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Projecting the effect of climate change on planting date and cultivar choice for South African dryland maize production

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ABSTRACT

The anticipated climate change in South Africa is of great concern as Southern Africa appears to be warming at twice that of the global average, limiting maize production in the country and threatening food security in the region. The formulation of effective adaptation measures calls for understanding how projected changes in temperature, precipitation, and climate extremes might become misaligned with the critical maize developmental stages, which are likely to impact crop development. We conducted an analysis of the climate change impacts for dryland maize phenology in Bloemfontein and Lichtenburg, which represent major maize growing regions of South Africa. The climate projections generated by six Global Climate Models under the Representative Concentration Pathways (RCP) 4.5 and 8.5 were used. Analyses were performed for four representative planting dates: November 15 (early), December 15 (optimal), January 15 (late), and February 5 (very late). Days to maturity decreased (by approx. 5-10 days) as years progressed from baseline period (1991-2020) to the far future period (2051-2080), at both locations with higher rates projected under RCP 8.5. The results suggest a longer summer season with receding freeze dates in these regions and might provide additional flexibility for adaptive strategies. At the optimal planting dates, future climate will likely affect both vegetative and reproductive stages of maize leading to the decrease in the days to maturity. A major factor affecting maize productivity is extreme temperature, with the number of days above 35 °C expected to increase 20–30% at the optimal planting date as climate changes progresses, which will likely limit grain filling and yield. Exploring maize phenology in the future at later planting dates revealed a decrease in days to maturity trending towards the optimal number of days required for each cultivar (100–110 days) in both regions. This coupled with the projected receding freeze date at these planting dates under future climates suggests there may be opportunities to shift planting to later dates in the region.

1. Introduction

Climate change poses a major risk to the agriculture sector across the globe, and notably in the sub-Saharan region (Calzadilla et al., 2014; Ortiz-Bobea et al., 2021). Southern Africa is considered a climate change hotspot, housing potential regional tipping points (Engelbrecht and Monteiro, 2021). While the global average appears to be set for a minimum increase of 1.5°C, Southern Africa appears to be warming at approximately twice the global average (Engelbrecht et al., 2015). These long-term changes in extreme weather patterns and rising temperatures are likely to negatively impact crop production and severely impact food security, particularly in regions such as Southern Africa with accelerated warming rates (Trnka et al., 2014; Lesk et al., 2016). The main factors limiting crop production under future climates include limited water availability, heat stress and increased pest infestations (Rosenzweig and Tubiello, 2007; Wiebe et al., 2015). It is estimated that increased temperatures have decreased global maize and wheat yields by 3.8% and 5.5%, respectively, between 1980 and 2008 (Lobell et al., 2011b). At a global scale erratic crop yields have been associated with climate change and the strongest trends have been observed at lower latitudes, such as in southern Africa (Nicholls, 1997; Rosenzweig and Tubiello, 2007).

South Africa (RSA) is ninth in terms of global maize production and second on the African continent, after Nigeria (Badu-Apraku and Fakorede, 2017). The country is a net exporter of maize, with most of its

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produce destined for markets in the nearby countries within the Southern African Development Community (SADC) region. As a result of the high demand within the country and for exports, the ability to attain high and stable maize yields are of great importance (Mangani et al., 2018).The rapid average warming projected for Southern Africa is likely to have severe consequences on maize production in the country and could have dire consequences not only for the country, but for the entire region (Engelbrecht and Engelbrecht, 2016, Adisa et al., 2018). Therefore, while regional studies are important, it is also important to explore the anticipated climatic changes at the provincial and district levels of RSA to understand the food security and production stability for the region. While the Free State province of RSA has been well studied in terms of environmental change, other provinces such as the North West province have been understudied even though these regions contribute up to 20% of the annual production (Adisha et al., 2018, Bello et al., 2020, Cammarano et al., 2020).

Temperature is a major environmental factor influencing plant growth and development, and as such growing degree days (GDD) are a key variable in crop models (Gordon and Bootsma, 1993; Olivier and Annandale, 1998; Khushu et al., 2008; Singh et al., 2008; Moeletsi, 2017; Prasad et al., 2018). Generally, GDD is used as a measure of the amount of heat required to reach a specific phenological stage and is defined as the number of degrees the daily temperature exceeds a base temperature (Worthington and Hutchinson, 2005; Matzneller et al., 2014). Additionally, extreme temperatures can significantly impact crop yields by negatively affecting plants at different growth stages (Lobell and Gourdji, 2012; Mangani et al., 2018). High temperatures during the vegetative growth phase (VGP) reduces photosynthetic capacity and biomass accumulation in maize (Karim et al., 2000; Lizaso et al., 2018). During the reproductive growth phase (RGP), heat stress can impact many aspects of anthesis including anthesis-to-silking interval and pollen viability (Wang et al., 2020, 2021). On the other hand, freeze damage is proportional to the stage of development and when temperatures fall below 0 °C, the stem, leaf, and ear can die back, negatively affecting yields (Carter and Hesterman, 1990; Crowley, 1998; Lauer, 2007).

Water deficit (difference between potential evapotranspiration and precipitation) is considered an important indicator of moisture availability during the various developmental stages of the growing season. During the vegetative stage of maize, drought has been found to reduce leaf area index impacting biomass accumulation and ultimately crop yield (Cakir, 2004; Mangani et al., 2018). Photosynthesis is also reduced by water deficit stress as a result of stomatal and non-stomatal limitations (Shangguan et al., 1999). Lobell et al. (2011a), also determined that maize yield is strongly impacted by stresses generated by the strong link between high temperatures and meteorological drought. The strong influence of moisture availability on growth, seed set and yield makes it another key variable to be included during crop modeling.

Adaptive agricultural practices, such as planting date optimization and cultivar choice are effective techniques for maintaining maize production in future climates (Tao et al., 2014; Dobor et al., 2016). Lv et al., 2020 determined that adjusting sowing dates would be an alternative way to extend post flowering periods and improve maize yields. Huang et al. (2020) reported that, in China, adopting late maturing cultivars in the future would achieve higher maize yields in comparison to early and middle maturing cultivars. In RSA, several climate change impact assessment studies have been conducted on maize with most of them using a fixed planting date and one cultivar (Abraha and Savage, 2006; Walker and Schulze, 2006; Mangani et al., 2019; Cammarano et al., 2020). Generally, there is a consensus that future climate change will result in reduction in maize yields if no adaptation practices are put in place. However, these studies did not evaluate the effects that climate change would have on planting date and how different planting dates might better align the crops phenological stages with environmental patterns to maintain growth and development in the future.

A number of crop simulation models have been used to project the potential yield outcomes of climate change in RSA (Zinyengere et al., 2013; Franke 2021). Generally, these models are based on process-based crop simulations, investigating the changes in yield based on plant physiology and projected climate change (Marin et al., 2014). In the last ten years 13 of these studies have been performed on maize in Southern Africa and only one of these focused on the Free State and Northwest provinces, despite these being the major maize producing regions of RSA (Franke, 2021). All these studies and modeling techniques focus specifically on the endpoint analysis of yield components based on general physiological parameters and do not assess the alignment of maize phenological stages with these changed environments. A study focused on maize production in the Northeast of the United States investigated the impact of climate change on the different phenological stages in maize and found a greater water deficit during the reproductive stages, suggesting that a shift in planting date might help limit future losses (Prasad et al., 2018). No such studies have investigated how climatic changes might align with phenological stages in Southern Africa, which is a critical climate change hot spot and could provide insight into adaptive strategies to maintain regional food security in the future.

In this study we aimed to assess the alignment of maize phenological stages with environmental shifts projected to be induced by climate change in the future at two major RSA maize producing sites, North West and Free State. The objectives are to analyse the effects of climate change on the development of maize at VGP and RGP, using baseline (1991-2020), near future (2021-2050) and distant future (2051-2080) climate projections for the IPCC Representative Concentration Pathways (RCP) 4.5 and 8.5 (Van Vuuren et al., 2011; Jubb et al., 2013). In our analysis, we used cultivar choice and planting date as adaptive measures that have been suggested to mitigate the effects of climate change. We hypothesized that:

1 The seasonal and developmental accumulation rate of GDD for maize in the study regions will increase in the future, which will drive a decrease in the number of days to maturity.
2 Water deficits at different maize growth stages will increase as we move to a distant future.
3 Freeze date regression associated with climate change will favor the use of early maturing maize cultivars or a shift in planting date.
4 During both growth phases, maize will be increasingly exposed to temperatures exceeding 35 °C.

The results of this study will not only provide information on the optimal planting dates and cultivars in the future, but will also identify the risks associated with a particular planting date in the future as climate change progresses in South Africa. These findings are important as South Africa is a major maize producer in the region and crop failure in these districts could threaten food security across the Southern African region.

2. Methodology

2.1. Study areas

Two major maize growing provinces in RSA, North West and Free State, representing two different agro-ecological regions were selected (Schoeman and Van der Walt, 2004). Specifically, the well-known maize districts of Lichtenburg in the North West (26.152 S 26.160 E) and Bloemfontein in the Free State (29.087 S 26.155 E), were selected as representatives for each province (Fig. 1). Lichtenburg is at 1503 m above sea level (ASL) and is a sub-humid region, receiving an annual precipitation of between 601 and 800 mm, with a monthly peak of 105 mm in February. Bloemfontein is approx.1395 m ASL and is a semi-arid region, receiving an annual precipitation of between 400 and 600 mm with a monthly peak precipitation of 85 mm in January. Temperatures are similar at both locations, with a mean daily temperature of 17 °C. The months of December and January are the hottest at both locations,

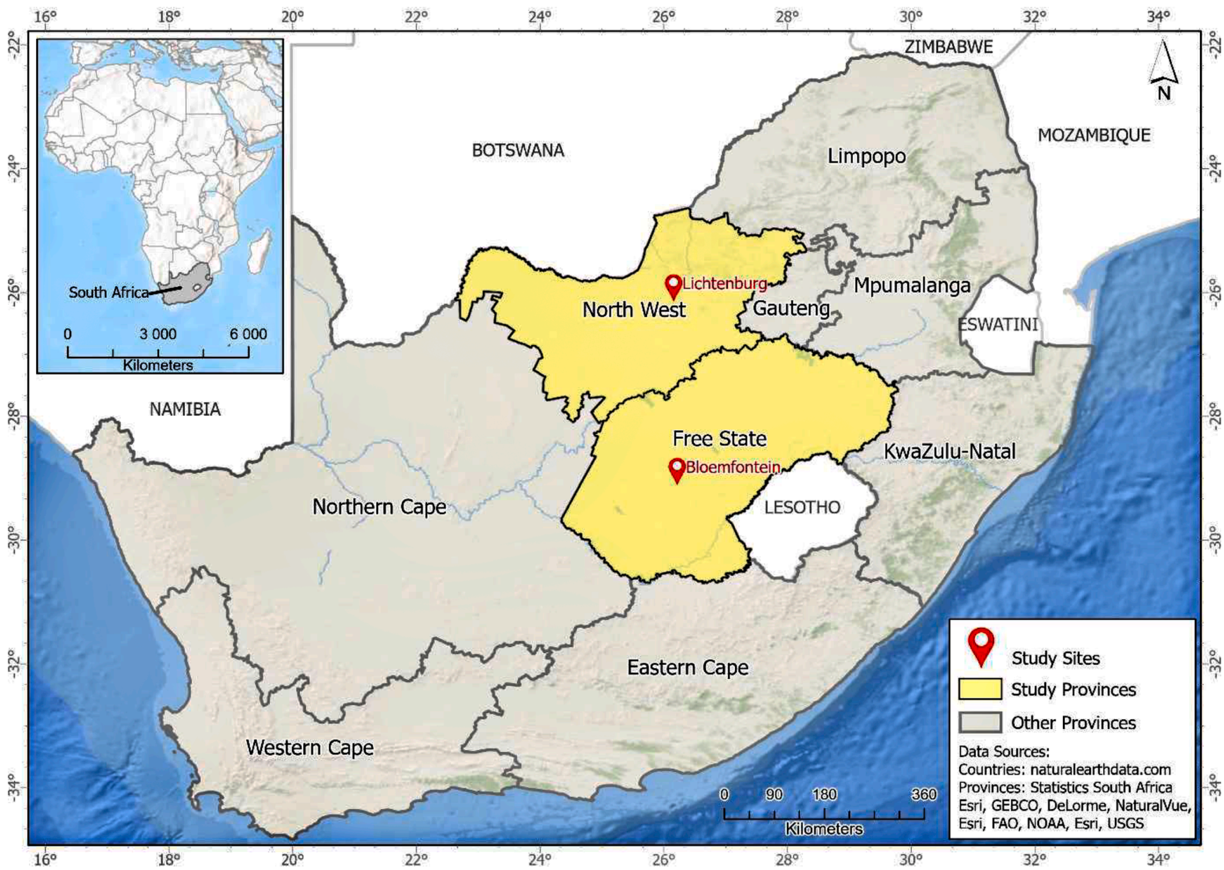

Fig. 1. Map of South Africa (RSA) showing the study sites (red markers) in the selected provinces (yellow shading). Grey shaded regions indicate the other seven provinces of RSA. Top left insert shows the position of RSA on the African continent.

with 22 °C, 23 °C mean temperatures. The coldest days occur in June and July with 9 °C, 10 °C mean temperatures. RSA is generally a dry country with an average annual precipitation of 464 mm (≤ world average of 806 mm). Mean annual sunshine received in RSA amounts to approximately 2500 h. The seasons are generally demarcated as: spring (Sep-Nov), summer (Dec-Feb), autumn (Mar-May), and winter (Jun-Aug).

2.2. Scenario

For each location of interest, we explored sixteen scenarios by combining 3 factors, including two maize cultivar types, four current assessments of planting (planting dates), and two RCP's across the 21st Century (Table 1).

The characteristic requirements for heat unit accumulation in order to reach the reproductive stage and maturity are listed in Table 2 for the cultivar types explored. In this study, we refer to maturity as the physiological stage where a black layer develops at the tip of the maize kernel (O'Keeffe, 2009). Medium maturing cultivars are widely used in RSA

Table 1
All combinations of variables tested, including two cultivars, two climate scenarios and four planting dates.

Cultivar types	Climate scenario*	Planting dates**
Short season	RCP 4.5	Early (15 November)
Medium season	RCP 8.5	Optimal (15 December)
		Late (15 January)
		Very late (5 February)

* RCP - Representative Concentration Pathway
** Optimal planting date, denotes the current optimal planting date used by producers if onset of rain allows

Table 2
Summary of the heat units and number of days required to complete the vegetative and the reproductive growth phases for the short and the medium maturing cultivars.

Cultivar Type	Heat unit accumulation during VGP‡	Heat unit accumulation at the end of RGP† at maturity*	Days to Flowering	Days to maturity
Short season	708 °C	1403 °C	58	115
Medium season	755 °C	1498 °C	65	127

* Maturity: the time when the maize starts showing black layer at the tip of the kernel.
‡ Heat Unit accumulation during vegetative growth phase (VGP).
† Total Heat Unit accumulation at the end of the reproductive growth phase (RGP) at maturity
Tbase used for calculation of degree days was 8 °C.

maize production, however, there is an indication that there might be a delayed onset of the summer rainfall under climate change and a shorter growing season could be expected (Abiodun et al., 2020). The short maturing cultivars were selected to assess their potential performance under future climates in comparison to the medium maturing varieties.

Climate change conditions were simulated using climate projections generated for the 1961-2099 time period using six General Circulation Models (GCM) of the Coupled Model Intercomparison Project Phase Five (CMIP5) (Appendix A.1). The projections included data for maximum and minimum temperature, precipitation, solar radiation, relative humidity, and wind speed (at 1m above ground) generated under the Representative Concentration Pathways 4.5 (RCP 4.5, ~490 ppm CO_2 eq atmospheric concentration by 2100) and 8.5 (RCP 8.5, ~1370 ppm CO_2 eq atmospheric concentration by 2100) of the Assessment Report Five (AR5) of the Intergovernmental Panel on Climate Change (IPCC). RCP 4.5 represents a global atmospheric condition with a low radiative forcing resulting from a high greenhouse gas emissions mitigation strategy, whereas RCP 8.5 simulates conditions with a high radiative forcing due to a low greenhouse gas emissions mitigation strategy (business-as-usual). The projections were bias-corrected and dynamically downscaled to the locations of interest; for more information on the weather data generation method, refer to Mangani et al. (2019).

2.3. Daily heat unit calculation

The method described by McMaster and Wilhelm (1997) and expanded by Lobell et al. (2011b) was employed for the daily heat unit calculations. The projections of maximum and minimum daily temperatures were used to calculate the potential daily heat energy accumulation (or GDD) for maize (Eqs. (1) and (2)). GDD was calculated for every day within the projected data.

$$GDD = airTmean - Tbase \quad (1)$$

We adopted the following rules for the GDD calculation:

- if airTmean < Tbase, airTmean=Tbase, therefore GDD=0
- if airTmean > Tut, airTmean = Tut, Therefore GDD= Tut – Tbase
- if Tbase <= airTmean <= Tut, GDD = airTmean – Tbase
- Tbase and Tut were set to 8 °C and 30 °C, respectively (Birch et al 1998; Lobell et al. 2011b).

Where:

$$airTmean = (airTmax + airTmin)/2 \quad (2)$$

- airTmax: daily maximum temperature
- airTmin: daily minimum temperature
- Tbase: temperature below which maize stops accumulating energy for growth processes.
- Tut: temperature above which maize is under stress and growth processes are curbed.

2.4. Daily potential evapotranspiration (PET)

Several methods have been employed to project PET into the future using projected climate data (McAfee, 2013; Xing et al., 2014; Wang et al., 2015), and the Penman-Monteith method (PM) was estimated to be the most appropriate method, given the nuancing effect of solar radiation, relative humidity, and wind speed on air temperature (McAfee, 2013). FAO-56 PM method (Allen et al., 1998), adopted by the United Nations, Food and Agriculture Organization and is widely regarded as a standard PET calculation method (Shuttleworth, 1993), is derived from the original PM method and can be used if all the daily weather data required (projected daily air temperature, relative humidity, wind speed, and solar radiation) are available. We used FAO-56 PM to estimate daily PET (Eq. (3)) and details of the procedure are provided in Appendix B.

$$ET_0 = [0.408\,\Delta\,(R_n - G) + \gamma(900/(T_i + 273))\,u_2\,(e_s - e_a)]/[\Delta + \gamma(1 + 0.34\,u_2)] \quad (3)$$

where:

- ET_0: daily PET (mm/day)
- Δ: slope of the saturation vapor pressure-temperature curve (kPa/°C)
- R_n: net radiation at the crop surface (MJ/m/d)
- G: heat flux density to the ground (MJ/m^2/d)
- γ: psychrometric constant (kPa/°C)
- T_i: mean daily air temperature at 2 m height (°C)
- u_2: wind speed at 2 m above ground (m/s)
- $e_s - e_a$: vapor pressure deficit (kPa)

2.5. GDD accumulation and water deficit calculation

A maize growing season in RSA starts during the second half of a year of the Gregorian calendar and ends during the first half of the following year. A growing season was assigned to the year in which it completes. For example, a growing season that starts in November 2000 and finishes in April 2001 was considered as the 2000–2001 growing season. We used a similar concept to describe a growing year, where the growing year 1999–2000 extends from July 1999 to June 2000 (Moeletsi and Walker, 2012).

For each climate scenario and climate model, daily GDD was cumulated on a growing season basis from a selected planting date until the total number of heat units meets the number required for maturity (Table 2). This procedure contributed to determining the number of days to reach maturity. We used a similar procedure to determine the number of days to complete the vegetative and the reproductive growth phases (VGP and RGP, respectively), based on the required heat units (Table 2).

Cumulative developmental stage water deficits affect crop yield more than daily deficits (Setter, 1990; Benjamin et al., 2014). Thus, we cumulated daily PET and precipitation as well, by the developmental stages determined from GDD cumulation, and used the accumulated values to estimate developmental stage water deficits as the difference between the cumulated PET and precipitation, on an annual basis, by climate scenario and model.

2.6. Assessment of the exposure to extreme temperatures

Given the existing concerns regarding a potential increase of the exposure rate to extreme weather events that could be associated with climate change (Hatfield and Prueger, 2015), exploring their projected frequencies was necessary. From the projected daily weather data, we evaluated the probability of exposure to freezing and hot days during any selected year, for the 21st Century, based on the annual frequency counts of days with maximum temperature greater than 35 °C (hot days) or minimum temperature less than 0 °C (freezing days). These probabilities were estimated within each developmental stage, and by climate scenario, planting date, and GCM.

2.7. Data analysis

Data used for analysis included annual series of last spring and first winter freeze, days to maturity, water deficit by developmental stage, and growing season probability of exposure to hot and freezing days. Variability and uncertainties included in climate projections are best addressed by utilizing the projections from several climate models under specific climate scenarios, and using various mathematical models to aggregate the results of the GCMs (Christensen et al., 2007; Rurinda et al., 2015). This study combined the results of the climate models under each scenario using their arithmetic averages by characterization period [baseline (1991–2020), near future (2021–2050) and distant future (2051–2080)]. Long-term trends in the time series of the calculated data for each climate model was analyzed, using rank based non-parametric Mann-Kendall test to determine if long-term trends were significant (p-value < 0.05), and Theil-Sen Slope method to estimate the time rates of change (Helsel and Hirsch, 2002). Median decadal Theil-Sen Slopes are reported by scenario and long-term trends were illustrated using locally weighted smoothing regressions. We also estimated the percent change of the considered parameters between the characterization periods.

Data analysis was performed in the R software environment (Version 4.0.0, R Core Team, 2020) using the zyp package version 0.10-1.1 (Bronaugh and Werner, 2019) for trend and change rate estimations. Given the source of the data series, the potential for the presence of serial correlation was present and may skew the results if not accounted for. Therefore, the Zhang method (Zhang et al., 2000), that evaluates the data series for serial correlation and proceeds to de-trending the series if needed before rate estimation, was employed.

3. Results and discussion

3.1. Future climate projections of warming and rainfall of RSA maize growing regions

On average, the climate projections indicated that Bloemfontein and Lichtenburg will trend towards warmer climates, especially during the second half of the 21st Century (Appendix C.1a). This assessment is consistent with recent regional climate assessments (Mangani et al., 2019), including the recent projections based on IPCC 6th Assessment report (Gutiérrez et al., 2021). In particular, mean annual temperature rises between the baseline and distant future periods will likely amount to 6.0 ± 1.2%–13.2 ± 1.2% (Bloemfontein) and 6.7 ± 0.8%–13.4 ± 1.1% (Lichtenburg) depending on the model used under RCP 4.5 (Appendix A.2). Mean annual temperature increases in Bloemfontein and Lichtenburg under RCP 8.5 during the same time span will likely be higher, reaching 10%–24% above current baseline temperatures.

Annual precipitation changes are also expected throughout the 21st Century in both locations, although unlike the trends for temperature, no clear unidirectional change can be inferred (Appendix C.1b). The majority of the GCMs used in this study projected wetter years for the distant future of the 21st Century, preceding a drop in precipitation toward the end of the century, in accordance with other climate change assessments (Hagemann et al., 2013; Engelbrecht et al., 2019; Gutiérrez et al., 2021). Under RCP 4.5, annual precipitation appears to rise between the baseline and the distant future periods, regardless of the projecting climate model, and projected rises reach 1.9 ± 4.6%–10.7 ± 5.0% in Bloemfontein and 1.2 ± 4.0%–7.4 ± 4.1% in Lichtenburg (Appendix A.2). Under RCP 8.5, all the GCMs signaled a rise of up to 14.7 ± 4.8% and 9.8 ± 3.5%, respectively in Bloemfontein and Lichtenburg, except for CNRM-CM5 (-2.4 ± 4.2% for Bloemfontein and -0.8 ± 3.4% for Lichtenburg). Regardless of the climate scenario, precipitation change signals were highly variable at the model and year levels, as evidenced by the large standard error values (and the spread of the boxplots in Appendix C.1b). These results suggest that the precipitation change signal is not consistent from one model to another, or from one year to the next. From a temporal precipitation distribution perspective, the expected precipitation increases will more likely occur in the spring and summer months (Mangani et al., 2019), which will potentially benefit earlier maize production in these locations.

The projected changes in temperature and precipitation in Bloemfontein and Lichtenberg provide insights into the effects of climate change on maize production in South Africa. The projected ambient temperature increases suggest that summer crops, like maize, will accumulate enough heat units to reach maturity faster, which may promote earlier harvests. However, very rapid advances to maturity may limit biomass accumulation and have a negative effect on yields (Porter, 2005; Borrás et al., 2007; Liu et al., 2010). Similarly, soil moisture fluctuations and potential heat wave events among other conditions (nutrient availability, pest or pathogen attacks, etc) may further limit yields (Jägermeyr et al., 2021). Taken together the increased temperatures and precipitation may enhance maize production in RSA maize growing regions at least in the near future, however, the variable nature of precipitation and threat of unpredictable extreme weather events such as heat waves and floods could severely affect yield stability.

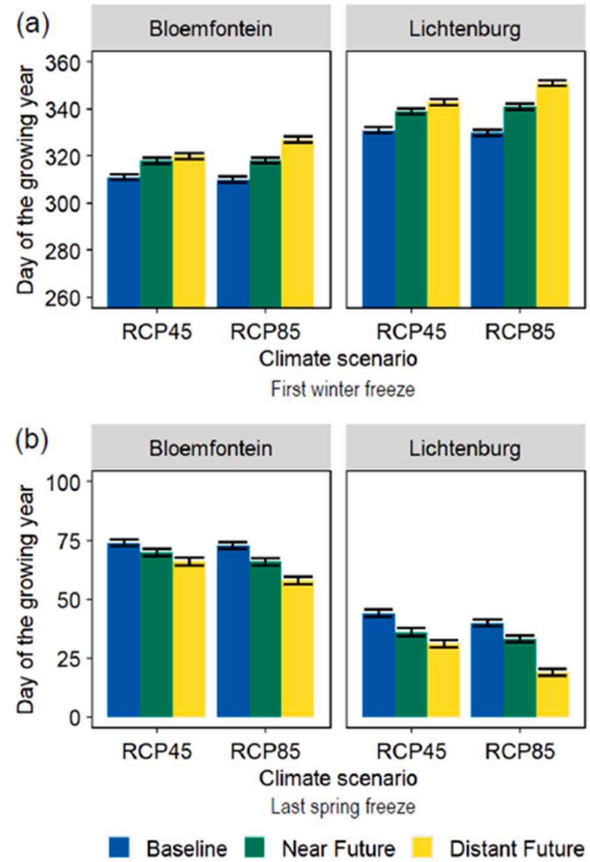

Fig. 2. The projected mean first winter freeze (a) and last spring freeze (b) for the 21st Century separated into baseline (1991–2020; blue), near future (2021–2050; green) and distant future (2051–2080; yellow) in Bloemfontein (left panels) and Lichtenberg (right panels) for RCP4.5 and RCP 8.5. A growing year extends from July 1st of the previous year to June 30th of the current year. Day of the growing year is in reference to the beginning of the growing year (July 1st). For example, day 100 refers to Sep 9th. Error bar shows variability related to climate models and years.

3.2. Projected duration of annual freeze free periods in RSA maize growing regions

Both RCP 8.5 and RCP 4.5 projections suggest that the onset of the winter freeze period will likely shift to later days, while the last spring freeze date will move earlier under future climates at both study sites (Fig. 2, Appendix A.3). For example, in Lichtenburg, under RCP 4.5 scenario, the first winter freeze is projeccted to start 8 ± 2 days later in the near future and up to 12 ± 2 days later in the distant future, relative to the baseline period (Appendix A3), while the last spring freeze date for the same scenario is projected to end 8 ± 3 days and 13 ± 3 days earlier for the near and distant future respectively. Similarly, under RCP 8.5 in Lichtenburg, the first winter freeze will likely shift even later, starting 11 ± 2 days later in the near future and 21 ± 3 days later in the distant future (Fig. 2a right panel). Again, the last spring freeze is projected to shift 6 ± 2 days and 20 ± 2 days earlier as the century progresses (Fig. 2b right panel). Similar trends were also simulated in Bloemfontein with the freeze-free period extending in most cases

(Fig. 2). All the GCMs provided a clear signal of forward shifting first winter freeze and receding spring freezes at both locations, except for CNRM-CM5 in Bloemfontein for both first and last freeze days (Appendix A.4). Other variations under RCP 4.5 included ACCESS1-0 in Lichtenburg for the first freeze date; and CCSM4, CNRM-CM5, and NorESM1-M projecting variable trends in Bloemfontein for the last freeze date. Only NorESM1-M projected variable trends at both locations for the last freeze date (Appendix A.4).

At baseline conditions, the first winter freeze was experienced 20 days earlier in Bloemfontein than in Lichtenburg. Statistical analysis of temperature observations made between 1904 and 2020[1] indicated that colder winter temperatures are generally experienced earlier in Bloemfontein than in Lichtenburg (May 7th and May 18th, respectively). Similarly, the end of the spring freeze season in Lichtenburg ends earlier than in Bloemfontein (May 2nd and May 16th, respectively). A similar trend was observed by the projections of up to 30 days difference between the two sites (Fig. 2b). The projected differences between first and last freeze dates in Lichtenberg and Bloemfontein are to be maintained throughout the 21st Century (Fig. 2). As the onset of the winter season advances and the last spring freeze regresses to earlier dates, the freeze free period will likely extend by 262–291 days on average at both locations and under the two climate scenarios, resulting in a shorter winter season (Appendix A.5).

Shorter winters and longer summers resulting from climate change have been projected by several studies for locations across the northern and the southern hemisphere (Su-Qin et al., 2013; Wang et al., 2021; Chervenkov and Slavov, 2022). Chervenkov and Slavov (2022) reported a lengthening of the freeze-free season primarily associated with an earlier date of last spring freeze rather than a delayed date of first autumn freeze for the central and southeast Europe region. Interestingly, this was not the case in our findings, longer summers were results of both regressing last spring freeze and advancing first winter freeze dates. Hemispheric climate distinctions and the different climate change progression in these hemispheres may explain this difference (Bastin et al., 2019). Seasonal changes resulting in longer summers may be beneficial for summer crops like maize. For example, under late maize plantings in RSA (January or February), delayed freeze dates may enable the crop to reach maturity before the first winter freeze. A regressing last spring freeze may also provide farmers with an opportunity for earlier plantings, especially when paired with the projected increase in spring and summer rains (Mangani et al., 2019).

3.3. Projected days to maturity for maize cultivars in RSA production regions

Projections point to a declining mean number of days required for maize to reach maturity, regardless of location, cultivar, climatic scenario, or planting date (Fig. 3), with larger decreases projected under the RCP 8.5 scenario. For example, under the RCP 8.5 scenario, a medium maturing cultivar planted early in Bloemfontein is expected to mature in 103 ± 1 days under the baseline conditions. However, the number of days to maturity will likely decrease by 5 ± 2% - 9 ± 1% by the near future period, and by 8 ± 1% - 18 ± 1% in the distant future (Appendix A.6). At the same location, under RCP 4.5, the number of days to maturity for the medium maturing cultivar can potentially decrease by 1 ± 2%–7 ± 1% in the near future and by 5 ± 2%–9 ± 1% in the distant future. Similar trends were observed for both cultivar and scenario in Lichtenburg, with significant decreases in the days to maturity through the 21st Century as climate change progresses (Appendix A.6). Therefore, the severity of climate change will have a major impact on the growth and development of maize cultivars in the future at both locations, which may eventually impact yields.

Location and cultivar did not appear to drive a significant difference in the decline of the number of days to maturity for either climate scenarios at the early or optimal planting dates for either cultivar. It is interesting to note that under the early and optimal planting date scenarios, both locations have a similar number of days to maturity (Fig. 3 left four panels). However, as we move to the late and very late planting scenarios, not only are the number of days to maturity higher at Bloemfontein than at Lichtenberg (Fig 3. right four panels), but also the number of days to reach maturity declines faster in Bloemfontein than in Lichtenberg (Table 3), especially as we move to the near and distant future (appendix A.6). This divergence highlights the potential effect of the agro-ecological zones during the near and distant future, if maize is planted late and very late during the growing season. However, the influence of cultivar on the decreasing rate of the number of days to reach maturity appears to only be notable for Bloemfontein under RCP 8.5 at the very late planting scenario (Table 3 – grey shading).

On average, the planting date scenarios explored indicated that the number of days to maturity decreased faster as the planting date moved toward later dates during the growing season, regardless of climate scenario, location, or cultivar (Fig. 3, Table 3, and Appendix A.6). For example, in Bloemfontein under RCP 8.5, the number of days to maturity decreased from the baseline to the near future period by 5 ± 2% - 9 ± 1% for the Early planting scenario, and by 2 ± 5%–22 ± 3% under the very late planting scenario (Appendix A.6). Similar trends were projected under the different location - RCP - cultivar combinations, although some of the GCM projections did not meet the heat unit requirement for maturity (not enough heat unit cumulation before winter onset) for the very late planting dates, especially as we move towards the end of the 21st Century.

Overall, simulations based on location, climate scenario, maize cultivar, and planting window indicated that expected changes in the number of days needed for maize to reach maturity is strongly influenced by planting window. Therefore, even under future climates, local maize producers should primarily focus on the planting period as an adaptation factor in combination with appropriate cultivar selection. For example, based on the results (Fig. 3), it takes approximately 100–110 days for the medium cultivar and 90–100 days for the short cultivar to mature under current conditions for November or December (early and optimal planting window) plantings. Assuming the same cultivars will be used in the future, moving to the Late planting date (15th January) at either location would maintain the baseline number of days (90–110 days) to maturity under future climates. Moving to the very late planting date would not be optimal due to the risk of freeze events occurring before the crop matures.

A decrease in the time to maturity is an illustration of a faster accumulation of growing degree days, as discussed by previous regional climate change impact assessments (Mtongori et al., 2015; Abbas et al., 2017; Xiao et al., 2019). It is certain that if there are no mitigation factors involved (genotypes or management practices), the warmer weather will negatively affect maize production if planting dates are maintained. A shorter growing season would likely result from higher temperatures accelerating the reproductive phase, which would lead to reductions in light interception during crop development and a decrease in yield potential (Porter, 2005; Liu et al., 2010; Hatfield et al., 2011). Additionally, a shorter growing season would further result in an inefficient use of water and nutrients, which again translates to lower yields (Harrison et al., 2011). This suggests that a decrease in the length of growing season can be beneficial only up to the point where yields are not affected. It may be possible to reduce loss due to decreased days to maturity in the future, by developing cultivars that are less sensitive to temperature changes or possibly considering alternate planting dates depending on rainfall (Zhao et al., 2017).

[1] weatherspark.com; https://climate.usu.edu/reports/freezeDates

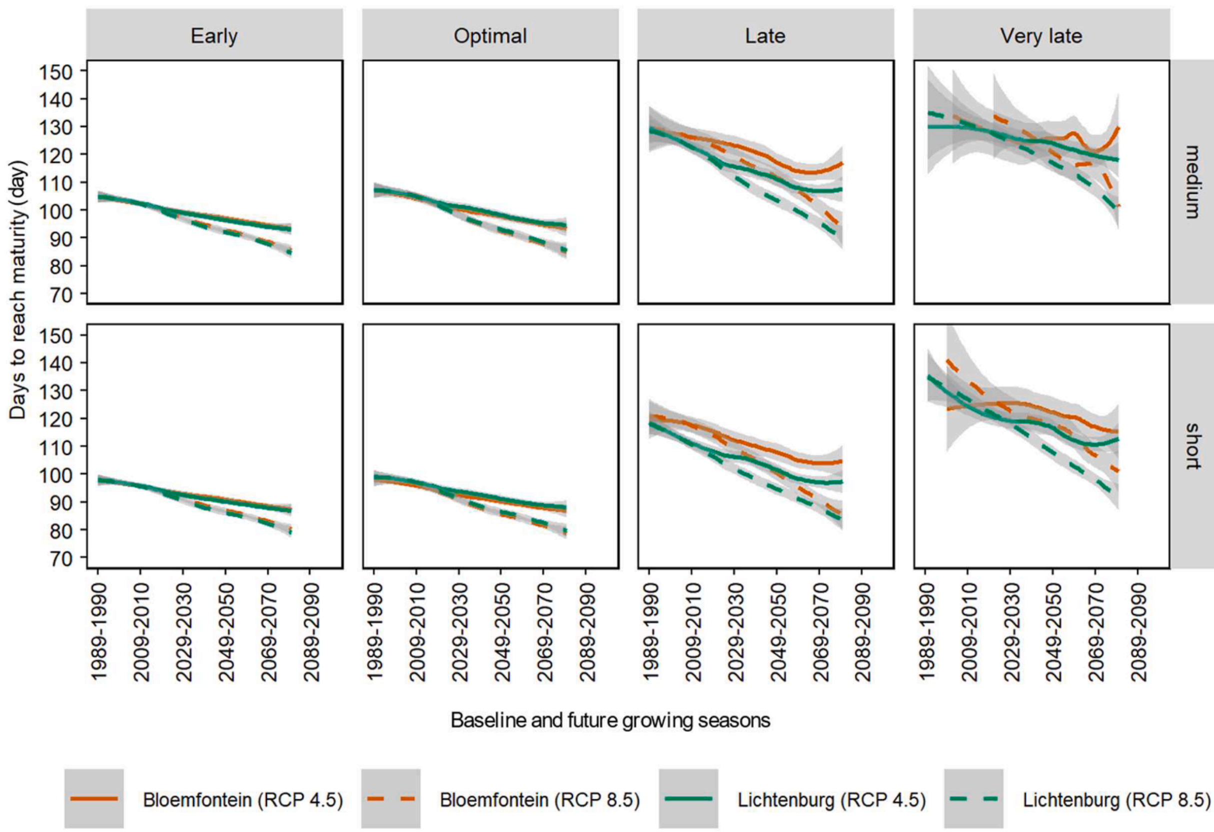

Fig. 3. Projected number of days to maturity decline across the 21st Century for different planting dates in Bloemfontein (green) and Lichtenberg (orange) for RCP4.5 (dashed line) and RCP 8.5 (solid line). Shading shows variability between climate models. The x axis represents specific growing seasons at twenty-year intervals from 1989 to 2090.

Table 3
Long term rates of change of the number of days to maturity per decade for two maize cultivars at four potential planting dates in two maize growing locations of RSA, and under RCP 4.5 and 8.5 emission scenarios. The change rates are reported as the median values from the 6 (six) Global Climate Models.

		Number of days to maturity change / decade			
		Bloemfontein		Lichtenberg	
Maize cultivar	Planting Date	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Short	Early	-1.1	-2.0	-1.3	-2.2
	Optimal	-1.5	-2.4	-1.5	-2.4
	Late	-2.7	-4.2	-2.4	-3.8
	Very late	NA	-6.1*	-3.0	-5.0
Medium	Early	-1.3	-2.2	-1.4	-2.3
	Optimal	-1.7	-2.8	-1.7	-2.6
	Late	-3.3	-3.7	-2.6	-4.4
	Very late	NA	-8.8*	-2.8	-4.7

* Grey shading indicating notable differences in days to maturity change rate between the trend of the two cultivars at the very late planting window.

3.4. Exposure to extreme temperatures

3.4.1. Probability of exposure to freezing temperatures in the maize growing regions of South Africa

In RSA, days with cold temperatures tend to become more frequent towards the end of April and into July as the region moves from autumn to winter. The probability of exposure to freezing temperatures during both the VGP and RGP is low throughout the 21st Century under the early or optimal planting window scenarios, regardless of location, climate scenario, and cultivar (Fig. 4). While this assessment is also similar for the VGP of maize planted during the Late or Very late planting window, the probability of exposure to freezing temperatures increases strongly during the RGP (Fig. 4). The medium maturing maize cultivar, in particular, will likely experience 38%–100% probability of exposure to freezing temperatures during the RGP under baseline conditions if planted under the Late and Very late windows at either location, with a lower anticipated probability of freeze exposure at Lichtenburg. Given shorter maturing and drying off phases of the short maturing maize cultivar, it will likely experience lower freeze exposure probabilities under the same conditions (23%–99%).

As the century progresses to the distant future, the onset of the winter season is expected to advance (Fig. 2), leading to lower probabilities of freezing exposure for both maize cultivars at both locations during the RGP (Fig. 4), especially under RCP 8.5 for the late planting window scenario (2%–16%, Appendix A.7). As expected, higher probabilities of exposure to freezing temperature are projected under the Very late planting scenario (9%–75%, Appendix A.7), suggesting that planting within this window would be considered risky even in the distant future.

Freezing has been reported as a limiting factor in maize production and yield (Carter and Hesterman, 1990; Aguilera et al., 1999; Ying et al., 2000; Lauer, 2007). Carter and Hesterman (1990) reported that exposure to temperatures below 0 °C for a period greater than 4 h and below -2.2 °C for only a few minutes can result in lethal damage to the stem, leaves and ears. During a freeze event, leaves scorch and die, reducing the photosynthetic area of the plant and arresting dry matter accumulation (Aguilera et al., 1999; Ying et al., 2000). The impact of freeze damage is directly proportional to the stage of development and the amount of leaf tissue affected (Lauer, 2007). The lower probability of freeze dates under future climates suggests that maize production may be at less risk of damage in the future, especially when considering the faster rate to maturity (Fig. 3). Fewer freezing days during the VGP and RGP of maize under the late planting date, suggests that in the future, the January planting window will have a lower risk of freeze exposure,

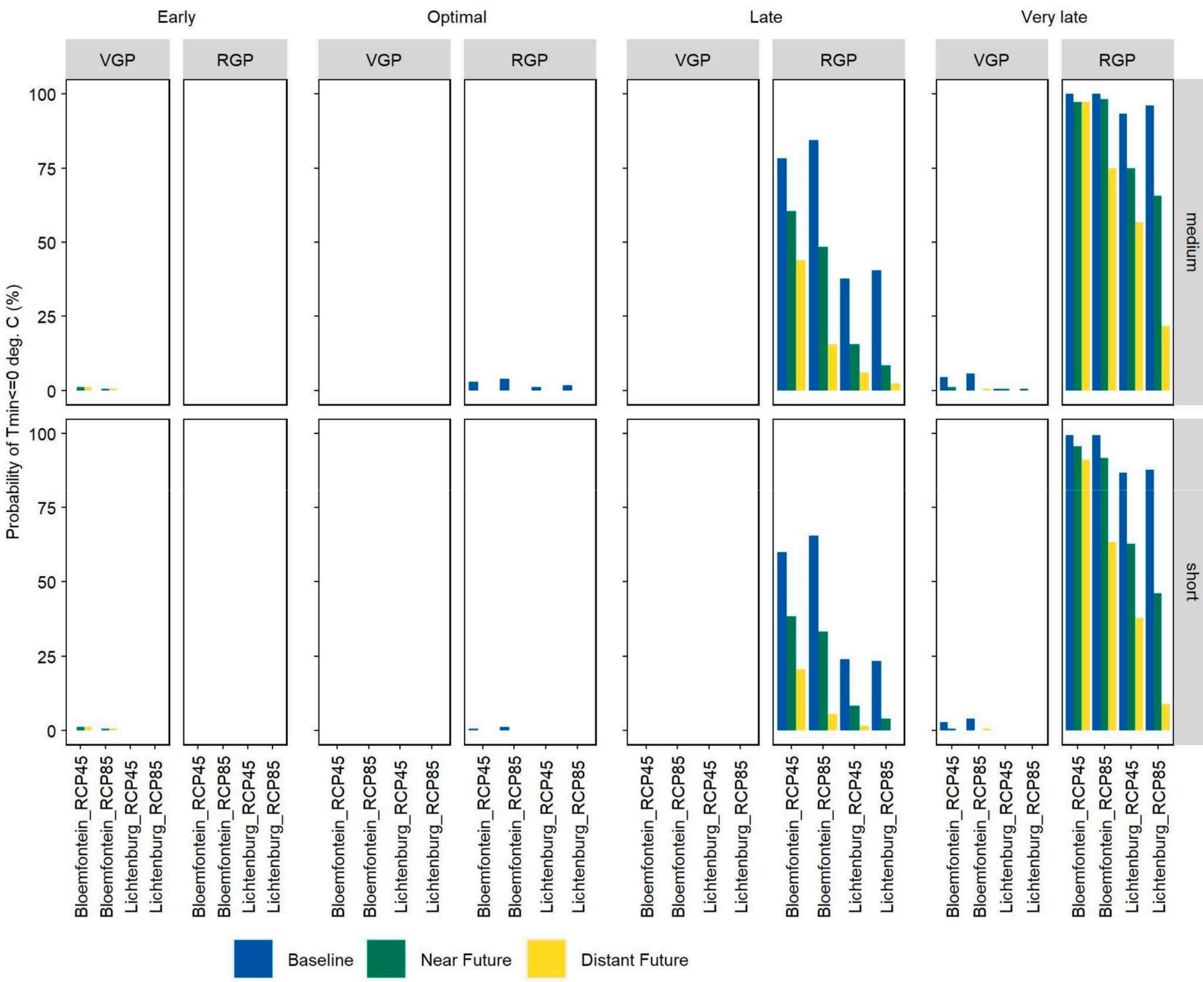

Fig. 4. Probability of exposure to freezing days (days below 0°C) increases during the RGP (reproductive growing period) when compared to the VGP (vegetative growth period) of two maize cultivars (short and medium maturing varieties) under different climate scenarios (Representative concentration pathway (RCP) 4. 5 and 8.5), time horizons (blue - baseline; 1991–2020, green - near future; 2021–2050, yellow - distant future; 2051–2080), for the 21st Century at the later two planting dates.

especially in Lichtenberg (Fig. 4) and a shift in planting date may be feasible in the future.

3.4.2. *Probability of exposure to extremely high temperatures*

Bloemfontein and Lichtenburg typically experience the most elevated temperatures during December through February[2], under baseline conditions. Therefore, it is expected that maize planted early or during the optimal planting window will experience a high probability of heat exposure (51%–89% depending on the growth stage; Fig. 5 and Appendix A.7). As the planting window moves to the second half of the growing season (Late and very late), it is projected that the probability of exposure to hot days will decrease markedly to 2%–73%, with the highest probabilities occurring close to the start of the late planting window. In both cases (Early to Very late planting), the VGP is more inclined to experience the highest probabilities of hot days exposure (44%–89% for VGP vs. 2%–74% for RGP). Both cultivars appear to experience a similar range in probabilities of exposure to hot days, suggesting that the use of either cultivar will not change the probability of exposure to hot days (Fig. 5, Appendix A.7).

As we move towards the near and distant future, the likelihood of hotter conditions increases regardless of the combination of scenarios (Fig. 5). While the projected increase in precipitation (Appendix C.1b) might go some way to limiting the effect of dual stressors, the number of days above 35 °C remain a concern for this temperature sensitive crop. For example, in Lichtenburg and under the RCP 8.5 projections, the medium maturing maize cultivar planted during the optimal planting window shows an increase in the probability of exposure to hot days between the baseline and the distant future periods for both the VGP (14% increase) and the RGP (34% increase) (Fig. 5). Only a single case (Bloemfontein - RCP 4.5 - Optimal - VGP scenario) shows an increase up to the Near future followed by a decrease during the Distant future. Therefore, in general under current practices with December planting dates, maize crops will likely be exposed to a higher number of hot days. Similarly, the probability of exposure to hot days also differs between the two locations at the Optimal, Late, and Very Late planting scenarios, notably during the RGP. Strong trends emerged at the Late and Very late planting dates that differed between locations, especially under the Near and Distant future conditions (Fig. 5). These findings suggest that in the future the risk of high temperature exposure affecting maize production will become more region specific under late to very late planting scenarios.

The projected increase in the number of hot days due to climate change was in agreement with (Engelbrecht et al., 2019).. Studies of

2 https://www.weatherbase.com/weather/weather-summary.php3?s=24486&cityname=Bloemfontein%2C+Orange+Free+State%2C+South+Africa&units=; https://www.weatherbase.com/weather/weather-summary.php3?s=604961&cityname=Lichtenburg%2C+North-West%2C+South+Africa&units=

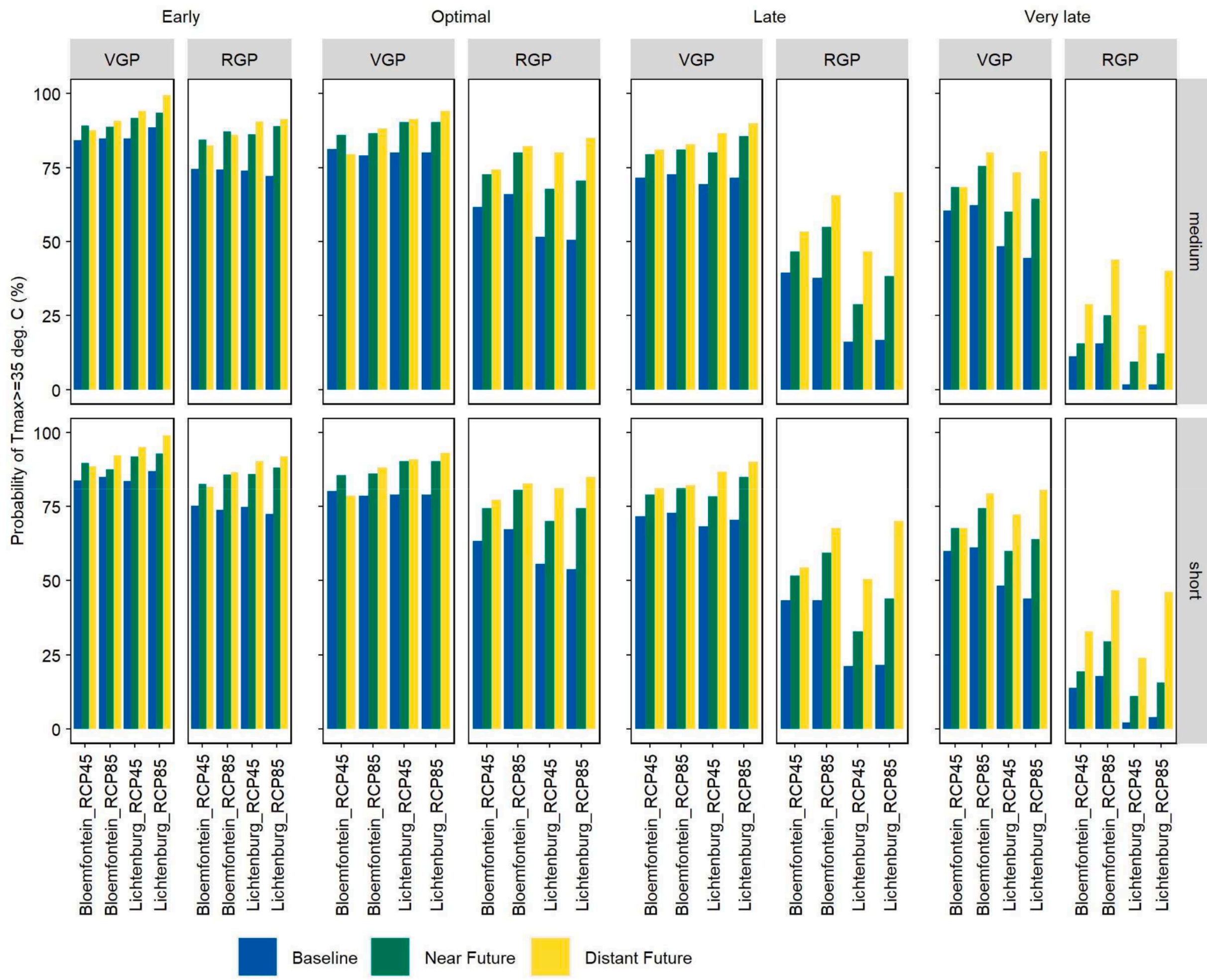

Fig. 5. Probability of exposure to hot days (above 35°C) increases more during the RGP (reproductive growing period) than the VGP (vegetative growth period) in future time horizons (blue - baseline; 1991–2020, green - near future; 2021–2050, yellow - distant future; 2051–2080), across the 21st Century as determined at four different planting dates in Bloemfontein and Lichtenburg for both the short and medium maize cultivars

maize physiology indicate that maize plants are most susceptible to high temperatures during their RGP, especially during the flowering phase leading to significantly reduced yield (Siebers et al., 2017; Wang et al., 2020; Wang et al., 2021). In their investigation of the effect of individual stressors or combined temperature and drought stress on maize yields in Africa. Lobell et al. (2011a) found that under optimal rain-fed conditions, each degree day above 30°C reduced the final yield by 1%, and this loss went up to 1.7% when these temperatures were combined with drought. Hotter, but wetter summers in the future (as suggested by our analyses) may limit the risk of dual drought and high temperature exposure potentially maintaining yield (Engelbrecht et al., 2019, Appendix C.1b). Recently, there has been a major focus on breeding for thermo-tolerant and drought-tolerant cultivars that can maintain yield in the African climate and these breeding programmes should be maintained and expanded in the future (Prasanna et al., 2021). Aside from developing and using new cultivars, which can be time consuming and expensive, our findings suggest that a shift to a later January planting may be used as an adaptation strategy to reduce exposure to very high temperatures during the RGP in the future.

3.5. Projections of future water deficits during the different developmental phases of maize for the main maize growing regions of RSA

Analysis of long-term water deficit trends conducted by growth stages produced mixed results with negative, positive, or neutral changes throughout the 21st Century (Fig. 6, Appendix A.8). Traditionally, it appears that Bloemfontein has had higher water deficits when compared to Lichtenberg, especially under the early and optimal planting windows for VGP, and that trend will most likely be conserved in the future. Negative trends (34% of all the scenario combinations) were the most common outcome under RCP 4.5, whereas positive water deficit trends (also 34% of all the scenario combinations) were mostly projected under RCP 8.5. Neutral changes (31% of all the scenario combinations) were also in large part projected under RCP 4.5, and mostly at Bloemfontein, which suggests a regionalization of climate change impacts on the water deficit for dryland maize crops in RSA.

Negative (and neutral) water deficit trends suggest that total growth stage rainfall amounts will likely compensate to some extent, in most cases, for potential increases in evapotranspiration. Scenario combinations that yielded negative water deficits would be favorable for maize farmers, especially during RGP, given that increased water deficits during the RGP, especially at tasselling and ear formation can drastically reduce yield (Cakir, 2004). If the global climate evolves in the direction projected under RCP 4.5, then all the scenario combinations explored would be appropriate, in regards to water deficit. But if the changes meet RCP 8.5 projections, planting late or very late would likely be the best option for the two maize cultivars.

However, evaluations of climate patterns have found that climate change will most likely lead to increased frequency of extreme rainfall events, with higher water volumes and intensity (Mason et al., 1999; Orlowsky and Seneviratne, 2012). Two outcomes may be expected under such change conditions:

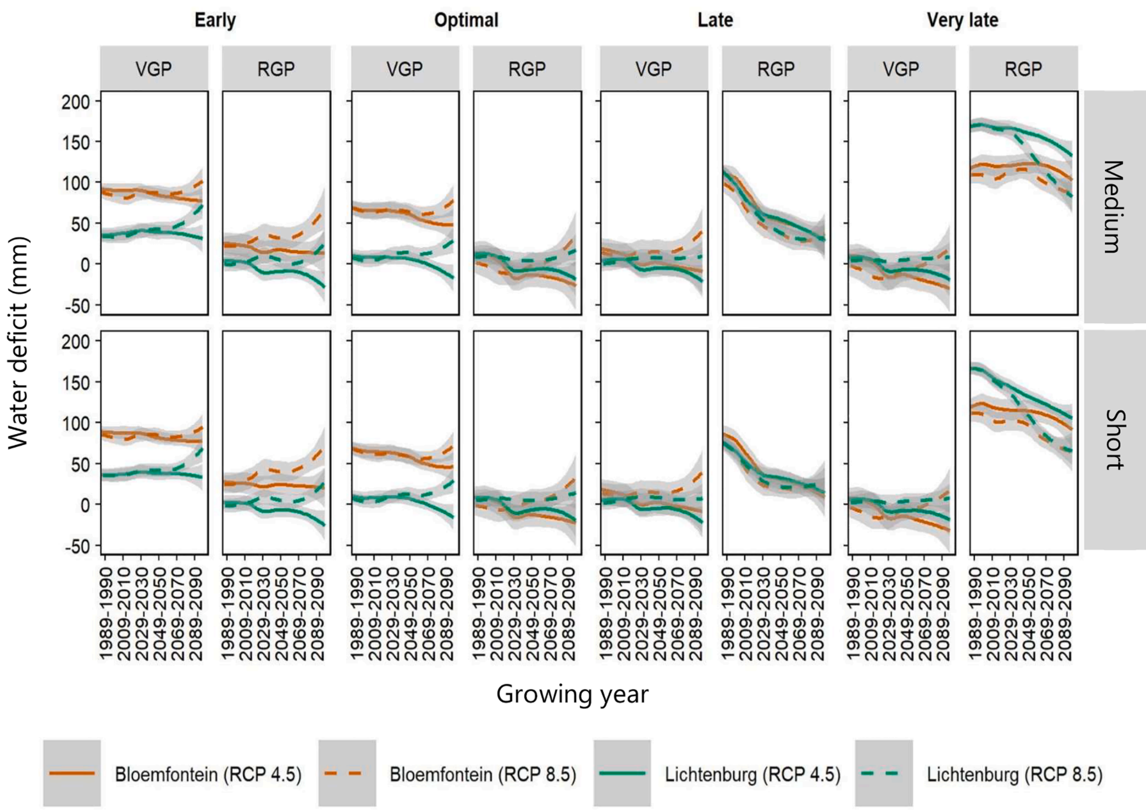

Fig. 6. Projected growing season water deficit by developmental stages for the 21st Century as determined for four different planting dates for Bloemfontein (orange) and Lichtenburg (green). The vegetative growing period (VGP) and reproductive growing period (RGP) assessed for the short and medium maturing cultivars. Shading shows variability due to the different climate models used. A negative trend (slope) indicates a reduction of water deficit over time.

(1) Rainfall events will concentrate in few storms, therefore reducing the temporal distribution of water received, and sustained soil moisture content throughout the growing season. Thus, crops may not receive the required amounts of moisture on time to fulfil their evapotranspiration needs, which could eventually translate into increased agronomic drought stress and reduced yields. (2) Depending on the topography and the soil type, consequences could be the formation of crusts on soil surface (sealing) leading to reduced infiltration and waterlogging. Waterlogging has been shown to reduce crop yields through nitrogen loss due to denitrification, oxygen deprivation, decreased gas diffusion in soil pores, altered soil solution mineral concentrations, and toxic waste production from bacterial activities (Lone et al., 2018). Furthermore, given reduced surface storage due to waterlogging, fields could experience increased sediment movement leading to erosion, gully formation, and water quality issues. In both cases, farmers will need to adopt water and land management practices that could contribute in reducing the adverse impacts of the less frequent but extreme rainfall events.

Positive water deficit trends describe higher disparities between evapotranspiration and rainfall amounts, where the total amount of rainfall received would not satisfy the evapo-transpirative demands. Increased water deficit can limit maize yields by reducing growth rates, reduction in the size of the root system, and altered carbohydrate distribution. The development of maize kernels can easily be aborted due to an inadequate water supply during the early stages (blister and milk) and excessive water stress during dough and dent stages can lead to yield reduction (Lauer, 2007). As noted earlier, positive trends were projected under RCP 8.5, and the highest positive trends for the short maize cultivar were 12.5 and 5.0 mm.decade^{-1} for optimal planting during RGP, at Bloemfontein and Lichtenburg, respectively. The optimal planting window generates also the highest positive water deficit trends for the medium maize cultivar during RGP (14.9 and 5.6 mm.decade^{-1} for Bloemfontein and Lichtenburg, respectively). This assessment suggests that under RCP 8.5 climate change conditions, avoiding planting maize during the optimal planting window would help reduce the chances for large water deficits during RGP in the future. The initial response to potential water deficit increase could be to avoid scenario combinations that would generate positive trends. Yet, even though this could be agreed upon, the impacts of high-water deficits could be reduced by implementing mitigation strategies that could help minimize the impacts of meteorological droughts (Fangmeier et al., 2006).

3.6. Evaluation of the methods and assumptions in this study

The study was carried out under the following three assumptions: (1) cultivars will remain relatively unchanged, (2) other management practices (i.e. irrigation and fertilization) beside planting date will stay more or less unchanged, and (3) soil qualities will stay similar. In light of this, any changes made to the assumptions given above could potentially offset the effects of global warming under climate change by, for example, developing cultivars whose duration is not altered by warming. Additionally, growing conditions such as soil properties and management measures (i.e. addition of cover crops, irrigation or fertilization) can affect crop performance and yield, which can cause climate change impacts to shift drastically. Since crop simulation models were not used in our study, it was impossible to determine the actual yield that might be obtained under the set scenarios. However, this study adds to these by providing an additional layer of information on the alignment of phenological stages with climatic changes that might influence yield in the future. All the interpretations that were given were based on the known knowledge of the single effect of a particular variable and its effects on maize development e.g. warming. However, in the real world, crop growth and yield are complex and are determined by the interaction of genotypes, environments, and management practices.

This analysis focused on the effects of climate change on:

1 Time to maturity; the results relate only to when maize will likely reach maturity, and have nothing to do with actual yields on a unit area basis. Actual yield can depend on several factors, including soil quality, amount and availability of light, moisture and nutrients, management, cultivar, and carbon dioxide in the air. CO_2 has a strong potential to alter the effect of temperature.
2 Probability of exposure to hot and cold days
3 Potential water deficit based on projected potential ET. Actual ET can be higher or lower, depending on different factors, such as crop characteristics, agricultural practices, and soil type and quality, and can result in a shift from the projections.

4. Conclusions and recommendations

The literature has largely so far covered the quantification of the gains or losses that will be realized on maize production under climate change by making use of process based and economic models. This is one of the first studies to investigated the agronomic implications of climate change impacts on maize phenology in southern Africa, a known climate change hotspot, that is projected to warm up to two times that of the global average (Engelbrecht and Monteiro, 2021). Here we focus on two major maize producing provinces of RSA under four different planting dates. Increased frequency of days with temperatures above 35°C and reduced days to maturity have the potential to limit yield due to early transitions to the reproductive stage limiting photosynthetic capacity and grain filling (Porter, 2005; Liu et al., 2010; Harrison et al., 2011). It is also expected that summer seasons will be lengthened and this in combination with the positive or neutral water deficits projected under RCP4.5 in this study suggests that there might be an opportunity for double cropping's with other summer crops. However, the variability in the water deficit projections across scenarios and models (Appendix A8 and C1) indicates caution should be practiced, because rainfall distribution across the season may still change limiting double cropping options.

The adaptation strategies proposed in this study alone are not enough to offset the effects of climate change on maize production. Based on the results of this study, we propose that planting dates could be shifted to the January planting in the distant future, given that the current number of days to maturity for both cultivars can still be maintained under a far future scenario. Additionally, we anticipate that the risk of exposure to freezing days and days with maximum temperatures above 35°C will be reduced under this planting window. This alternative does not consider the advent of extreme weather phenomena, which could negatively affect production at any point during the season.

Other adaptive measures for example development of cultivars that are able to withstand warming as well as the use of precision agriculture can help alleviate the challenges brought about by warming and soil moisture shortages. Full irrigation would not be feasible due to a lack of water and financial resources in RSA, however, advances in remote sensing and precision agriculture can pinpoint water deficits and allow for limited, targeted irrigation strategies that may be feasible for producers (Bwambale et al., 2022). In addition, we have noted substantial variation in the effects of climate change between the two test locations and indicates that more location specific research is required to fully grasp the climate change impacts in the maize production provinces of RSA. Our results suggest that planting date evaluations should be periodically performed in the major maize producing regions on a continuous basis to ensure maize phenological stages are properly aligned with optimal environmental conditions to maintain yields and food security in the region. Long term trials such as these require a concerted effort and strong partnership between the private and public sectors to maintain continuity and preserve food security in the region.

Declaration of Competing Interest

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.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.agrformet.2023.109695.

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