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Unprecedented climate extremes in South Africa and implications for maize production

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Abstract

Maize is the most important crop grown in South Africa, but yields can be severely reduced by extreme high summer average temperatures and low precipitation, potentially adversely affecting both domestic consumption and regional food security exports. To help understand and manage climate risks to food security in Southern Africa it is essential to quantify the present-day likelihood and magnitude of climate extremes in South Africa's maize-growing region and explore the potential for unprecedented climate conditions which would likely result in record low maize yields. We analyse a large ensemble of initialised climate model simulations, which provides almost 100 times as many plausible present-day summers as the equivalent observational dataset. We quantify the risk of unprecedented climate extremes affecting maize production in South Africa and examine the role of the El Niño-Southern Oscillation. We find that the South African maize region is at risk of experiencing record-breaking hot, cold, dry or wet events under current climatic conditions. We find that the annual chance of unprecedented high temperatures in South Africa is approximately 4%, increasing to 62% during very strong El Niño years. We also find that the chance of exceeding the present day seasonal high temperature record has increased across the 1979–2018 period, being five times more likely now than it was in 1980. These extreme events could result in a record-breaking number of days above the optimum, or even the maximum, temperature for maize production, and lead to more severe floods or droughts. Under climate change scenarios, the magnitude and frequency of climate extremes is projected to increase meaning that the unprecedented extremes studied here could become commonplace in the future. This suggests that significant investment is needed to develop adaptations that manage the climate-related risks to food systems now and build resilience to the projected impacts of climate change.

1. Introduction

Maize is the most important staple crop grown in South Africa, accounting for 46% of the total crop area in 2020 (FAO 2022). South Africa was ranked 9th in the world's largest maize-producing countries in 2020 and, as the largest in Africa, is a crucial regional exporter often relied on to achieve food security across Southern Africa. For example, in 2020 South Africa provided nearly all the maize imported by Botswana and Namibia (FAO 2022).

However, due to heavy reliance on rainfed agriculture (van Niekerk *et al* 2018), maize harvests in South Africa can be severely reduced by extreme weather events such as heatwaves, droughts and floods. In 1992 and 2015/16, droughts destroyed maize crops

across South Africa and the wider sub-Saharan region necessitating substantial humanitarian assistance (Callihan and Eriksen 1994, Rembold *et al* 2016), while ongoing flooding in 2022 has destroyed 60% of planted maize (Coleman 2022). Limited access to technology and agrochemicals contributes to low maize yields compared to other countries, such as the USA and Argentina, making the food system more vulnerable to extreme climate events. Trade networks mean the impacts of these extreme events can be felt across domestic, regional, and global scales.

South Africa has been warming at a rate of 0.2 °C per decade since 1961, which is slightly below the global average but equivalent to the rest of Africa (IPCC 2021). Whilst South Africa has not yet seen major reductions in average yields associated with the observed warming trend because of increases in production inputs over the same period (Akpalu *et al* 2011), evidence from other countries globally suggests that climate change will negatively impact maize yields (Pachauri *et al* 2014). Furthermore, rising temperatures and changing rainfall patterns are likely to increase the occurrence of climate extremes (including unprecedented events, i.e. magnitudes that have not been observed before) and further reduce maize yields (Müller *et al* 2011, Thornton *et al* 2011, Hoffman *et al* 2018, Mangani *et al* 2018, 2019, Chapman *et al* 2020). Maize in Southern Africa has therefore been identified as one of the most important crops requiring adaptation option investment (Lobell *et al* 2008).

The El Niño-Southern Oscillation (ENSO) mode of natural climate variability is associated with far-reaching global teleconnections affecting temperatures and precipitation (e.g. Davey *et al* 2014) that link strongly to agricultural production (e.g. Iizumi *et al* 2014). ENSO is in a positive (El Niño) phase when sea surface temperatures (SSTs) in the tropical eastern Pacific are anomalously warm, and in a negative (La Niña) phase when anomalously cool. Some of the largest climate extremes on record in South Africa are associated with ENSO variability; for example, two-thirds of the extreme hot temperature events in South Africa between 1970 and 2015 can be related to El Niño (Nangombe *et al* 2018) and La Niña events are associated with the development of tropical-temperate troughs which increase rainfall over South Africa (Cook 2001, Mulenga *et al* 2003). Climate models project increasingly extreme ENSO states in the future (Timmermann *et al* 1999, Yeh *et al* 2009, Cai *et al* 2014), even if global mean temperature is stabilised at 1.5 °C above preindustrial temperatures (Wang *et al* 2017).

To assess future risk to agriculture of climate extremes, we first need to understand the present-day risk due to natural climate variability. A key part of this assessment involves quantifying the risk of unprecedented climate extremes in the present-day, i.e. events more extreme than any on record. This new

information about the current risk of record-breaking extremes will provide a vital first step in guiding adaptations to future climate change.

However, our understanding of extremes is limited by the short duration of the observational record. To better understand the present-day likelihood of climate extremes in South Africa and their large-scale drivers, we apply the UNprecedented Simulated Extremes using ENsembles (UNSEEN; Thompson *et al* 2017) approach to a large ensemble of high-resolution initialised climate simulations. The ensemble consists of nearly 100 times more plausible realisations of the climate than observations over the same period, enabling a more comprehensive analysis of extremes and providing the opportunity to explore the characteristics of unprecedented events.

In this first application of the UNSEEN approach in sub-Saharan Africa we:

- Estimate the annual chance of experiencing unprecedented seasonal temperature and precipitation extremes during the peak of the maize growing season, January–March (JFM; FAO 2021)
- Assess how the likelihood of unprecedented seasonal extremes has already altered due to climate change
- Explore how the likelihood of extremes is linked with ENSO variability, and
- Investigate the implications for maize production and trade.

2. Data and methods

2.1. Observational data
The observational climate data used is the WATCH Forcing Data methodology applied to ERA5 reanalysis data, hereafter 'WFDE5' (Cucchi *et al* 2020). The WFDE5 dataset runs from 1979 to 2018 at a horizontal resolution of 0.5° by 0.5° (∼50 km × 50 km in South Africa).

2.2. UNSEEN climate model data
The UNSEEN approach is defined as using a large ensemble of initialised climate model simulations to identify plausible climatic conditions that could have occurred during the recent historical period (see Thompson *et al* 2017, Squire *et al* 2021). In this study we use the hindcast ensemble of the third version of the Met Office Decadal Prediction System, DePreSys3 (Dunstone *et al* 2016), which is based on the high resolution (0.83° longitude, 0.55° latitude; about 60 km at mid-latitudes) model HadGEM3-GC2 (Williams *et al* 2015). The model is initialised with observations on 1 November and 1 May each year and is driven with observed anthropogenic forcings. Each hindcast year consists of 40 ensemble members, created by using different seeds to the stochastic physics scheme (Bowler *et al* 2009). The JFM season represents forecast months 3–5 of the
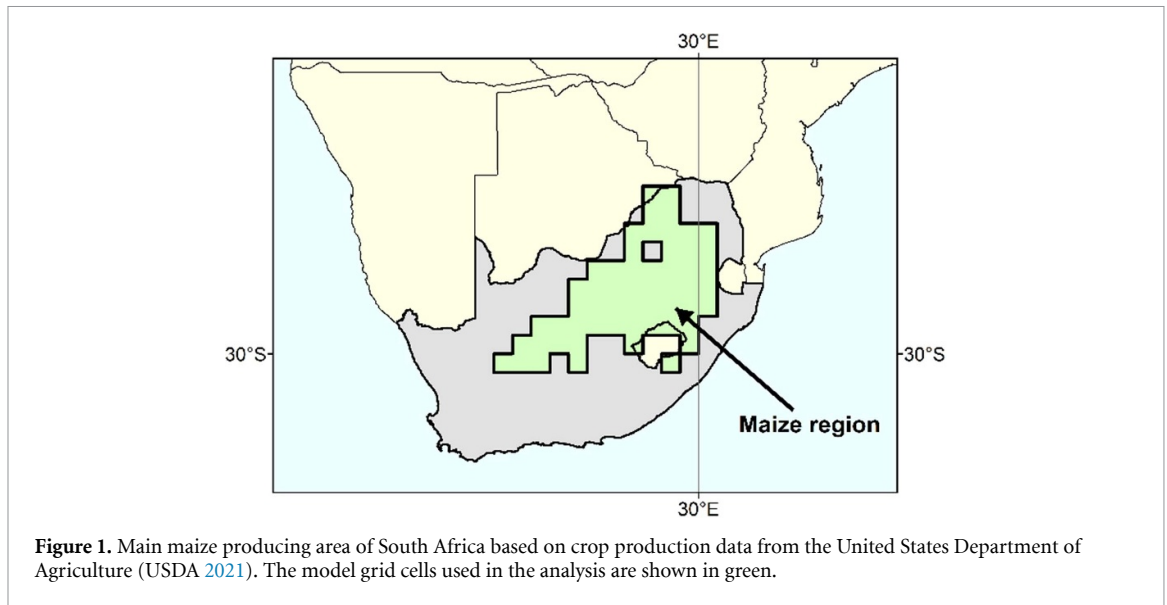
Figure 1. Main maize producing area of South Africa based on crop production data from the United States Department of Agriculture (USDA 2021). The model grid cells used in the analysis are shown in green.

November ensemble and months 9–11 of the May ensemble. Due to WFDE5 starting in 1979, we use only 1979–2018 DePreSys data.

2.3. Crop data

Maize crop yield data for 1979–2018 is taken from the FAOSTAT database (FAO 2022). The climate model and observational data were restricted to the northeast area of South Africa, where maize is the predominant crop (figure 1).

2.4. Pre-processing steps

Because climate model data can exhibit spatial and temporal biases, we first assess where the simulations are consistent with the observations using a set of fidelity tests which compare the mean, standard deviation, skewness, and kurtosis. Both the temperature and precipitation variables required a bias correction to the mean to pass the fidelity tests. Any long-term trends were removed to make the climate estimates representative of the current climate (taken as the year 2018). Full details of the steps, tests and results are given in the Supplementary Information (figures S1–S3). To isolate year-to-year climate variability in the maize yield data, we remove the long-term trend by subtracting a 2nd order polynomial line of best fit, giving a time series of yield anomalies (shown in figure 2(D)).

2.5. Analysis steps

The UNSEEN approach was used to identify the model realisations that produce record-breaking extremes for the maize region of South Africa and to calculate the annual chance of experiencing record-breaking climate extremes (the number of realisations in which the observational record was broken divided by the total number of realisations).

At large spatial scales, maize yields can be characterised by a two-dimensional Gaussian function of temperature and precipitation (the yield response function (YRF); Shirley *et al* 2020). To improve robustness, in this study we linearise the relationship by taking the natural logarithm of the relative yield (Y; defined as the yield time series divided by the polynomial best fit) and use ordinary least squares regression to fit a quadratic relationship with temperature (T) and precipitation (P) that represents the argument of the Gaussian YRF, i.e.

$$
\begin{aligned}
\ln(Y) = \ln(Y_0) &- \frac{1}{2(1-\rho^2)} \\
&\times \left[\left(\frac{T-T_{\mathrm{opt}}}{W_{\mathrm{T}}} \right)^2 + \left(\frac{P-P_{\mathrm{opt}}}{W_{\mathrm{P}}} \right)^2 \right. \\
&\left. - 2\rho \left(\frac{T-T_{\mathrm{opt}}}{W_{\mathrm{T}}} \right) \left(\frac{P-P_{\mathrm{opt}}}{W_{\mathrm{P}}} \right) \right] \\
= aT^2 &+ bT + cP^2 + dP + eTP + f
\end{aligned}
$$

where Y_0 is the yield at the optimal temperature and precipitation total, T_{opt} is the optimal temperature, P_{opt} is the optimal precipitation total, W_{T} and W_{P} are the respective widths of the Gaussian YRF; a, b, c, d, e, and f are regression coefficients, from which simultaneous equations enable the parameters of the Gaussian YRF to be obtained (see supplementary information). JFM temperature and precipitation are strongly anti-correlated and do not cover a sufficient range to be able to constrain a physically meaningful value of e. For this reason, we set $e = 0$, so that yield does not depend on the interaction between temperature and precipitation. While this simplifying assumption affects some details of the results, the overall conclusions are not strongly dependent on it.

This method is more robust than a non-linear fitting procedure for the small sample of available observations, while still allowing some exploration of non-linear yield dependence on temperature and rainfall without needing cardinal temperatures.

This transparent framework allows determination of optimal JFM temperature and precipitation (at YRF maxima) for maize varieties grown in South Africa and estimation of yield reductions associated with record-breaking extremes.

The amplitude of ENSO is measured through several different indices; here we use one of the most common, the Niño 3.4 index: the SST anomaly to climatology in the tropical Pacific Ocean region (5° N–5° S, 120°–170° W); hereafter referred to as the N3.4 region. As no WFDE5 bias-corrected version is available for SST, ERA5 SST data (Hersbach *et al* 2020) are used to calculate the observed ENSO timeseries. ENSO indices are also calculated from the DePreSys SSTs.

To understand how ENSO affects the chance of record-breaking extremes, DePreSys data are split into 0.5 °C bins according to the SST anomaly in the Niño 3.4 region. For each bin, the chance of unprecedented hot, cold, wet and dry events, and their combinations, are calculated as the fraction of ensemble member realisations that exceed or subceed[7] the observed records, together with how those fractions have changed over time.

3. Results

3.1. The relationship between maize yields, temperature, precipitation and ENSO

Figures 2(A)–(C) demonstrates that South Africa during the El Niño years of 1983 and 1992 was hotter and drier than average; however, this association was weaker during the El Niño years of 1998, 2003 and 2010. Similarly, the La Niña years of 1989, 1996 and 2000 were wetter and cooler than average, but near-average conditions occurred during the La Niña year of 2008. In addition, during the La Niña year of 1999, South Africa experienced hotter and drier conditions than average.

Closer examination of the relationship between maize yields in South Africa and the observed JFM seasonal temperatures and precipitation amounts (figure 3) shows that yields tend to be higher when JFM temperatures are lower and precipitation amounts are higher than average, and that all the yield shocks (yield anomalies <-0.25 t ha^{-1}; shown in pink in figure 3) occur when the JFM seasonal temperature is higher and precipitation amounts are lower than average.

In addition, maize yields in South Africa are correlated with observed SSTs in the tropical Pacific Ocean (figure 4(A)). The observed relationship between the ENSO phase and maize yields is strong, with a Pearson correlation of -0.47 (p-value = 0.005), equivalent to other recent findings

(Anderson *et al* 2019). This relationship is likely to be the result of ENSO's influence on JFM temperature/precipitation in the maize growing area.

Figures 4(B) and (C) show the relationship between ENSO and JFM temperature and precipitation respectively and demonstrate that the DePreSys model reproduces the relationship found in the observations for JFM temperature, while the relationship with JFM precipitation is less well represented (although the sign of the correlation generally agrees).
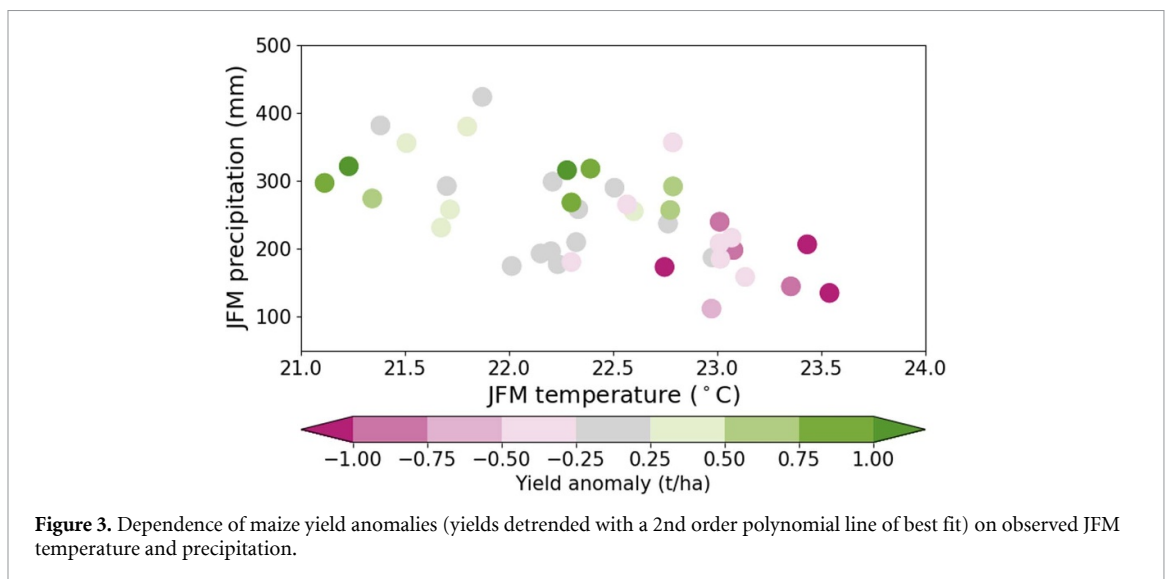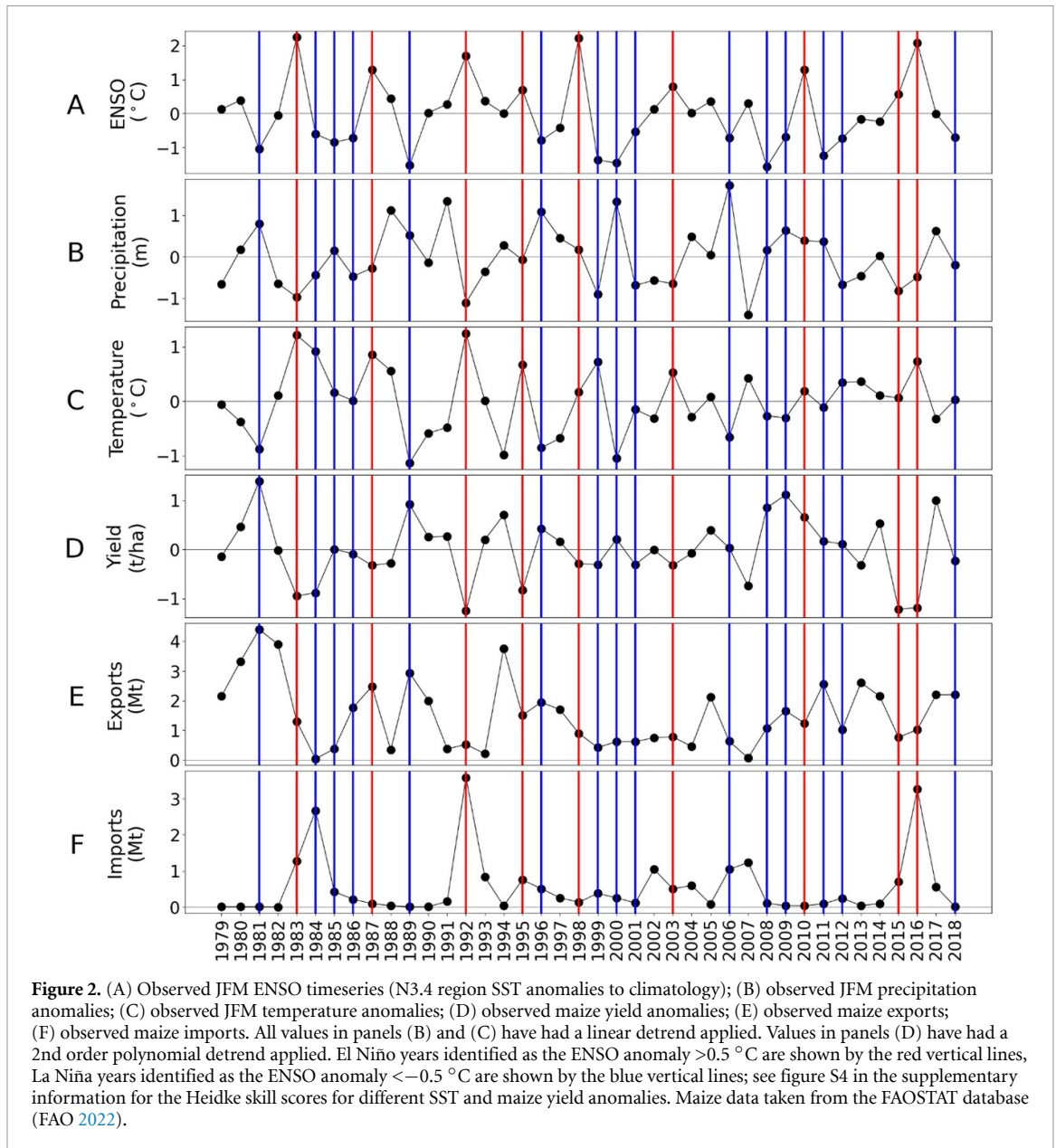
As well as affecting domestic maize supply, ENSO-related yield shocks can affect maize availability to trading partners, which is reflected in the South Africa's maize import and export data (figures 2(E) and (F)). Maize yield and exports are positively correlated (Pearson's correlation 0.50, p-value = 0.000 89) whereas yield and imports are negatively correlated (Pearson's correlation -0.63, p-value = 0.000 01), i.e. exports tend to increase and imports tend to decrease for higher maize yields. Figure 5 shows that South Africa typically exports to both nearby Southern African Development Community (SADC) countries in Africa and to Southeast Asia. The 2015–2016 El Niño event was one of the strongest climatic warming events of its kind recorded to date and caused extreme drought conditions in southern Africa. The agricultural impacts in sub-Saharan Africa were severe, with over 40 million people in the SADC (23%) being food insecure and requiring international aid (South African Development Community 2016), ∼35% more than the five-year average (National Vulnerability Assessment Committee 2017). South Africa experienced notably lower than average yields (figure 2(D)), necessitating 3.3 million tonnes of imports (∼2 million tonnes more than the 2014–2018 average), one-third of which was redistributed and exported primarily to nearby countries (figures 2(E) and 5, SAGL 2016, FAO 2022).

3.2. Chance of an unprecedented climate event and impact on maize yield

Table 1 shows the observed seasonal records, the annual chance of breaking those records, and the maximum and minimum unprecedented amounts. South Africa experiences some of the most extreme droughts in the world, and even multiyear droughts are not uncommon (Rouault and Richard 2003). For example, according to the WFDE5 data, the lowest observed precipitation amount for JFM occurred in 2007, when South Africa's maize-growing region received less than half the expected amount (115 mm compared to the climatological mean of 252 mm). Figure 2 shows that this was associated with reduced maize yield, decreased maize exports, and increased imports.

The estimated chance of subceeding the observed JFM precipitation record of 115 mm in the maize region of South Africa is 0.8% yr^{-1} (figure 6). The

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[7] The term subceeded is used to mean the opposite of exceeded: i.e. if the minimum record is broken it has been subceeded, if the maximum recorded has been broken it has been exceeded.

Figure 2. (A) Observed JFM ENSO timeseries (N3.4 region SST anomalies to climatology); (B) observed JFM precipitation anomalies; (C) observed JFM temperature anomalies; (D) observed maize yield anomalies; (E) observed maize exports; (F) observed maize imports. All values in panels (B) and (C) have had a linear detrend applied. Values in panels (D) have had a 2nd order polynomial detrend applied. El Niño years identified as the ENSO anomaly >0.5 °C are shown by the red vertical lines, La Niña years identified as the ENSO anomaly <−0.5 °C are shown by the blue vertical lines; see figure S4 in the supplementary information for the Heidke skill scores for different SST and maize yield anomalies. Maize data taken from the FAOSTAT database (FAO 2022).

Figure 3. Dependence of maize yield anomalies (yields detrended with a 2nd order polynomial line of best fit) on observed JFM temperature and precipitation.

Figure 4. (A) Relationship between observed maize yields and JFM sea surface temperatures, the ENSO Niño 3.4 region is highlighted by the black box and hatching shows regions that are significant at the 95th percentile confidence level; (B) relationship between JFM ENSO (N3.4 region SST anomaly) and JFM temperature in the observations and in the DePreSys model; (C) Pearson correlation between JFM ENSO (N3.4 region SST anomaly) and JFM temperature in the observations and in the DePreSys model; (D) relationship between JFM ENSO (N3.4 region SST anomaly) and JFM precipitation in the observations and in the DePreSys model; (E) Pearson correlation between JFM ENSO (N3.4 region SST anomaly) and JFM precipitation in the observations and in the DePreSys model. In all cases, observations and model data have been detrended. Confidence intervals for the correlations were calculated using 1000 resamples of 38 years in length from the WFDE5 reanalysis for 1979–2018 and 1000 resamples of length 40 years for 1979–2018 for the DePreSys data where a random selection from the 40 realisations was selected for each year. The confidence intervals quoted in brackets are the 5th and 95th percentile correlations. For temperature (panel (C)), the model distribution does not span zero and suggesting the relationship is statistically significant. For precipitation (panel (D)), the model distribution spans zero and suggesting the relationship is not statistically significant.

lowest simulated rainfall total for JFM is 67 mm, which would represent a severe drought, likely resulting in significantly reduced maize production, unless irrigated. For comparison, the total growing season precipitation requirements for maize are optimally 600–1200 mm and absolutely 400–1800 mm (FAO 2010). The WFDE5 data show that the maize growing region of South Africa receives on average just 493 mm between October and April, and typically half falls in the JFM season. This means
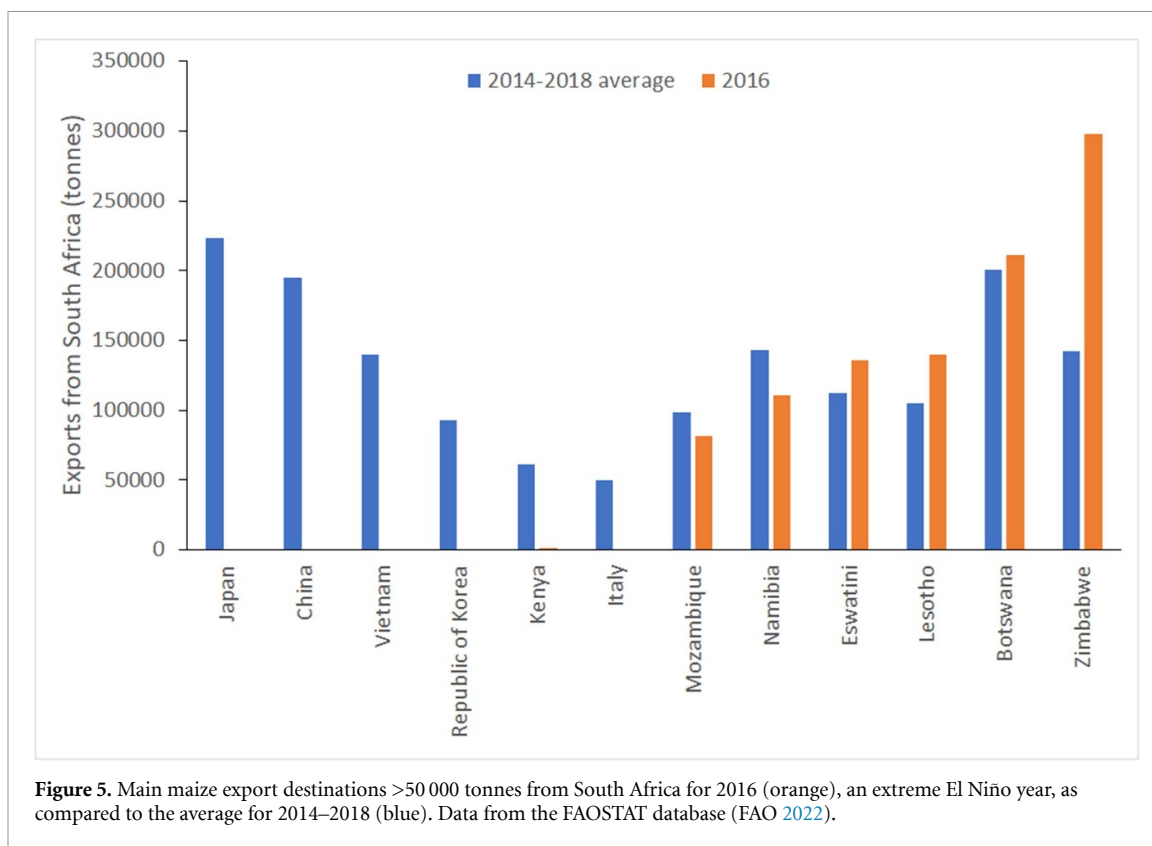
Figure 5. Main maize export destinations >50 000 tonnes from South Africa for 2016 (orange), an extreme El Niño year, as compared to the average for 2014–2018 (blue). Data from the FAOSTAT database (FAO 2022).

Table 1. Key statistics from the observations and UNSEEN analysis for the maize region of South Africa. Note that the data are linearly detrended, pivoting on the year 2018. The numbers in brackets show the 5–95th percentile confidence intervals around the probabilities.

Observed mean JFM temperature	Minimum	21.6 °C
	Maximum	24.0 °C
	Mean	22.7 °C
	Standard deviation	0.6 °C
Observed JFM precipitation total	Minimum	115 mm
	Maximum	427 mm
	Mean	254 mm
	Standard deviation	73 mm
Unprecedented mean JFM temperature	Minimum	20.9 °C
	Maximum	25.4 °C
Unprecedented JFM precipitation total	Minimum	67 mm
	Maximum	569 mm
Annual chance of subceeding minimum observed temperature record		2.8% (2.2%–3.4%)
Annual chance of exceeding maximum observed temperature record		4.1% (3.4%–4.8%)
Annual chance of subceeding minimum observed precipitation record		0.8% (0.5%–1.1%)
Annual chance of exceeding maximum observed precipitation record		1.2% (0.8%–1.5%)

that the current South African climate sits on the borders of suitability for maize production, as indicated by figure 7.

There is also a 4.1% yr^{-1} chance of exceeding the present-day JFM temperature record (figure 6), which could contribute to damaging soil moisture reductions even during years of average JFM rainfall. Temperature requirements for maize production are optimally 18 °C–33 °C (FAO 2010), showing that South African temperatures are well suited to maize.

Combinations of extremely high temperature and low rainfall also pose a significant risk to maize productions, with a 0.2% chance per year of both subceeding the JFM precipitation record at the same time as exceeding the JFM seasonal temperature record (figure 6).

Figure 7(A) shows the best-fit model for relative yield as a function of JFM precipitation (adjusted $R^2 = 0.42$), and figure 7(B) shows the equivalent model expressing yield as a function of JFM temperature (adjusted $R^2 = 0.59$). Figure 7(C) shows the best-fit bivariate Gaussian model for yield as a function of both JFM temperature and JFM precipitation (adjusted $R^2 = 0.66$). The darker green contours show where the yield is expected to be higher, suggesting that yield tends to be maximised for a JFM temperature of approximately 21 °C and JFM precipitation of 292 mm.
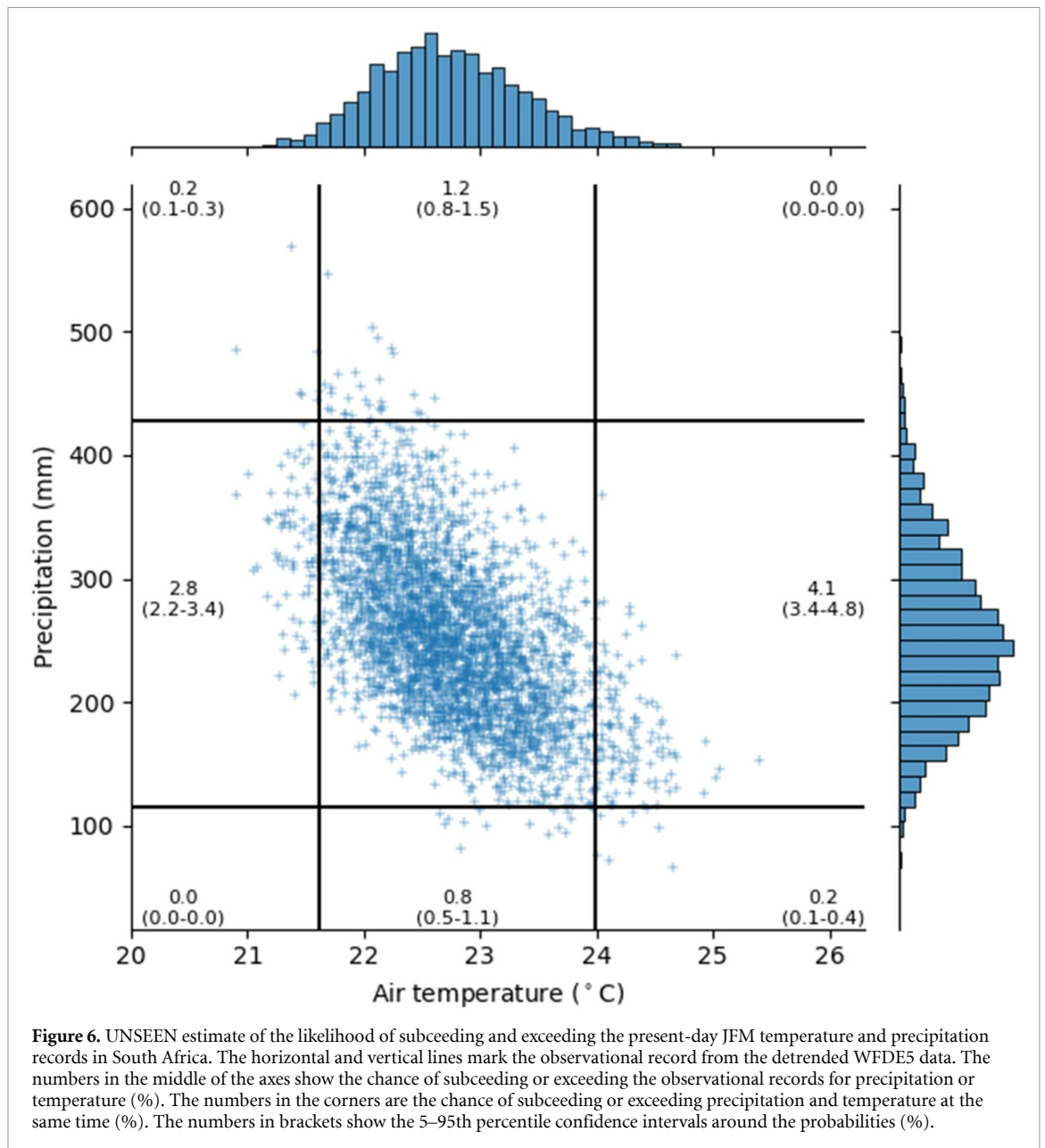
Figure 6. UNSEEN estimate of the likelihood of subceeding and exceeding the present-day JFM temperature and precipitation records in South Africa. The horizontal and vertical lines mark the observational record from the detrended WFDE5 data. The numbers in the middle of the axes show the chance of subceeding or exceeding the observational records for precipitation or temperature (%). The numbers in the corners are the chance of subceeding or exceeding precipitation and temperature at the same time (%). The numbers in brackets show the 5–95th percentile confidence intervals around the probabilities (%).

Figure 7(A) shows that observed precipitation totals are generally below the optimal amount (292 ± 206 mm) and figure 7(B) shows that observed JFM temperatures are generally above the optimum (20.9 ± 2.3 °C). In addition, figure 6 and table 1 show the potential for climate events that are more extreme than any recorded over the past 40 years. These unprecedented events fall well outside the central peak of the YRF (see figure 7), likely resulting in very large yield reductions.

For example, using the best-fit YRF, for the minimum simulated JFM precipitation (66.6 mm; table 1) and corresponding temperature (24.7 °C), the estimated relative yield is 0.16 (0.12–0.22), i.e. 16% of the yield obtained at the optimal JFM temperature and precipitation. For the maximum simulated JFM temperature (25.4 °C; table 1) and corresponding precipitation total of 152 mm, the estimated relative yield

is 0.12 (0.067–0.22), i.e. 12% of the yield obtained at the optimal temperature and rainfall. These results suggest that temperature extremes are likely to be the stronger driver of exceptionally low maize yields in South Africa. However, caution is needed in interpreting these results because they extrapolate the YRF far beyond the range of recent observations, and we do not account for interactions between temperature and rainfall.

Previous work (Sazib *et al* 2020) has found that maize yield decreases associated with El Niño events tend to be larger than corresponding yield increases during La Niña events. The YRF derived here suggests that this could in part be because maize yield has a non-linear dependence on temperature and precipitation. La Niña years bring the growing conditions closer towards the optimum, where the YRF is flatter whereas El Niño years push the growing conditions
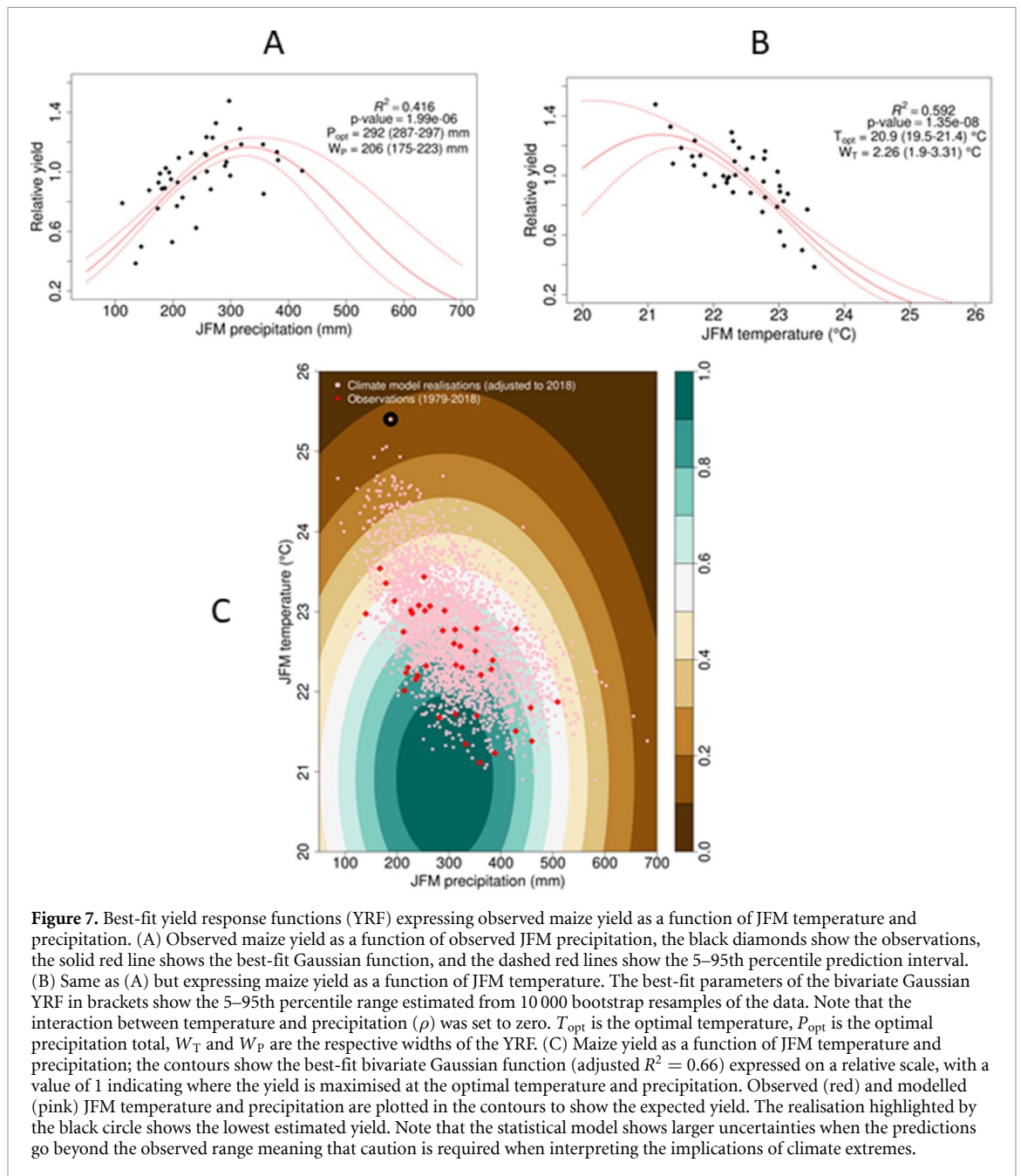
Figure 7. Best-fit yield response functions (YRF) expressing observed maize yield as a function of JFM temperature and precipitation. (A) Observed maize yield as a function of observed JFM precipitation, the black diamonds show the observations, the solid red line shows the best-fit Gaussian function, and the dashed red lines show the 5–95th percentile prediction interval. (B) Same as (A) but expressing maize yield as a function of JFM temperature. The best-fit parameters of the bivariate Gaussian YRF in brackets show the 5–95th percentile range estimated from 10 000 bootstrap resamples of the data. Note that the interaction between temperature and precipitation (ρ) was set to zero. T_{opt} is the optimal temperature, P_{opt} is the optimal precipitation total, W_T and W_P are the respective widths of the YRF. (C) Maize yield as a function of JFM temperature and precipitation; the contours show the best-fit bivariate Gaussian function (adjusted $R^2 = 0.66$) expressed on a relative scale, with a value of 1 indicating where the yield is maximised at the optimal temperature and precipitation. Observed (red) and modelled (pink) JFM temperature and precipitation are plotted in the contours to show the expected yield. The realisation highlighted by the black circle shows the lowest estimated yield. Note that the statistical model shows larger uncertainties when the predictions go beyond the observed range meaning that caution is required when interpreting the implications of climate extremes.

further away from the optimum, where the YRF is steeper.

3.3. Dependence of unprecedented high temperature events on ENSO

ENSO is a strong driver of interannual JFM temperature variability in South Africa, and therefore maize yield. We now build on this finding by evaluating the influence of ENSO on the likelihood of unprecedented high JFM temperatures (see Squire *et al* 2021). Because DePreSys and the observations both show a similar relationship between ENSO and JFM temperature (figure 4(B)), we have confidence that the UNSEEN approach remains suitable for this analysis.

Figure 8(A) shows that the annual chance of South Africa's maize region experiencing JFM average temperatures that exceed the observational record (up to 2018) increases with the magnitude of positive SST anomalies in the N3.4 region (i.e. El Niño events). There is also evidence that the chance of experiencing unprecedented cold JFM temperatures increases with the very largest negative SST anomalies (La Niña events; figure 8(B)). These results from the climate model are consistent with the observations: as shown in figures 4(B) and S5 in the supplementary information, the observed correlation between JFM temperatures in South Africa and positive SST anomalies in the N3.4 region in JFM is much stronger than the correlation with negative SST anomalies (correlations of 0.72 and 0.34 respectively). Note that this is not the case for JFM precipitation where the correlations are very similar (figure S5). Figures 8(C) and (D) also reveal an
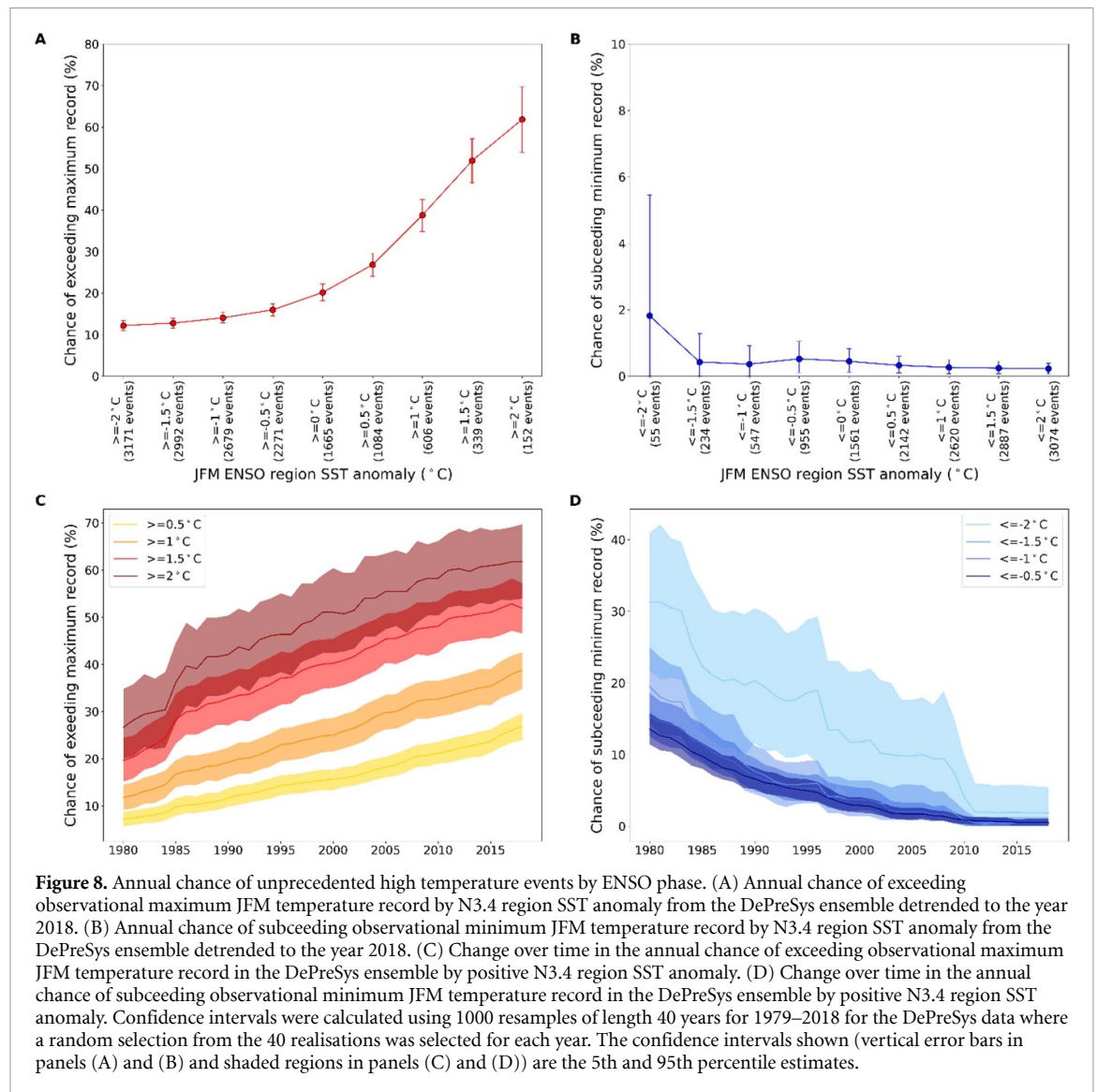
Figure 8. Annual chance of unprecedented high temperature events by ENSO phase. (A) Annual chance of exceeding observational maximum JFM temperature record by N3.4 region SST anomaly from the DePreSys ensemble detrended to the year 2018. (B) Annual chance of subceeding observational minimum JFM temperature record by N3.4 region SST anomaly from the DePreSys ensemble detrended to the year 2018. (C) Change over time in the annual chance of exceeding observational maximum JFM temperature record in the DePreSys ensemble by positive N3.4 region SST anomaly. (D) Change over time in the annual chance of subceeding observational minimum JFM temperature record in the DePreSys ensemble by positive N3.4 region SST anomaly. Confidence intervals were calculated using 1000 resamples of length 40 years for 1979–2018 for the DePreSys data where a random selection from the 40 realisations was selected for each year. The confidence intervals shown (vertical error bars in panels (A) and (B) and shaded regions in panels (C) and (D)) are the 5th and 95th percentile estimates.

increasing chance of unprecedented hot events and a decreasing chance of unprecedented cold events with time. For example, the annual chance of JFM average temperatures higher than 24 °C is now five times more likely than in 1980 and occurs for all N3.4 region SST anomaly categories.

4. Discussion

Our analysis shows that the risk of unprecedented high JFM average temperatures is increasing, posing a growing threat to agriculture in South Africa. Warmer seasonal temperatures speed up plant development, which shortens the growing season for optimal growth leading to reduced yields (Lizaso *et al* 2018).

There is a strong relationship between the mean JFM seasonal temperature and the maximum daily temperature in JFM (figure S6 in the supplementary information). This suggests an increasing risk of high daily maximum temperatures which could exceed the optimal daily mean temperature for maize in JFM

(estimated to be 30.5 °C; Sánchez *et al* 2014) and damage crops through reductions in stomatal conductance and therefore transpiration and photosynthesis (Sabagh *et al* 2020).

The WFDE5 observations show days above the optimal temperature for maize are already experienced in the current climate (figure S6), and that some parts of the maize-growing region of South Africa also experience daily maximum temperatures that approach the maximum maize temperature threshold during anthesis of 37.3 °C (Sánchez *et al* 2014). During unprecedented hot seasonal temperatures, it is likely that this maximum daily temperature threshold would be exceeded more frequently, particularly in the north and west, which are generally warmer than the regional average temperature.

Similarly, there is a clear relationship between JFM precipitation and the maximum number of consecutive wet and dry days over the same season (figure S7 in the supplementary information). This means that unprecedented wet and dry seasonal JFM events could lead to more severe floods or droughts.

Increasing dry spell duration is of concern because maize yields reduce when water stressed, especially during the most sensitive reproductive growth stages (Daryanto *et al* 2016)—which occurs in the JFM season in South Africa. Increasing wet spell duration is also concerning because maize yields decrease as excessive wetness increases (Kanwar *et al* 1988).

From the observational record we find significant correlations between JFM temperature and precipitation in South Africa's maize region and ENSO. It may, therefore, be possible to provide early warnings of extreme conditions that could affect maize production because ENSO has predictability (Monerie *et al* 2019, L'Heureux *et al* 2020). However, whilst the model reproduces the observed temperature relationship with ENSO, the precipitation relationship is less well simulated. To obtain a more complete understanding, it will be important to explore other large-scale drivers of climate extremes in South Africa and how they interact with ENSO variability. For example, the influence of the Antarctic Oscillation pattern on South Africa precipitation has been shown to be stronger during La Niña years (Pohl *et al* 2010).

While this study has examined the likelihood and magnitude of potential record-breaking extremes in the current climate, the magnitude and frequency of temperature extremes is expected to be higher in the future due to climate change (Coumou and Robinson 2013, Coumou *et al* 2013). This implies future climate changes in the region could result in the unprecedented extremes of our analysis becoming commonplace by the 2040s, with an increasing likelihood of experiencing temperatures exceeding the maximum threshold for maize production. Even though the critical temperature thresholds for maize may not regularly be exceeded under the current climate, warmer temperatures can reduce maize yields and quality by making conditions more favourable for weeds, pests and diseases and by causing more rapid crop development (Mukanga *et al* 2010, Luo 2011). For example, estimates suggest that each degree day above 30 °C can reduce the yield by 1% under optimal rain-fed conditions and by 1.7% under drought conditions (Lobell *et al* 2011). Future changes in precipitation may also lead to further erosion and water-logging of soil in the region (Chapman *et al* 2021).

5. Conclusions

Maize production in South Africa is a crucial component of food security domestically and internationally, particularly through exports to neighbouring countries. Yields in South Africa are strongly dependent on summer temperature and precipitation, tending to be reduced during hot and dry conditions. In turn, hot summer conditions and low maize yields are strongly associated with El Niño events.

Using a large ensemble of initialised climate model simulations, we find that South Africa's maize region is at risk of experiencing record-breaking hot, cold, dry, or wet events under current climatic conditions. The likelihood of hot conditions has already increased and is likely to increase further, suggesting that significant investment is needed to develop adaptations that manage the risk to sub-Saharan African food systems now and to build resilience to the projected impacts of climate change. Adaptations could include changing sowing dates, using and developing suitable crop varieties, and building irrigation capabilities (Fisher *et al* 2015). Although breeding new drought and heat-tolerant maize varieties is likely a research priority for the region, maize yields in southern Africa are among the lowest in the world and breeding alone is unlikely to be sufficient to build the required resilience. Changes to agricultural management practices are also likely to be critical, such as adopting climate-smart agriculture techniques to increase soil water storage (Cairns *et al* 2013) and increasing crop diversification, which could have the added benefit of improving nutrition security (Renwick *et al* 2021).

In addition, because the influence of El Niño events is felt globally, actions taken in South Africa to combat poor harvests can benefit food systems in other African countries. To manage the impact of El Niño events, we therefore recommend a coordinated regional approach, such as was conducted during the devastating El Niño event of 1992 (Callihan and Eriksen 1994, World Food Programme 2016), and that trade relationships are built and maintained with countries that experience the opposite impacts to the same ENSO phase, such as Argentina.

Data availability statement

Any data that support the findings of this study are included within the article.

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Author contributions

Catherine Bradshaw: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing - Original Draft, Writing - Review & Editing, Visualization; Edward Pope: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing - Review & Editing, Visualization, Supervision, Project Administration, Funding Acquisision; Gillian Kay: Methodology, Software, Validation, Writing - Review & Editing, Visualization; Jemma Davie: Investigation, Resources, Software, Validation, Writing - Review &

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