, respectively. The lowest mean maximum and minimum temperatures were observed in Lydenburg (Tmax 20.82 °C/ Tmin 11.86 °C). The highest average Tmin temperatures (summer night time temperatures), were recorded in the North West province (Tmin Schweizer-Reneke 15.45 °C, Tmin Klerksdorp 14.60). The number of days with EHT (Tmax \geq 35 °C) was also calculated (Table 1), and again Bloemfontein had the highest EHT count (15.33 days), followed by Schweizer-Reneke (10.61 days). The lowest number of EHTs was observed at Lydenburg (0.21 days), Bethlehem (0.33 days), and Standerton (0.86), suggesting these regions are less prone to extremely high temperatures that can negatively affect maize production (Table 1).

Overall, Lydenburg is the coolest, wettest maize-growing region in this study and Bloemfontein is one of the hottest driest regions in the study. However, the tested climate variables over the 30-year period show high variability in most cases. This is apparent in all the parameters measured except for Tmin and Tmax measurements. Different parameters showed higher variance in different locations, for example, a relatively high variance was observed for rainfall in Lydenburg, a high variance in rain onset was observed in Schweizer-Reneke, a high variance in cessation was observed

Table 1 The mean and variance of maize yields and agro-climatic variables from the North West (Schweizer-Reneke and Klerksdorp), Free State (Bethlehem and Bloemfontein), and Mpumalanga (Standerton and Lydenburg). The agro-climatic variables are rainfall, rain-

fall onset, rainfall cessation, maximum temperature (tmax), minimum temperature (tmin), extreme heat temperature (EHT) days and maize yield

Province	Location	Variable	Mean	Variance	Location	Variable	Mean	Variance
North West	Schweizer-Reneke	Yield (Ton/ha)	2.88	2.66	Klerksdorp	Yield (Ton/ha)	2.28	1.00
		Rainfall (mm/season)	387.37	20 658.41		Rainfall (mm/season)	454.28	22 949.35
		Rainfall onset	31.91	9.96		Rainfall onset	30.88	7.98
		Rainfall cessation	11.82	6.93		Rainfall cessation	12.59	9.39
		Tmin (°C)	15.45	0.85		Tmin (°C)	14.60	0.63
		Tmax (°C)	29.82	1.57		Tmax (°C)	29.42	2.15
Free State	Bethlehem	EHT days	10.61	101.68	Bloemfontein	EHT days	9.39	110.00
		Yield (Ton/ha)	2.17	1.36		Yield (Ton/ha)	3.55	0.96
		Rainfall (mm/season)	557.55	29 207.15		Rainfall (mm/season)	365.83	16 755.34
		Rainfall onset	29.97	2.61		Rainfall onset	30.69	5.77
		Rainfall cessation	13.41	12.97		Rainfall cessation	13.04	12.26
		Tmin (°C)	12.52	0.38		Tmin (°C)	14.14	0.48
Mpumalanga	Standerton	Tmax (°C)	25.96	1.64	Lydenburg	Tmax (°C)	30.13	1.90
		EHT days	0.33	1.10		EHT days	15.33	140.10
		Yield (Ton/ha)	3.3	2.50		Yield (Ton/ha)	4.78	4.99
		Rainfall (mm/season)	481.53	25 622.78		Rainfall (mm/season)	681.76	45 529.06
		Rainfall onset	29.54	1.52		Rainfall onset	29.50	1.55
		Rainfall cessation	11.42	9.99		Rainfall cessation	13.62	11.82
		Tmin (°C)	12.90	1.39	Tmin (°C)	11.86	0.37	
		Tmax (°C)	26.73	1.38	Tmax (°C)	20.82	1.68	
		EHT days	0.86	4.62	*EHT days	0.21	1.11	

EHT day - Any day with a maximum temperature ≥ 35 °C

in Bethlehem, and a high variance in ETH was observed in Bloemfontein (Table 1, Figure S1). The high variance observed for the different parameters suggests that these parameters are not as stable as temperatures across the 30 seasons and so shifts and trends over this period should be investigated.

In our selected study sites, Mpumalanga had the highest yields in the Standerton and Lydenburg districts. While the Free State districts (Bloemfontein and Bethlehem) and the Northwest districts (Klerksdorp and Schweizer-Reneke) had comparable yields (Table 1). Generally, maize yields varied across the different study sites with Lydenburg having the highest mean (4.78 tons/ha) followed by Bloemfontein with yields averaging 3.55 tons/ha over the 30 years (Table 1). Klerksdorp and Bethlehem had the lowest average maize yields with 2.28 tons/ha and 2.17 tons/ha, respectively. There was a marked difference in yield across locations with the same climate. For instance, Bethlehem (2.28 tons/ha), Standerton (3.3 tons/ha), and Lydenburg (4.78 tons/ha), all of which fall under the dry-winter subtropical highland climate (Fig. 1). This was also true for locations within the same province, such as Bethlehem and Bloemfontein, which each had 2.28 tons/ha a 3.355 tons/ha respectively (Table 1). Maize yields were highly variable between the

years in Lydenburg and Schweizer-Reneke, suggesting shifting trends or high seasonal variability.

3.2 Trend analysis of climatic variables and maize yields across the magisterial districts

Given the high variability observed across the 30 years at each location for the different parameters (Table 1), we evaluated whether maize grain yield and climate variables showed any significant upward or downward trends over the 30-year study period. Rainfall onset, cessation and total rainfall in Schweizer-Reneke, Standerton and Bethlehem showed no significant changes or shifts in trends over the last 30 years (Table 2; Fig. 2). Interestingly, these study sites were each in a different province and the other district in each province did show significant changes in several of these parameters. Klerksdorp (North West) showed a significant decreasing trend in rainfall over the last 30 years and is likely getting drier by 5.73 mm per season (Table 2; Fig. 2d). Lydenburg presented with a significant decreasing trend in the onset of rainfall suggesting the rainy season is becoming shorter in this district (Fig. 2b). Bethlehem also appears to have a shortening rainy season, however, this is due to a later onset of rain,

as indicated by the significant upward trend observed over the 30 years. These results indicate that rainfall patterns and amounts are shifting in different ways in each district (Table 2; Fig. 2), which suggests that a district-level approach will provide better insights into the changes in water availability as climate change progresses.

The average maximum temperatures were observed to have significant upward trends in most locations (Fig. 2a-c),

which is in keeping with our understanding of how climate change is progressing. Notable exceptions were the Schweizer-Reneke and Bethlehem districts, which did not show any significant trends in Tmax over the study period. The fastest rate of change was observed at Klerksdorp, and the slowest rate was observed in Schweizer-Reneke, with values of 0.1 °C and 0.05 °C over the study period (Fig. 2a and c). In support of the regions generally getting warmer over time,

Fig. 2 Trend rate of change for of maize yield, maximum (Tmax) and minimum (Tmin) temperatures, extreme high temperature (EHT) days, rainfall onset and cessation for each location in each province including North West (a), Mpumalanga (b) and Free State (c). The seasonal rainfall for all locations was plotted separately due to the larger rate of change values (d). Asterisks above a bar denotes a significant rate of change as indicated by the Mann–Kendall test with a *p*-value < 0.05.

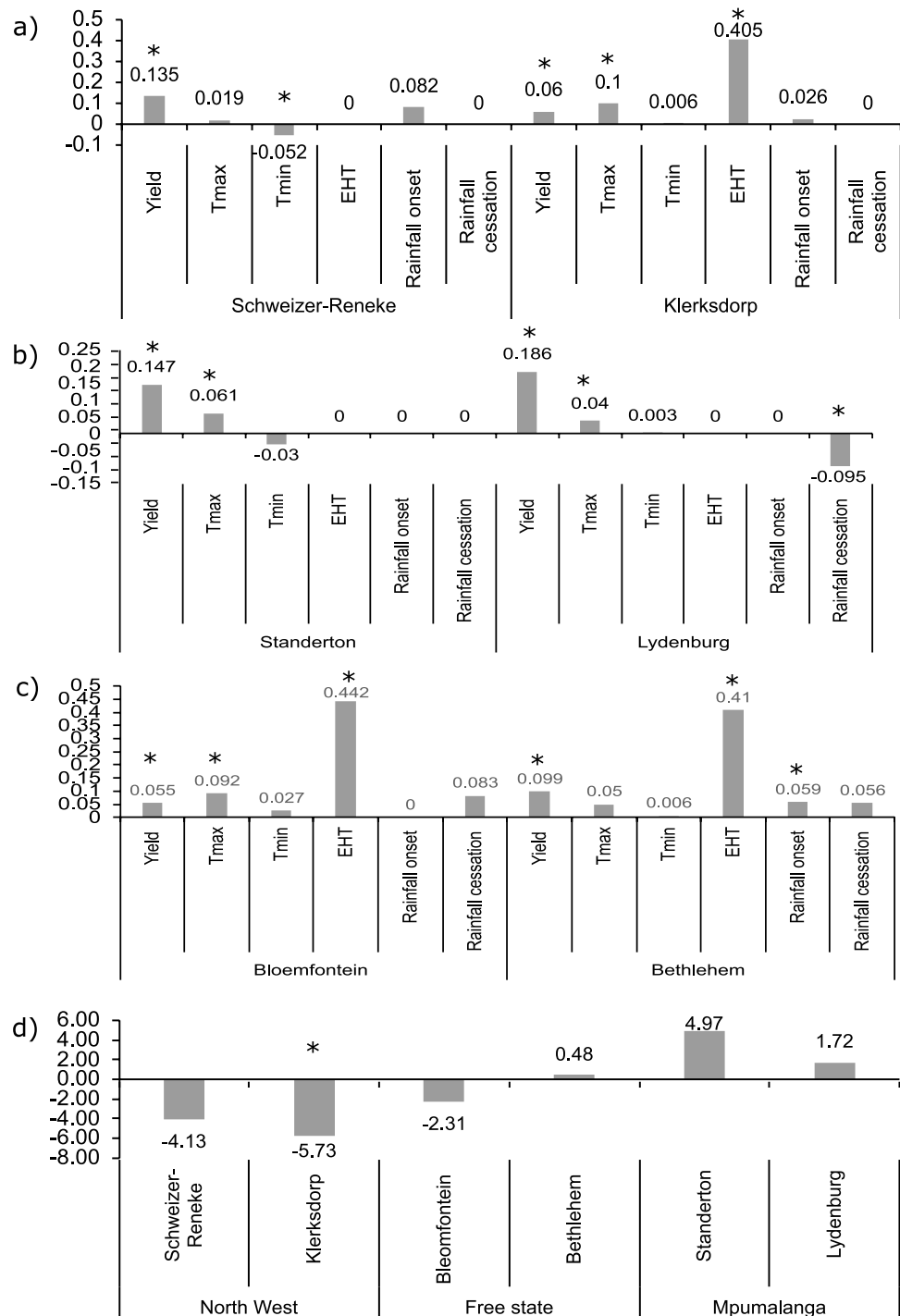


Table 2 Trends in maize yields and agro-climatic variables from the North West (Schweizer-Reneke and Klerksdorp), Free State (Bethlehem and Bloemfontein), and Mpumalanga (Standerton and Lydenburg). The variables were rainfall, rainfall onset and cessation, maximum temperature (tmax), minimum temperature (tmin), extreme heat temperature (EHT), and maize yield

Province	Location	Variables	p-value	Significance	Trend	Location	Variables	p-value	Significance	Trend
North West	Schweizer-reneke	Rainfall (mm/season)	0.188	No	No trend	Klerksdorp	Rainfall (mm/season)	0.023	Yes	Downward
		Rainfall onset	0.163	No	No trend		Rainfall onset	0.06	No	No trend
		Rainfall cessation	0.627	No	No trend		Rainfall cessation	0.773	No	No trend
		Tmax (°C)	0.394	No	No trend		Tmax (°C)	0.000	Yes	Upward
		Tmin (°C)	0.000	Yes	Downward		Tmin (°C)	0.609	No	No trend
		EHT days	1.000	No	No trend		EHT days	0.001	Yes	Upward
Free State	Bethlehem	Yield (Ton/ha)	<0.0001	Yes	Upward	Bloemfontein	Yield (Ton/ha)	0.001	Yes	Upward
		Rainfall (mm/season)	0.938	No	No trend		Rainfall (mm/season)	0.345	No	No trend
		Rainfall onset	0.025	Yes	Upward		Rainfall onset	0.554	No	No trend
		Rainfall cessation	0.344	No	No trend		Rainfall cessation	0.282	No	No trend
		Tmax (°C)	0.0570	No	No trend		Tmax (°C)	0.000	Yes	Upward
		Tmin (°C)	0.676	No	No trend		Tmin (°C)	0.070	No	No trend
Mpumalanga	Standerton	EHT days	0.009	Yes	Upward	Lydenburg	EHT days	0.047	Yes	Upward
		Yield (Ton/ha)	<0.0001	Yes	Upward		Yield (Ton/ha)	0.003	Yes	Upward
		Rainfall (mm/season)	0.149	No	No trend		Rainfall (mm/season)	0.745	No	No trend
		Rainfall onset	0.837	No	No trend		Rainfall onset	0.193	No	No trend
		Rainfall cessation	0.563	No	No trend		Rainfall cessation	0.02	Yes	Downward
		Tmax (°C)	0.037	Yes	Upward		Tmax (°C)	0.046	Yes	Upward
		Tmin (°C)	0.223	No	No trend		Tmin (°C)	0.768	No	No trend
		EHT days	0.104	No	No trend		EHT days	1	No	No trend
		Yield (Ton/ha)	<0.0001	Yes	Upward		Yield (Ton/ha)	<0.0001	Yes	Upward

EHT day - Any day with a maximum temperature ≥ 35 °C

most districts showed no significant changes in trends for the T_{min} . The only exception was observed for Schweizer-Reneke, which showed a downward trend, indicating that the minimum temperatures have decreased over the last 30 years by a significant rate of $0.052\text{ }^{\circ}\text{C}$ (Fig. 2a).

Both Mpumalanga districts showed no trends or changes in ETH, which remained at an average of 0.86 days (Standerton) and 0.21 days (Lydenburg) over the study period (Fig. 2b; Table 1). Schweizer-Reneke also showed no significant rate of change in the number of EHT days over the 30 years and this remains at a high of approximately 10 days over the study period (Fig. 2a; Table 1). The two Free State districts, Bethlehem and Bloemfontein, showed a significant change in the rate of EHT days over the 30 years, with an increase of 0.44 and 0.41 days over the study period (Fig. 2c). A similar significant rate of change (0.41) was observed in Klerksdorp, which suggests these regions may be more prone to longer and more frequent heat waves as climate change progresses.

The trend analyses of climatic variables show clear signs of climate change in each district we assessed across the three main maize-producing regions. The same trend analysis of maize yields was performed for the same period and district. The maize yield showed a significant increasing trend at all study sites (Fig. 2a-c). However, the rate of change across the districts was different. The Free State locations, Bloemfontein and Bethlehem, showed the smallest rate of change only increasing by 0.055 and 0.099 tons per hectare over the 30 years. Standerton, Lydenburg and Schweizer-Reneke all showed a moderate rate of increase ranging from 0.135 to 0.186. Klerksdorp showed the fastest rate of change over the 30 years improving by 0.405 tons per hectare.

3.3 The influence of agroclimatic parameters on seasonal yields

A correlation analysis was conducted to understand the relationship between the climatic variables and maize yield, and

an analysis of each climatic factor and its contribution to the observed variation throughout the growing season (from germination to maturity) was performed (Table 3). In the North West province, for both districts (Schweizer-Reneke and Klerksdorp), most of the variation in yield observed across the 30 years can be correlated with changes in ETH days (12.76% and 15.35% respectively) and rainfall averages (18.25 and 40.02% respectively), for Klerksdorp these two variables explain more than 50% of the variation in yield observed over the study period (Table 3). In Bethlehem, rainfall also explained 16.58% of the variation in yield, but T_{max} explained 39.82% of the yield variation over the same period and together these variables explain more than 50% of the variation (Table 3). In Bloemfontein T_{max} also contributed 21.52% to the yield variation and together with ETH and rainfall cessation accounted for over 50% of the yield variation observed over the study period. Interestingly, in the Mpumalanga province, significant differences were observed at the district level (Table 3). In Standerton, 93.79% of the yield variation over the 30-year study period could be attributed to three variables (T_{max} , T_{min} and average rainfall), with temperature driving 71.95% of the variation. Conversely, in Lydenburg, the variation in yield, which is high (Table 1), was not well explained by any of the climatic variables tested in this study with none contributing over 5% to the observed yield variation (Table 3). This suggests that other variables or interactions of multiple variables are driving yield variation in Lydenburg and remain to be identified.

3.4 Linear regression models estimate the effect of climatic variables on changes in maize yield

Table 3 presents an assessment of the contribution of individual variables to the variation in observed yields at each of the study locations. Here, we used multiple linear regression models to estimate the effects of changes in T_{max} , T_{min} , rainfall, EHT, rainfall onset, and rainfall cessation on the year-to-year changes in maize yield (Table 4). Linear models explained the amount of change in maize yield variation and

Table 3 Influence of agro-climatic parameters on maize yield over 30 years across different locations in the main maize-producing areas of South Africa. Values represent coefficients of determination (r^2)

Location	T_{max}	T_{min}	EHT	Rainfall	Rainfall Onset	Rainfall cessation
Schweizer-Reneke	0.08%	5.99%	12.76%	18.25%	6.82%	0.22%
Klerksdorp	0.05%	2.05%	15.35%	40.02%	2.52%	0.71%
Standerton	32.61%	39.34%	0.86%	21.84%	2.00%	0.88%
Lydenburg	2.01%	0.32%	0.42%	3.51%	4.48%	4.43%
Bloemfontein	21.52%	2.58%	17.46%	1.00%	0.66%	13.14%
Bethlehem	39.82%	8.39%	1.35%	16.58%	4.15%	2.92%

derived from correlating seasonal yield and agroclimatic parameters over 30 years and are expressed as a percentage of yield variation explained by the climatic factor

* T_{min} and T_{max} indicate maximum and minimum temperatures. ** EHT = Extreme High Temperature

how well the data fit the regression model is represented by the coefficient of determination (r^2), which varied from 27–81% across all the selected locations. In the North West province, the coefficient of the changes in Tmax and rainfall cessation was observed to be statistically significant in both locations (Table 4). The coefficient of the change in rainfall onset is, however, significant for Schweizer-Reneke, but not for Klerksdorp. Using a similar interpretation for the other provinces, it is evident that, although a variable may have a significant influence on the change in yield in one location, it may not have a significant impact on a different location even within the same province.

The intercept of the regression models gives the average year-to-year change in yield when the year-to-year change of all climate variables is held constant. For Standerton and Lydenburg, the results indicate that the average change in yield is 0.153 and 0.128 tons/ha, respectively, when all the other variables are held constant. According to the regression model for Standerton, if the year-to-year change in Tmax increases by 1 °C, the change in yield is expected to decrease by 0.454 tons/ha (with all the other climate variables fixed). However, a 1 °C increase in the year-to-year change in Tmin is expected to increase the change in yield by 0.674 tons/ha.

Generally, the models indicate that an increase in the changes in Tmax and rainfall cessation tends to decrease (except in Bloemfontein, Standerton and Lydenburg) the yield in half the locations, while increases in Tmin and rainfall onset typically has the opposite effect (except in Bloemfontein, Standerton and Schweizer-Reneke). The impact of changes in EHT varies from location to location, but changes in rainfall do not appear to have a large impact on the year-to-year change in yield. Lastly, it is important to note that the impact of the variables on the yield is not often the same for locations in the same province. For example, in Mpumalanga, the impact of changes in Tmin in Standerton (0.674 tons/ha) is greater than in Lydenburg (0.410 tons/ha). In addition, the impact of a change in rainfall onset on the year-to-year change in yield not only has differing

magnitudes, but the results indicate that a one-unit change would on average result in an increase in the change in yield in Lydenburg, but a decrease in Standerton. The expected change in yield given new values for the changes in the climate variables, can be calculated according to Eq. (1) to (6) (Equations S1). Overall, the results of the regression analysis demonstrate the importance of considering smaller areas constituting the same climate as opposed to entire provinces with differing climates, as the impact of climatic variables may vary, even if the locations are within the same province.

4 Discussion

South Africa is mostly an arid and semiarid zone, yet maize is still the most important grain crop in this region. These highly variable weather and climatic conditions significantly influence the success of maize production in South Africa. In this study, we analysed the climatic trends and changes observed over the past three decades and investigated their effects on maize yields. The results showed that most of the locations had an increasing trend in extreme high-temperature days (ETH) and maximum temperatures (Fig. 2; Table 2). The locations that showed warming trends included Bloemfontein, Klerksdorp, Standerton, and Lydenburg, whereas Schweizer Reneke and Bethlehem showed non-significant directional changes in high temperatures. EHT days provide some indication of heat waves and the likelihood of these, becoming longer or more frequent as climate change progresses. We also noted, over and above general warming, that half of the districts had an increasing trend in the number of EHT days. This was true for Bethlehem, Klerksdorp and Bloemfontein, whereas for Schweizer Reneke, Standerton and Lydenburg there was no significant directional change. This confirms the results of Engelbrecht and Monteiro (2021), which show that South Africa is trending towards a warmer climate in the Southern African region. Temperature increases are projected to be approximately 1.5 to 2 times higher than the global average. Our

Table 4 Multivariate model coefficients for seasonal average daily maximum temperature (tmax) in °C; seasonal average daily minimum temperature (tmin) in °C, seasonal rainfall in mm/growing season;

extreme high temperature (ETH) days (Tmax 35 °C), rainfall onset and cessation for magisterial locations in North West, Free State and Mpumalanga Provinces of South Africa

Province	Location	Constant	Tmax	Tmin	Rainfall	EHT	Rainfall onset	Rainfall cessation	R^2
North West	Schweizer-Reneke	0.024	-0.691*	0.158	0.000	0.003	-0.045*	-0.022	0.72
	Klerksdorp	0.076	-0.703*	0.174	-0.001	-0.005	0.003	-0.017*	0.81
Free State	Bethlehem	0.039	-0.551*	0.208	0.000	0.001	0.170	-0.001	0.49
	Bloemfontein	0.065	0.057	-0.016	0.001	-0.063*	0.119	-0.046	0.56
Mpumalanga	Standerton	0.153	-0.454*	0.674*	-0.001	-0.001	-0.021	0.046	0.68
	Lydenburg	0.128	-0.607	0.410	-0.001	0.177	0.265	0.074	0.27

*Significant at $p < 0.05$

study has revealed that the effects of climate change are not a distant problem, but are already visible in the current data affecting important agricultural regions of South Africa.

Our results suggest that these increasing temperature trends have a negative influence on maize yield. This influence was demonstrated by the impact of EHT and maximum temperatures on the average crop yields of the studied locations during the study period. Extreme temperature days contributed to variations in crop yields, ranging from 13 to 17% in Schweizer Reneke, Klerksdorp, and Bloemfontein (Table 3). In the case of Bloemfontein, Bethlehem, and Standerton, Tmax contributed significantly, accounting for between 20 and 40% of the variation in average crop yields (Table 3). Warming increases the rate of crop development taking fewer days to reach flowering (silking) and physiological maturity, which leads to lower yields (Fatima et al. 2020). Other negative effects of warming are related to high evapo-transpirative demand that cannot be satisfied by rainfall, which thereby inhibits plant growth (Medlyn et al. 2002; Cuo et al. 2015).

Researchers have observed that yield declines at temperatures of 30 °C or higher, are less likely related to direct heat stress on reproductive organs than they are to heating-induced water stress caused by increased water demand and less water supply (Barlow et al. 2015; Rezaei et al. 2015). Extreme heat days are also catastrophic for maize production, especially when they coincide with the flowering phase. Studies have shown that high temperatures during flowering reduce pollen shedding, seed set, and kernel number, resulting in a yield reduction of up to 74% (Wang et al. 2019). It would be beneficial to include the following two breeding goals to improve or maintain yields under these adverse conditions: (i) the development of maize genotypes with longer grain-filling periods, which may be beneficial for coping with high temperatures; (ii) the development of genotypes that consume less water during the growing season (Casali et al. 2022). Based on the changes and trends observed so far, it is important for crop management to evaluate the planting windows and align plant phenology with specific parts of the season to protect yield (Mangani et al. 2023). Evaluating and updating agricultural practices and planting dates thus become critical as climate change progresses. Mangani et al. (2023), show that shifting the planting date a month later in the future at the Bloemfontein location slows days to maturity, and limits the number of days above 35 °C that the plants are exposed to during flowering.

Seasonal rainfall quantities showed significant trends in one district in each province and these changes were different for each, with earlier cessation in Lydenburg, later onset in Bethlehem and lower average rainfall in Klerksdorp. The seasonal rainfall quantity received remained mostly constant over the studied locations during the study period, except for Klerksdorp, which showed a decrease in rainfall quantities.

The seasonal rainfall explained approximately 40%, 22%, 18%, and 17% of the variation in maize yield in Klerksdorp, Standerton, Schweizer Reneke, and Bethlehem, respectively. These findings suggest that management practices may have to be tailored to specific districts in the future and should include a focus on soil water conservation, including reduced or no-till, enhanced fertilization, crop rotations that leave a large amount of residue, and effective weed control (Howden et al. 2007; Adisa et al. 2018; Casali et al. 2022). Increasing production by irrigation may be an effective management strategy during a water shortage, provided that there is sufficient rainfall. However, future predictions indicate that there might be less rain in Southern Africa, which is already considered a water-scarce country and so would not be a feasible solution in most districts (Christensen et al. 2007; Niang et al. 2014; Hoegh-Guldberg and Bindi 2018). There is a clear need to focus on breeding strategies that can promote water use efficiency, especially in developing, water-scarce countries such as South Africa (Casali et al. 2022).

South African maize production relies heavily on rain-fed agriculture making it fully dependent on the timing of rain onset for an appropriate planting date and duration of the rainy period to maintain moisture availability during crop development. In our study, we examined rainfall cessation and onset across six major maize-producing districts in South Africa. Contrary to the prevailing perception within the South African maize production community that rain patterns have been shifting later across the country, we found no discernible trends in rainfall onset or cessation in most of the study sites. There was, however, a shortening of the rainfall season length in Bethlehem due to an upward trend in rainfall onset, suggesting that rainfall started later, while rainfall cessation remained the same (Table 2 Fig. 2). In these instances farmers are often forced to plant late, which will misalign crop phenology and environment, resulting in lower yields (Tsimba et al. 2013; Masereka et al. 2019). If such a trend persists into the future, short-season cultivars and early medium ones might be a good option for farmers growing maize at such a location, which has previously been proposed (Kogo et al. 2022). However, it is important to assess these cultivars against the harsh South African climate to ensure their heat tolerance and water use efficiency before they can be employed in these regions.

It is of interest to note that Lydenburg's rainfall season also trended towards a shorter season this was, however, due to the significantly negative trend in rainfall cessation (Fig. 2), which indicates an earlier end to the rainfall period. This will likely not have as significant effect on maize production in the region when compared to late-onset because as maize reaches physiological maturity the water requirements become less and the crop may progress as expected. This trend will become concerning if these dates shift into the flowering and kernel formation stages, which are known

to be negatively impacted by dry spells (Liu et al. 2020, 2022). If anything, the earlier rain cessation might improve the drying of the crop and limit frost exposure. We have not, however, assessed the spatial-temporal distribution of the rains in this region which could have a major impact on maize production and phenology. It is recommended to further study the rainfall patterns in this region to better understand how these might influence maize production. This is particularly important given that our correlation analysis did not identify any of the traits in this study as major contributors to the observed yield variation (Table 3). Identifying the factors underlying this variation will help tailor mitigation strategies to the region to limit yield losses.

One of the main findings is that within the same province, climatic variables vary widely and can show very different trends. We also show that the influence of climate variables on maize yield varies from district to district even in the same province. This may be due to different climate zones that exist within the same province (Fig. 1). Studies conducted on a coarser spatial scale can be useful (Adisa et al. 2018; Mapfumo et al. 2020; Tshikovhi and van Wyk 2021), since they provide an overview of what can be done in terms of future planning on a larger provincial or regional scale. However, this information is less useful to farmers, especially when it comes to management practices at the farm level where coarser scale studies may not adequately represent the climate that prevails at their specific locations. For instance, the findings of Adisa et al. (2018), indicated that both the North West and Free State provinces were moving toward warmer climates during the period under investigation, which closely aligns with the timeframe examined in our current research. However, our study has revealed distinctions between these two regions. Specifically, in the Free State province, Bethlehem exhibited no significant changes in Tmax, whereas Bloemfontein indicated a warming trend. This pattern was also evident in the North West province, where Schweizer Reneke showed non-significant changes in Tmax, while Klerksdorp exhibited warming trends. Moreover, Adisa et al. (2018), noted that Tmax influenced yields by 24% in Mpumalanga on the provincial level. A finer-scale analysis revealed that Tmax contributed 32% and 2% to the Standerton and Lydenburg locations, respectively. In the example given above, if we make recommendations based on the coarse-scale study by Adisa et al. (2018), it implies that the entire province is impacted to some extent, with a 24% impact. However, the same province also includes areas such as Lydenburg, which appear unaffected, so this might be misleading and add unnecessary costs to apply adaptive measures in regions that do not require it.

There were a few differences in climate variables in Bethlehem, Standerton and Lydenburg, where all study sites belong to the same climate zone (Fig. 1). For example, Standerton and Lydenburg did not show any trends in EHT

days, whereas Bethlehem exhibited an increase in the occurrence of EHT days (Table 2). Regarding Tmax, Standerton and Lydenburg showed warming trends whereas Bethlehem showed non-significant directional change (Table 2). Additionally, Lydenburg had more variation in rainfall when compared to Standerton and Bethlehem (Table 2). These results reinforce the importance of downscaled climate change studies focusing on specific locations. Zinyengere et al. (2014), highlighted that with a bottom-up approach, location-specific studies can provide information that informs larger-scale research outcomes and facilitates the development of policies that support local farmers' self-management of climate change. Higgins (2014), also highlighted that adaptation policies require a thorough consideration of location-specific factors due to the geographic nature and uneven distribution of climate change impacts, which is why studies on location-specific climate change effects, such as this one, are important.

5 Conclusion

Many previous studies on the relationship between climate and maize crop production in South Africa have been conducted on a coarser provincial scale. Implementing recommendations from such studies at the farm level can, however, be challenging due to their limited granularity. This study makes a significant contribution to this crucial field by delving into the primary climatic factors affecting maize yields in South Africa's maize-producing provinces, focusing on specific magisterial districts. The results showed that most locations had increasing maximum temperatures and extreme temperature days, and that temperature significantly affected maize yields in most locations. Rainfall patterns remained relatively stable in most of the study areas during the research period. Contrary to community perceptions of shifting rain patterns, our findings show no clear trends in rainfall onset or cessation across most study sites, preserving the consistency of the duration of the rainfall season. There is, however, still no indication of the spatio-temporal distribution of rainfall through the season or if this is shifting as climate change progresses.

Farmers are confronted with significant climate-related risks, which play a substantial role in the variability in maize yields. To ensure yield stability in the future, it is imperative to customize maize cultivars for specific districts. Our findings revealed distinct local conditions that impede production, highlighting the need for tailored mitigative and adaptive approaches in trying to reduce the impact on the crop. Considering that crops are often subjected to multiple stresses simultaneously, mainly drought and heat, developing germplasm that are tolerant to several polygenic

inherited abiotic and biotic stresses is a crucial step toward ensuring the resilience of cropping systems to climate change. Recent advances in genomics, proteomics, and metabolomics have made it possible to improve maize production (Galvez Ranilla 2020). A limitation of our study is that, despite detrending to decrease the impact, we could not account for different soil types across districts, which could affect yields. In the future obtaining soil data and more fine-scale weather data can improve the trends and estimations presented here. It is also recommended that further studies similar to this be conducted at several locations, especially in the maize-producing regions of South Africa, so that farmers can apply climate change information to their specific districts to improve agronomic management activities in a targeted manner. This information also provides information on different crop traits that need attention by breeders and provides information that can improve cultivar recommendations at a district level.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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