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MODEL PREDICTION OF MAIZE YIELD RESPONSES TO CLIMATE CHANGE IN NORTH-EASTERN ZIMBABWE

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ABSTRACT

The increasing frequency and severity of droughts and floods, the shift in onset of the rains, increasing intensity of mid-season wet and dry spells and variations in the cessation of the rains in the last 50 years have been identified in the Intergovernmental Panel on Climate Change Third Assessment Report (IPCC-TAR) as a major consequence of climate change. This paper presents a study that was conducted to project climatic trends in Zimbabwe by the end of the 21st Century. Observed data of the last three decades (1971 to 2000) from several climatological stations in north-eastern Zimbabwe and outputs from several global climate models were used. The downscaled model simulations consistently predicted a warming of between 1 and 2 ºC above the baseline period (1971-2000) at most of the stations in the period 2046-2065. Most of the models predicted that for the same period, rainfall will decrease by an average of 10 mm for each month for October to December; while there will be an average increase of 10 mm for the months of January to April. The AquaCrop crop production model simulations predicted that climate change will shift planting dates towards delayed planting in the period 2046-2065. The results further showed that using traditional static sowing practices in the period 2046-2065 will result in maize (*Zea mays* L.) yield reductions, while adopting dynamic planting strategies will result in highest maize yields for short season cultivars.

Key Words: AquaCrop, delayed planting, *Zea mays* L.

RÉSUMÉ

La fréquence sans cesse croissante et la gravité des sécheresses et inondations, le changement dans l'apparition des pluies, l'intensité croissante de la mi-saison humide et la sécheresse ainsi que les variations dans la cessation des pluies au cours des 50 dernières années, ont été identifiées comme étant une conséquence majeur du changement climatique dans le Panel intergouvernemental du troisième rapport d'évaluation (PICC-TAR) du changement climatique. Cet article présente une étude conduite pour projeter les tendances climatiques au Zimbabwe à la fin du 21^{e} siècle. Les données des trois dernières décennies (1971-2000) dans plusieurs stations climatologiques au Nord-Est du Zimbabwe et les résultats de plusieurs modèles climatiques du Globe étaient utilisées. Les modèles de simulation à échelle réduite ont avec consistance prédit un réchauffement d'entre 1 et 2 ºC au-dessus de la période de référence (1971-2000) dans la plupart des stations pour la période 2046-2065. La plupart des modèles ont prédit que pour la même période, les précipitations diminueront en moyenne de 10 mm pour chaque mois d'Octobre à Décembre, alors qu'il y aura une augmentation moyenne de 10 mm pour les mois de Janvier à Avril. Les modèles de simulation AquaCrop pour la production agricole ont prédit que le changement climatique entrainera le retard dans les dates de plantation au cours des années 2046-2065. Les résultats ont en plus montré que par l'utilisation des pratiques traditionnelles statiques de plantation dans la période 2046-2065, la culture du maïs (*Zea mays* L.) connaîtra une réduction du rendement alors que adoption des stratégies dynamiques de plantation entrainera des rendements les plus élevés du maïs pour les cultivars de courtes saisons.

Mots Clés: AquaCrop, retard de plantation, *Zea mays* L.

INTRODUCTION

The economies of most countries in southern Africa are agro-based and agriculture in the region is predominantly rain fed. The Intergovernmental Panel on Climate Change (IPCC, 1996; 2001) identifies the increasing frequency and severity of droughts and floods, the shift in onset of the rains, and increasing intensity of mid-season dry spells in the last 50 years as a major consequence of climate change. According to the IPCC (2007) A2 climate change scenarios, global mean temperatures are expected to increase by 1.0 to 3.0 °C by 2100 (relative to the 1990-2000 average level); while southern Africa is expected to record a warming of between 0.6 and 0.7 °C by 2020. Trends from 1900 show that precipitation increased significantly in the eastern parts of north and south America, northern Europe and northern and central Asia whereas precipitation declined in the Sahel, the Mediterranean, southern Africa and parts of southern Asia. Time series graphs of the global mean surface temperature show that eleven of the twelve years between 1995-2006 rank among the warmest years in history (since 1850). The linear warming trend over the 50 years 1956-2005 (0.13 °C per decade) is nearly twice that for the 100 years from 1906-2005. In Zimbabwe, temperatures have risen by 0.6-1.0 °C in the past 30 years, and rainfall has undergone significant changes during the same period although total amounts had not shown any significant change (Matarira, 1990; Matarira *et al*., 2004; Sithole and Murewi, 2009). The IPCC fourth assessment report (IPCC, 2007) concluded that climate change will impede the country's abilities to achieve sustainable development and the Millennium Development Goals, and that southern Africa will experience increased levels of water stress and reduced maize yields by up to 50% (relative to 1990) by 2050, assuming current varieties continue to be grown (Lobell *et al*., 2009).

The vulnerability of sectors that are highly dependent on climate, like agriculture and water, is expected to increase with predicted climate change and associated increased climate extremes such as droughts and floods, and higher temperatures. The resilience of the above sectors and of livelihoods of the poor must be improved in response to current and future climate change. Assessment of the effects of global climate changes on agriculture might help to properly anticipate and adapt farming to maximise agricultural production (Arntzen *et al*., 1996; Costa *et al*., 2009). Means must be sought to ensure the transition from coping with shocks towards more adaptive resilient systems that can confront future climate extremes. Existing data, tools and methods to facilitate these changes, while available, are inadequately utilised by decision makers to address the challenges of climate change. Recent IPCC and global environmental change (GEC) reports indicate that there is now increased confidence in predictions of climate change at the global level, but there is still great uncertainty at regional and local levels. The challenge is to link climate change science with sound agricultural innovations at the local and regional scale.

Climate change issues have been extensively investigated in Zimbabwe (Makadho, 1996; Matarira *et al*., 2004; Sithole and Murewi, 2009). However, these climate change projections need to be regularly revised and updated using the most recent climatic data. The impact of climate change on maize and other cereal production systems has not yet received adequate attention; in particular there is lack of systematic evaluation of climatic-yield trends (Lobell and Asner, 2003). It is, therefore, necessary to carry out studies on climatic change and find possible ways of addressing food insecurity in Zimbabwe.

In this study, we used a combination of different future emission scenarios and climate models to simulate the responses of maize yields in north-eastern Zimbabwe to a changing climate, as a prelude to detailed targeting of appropriate options that can help smallholder households adapt to climate change. We deliberately focused on maize, as it is one of the staple food crops and a source of income of many communities vulnerable to climate change in Zimbabwe. In addition, the crop is largely rain fed with little or minimal irrigation, making the production predominantly a response to rainfall amounts received. This makes it imperative to investigate the impacts of climate change on maize production in the country and for the approach we adopted.

MATERIALS AND METHODS

The study area. The study was carried out in Natural Region (NR) 2 of Zimbabwe. Natural Region 2 is an agroecological zone that is located in north-eastern Zimbabwe, covering parts of Harare, Mashonaland East, Mashonaland West, Mashonaland Central and Manicaland provinces. In Zimbabwe, most of the maize is grown in Natural Region 2 (Vincent and Thomas, 1961), and in most years, this region accounts for 75-80 percent of the planted area assigned to crop production in Zimbabwe (FAO, 1999). The main meteorological parameters used to specify the climate in this study were rainfall and air temperature. Although radiation is the main source of energy required for crop growth and development and water loss by evapotranspiration, air temperature may be used in the absence of radiation measurements. Rainfall and air temperature are normally measured at climatological stations, distributed across the country and run by the Zimbabwe Meteorological Services Department (ZMSD). The mean monthly temperature and rainfall data (1971 - 2000) for the following climatological stations: Karoi, Mutoko, Mt Darwin, Rusape and Wedza were used in the study. The station characteristics are shown in Table 1.

Modelling the impact of climate change on maize yield. The impact of climate change on maize yield was investigated using past and downscaled model predictions of climatic data and a crop production model. The results were used to derive probabilistic projections of agricultural production impacts from climate change in Zimbabwe, which are useful for a better understanding of climate change and for implementing adaptation and mitigation measures.

TABLE 1. Features of the stations used in the study in Zimbabwe

Station	Region	Location		Altitude (m)
Karoi	2a	16° 50´S	29° 37´E	1343
Wedza	2b	18° 37´S	31° 34´E	1384
Rusape	2b	18° 32´S	32° 08´E	1430
Mt Darwin	2b	16° 47´S	31° 35´E	965
Mutoko	2b	17° 25´S	32° 13´E	1244

Downscaled climate change data. Data from five different Global Climate Models (GCMs) from the IPCC AR4 directly downloaded from the Earth System Grid (ESG) data portal (http://data.csag.uct.ac.za/) for the emission scenarios SRES-A1B, SRES-A2, and SRES-B1 were used in this study. The GCMs used are listed in Table 2.

Each of the five global climate models listed in Table 2 is based upon different climate scenarios. All the models use downscaled data of mean maximum and minimum temperature and total rainfall at a monthly time-step to investigate the past and future climates at a given site. The performances of the models were evaluated in a separate study by comparing hindcast model simulations with observed climatic data in order to rank the models and to be able to select the model best suited to a particular station (Masanganise, 2010). All further analysis at that station was based on that model.

Crop modelling. We used a crop growth simulation model AquaCrop (Raes *et al*., 2009; Steduto *et al*., 2009) to test the response of maize to climate change. AquaCrop has been used to simulate accurately maize production in many studies globally (Heng *et al*., 2009; Hsiao *et al*., 2009; Masanganise, 2010; Zinyengere *et al*., 2011). AquaCrop is a crop water productivity model developed by the Land and Water Division of the Food and Agricultural Organisation (FAO) of the United Nations. The functional components of the model are: soil and its balance with water, the plant and its processes, the atmosphere and its thermal regime and rainfall. Other components include: evaporative demand, carbon dioxide concentration and management practices (e.g. planting date, fertiliser use, irrigation, etc). It simulates yield response to water of herbaceous crops and is particularly suited to address conditions where water is a key limiting factor in crop production. The main advantage of the AquaCrop model (Raes *et al*., 2009) is that it is a user-friendly model that has merit in its optimal balance between accuracy, robustness, simplicity and it requires a relatively small number of parameters. The AquaCrop model also uses input variables that require simple methods for their determination (FAO, 2009). AquaCrop, however, does not take into consideration such factors like pests, diseases and weeds (FAO, 2009).

Input data for AquaCrop were obtained from the mean monthly minimum and maximum air temperatures and total rainfall data from the downscaled GCM data sets, and reference evapotranspiration values were calculated using ETo calculator (Raes, 2009). The AquaCrop model was run to predict maize yields under the following conditions:

(i) the baseline climate (1971-2000) using traditional (static) planting dates to simulate historic yields;
(ii) projected climate (2046-2065) maintaining traditional planting dates; and
(iii) projected climate (2046-2065) using recommended planting dates generated using the AquaCrop model and based on the Department of Agricultural, Technical and Extension Services (AGRITEX) criterion (25 mm of rainfall in 7 days) for the first planting date.

The first two simulation scenarios were designed to investigate the impact of climate change on maize yield, while employing the traditional sowing practices. The third simulation scenario was designed to investigate the utility of recommended planting dates as adaptive strategies to climate change.

We used three maize hybrids that differ in their characteristics. These were SeedCo (SC) SC 513, SC 633 and SC 715. The crop characteristics for the cultivars are listed in Table 3.

RESULTS AND DISCUSSION

Baseline climates

Temperature. Figure 1 shows that during the period 1971 to 2000, Mt Darwin was the warmest

TABLE 2. Global climate models used in the study

Acronym	Name and Institute	Atmospheric resolution (latitude x longitude)
CCCMA_CGCM3_1	The third generation coupled global climate model (CGCM3.1 Model, T47). Canadian Centre for Climate Modelling and Analysis, Canada	3.75 º x 3.75 º
CSIRO_MK3_5	Mark 3.5 Model. Commonwealth Scientific and Industrial Research Organization, Australia.	1.88 º x 1.88 º
GFDL_CM2_0	CM2.0 coupled climate model. Geophysical Fluid Dynamics Laboratory, United States	2.0 º x 2.5 º
GISS_MODEL_E_R	ModelE20/Russell. Goddard Institute for Space Studies, United States.	4.0 º x 5.0 º
MPI_ECHAM5	European Centre Hamburg Model. Max Planck Institute for Meteorology, Germany	1.88 º x 1.88 º

TABLE 3. Cultivar specific crop characteristics used in the research

Category	Variety	Time to maturity (days)	Time to silking (days)	Potential yield range (t ha^{-1})
Early maturity	SC513	137	68	4-8
Medium maturity	SC633	140	69	6-12
Late maturity	SC715	152	73	6-11

Adapted from SeedCo (2008)

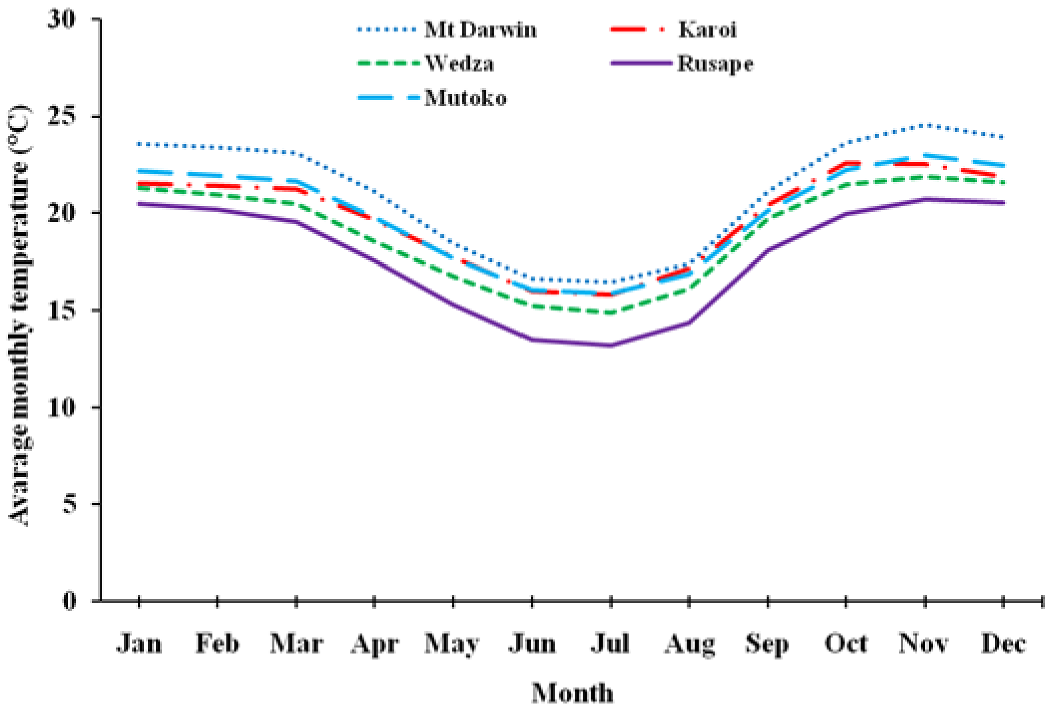

Figure 1. Baseline temperatures for the stations.

station, while lowest temperatures were recorded at Rusape. Maize is a tropical crop that grows best in areas with maximum temperature range of about 30 to 33 °C (Loomis and William, 1963). Physiological studies indicate that maize requires a mean temperature of 12 °C for it to photosynthesize. Figure 1 shows that there were favourable temperatures for growth and development of maize at all stations in the period 1971 to 2000.

Rainfall. Figure 2 shows that the past rainfall season starts from November to March. The months of December, January and February are the peak rainfall months. Maize can successfully grow in areas receiving an annual rainfall of 600 mm, which should be well distributed throughout the growing season.

Projected climates

Temperature. The CCCMA_CGCM3_1 model was found to be the best model for simulating temperature at all stations. Minimum temperature anomalies predicted by the CCCMA_CGCM3_1 model are shown in Figure 3.

Maximum temperature anomalies predicted by the CCCMA_CGCM3_1 model are shown in Figure 4.

The CCCMA_CGCM3_1 model consistently predicted that the average temperatures during the period 2046-2065 (Figs. 3 and 4) will be above the average temperatures recorded during the 1971-2000 baseline (Fig. 1), an indication that the future climate will be warmer than the past. A maize hybrid requires a specific number of growing degree days (GDDs) or heat units that are accumulated from emergence to maturity. The predicted warmer conditions imply that there will be ideal conditions for maize production if there is adequate water supply.

Rainfall. There was wide variation in rainfall prediction by the five models. The GISS_MODEL_E_R was most suitable for predicting rainfall at Mt Darwin, Karoi and Mutoko, while the MPI_ECHAM5 and the GFDL_CM2_0 models were most suitable for

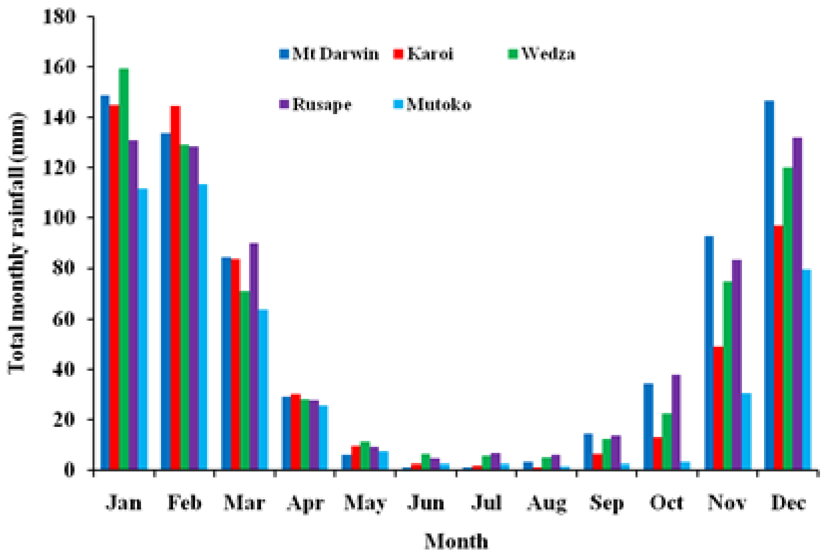

Figure 2. Baseline total monthly rainfall for the stations.

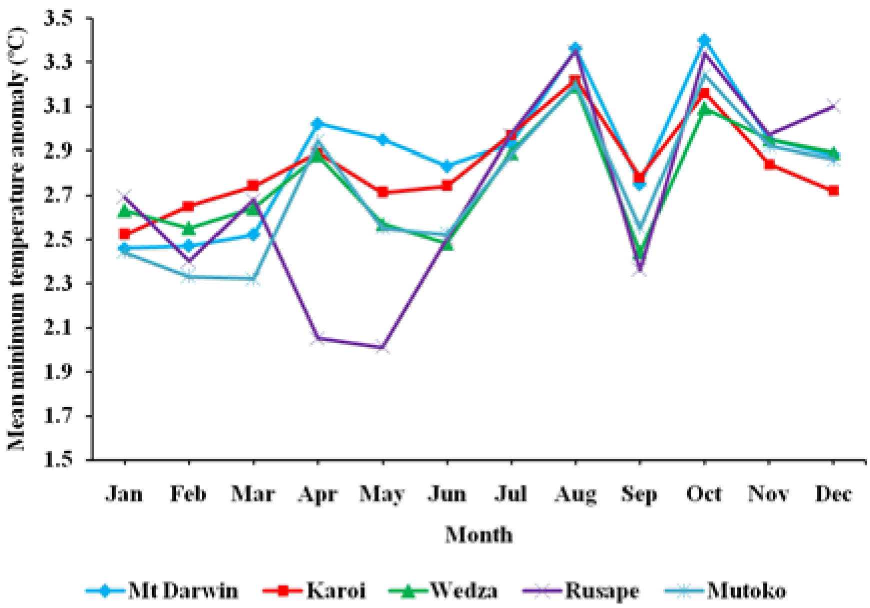

Figure 3. Predicted mean monthly minimum temperature anomalies for the five stations in the period 2046 - 2065.

Wedza and Rusape respectively. The other two models performed poorly at all stations and were not selected. The predicted rainfall anomalies for the five stations are shown in Figure 5.

Analyses of model outputs shows that, in general, there will be a slight increase in rainfall during the period February to April, while the period October to January will be characterised by slight decrease in rainfall (Fig. 5). It is worth noting that the average rainfall (Fig. 2) recorded at Mt Darwin in November (100 mm), December (150 mm) and January (145 mm) is much higher

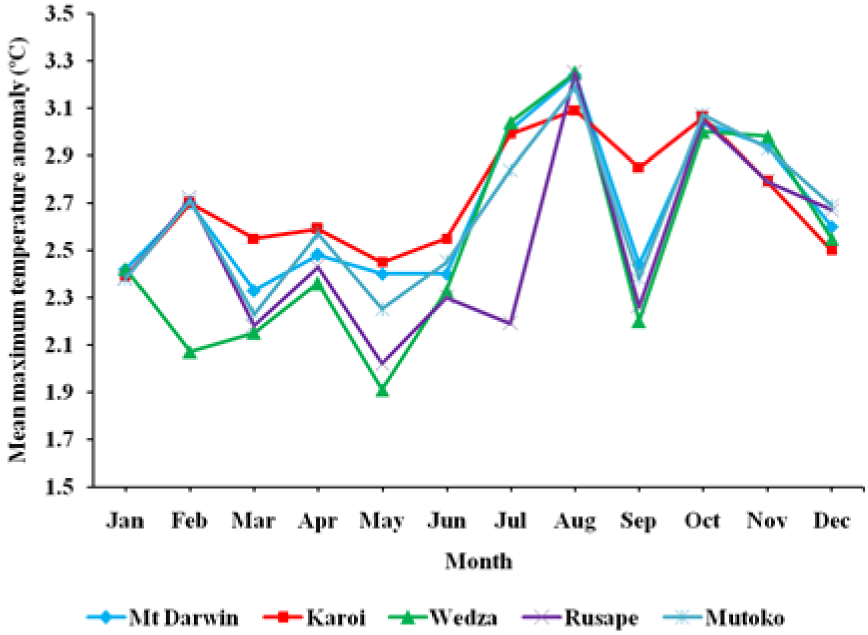

Figure 4. Predicted mean monthly maximum temperature anomalies for the five stations in the period 2046 - 2065.

than the rainfall recorded in March (80 mm) and April (25 mm). This means that the expected reduction of 10 mm in the period November to January may not be significant; while an increase of 10 mm in March and April may not have a major impact on maize production because the months are already characterised by low rainfall. If the predicted wetter conditions are realised for February and March, the available moisture will be beneficial to late planted maize. The projected reduced rainfall in the period October to January may only affect long season maize varieties. The late planted maize, however, usually matures in April and according to the GFDL_CM2_0 model, the expected anomalously wet month of April at Rusape (Fig. 5) might be conducive to maize rot resulting in reduced yields.

Predicted maize yields. Figure 6 shows the expected maize yields under different planting dates. At Mt Darwin, both past and projected yields were shown to increase with delayed planting for all cultivars (Fig. 6). If traditional planting dates are maintained in the period 2046-2065, for each cultivar, the projected yields will be lower than corresponding historical yields. The crop model showed that delayed planting resulted in higher yields for short season varieties and lower yields for medium and long season ones. Crop model predictions for the period 2046-2065 show similar trends. For example, the SC513 (short season cultivar) yields more than the SC715 (long season cultivar) when the two cultivars are planted on 5 December (late planting). Simulations by the AquaCrop model, therefore, show that if the traditional practice is maintained in the 2046-2065 period, maize yields will decrease at Mt Darwin. We obtained a similar trend at all other stations. We then used AquaCrop to generate and recommend new planting dates for the period 2046-2065 based on the projected climatic conditions for that period. These projections showed that climate change will shift planting dates from 20 October (the traditional practice) to as late as 16 January by 2046-2065. The change in planting dates is mainly attributed to the expected increase in temperature rather than rainfall change.

Expected yields with recommended planting dates. Figure 7 shows how the yields are expected to change when recommended planting dates are employed.

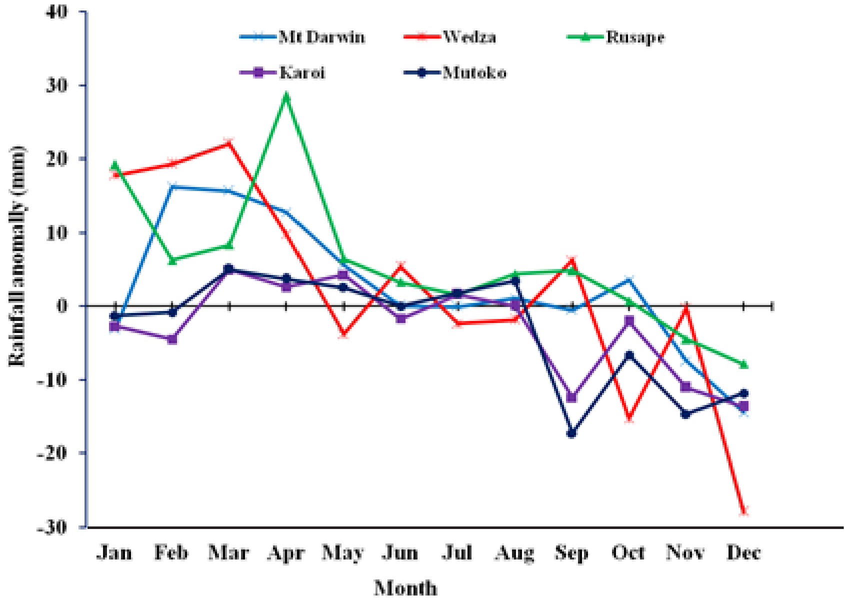

Figure 5. Predicted mean monthly rainfall anomalies for the five stations in the period 2046 - 2065.

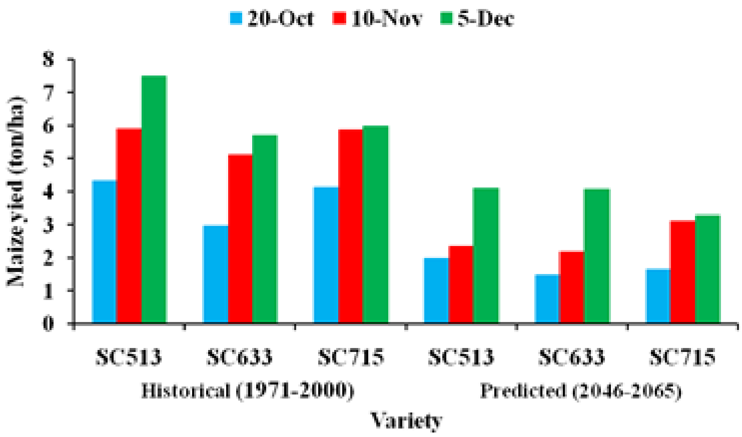

Figure 6. Changes in maize yields at Mt Darwin when traditional planting dates are maintained in the new climate regime.

The AquaCrop model predicted increased yields with recommended planting dates at Mt Darwin (Fig. 7). All stations showed similar trends. In the period 2046-2065, the new planting dates are expected to result in increased maize yield with delayed planting for each cultivar. In addition, short season varieties yield more than medium and long season ones under these conditions.

Model rainfall projections for the period 2046 -2065 show that changes in rainfall for the period December to March may not be large enough to have a major effect on maize production. Projected increase in temperatures may enhance suitability of maize production in all stations considered (Figs. 3 and 4). This explains the observed increase in maize yield with delayed planting. The short season variety (SC513, 137 days) is expected to perform well (when planted late) under increased rainfall and optimal temperatures. The long season variety (SC715, 152 days) will not be able to reach maturity under the expected reduced

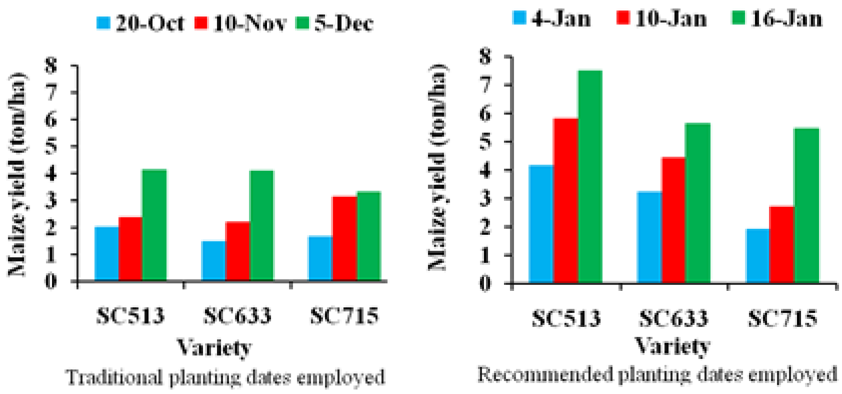

Figure 7. Expected maize yields at Mt Darwin with recommended planting dates.

length of growing period. These results of the model simulations are consistent with findings by Makadho (1996).

It should, however, be noted that increased yields will be realised on condition that the necessary inputs are available and that soil conditions do not change significantly. It should also be assumed that by the period 2046-2065, maize will remain palatable and marketable.

Adaptation strategies. Predictions of downscaled model simulations indicate that the period 2046-2065 will be warmer than the past in north-eastern Zimbabwe. Maize growers in north-eastern Zimbabwe will be advised to take advantage of the expected higher temperatures. However, the projected temperature rise may increase evapotranspiration leading to rapid depletion of the available water from reservoirs and from the soil. These simulations also indicate that climate change will create times of both excess and deficit rainfall. The onset of the rainfall season and the intra-seasonal distribution is currently erratic and these variations will be more severe with climate change, so there is need for establishment, expansion and rehabilitation of existing irrigation systems as a source of supplementary water for agriculture in the region.

Downscaled model simulations predict that climate change will shift planting dates towards delayed planting in the period 2046-2065. As an adaptation strategy, maize growers in Zimbabwe are advised to stagger their planting and seek advice from the ZMSD and agricultural extension officers on the onset and cessation of the rains together with intra-seasonal wet and dry spells so that they can observe proper timing of planting.

In the same period, AquaCrop demonstrated that expected yields will be highest for the SC513 cultivar as compared to the SC633 and SC715 cultivars. Farmers can adapt to climate change by growing short season maize varieties in order to maximise production. Crop breeders are encouraged to embark on breeding heat tolerant maize seed varieties. Breeding and biotechnology coupled with improved agronomy will help reduce the negative impacts of climate change in Zimbabwe.

CONCLUSION

The CCCMA_CGCM3_1 model indicates a warming of between 1 and 2 °C in north-eastern Zimbabwe by 2046-2065. The wide variation of global climate models in predicting rainfall and temperature means that there is need for further research in developing global climate models that will reduce uncertainty in predictions. Crop producers are encouraged to take advantage of positive impacts of climate change in order to increase maize production in north-eastern Zimbabwe. This will assist in increasing food security in the country.

REFERENCES

Arntzen, J., Downing, T., Leemans, R., Malcolm, J., Reynard, N., Ringrose, S. and Rogers, D. 1996. Climate change and Southern Africa: An exploration of some potential impacts and implications in the SADC region. Climatic research unit, Norwich, UK. pp. 45-46.

Costa, L.C., Justino, F., Oliveira, L. J. C., Sediyama, G. C., Ferreira, W.P.M. and Lemos, C. F. 2009. Potential forcing of CO_2, technology and climate changes in maize (*Zea mays*) and bean (*Phaseolus vulgaris*) yield in southeast Brazil. *Environmental Research Letters* 4:10.

Food and Agriculture Organisation of the United Nations (FAO). 1999. Fertiliser use by crop in Zimbabwe. (www.fao.org). Accessed: 17 September 2009.

Food and Agriculture Organisation of the United Nations (FAO). 2009. Software: AquaCrop. (http://www.fao.org/nr/water/index.html). Accessed: 22 October 2009.

Heng, L.K., Hsiao,T., Evett, S. Howell, T. and Steduto, P. 2009. Validating the FAO AquaCrop Model for Irrigated and Water Deficient Field Maize. *Agronomy Journal.* 101:488-498.

Hsiao, T.C., Heng, L.K., Steduto, P., Rojas-Lara, B. Raes, D. and Fereres, E. 2009. AquaCrop-The FAO crop model to simulate yield response to water: III. Parameterization and testing for maize. *Agronomy Journal.* 101:488.

Inter-Governmental Panel on Climate Change (IPCC). 1996. Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses. Contribution of Working Group II to the Second Assessment Report of the Inter-Governmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Inter-Governmental Panel on Climate Change (IPCC). 2001. Climate Change 2001: Synthesis Report, Contribution of Working Groups I, II, and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, ISBN 0 521 80770 0. (http://www.ipcc.ch/ipccreports/tar/vol4/english/index.htm). Accessed: 06 October 2009.

Inter-Governmental Panel on Climate Change (IPCC) 2007. Climate Change 2007. The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (Eds.). Cambridge University Press, Cambridge, UK. and New York, USA.

Lobell, D., Naylor, R., Falcon, W., Burke, M.L., Albertsen, M., Banziger, M., Battisti, D., Deikman, J., Field, C., Fowler, C., Khush, G., McGrath, J., Ortiz Monasterio, I., Reynolds, M., Rumbaitis Del Rio, C., Schlenker, W. and Tebaldi, C. 2009. Climate Extremes and Crop Adaptation. Summary Statement from a Meeting at the Program on Food Security and Environment, Stanford, CA. June 16 18, 2009.

Lobell, D. and Asner, G. 2003. Science. *Environmental Research Letters* 4: 10.

Loomis, R. S. and Williams, W. A. 1963. Maximum crop productivity: An estimate. *Crop Science* 3: 67-72.

Makadho, J.M. 1996. Potential effects of climate change on corn production in Zimbabwe. *Climate Research* 6: 147-151.

Masanganise, J. 2010. Climate variability and change and its potential impact on maize yield. in North-eastern Zimbabwe. MSc Thesis, Faculty of Science, University of Zimbabwe, Zimbabwe. 155 pp.

Matarira, C.H. 1990. Drought over Zimbabwe in a regional and global context. *International ournal of Climatology* 10: 609- 625.

Matarira, C.H., Makadho, J. M. and Mukahanana-Sangware, M. 2004. Vulnerability and adaptation of maize production to climate change in Zimbabwe. Government of the Republic of Zimbabwe, Ministry of Environment and Tourism, Harare, Zimbabwe.

Raes, D. 2009. The ETo calculator: Evaporation from a reference surface. Reference Manual Version 3.1. Food and Agriculture Organisation of the United Nations (FAO), Rome, Italy.

Raes, D., Steduto, P., Hsiao, T.C. and Fereres, E. 2009. AquaCrop - The FAO crop model to simulate yield response to water: II. Main algorithms and soft ware description. *Agronomy Journal* 101:488-498.

SeedCo. 2008. SeedCo Agronomy Manual, Seed Co Limited, Harare, Zimbabwe. pp. 1-8.

Sithole, A. and Murewi, C.T.F. 2009. Climate variability and change over Southern Africa: Impacts and challenges. *African Journal of Ecology* 47 (Suppl. 1): 17-20.

Steduto, P., Hsiao, T.C., Raes, D. and Fereres, E. 2009. AquaCrop: The FAO crop model to simulate yield response to water: Concepts and underlying principles. *Agronomy Journal* 101:488-498.

Vincent, V. and Thomas, R.G. 1961. An agricultural survey of Southern Rhodesia part 1: Agro-ecological survey, Government printers, Salisbury.

Zinyengere, N., Mhizha, T., Mashonjowa, E., Chipindu, B., Geerts, S. and Raes, D. 2011. Using seasonal climate forecasts to improve maize production decision support in Zimbabwe. *Agricultural and Forest Meteorology* 151:1792-1799.