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Potential Impacts of Extreme Weather Events in Main Maize *(Zea mays* L.*)* Producing Areas of South Africa

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Abstract

An important topic of global concern is the likely reduction of maize production in response to climate change, in association with increased frequency and intensity of extreme weather events, which likely threatens food security. We quantified yield the response of maize to projected climate changes in three main maize growing areas of South Africa (Bloemfontein, Lichtenburg and Nelspruit) using two crop modelling solutions: existing (EMS) and modified (MMS) CropSyst. The MMS considers explicitly the impact of extreme heat and drought. Both solutions were run with climate data generated from two radiative forcing scenarios using six general circulation models and three time horizons representing baseline (1990-2020), near-future (2021-2050) and far-future (2051-2080) time periods. Overall, reduced yields were projected with both modelling solutionsunder future climate, especially for the far future time period . Simulated maize grain yield using EMS with high radiative forcing for far future decreased (compared with the baseline) by 30%, 25.9%, and 18.3% at Bloemfontein, Lichtenburg and Nelspruit, respectively. While simulated grain yield With MMS, reductions were 27.6%, 24.3%, 18%, respectively. Simulated grain yield differences between the EMS and MMS ranged between 9 and 21%. This difference showed an increasing trend as time progressed from the baseline to the far future and varied across locations. Accounting explicitly for the impact of extreme weather events (MMS) resulted in lower simulated yields compared with the model without (EMS). Findings from this study warrant the need for location-specific model simulation using MMS-type models to improve crop yield predictions under climate change for better food security planning and policy formulation.

Keywords: Climate change scenario, food security, maize production, modified CropSyst, radiative forcing

1. Introduction

An important topic of global concern is the probable reduction in maize (*Zea maize* L.) production in response to climate change, in association with extreme weather events (Abraha and Savage 2006). Immense progress has been made in dispensing climate-related data and agricultural yield projections. However, uncertainties persist around the reliability of the data used for climate projections, the inability to mimic experimentally future ecosystems or the atmospheric conditions that will prevail in the future and, lastly, the inability of existing crop models to fully account for the impacts of climate change (Abraha and Savage 2006; Zinyengere et al. 2014). This has been exacerbated by the projected increase in the intensity and frequency of extreme weather events under climate change. In fact, most crop models have shown limits in taking into account the impacts of extreme weather events (van der Velde et al. 2012; Zinyengere et al. 2014). For this study, we have used a modified version of the crop model CropSyst (after Stöckle et al. 2003), which includes algorithms explicitly taking into account the impacts of extreme weather events on crop production, and can thus be used to simulate maize production. The model has been calibrated and validated for maize in South Africa (Mangani et al. 2018).

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A few modelling studies have been performed in South Africa to try to understand and quantify the impacts of projected climate change on maize production (Abraha and Savage 2006; Walker and Schulze 2006; Walker and Schulze 2008). These studies used CERES-maize and CropSyst crop models to predict maize production under climate change without taking into account explicitly the impact of extreme weather events on crop growth and development. Mangani et al. (2018) reported that crop models, which do not take extreme weather events into account, tend to overestimate crop yields when extreme weather events prevail in projected future climate change. This has some implications on food security planning at country level. Policy making not accounting properly for the impacts of extreme events could likely underestimate the expected food supply, with the risk to leave a sizeable number of people food insecure.

Maize is the most important grain crop in South Africa, being both the major feed grain and the staple food of the majority of South African population (DAFF 2016). At global scale, South Africa is ranked 9th and on Sub-Saharan Africa 2nd in terms of maize production (Estes et al. 2013). In this country, approximately 60% of the agricultural land comprises maize cultivation, maize contributing nearly 70% of the grain production (Akpalu et al. 2009). South Africa produces on average nearly 10.2 million tons a year, and approximately 8 million tons of this annual production is used locally as food and fodder (FAO 2012). Over the past five growing seasons, maize has been the largest contributor to the gross value of field crops (48%), followed by sugar cane (13.2%), wheat (9.7%) and both soybean and hay (7.4%) (DAFF 2017). In the 2015/16 season, maize gross value was approximately equal to R27.5 million (DAFF 2017).

The main maize production regions of South Africa are located in Mpumalanga, Free State and North West provinces, which contributed 21%, 39%, and 23% of the total maize production, respectively, in the 2011/12 season (South African Grain Quality, 2011). Mid-summer droughts are commonly experienced in these areas and they normally occur at the end of January (Kgasango, 2006). Dry spells and erratic rainfall largely vary by year to year. Such variations are difficult to predict and play a significant role on maize growth and yield (Benhil, 2002). Recently, during the 2015/16 growing season, South Africa encountered one of the worst drought of its history, accompanied by heat waves, which affected greatly the main maize producing regions. Agricultural statistics indicate that maize production was reduced by 24.3% compared to the previous season 2014/15 (DAFF, 2016). Climate projections show that these extreme weather events are likely to increase in the future, which needs to increase our ability to face adverse conditions.

The objective of the study was to quantify maize yield response to projected climate scenarios in the main maize growing areas of South Africa using two crop modelling solutions (existing and modified CropSyst), which were assessed in a comparative fashion. To achieve the stated objective the following hypotheses were tested: i) the average maize grain yields in the near and far future will be lower than previously predicted using models that does not take into account explicitly extreme weather events (EMS) due to the prevalence of increased extreme droughts and high temperatures in the main maize growing areas of South Africa, ii) the average maize grain yields in the near and far future will decrease compared with the baseline climate due to the prevalence of increased extreme droughts and high temperatures besides a general climatic change in the main maize growing areas of South Africa, and iii) food security policy based on modelling solutions taking into account explicitly the impacts of extreme events can better unveil the potential uncertainties associated with future food security.

2. Materials and methods

2.1 Study sites

The following three study sites (Appendix 1), with contrasting climates, represent the main maize growing areas in South Africa. Bloemfontein has a dry semi-arid climate with annual rainfall ranging from 400 to 600 mm, Lichtenburg has a sub-humid climate with annual rainfall range of 601 to 800 mm, and Nelspruit has a super humid climate with annual rainfall exceeding 1000 mm. All three study-sites lie in the Highveld region at an altitude range of 900 to 1800 m above sea level. As in most of southern Africa, the study sites experience the peak of rainfall in summer, between October and April, with most rainfall falling in December and February. A Hutton soil type (sandy clay loam texture) characterizes Nelspruit and Bloemfontein regions, with organic content of 1.4 and 0.7% respectively (Land Type Survey Staff 2004). Lichtenburg region is instead characterised by Avalon soil type (sandy clay loam texture), with organic content of 0.9% (Land Type Survey Staff 2004).

2.2 Description of the climate data

To simulate potential extreme event impacts on maize, generated climate for the baseline (1991-2020), near future (2021-2050) and the far future (2051-2080) time-periods was used. Six GCM (General Circulation Model) simulations from the Coupled Model Intercomparison Project Phase Five (CMIP5) and Assessment Report Five (AR5) of the Intergovernmental Panel on Climate Change (IPCC), obtained for the emission scenarios described by Representative Concentration Pathways (RCPs) 4.5 and 8.5, were first downscaled to 50-km resolution. Low radiative forcing RCP 4.5 corresponds to a high mitigation scenario, whilst high radiative forcing RCP 8.5 matches a low mitigation scenario. The downscaled GCMs include: the Australian Community Climate and Earth System Simulator (ACCESS1-0), the Geophysical Fluid Dynamics Laboratory Coupled Model (GFDL-CM3), the National Centre for Meteorological Research Coupled Global Climate Model version 5 (CNRM-CM5), the Max Planck Institute Coupled Earth System Model (MPI-ESM-LR), the Norwegian Earth System Model (NorESM1-M) and the Community Climate System Model (CCSM4) (Appendix 2). The simulations were performed on supercomputers of the Centre for High Performance Computing (CHPC) of the Meraka Institute of the CSIR in South Africa. In these simulations, conformal-cubic atmospheric model (CCAM) was forced with the bias-corrected daily sea-surface temperatures (SSTs) and sea-ice concentrations of each host model, and with CO_2, sulphate and ozone forcing consistent with the RCP 4.5 and RCP 8.5 scenarios. The models' ability to realistically simulate present-day Southern African climate has been extensively corroborated (e.g. Engelbrecht et al. 2011; Malherbe et al, 2013; Engelbrecht et al. 2015). Most current coupled GCMs do not employ flux corrections between atmosphere and ocean, which contribute to the existence of biases in their simulations of present-day SSTs – more than 2 ºC along the West African coast. An important feature of the downscaling performed here is that GCMs were forced with bias-corrected sea-surface temperatures (SSTs) and sea-ice fields. The bias was computed by subtracting for each month the Reynolds (1988) SST climatology (for 1991-2000) from the corresponding coupled general circulation model (CGCM) climatology. The bias-correction was applied consistently throughout the simulation. Through this procedure, the climatology of the SSTs applied as lower boundary forcing is the same as that of the Reynolds SSTs. However, the intra-annual variability and climate-change signal of the CGCM SSTs are preserved (Katzfey et al. 2009).

A multiple-nudging strategy was followed to obtain the 8 km resolution downscaling. After completion of the 50 km resolution simulations described above, CCAM was integrated in stretched-grid mode over a domain of about 1500 x 1500 km^2 in size. The high-resolution part of the model domain was about 2000 x 2000 km^2 in size. The higher resolution simulations were nudged within the quasi-uniform global simulations, through the application of a digital filter using a 600 km length scale. The filter was applied at six-hourly intervals and from 900 hPa upwards.

2.3 Crop simulations

Maize grain yields were simulated using a medium season maize (*Zea maize* L.*)* hybrid (PAN6966). The simulations were performed for non-limiting soil fertility conditions. Planting dates at Lichtenburg and Bloemfontein were set to day of year (doy) 330 (i.e. just after late-November), whereas for Nelspruit it was set to day of year 306 (i.e. early November), as practiced by local maize growers. Both the existing (EMS) and the modified (MMS) versions of the crop model CropSyst were calibrated and validated previously for a similar maize hybrid (Mangani et al. 2018). The two modelling solutions were run to simulate crop yields for the baseline, near future and far future by changing climate and holding constant all other factors (soil inputs and management strategies). Each individual GCM was used to run the crop model and afterwards maize yields were averaged across the six GCMs. This was done separately for each location and radiative forcing. This method proved more effective than using an ensemble of GCMs (Rurinda et al. 2015). In as much as ensembles help in improving the modelling of climate data, it may mask the effects of seasonal dry spells. The sensitivity of the maize yield to increased extreme droughts and high temperatures was assessed for the two future climates - 2021-2050 (near future) and 2051-2080 (far future) - and was compared to the baseline period (1990-2020). Negative or positive changes of mean yield were calculated for each location, RCP, modelling solution and time period. The baseline maize yield was simulated using bias corrected GCM data output from the three study sites. The effect of atmospheric CO_2 level was not investigated as its effect is not well understood on C4 crops, which are known to be less sensitive to increased levels of atmospheric CO_2 (Tubiello, et al. 2007; Ainsworth and Ort 2010; Gornall et al. 2010).

3. Results

3.1 Climate projections under different radiative forcing scenarios (RCPs 4.5 and 8.5)

In all the three study locations, climate projections have shown rainfall seasonality patterns with wet summers (November-March) and dry winters (May–August) (Fig 1 - i, iii, and v and Fig 2 – i, iii and v). The projections have also shown that the rainfall amount received during the summer period was greater in Nelspruit (Fig 1 – v) followed by Bloemfontein (Fig 1 – i). Generally, the far future projections showed increased rainfall amounts during summer period (cropping season) at Bloemfontein and Lichtenburg compared with the baseline and the near future time horizons. During the winter period, the rainfall amounts of the three time slices seem to be indistinguishable for all the three study sites.

The climate models consistently projected increased temperatures for all the study locations as moving from the baseline to the far future (Fig 1 – ii, iv and vi and Fig 2 – ii, iv and vi). This is true for both the average monthly maximum and minimum temperatures of the ensemble models. Differences in monthly temperatures between time horizons are much clearer with the projections from the high radiative forcing (RCP 8.5) (Fig 2) in comparison to low radiative forcing climate projections (RCP 4.5) (Fig 2). Likewise rainfall, temperature projections show seasonality.

An analysis of extreme temperature events using **webXTREME** (A web-based tool for the assessment of extreme years) (http://www.modextreme.org/webxtreme) shows a positive shift in the median of the number of days with temperature above 30 ℃ in a growing season as we move from the baseline to the far future scenario (Fig 3). This is true for all three study locations.

Additionally, differences in the median values were noted between the climate projections from the two RCPs with the climate data generated by the high radiative forcing (RCP 8.5), having a median value higher than that of the lower radiative forcing

(RCP 4.5) at all time periods. With respect to aridity, there was no significant difference between radiative forcing scenarios within a site over time and results for only one radiative forcing was shown in each location (Fig 4). There was, however, significantly different arid conditions among study sites (Fig 4). Bloemfontein appeared to be more arid with a high number of days with ARID >0.5 followed by Lichtenburg and Nelspruit, respectively. This was true at all three time horizons.

3.2 Projected impacts on maize grain yield

Simulated crop yield projections using two CropSyst versions (EMS and MMS) varied among time slices and study sites (Fig 5). Projected mean maize grain yield at all study sites decreased as the time slice progressed from the baseline to the far future climate scenario. This was true for both modelling solutions and climate datasets produced by different RCPs. This was also evident in the negative shift in the median of grain yields as we move to the far future climate (Fig. 6).

Generally maize grain yield simulated by EMS was higher than that simulated by MMS. For instance, the mean EMS simulated maize grain yield obtained using the low radiative forcing (RCP 4.5) for the baseline climate scenario at Bloemfontein, Lichtenburg, and Nelspruit was 8.5, 8.5 and 9.8 t ha^{-1}, respectively. While the mean MMS simulated maize grain yield for the same low radiative forcing (RCP 4.5) for the baseline climate scenario was 7.8, 7.4 and 9.0 t ha^{-1}, for Bloemfontein, Lichtenburg, and Nelspruit, respectively. Similar trends were observed for simulations ran by high radiative forcing data.

Maize grain yield simulated using low radiative forcing RCP 4.5 climate data was generally higher than high radiative forcing RCP 8.5 at all-time slices and at all locations except for Nelspruit at the baseline period where the grain yield simulated by high radiative forcing data was higher by 0.1 t ha^{-1} than that of the lower radiative forcing. The mean (EMS) simulated maize grain yield for Bloemfontein, Lichtenburg and Nelspruit at the far future time slice were 6.7, 7.1 and 8.7 t ha^{-1} for RCP 4.5 and 5.8, 6.0 and 8.0 t ha^{-1} for RCP 8.5, respectively. A similar trend of higher simulated yields using a lower radiative forcing in comparison to the higher radiative forcing were also observed with MMS simulations.

Overall, the percentage mean grain yield change between baseline and near future, as well as baseline and far future, was the lowest for Nelspruit, which is located in the super-humid agro-ecological zone of South Africa (Table 1). In contrast, the percentage mean grain yield change between base line and far future was highest for Bloemfontein which is located in the semi-arid region. The mean grain yield change between base line and far future in Bloemfontein for the far future time slice decreased by 23% for RCP 4.5 and 30% for RCP 8.5 using EMS and by 29% for RCP 4.5 and 28% for RCP 8.5 using MMS (Table 1).

The percentage yield deviation between MMS and EMS was the lowest for Nelspruit and the highest for Bloemfontein (Table 2). The percentage yield deviation of MMS from EMS increased as the time slice progressed from baseline to far future at all study sites for both RCPs. In each study site, the deviation between MMS and EMS was higher for RCP 8.5 compared with RCP 4.5 at similar time slices.

Projections indicate a reduced number of days to reach maturity as with the far future climate in all study sites (Fig. 7). No significant differences were noted on the projected number of days to reach maturity with different crop modelling solutions. Yield response variations across all locations and radiative forcing scenarios ranged between a mean coefficient of variation (CV) of 6.9 and 39% (Appendix 3). Similar trends were observed across all locations with significantly higher mean CVs obtained with MMS than EMS simulations.

4. Discussion

4.1 Crop yield changes

There has been a gradual decline in simulated maize yields as time slice progresses from the baseline time period to the far future at all three study sites, irrespective of the crop modelling solution used. Such a trend shows the manifestation of climate change effects on crop yields. Yield declines are mainly attributed to the increased temperatures projected in future climate scenarios. Greater yield losses were realised in the much warmer locations (Bloemfontein and Lichtenburg) compared with a cooler area (Nelspruit). Increased temperatures triggered anticipated maturity dates, that is, reduced growing seasons for maize (Springate and Kover 2014). A shorter growing period implies less time available to accumulate crop biomass, which consequently translates into yield reductions (Haverkort et al. 2013). Yields also decreased more with the use of high radiative forcing climate data in comparison to low radiative forcing data. Indeed, projections from the high radiative forcing generate increased temperatures compared to the low radiative forcing. Similar findings of greater declines in yield using high radiative forcing in comparison with the yields simulated using climate data from low radiative forcing have been reported by Rurinda et al. (2015).

A few studies related to climate change impact on maize have been carried out in the same regions covered by the current study. Previous studies used modelling solutions (comparable to our EMS) that do not take into account explicitly the impacts of extreme weather events (Jones and Thornton 2003; Walker and Schulze, 2006; Parry et al. 2004; Lobell, 2010; Rurinda et al. 2015). For instance, Jones and Thornton (2003) projected yield reductions of approximately 20% for South Africa in 2055.

These simulated results were obtained with the crop model CERES-Maize and climate data generated from one GCM, not from an ensemble of GCMs as in our study. A number of uncertainties have been cited previously from using one GCM, which might have led over predictions (~20%) of yield decline in comparison to our results (maximum of 13%) during the same period. Parry et al. (2004) projected yield declines of 10% and 30% during the 2050s and 2080s, respectively, using the A1FI climate scenario which is considered as the warmest of the Special Report on Emissions Scenarios (SRES) of the Intergovernmental Panel on Climate Change (IPCC, 2007). Although these values were representing the larger part of Africa where maize is grown, they were within the range of results we obtained using an existing CropSyst model. In another study conducted in a nearby country, Zimbabwe, in which the agricultural production systems simulator (APSIM) model was used, maize yield was estimated to decline by ~32% for the period 2070-2099 under the high radiative forcing and by 20% using the low radiative forcing. The climate data scenarios used in these studies agree well with ours, and these findings fall within our range of values.

Our analysis suggests that the mean maize grain yield in the main maize producing areas of South Africa will likely decrease as a result of the projected increase in the number of days with extreme temperatures (>30 ℃), as illustrated by the modified modelling solution (MMS). With no trends of increasing aridity in the three study areas, temperature is the main cause for the projected future yield losses. The modified CropSyst version used in the study shows some decreasing trends in future maize yields, which is consistent with the projected increase in the number of days with temperatures above 30 ℃. While similar trends of decreasing yields have been observed in all the studied locations, the potential impacts of extreme weather events are expected to be more pronounced in the Bloemfontein area. In this area, differences between EMS and MMS in the projected maize grain yield were on average of 20% and 15% at the far future time horizon using the high and low radiative forcing, respectively (Table 2). In Nelspruit, which is less arid and less affected by extreme temperatures compared to the other two study sites, differences in yield between the two modelling solutions at the far future time horizon were ~12% and ~9% with high and low radiative forcing, respectively. Such differences indicate the ability of MMS to capture the impacts on yield of extreme drought and heat events. This suggests that using models not taking explicitly into account the impact of extreme weather events can be misleading and may have some repercussions on the country's food security preparedness.

According to DAFF (2015), in 2014/15 the area under maize (both white and yellow) production in Free State Province of South Africa was 1 220 000 hectares. If simulations are performed using the two modelling solutions and it is assumed that: i) the weather and basic soil properties are the same across Free State Province and ii) the agricultural management practices also remain the same and iii) also assume that the average yield per hectare will be 8 tonnes. This implies that if we make use of the upper limit of the differences obtained in the study from the two modelling solutions for Bloemfontein (which is 20%), the projected yields will be 9 760 000 and 7 808 000 tons with EMS and MMS, respectively. The difference in maize yield per given area under production between the two modelling solutions would be ~2 million tons. Failing in production estimation by approximately 20% can have fatal implications on food security planning and policy formulation. This illustrates the negative implications that can be brought about on current and future food security projections and policy, depending on the modelling solution used.

From the simulations carried out, results indicate that Bloemfontein followed by Lichtenburg will be mostly affected by extreme temperature events associated with temperature increase. It is recommended that researchers look into options that can help to reduce the risk that extreme weather events might have on maize production in the future. These areas lie in the largest producing areas of maize in South Africa and this calls for urgency in finding ways to adapt. New maize genotypes with improved drought and heat tolerance will play an important role in adapting maize-based systems to climate change and extreme weather events in South Africa and the Sub Saharan African region.

4.2 *Uncertainties and limitations of the study*

The limitations to this study include the fact that farmers respond to changes in climate, and any adaptive measures that can be implemented by farmers would result in a different response of crops e.g. in the case that maize hybrids that can resist high temperature will be used of in the future. Secondly, the modified CropSyst model used in this study did not consider the impacts of flooding, which can also have some other negative effects on crop production. Similarly, the model does not consider the negative impacts of pests, diseases and weeds on grain yield hence the values obtained must be treated with caution as they may underestimate the impact of extreme weather events on maize. Lastly, one hybrid was used in this study as was the case for model calibration by Mangani et al. (2018). Extrapolation of these results to other study sites should be made with caution as using different hybrids might lead to different results

5. Conclusions and recommendations

Models that do not take into account the impact of extreme weather events might underestimate the potential impact of future climate on maize production in South Africa, resulting in higher yield projections. This has adverse effects on food security planning and policy formulation. As we have observed in the studied locations that yields can be overestimated by ~20%, which, converted to tons, can be a sizeable figure that can emanate food insecurity. Location specific studies are crucial, as the incidence and frequency of extreme events in future climate might be different from one to the other. This calls for different adaptive options for different locations to face extreme climate. The results of this study show that Bloemfontein needs policies that can make maize growers able to face future extreme weather events before yields drop drastically. Future research should focus on using ensembles of crop models with algorithms that take into account the impact of extreme weather events. This would reduce the uncertainties brought about by using one crop model only.

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