Assessing the Effects of Climate Change on Irrigation Water Requirement for Corn in Zimbabwe

기후변화가 짐바브웨 옥수수 필요수량에 미치는 영향 평가

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ABSTRACT

기후변화는 피할 수 없으며 다음 세기에도 계속될 것이다. 이는 생태계와 토지와 물과 같은 자연자원의 이용에도 영향을 미칠 것이다. 연구 결과에 의하면 아프리카는 낮은 경제수준과 지역적 다양성으로 인하여 기후변화에 가장 취약한 지역 중의 하나이다. 짐바브웨는 한계농지가 황폐화가 되는 등 농업분야가 특히 기후변화에 취약하다. 본 논문에서는 짐바브웨의 주요 옥수수 재배지역에 대하여 기후변화가 옥수수의 필요수량에 미치는 영향을 공간적 및 시간적으로 분석하였다. 미래 기후예측은 HadCM3 전지구 모형 결과에 change factor를 곱하여 추정하였다. 배출가스 시나리오는 A2b 및 B2a를 선정하였고, 시간대는 2020s, 2050s 및 2080s 각각 30년간에 대하여 분석하였다. 기준작물 증발산량은 Penman-Monteith 공식으로, 순관개량은 CROPWAT 모형을 이용하여 구하였다. 순관개량의 공간적인 분석은 GIS를 이용하였다. 분석 결과 대상지역은 강우량이 감소하고 관개의 필요성이 크게 증가할 것으로 나타났다. 2080s의 필요수량은 기준년도 (1961-1990)에 비하여 93 내지 115 % 증가할 것으로 예측되었다. 이 증가는 기온의 증가와 강우량의 감소에 기인한다. 대상 지역에 대한 기후변화 대응 전략 수립과 영향 저감대책에 대한 추가적인 연구가 필요하다고 하겠다.

Keywords: Climate change; corn; irrigation; zimbabwe

I. Introduction

Climate change projections and studies acknowledge that Africa will experience a warming trend over the 21st century, which is expected to be stronger than the global average. Most climate models agree on the spatial pattern of temperature change in Africa with the strongest warming in the Sahara and southern Africa. (Müller, 2009). Anthropogenic climate change could therefore lead to decreased water availability that will be exacerbated by increased water demand if the region becomes drier and warmer. Agricultural water use is likely to be the most influenced water use sector by climate change in Zimbabwe. Agriculture water withdrawals account for 79 % of total water use in Zimbabwe. Agricultural water is used for

irrigation, fish farming and livestock. Irrigated agriculture will continue to dominate the water demands for Zimbabwe in the foreseeable future. In one study, the Global irrigation model GIM (a module of WaterGap) was used to assess global net irrigation requirements using Hadley Centre Coupled Model, version 3 (HadCM3) output data and the assessment predicted an increase in net irrigation requirements by 4 % and 1 % for the 2020s and 2070s respectively for southern Africa (Doll, 2002). Maximum temperature increased by 1.2 °C in 96 years (1897 to 1993) and mean total seasonal rainfall decreased by 10 % in 94 years (1900 to 1994) (Unganai, 1996).

Corn (Zea mays L.) is the primary staple crop for 95 % of Zimbabwe's population. Ambient temperature, precipitation and soil moisture as well as frequency of heat waves and drought are significant factors influencing corn production in southern Africa. Soil water is the most scarce essential plant input in southern Africa and according to Liebig's law of the minimum any reduction in water availability will directly aggravate the current crop situation. In Zimbabwe, research has predicted a 42 % decrease in corn producing area and

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25 % shortening of the growing season in the future (Zhakata, 2004). Research on climate change impact on crop water use and yield has gained prominence for Zimbabwe. Earlier attempts carried out sensitivity analyses of regular evapotranspiration (ET) equations and/or crop simulation models to estimate climate scenarios based on projections of weather scenarios (e.g. Unganai, 1996; Makhado, 1996) and more recent attempts have used global circulation models(GCMs) as climate basis (e.g. Matarira et al., 2004)

Makhado (1996) predicted 11 to 17 % corn yield reduction under irrigated conditions due to climate change using CERES Corn simulation model and 2 GCMs (Geophysical Fluid Dynamics Laboratory (GFDL) Model and the Canadian Climate Model (CGCM)). The reductions in corn yields were primarily attributed to ambient temperature increases which shorten the crop growth period, particularly the grain-filling period. Review of pertinent literatures revealed that the regional climatic impacts on the corn irrigation requirement in Zimbabwe have not been previously reported.

The objective of this research was therefore to assess the impacts of climate change on future net irrigation water requirements (IWR) under different climate scenarios for an intensive corn producing area covering three administrative provinces in the Northern part of Zimbabwe. Climate projections were derived from the HadCM3 (Gordon et al., 2000) and baseline climatology data, which was developed by the International Water Management Institute (IWMI) (New et al., 2002).

II. MATERIAL AND METHODS

1. Study Area and Irrigated corn

Zimbabwe is a landlocked country, located in southern Africa (latitude 15-22° south and longitude 26-34° east) and has a total area of 390,760 km^2. The country is bordered by Zambia in the north, Mozambique in the east, South Africa in the south, and Botswana and Namibia in the west. 8.6 % of the land area is cultivated land (FAO, 2005). Corn is the primary staple crop and usually occupies about 50 % of the annual planted area. 63 % of corn (by planted area) is grown under supplementary irrigation particularly in the large scale commercial areas (Musara et al., 2010). Corn production is increasingly coming under threat due to high temperature and low rainfall conditions. Zimbabwe, which is highly dependent on agricultural production sector, could see a rapid deterioration in the livelihood of the population as a result of climate change.

Climatic conditions in Zimbabwe are largely subtropical with one rainy season, from October to April, a cool winter season from April to August and the hottest and driest period from September to mid-November. Average annual
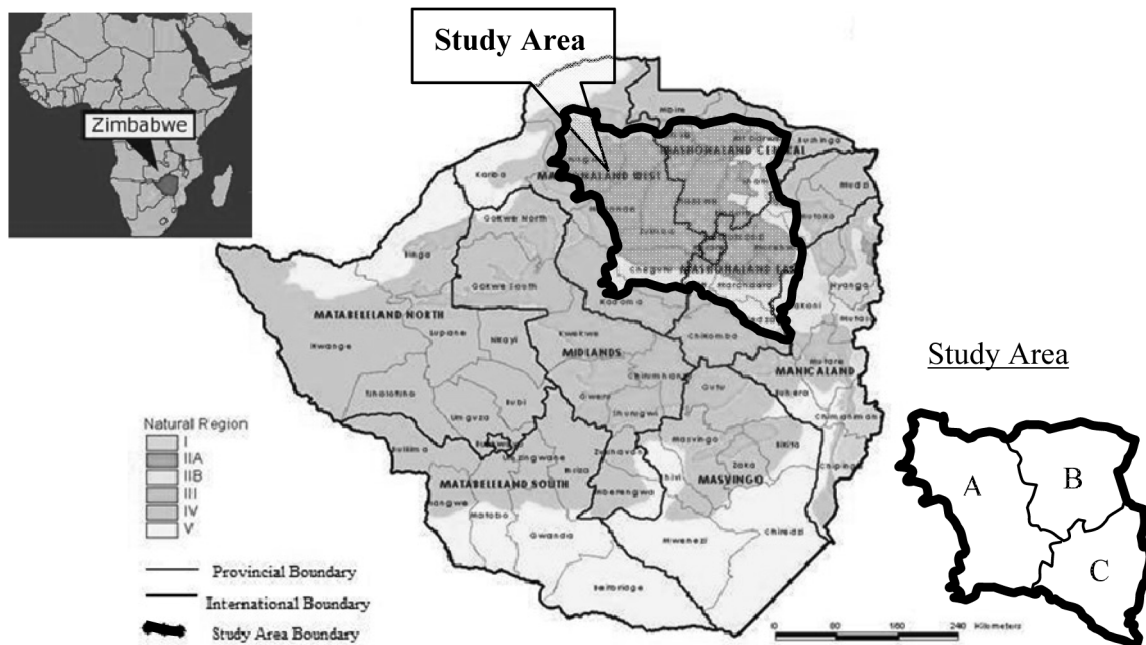

Fig. 1 Zimbabwe agro-ecological zones and the location map of the study area

rainfall is 657 mm, but ranges from over 1,000 mm in the eastern highlands to around 300–450 mm in the lowveldt in the south. Values of annual pan evaporation range from 1,400 mm in the eastern highlands up to 2,200 mm in the lowveldt. Only 37 % of the country receives adequate rainfall for agriculture. The country is divided into five natural agro-ecological regions (NRs) which relate climate, soils and topography to appropriate farming systems. NR II is suitable for intensive cropping and livestock production and accounts for 75-80 percent of the area planted to crops in Zimbabwe. This study will focus on NR II areas from which 75 % of corn is produced in Zimbabwe covering 3 administrative provinces i.e. Mashonaland West (A), Central (B) and East (C) as shown in Fig. 1.

2. Methodology

In order to assess the impact of climate change on net IWR of the study area, an assessment methodology similar to previous studies e.g. Chung (2009a) was followed using the change factor method. This method involves 3 steps, first the establishment of long term baseline climatology data (1961-1990). Secondly, calculation of relative or absolute changes in the equivalent variable for the GCM grid box closest to the target site. Relative changes are used for rainfall, radiation, wind speed and relative humidity and absolute changes for temperature. Thirdly, the change suggested by the GCM for a particular time slice is applied to each monthly average in the baseline time series as shown in Fig. 2 (Diaz-Nieto and Wilby, 2005; Ahn et al., 2009).

A 10' by 10' latitude/longitude climate dataset assembled by IWMI from weather stations around the world for the period 1961-1990 was extracted and adopted as the baseline climatology for the study area. Change factors to the climate predicted by the HadCM3 were applied to an observed baseline for each pixel in the study catchment area to produce future projections. Climate projections from 30 year period time frames namely short-term 2010-2039 (2020s), mid-term 2040-2069 (2050s) and long-term 2070-2100 (2080s) are addressed.

Scenarios are coherent, internally consistent and plausible descriptions of a possible future state of the world. They are used to characterize the demographic, agricultural, energy, socio-economic and technological driving forces underlying anthropogenic greenhouse gas emissions which cause climate change. The IPCC developed four scenario families combining two sets of divergent tendencies: one set varying between strong economic values and strong environmental values, the other set between increasing globalization and increasing regionalization. The A2 scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and
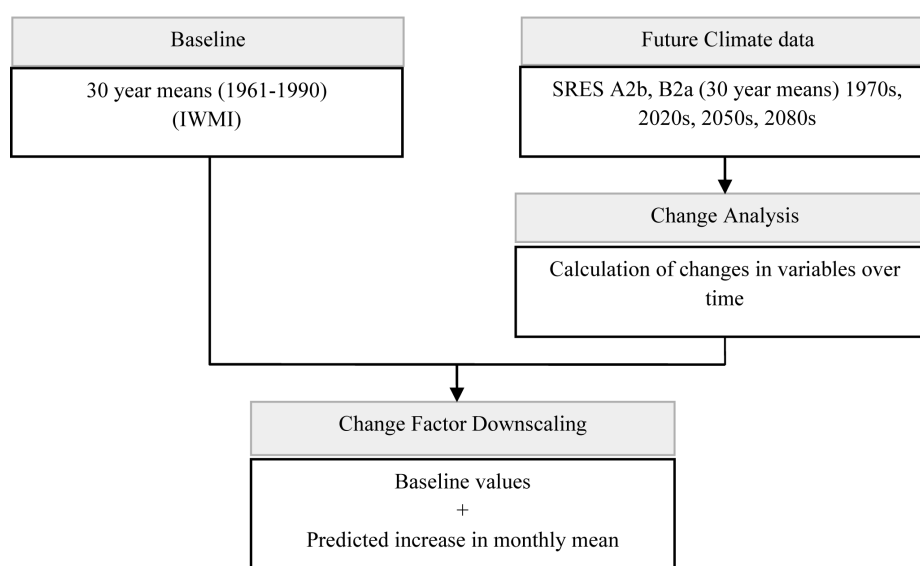

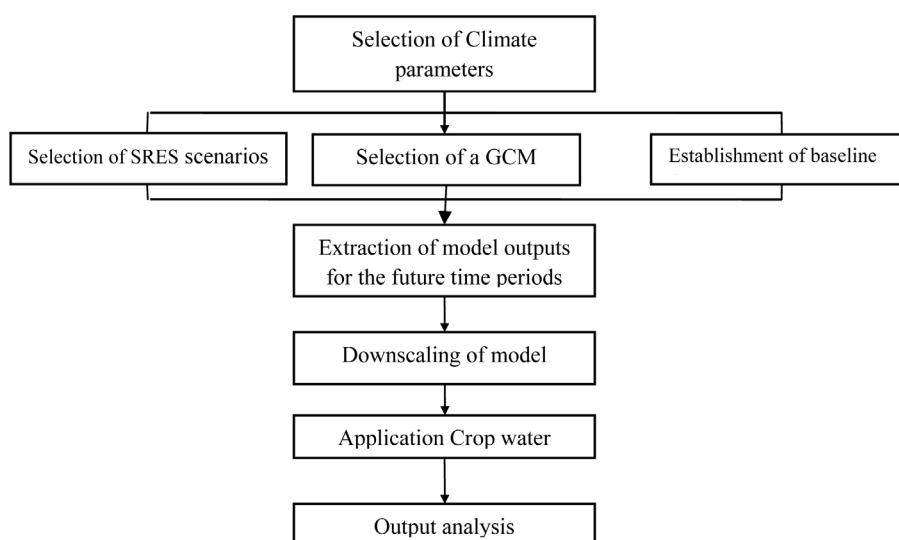Fig. 2 Stages of the change factor method (modified from Ahn et al., 2009)

Fig. 3 Methodology flowchart

per capita economic growth and technological changes are more fragmented and slower than in other storylines. The B2 scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels. Carbon dioxide levels have been projected to increase to 611ppm for B2 and to 836ppm for A2 by 2100 (IPCC, 2007).

Future climate change is subject to a large degree of uncertainty. Predictions are difficult due to the high complexity and interrelations of the influencing factors and feedback mechanisms. SRES A2 and B2 scenarios were selected for this study, because they represent regional emphasis with either economic or environmental emphasis which might be suitable for Zimbabwe. Scenarios A2b is one of the additional ensemble experiments for A2 scenario (A2a, A2b and A2c). The ensemble members differ in the initial condition of the climate system, and predicted global average temperature changes are similar. There are pronounced differences in projected regional temperature and precipitation.

Due to computational constraints and input data availability, GCMs typically have large spatial resolution and each grid covers wide areas (e.g. HadCM3, 2.5°×3.75°, latitude by longitude). HadCM3 outputs were used to derive change factors which were applied to a smaller scale historical baseline database in order to obtain future projections. A summary of the methodology is shown in Fig. 3.

Gridded future projection datasets for each time slice were then used to calculate reference ET (ET_o) for the corn growing season in the study area using the Penman-Monteith equation for each grid pixel. Mean temperature, solar radiation, wind speed and relative humidity were the input parameters for the ET_o calculation. 152 IWMI grid pixels covered the study area.

3. Modeling and mapping IWR

Net IWR can be defined as the depth of water applied in addition to effective rainfall to meet water loss through ET of a disease-free crop, growing in large fields under non restricting soil conditions and achieving full production potential under the given growing environment excluding conveyance deep percolation water losses. Effective rainfall can be defined as the portion of total rainfall which is used directly in the corn field i.e. total rainfall minus losses due to surface runoff and deep percolation. A spreadsheet model developed to replicate the CROPWAT methodology was used to compute the net IWR for 152 gridded points. A 150-day growth period was used with October 15th as the planting date and March 15th as the harvesting date. Growth stages for the initial, crop development, mid-season and late season were taken as 20, 45, 50 and 35 days respectively (Savvy and Frenken, 2002).

The United States Department of Agriculture Soil Conservation Service (USDA-SCS) method is used to estimate effective rainfall in this study and shows similar results to observed values. (Moyo and Hagmann, 1994).

$$P_{eff}=P_{tot}\times(125-0.2\times P_{tot})/125 \text{ for } P_{tot} < 250 \; mm/month \quad (1)$$

$$P_{eff}=125+0.1\times P_{tot} \qquad \text{for } P_{tot} > 250 \; mm/month \quad (2)$$

where P_{eff} is the effective rainfall (mm) and P_{tot} is the total monthly rainfall.

The crop ET and the net IWR was calculated as

$$ET_{crop}=K_c\times ET_o \qquad\qquad (3)$$

$$Net\; IWR=ET_{crop}-P_{eff} \qquad (4)$$

where K_c is the crop coefficient and *Net IWR* is the net irrigation water requirement.

Using the IWMI baseline and change factor adjusted projections for the 30 year periods, the net IWR for each grid pixel in the study area was estimated for scenarios A2b and B2a. A gridded dataset was processed by a GIS and a series of maps were generated showing the spatial variation in precipitation and IWR for the baseline and each future scenario.

III. RESULTS AND DISCUSSION

1. Potential changes in agro-climate

Table 1 shows the estimated rainfall during the growing season for the baseline and future scenarios in the major corn-growing areas of the three provinces. Average rainfall decreases by 13 % (2020s A2b), 6 % (2020s B2a), 15 % (2050s A2b), 1 % (2080s A2b), 2 % (2080s B2a) and increases by 7 % (2050s B2a) in comparison to a 30 year baseline average of 765mm. However effective rainfall changes by 5 to 11 % because as the rainfall increases, the effective rainfall ratio decreases. Despite the average decline in the 2020s (A2b and B2a) and 2050s (A2b), rainfall increases again in the 2050s (B2a) and 2080s (B2a and A2b). The spatial variation of rainfall in the study area during the

Table 1 Projected total rainfall for the growing season (October to March) for the future scenarios (unit: mm)

Province (Symbol in Fig. 1)	Baseline	2020s A2b	2020s B2a	2050s A2b	2050s B2a	2080s A2b	2080s B2a
Mash west (A)	742	643	698	631	794	737	727
Mash Central (B)	795	689	748	676	851	790	780
Mash East (C)	761	659	716	647	815	756	746
Mean	762	660	716	648	815	756	747
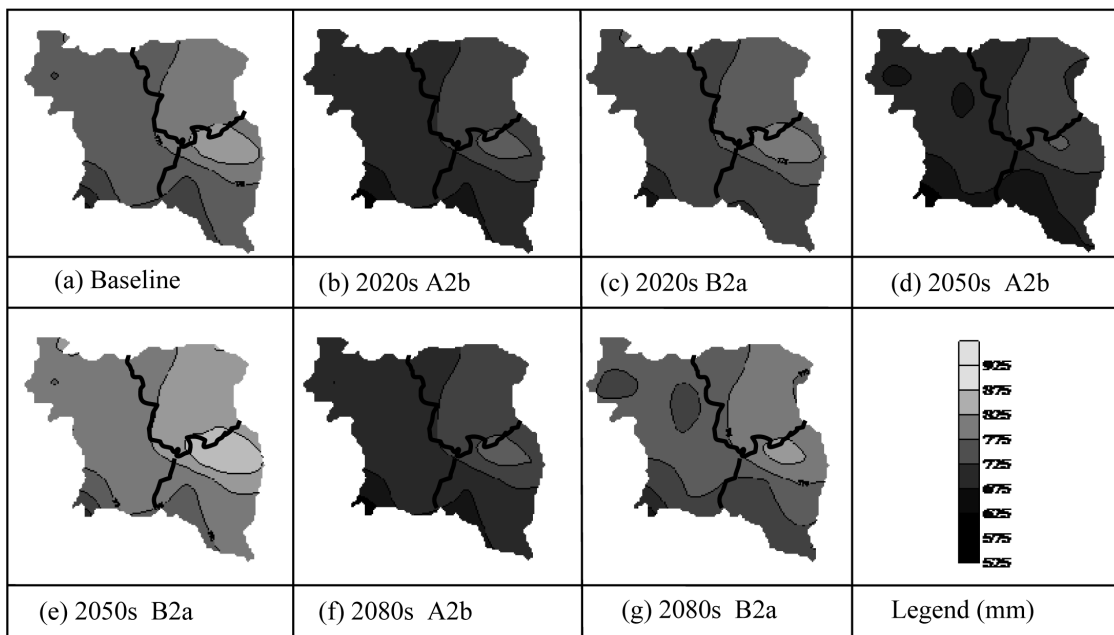
Fig. 4 Spatial variation in mean seasonal rainfall (October to March) for the baseline and future scenarios

growing season (October to March) for the baseline and future scenarios is shown in Fig. 4. The mean annual temperature averaged across the study region was 19.8 ℃ for the baseline period and projected to increase by 1.7 ℃ (2020s A2b), 1.6 ℃ (2020s B2a), 3.3 ℃ (2050s A2b), 2.2 ℃ (2050s B2a), 5.3 ℃ (2080s A2b) and 4 ℃ (2080s B2a). The analysis reveals that in all scenarios, temperature has an increasing trend.

For rainfall, the 2 scenarios give different predictions. For the A2b scenario, rainfall will decrease significantly in the 2020s but slowly approach baseline values by the 2080s. For the B2a scenario, however, rainfall is set to decrease in the 2020s but rise above baseline values for the 2050s and slowly decrease to near baseline values by the 2080s. Mashonaland Central has the highest rainfall followed by Mashonaland East and lastly Mashonaland West.

Precipitation variations are strongly influenced by vertical movement of air due to atmospheric instabilities of various kinds and by the flow of air over orographic features. For models to accurately simulate the seasonally varying pattern of precipitation, they must correctly simulate a number of processes that are difficult to evaluate at a global scale. Many models therefore individually display substantial precipitation biases. Biases can be attributed to errors in the sea surface temperature field of the ocean-atmosphere coupled model, and failure of models to capture the regional rainfall patterns. The inaccuracy of predicted rainfall by the GCM is carried over to the downscaled rainfall predictions. Therefore, the large differences between the A2b and B2a rainfall predictions in the 2050s can be attributed to the

Table 2 Projected corn net IWR for the future scenarios by province (unit: mm)

Province	Baseline	2020s A2b (% change)	2020s B2a (% change)	2050s A2b (% change)	2050s B2a (% change)	2080s A2b (% change)	2080s B2a (% change)
Mash West	171	280 (64)	251 (47)	334 (96)	214 (25)	346 (103)	312 (83)
Mash Central	140	243 (74)	215 (54)	293 (110)	181 (29)	303 (117)	272 (94)
Mash East	123	234 (89)	203 (65)	287 (133)	165 (33)	297 (41)	264 (114)
Mean	149	257 (73)	228 (53)	310 (108)	191 (28)	321 (115)	288 (93)
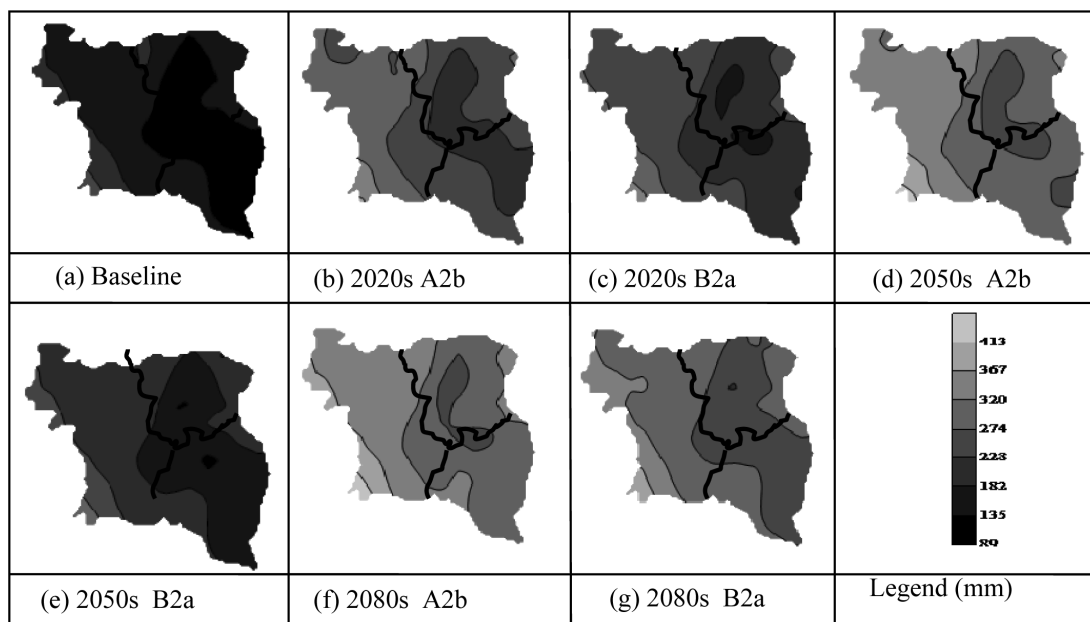
Fig. 5 Spatial variation in seasonal net irrigation water requirements for the baseline and future scenarios

lower confidence in rainfall predictions of the GCM.

2. Corn net IWR

The long term average ET_o is projected to increase by 10 % (2020s A2b), 9 % (2020s B2a), 17 % (2050s A2b), 10 % (2050s B2a), 27 % (2080s A2b) and 21 % (2080s B2a) from the baseline value of 720mm. The IWR is projected to increase by 73 % (2020s A2b), 53 % (2020s B2a), 108 % (2050s A2b), 28 % (2050s B2a), 115 % (2080s A2b) and 93 % (2080s B2a) compared to the baseline value of 149mm as shown in Table 2. Both crop ET and IWR show increasing trends in line with temperature increases. Fig. 5 shows the spatial variation of the net IWR for each scenario and time slice.

For all future time periods, the net IWR shows an increasing trend. Despite projections that rainfall will increase by 7 % in the 2050s for the B2a scenario, the net irrigation water requirement was still greater than the baseline. This is due to that the temperature and radiation increase have a higher effect on IWR than the rainfall increase. A similar trend was demonstrated by Chung (2009b) in a sensitivity analysis of parameters that affect ET and in turn IWR. Mashonaland East has the least irrigation water requirement because it experiences lower temperatures than the other provinces and hence significantly lower ET. Increases in net IWR are higher for the A2b scenario than for the B2a scenario. This arises from the differences in the two storylines. A2 family scenarios project higher carbon dioxide emissions, which will have higher temperature and then ET than B2 family scenarios.

3. Monthly variations

The monthly values are just as important as the total seasonal values because water stress in corn varies significantly with growth stages e.g. emergence, vegetative, flowering, grain filling and maturity. Fig. 6 compares the
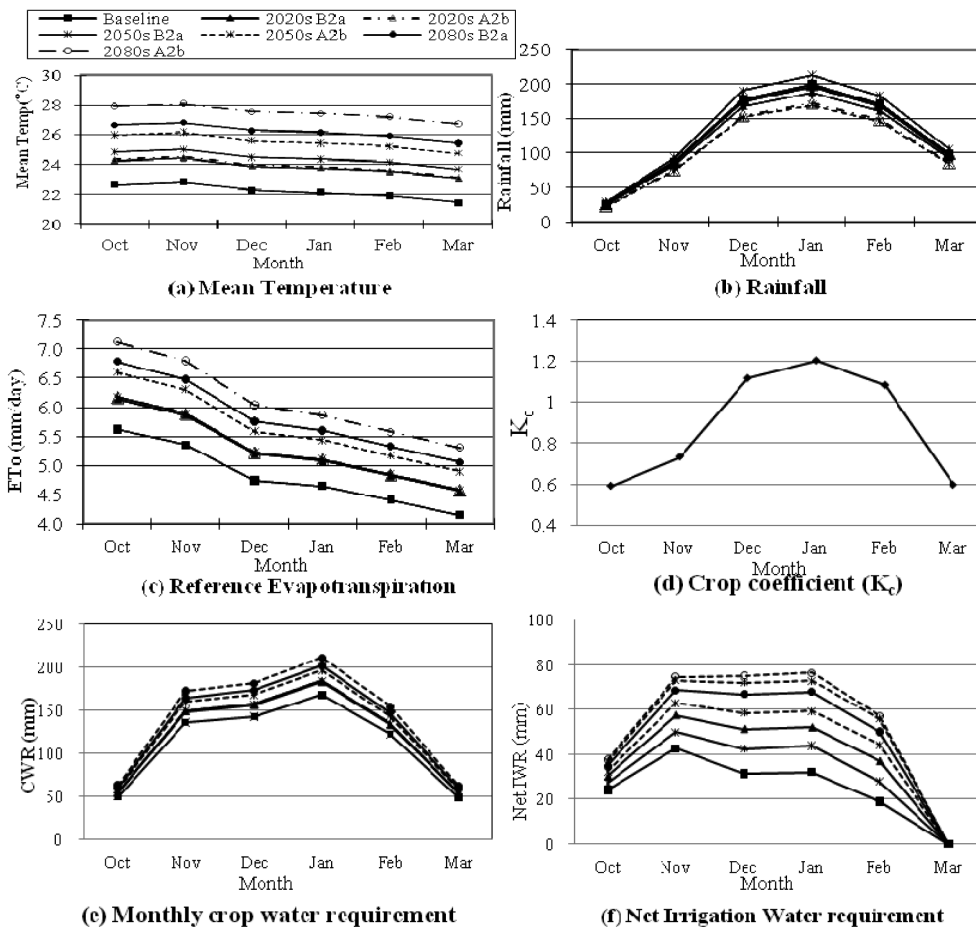

Fig. 6 Monthly weather parameters and irrigation water requirements for the baseline and future scenarios.

projected monthly mean temperature, rainfall, ETo, Kc, Crop water requirement (CWR) and net IWR for the baseline and future scenarios. The seasonal average temperature was 22.2℃ and will increase for all future scenarios. The ETo increases in line with temperature because the energy available for ET i.e. net radiation increases. The rainfall will affect net radiation and then ETo. In Fig. 6 (b) the rainfalls in January are about 100 mm larger than in March. However, the effect of the rainfall amount is not large compared with that of the high temperature in January.

The high net IWR in November can be attributed to high temperatures and low rainfall. In November and December, the plant gradually attains effective ground cover and evaporation becomes constricted and transpiration becomes dominant. In January the crop reaches full ground cover and the Kc reaches its maximum hence the high irrigation water demand. Irrigation will not be required in March for all scenarios because the effective rainfall was higher than the crop water requirement.

4. Adaptation strategy

An adaptation strategy based only on water resources might be to postpone the corn planting day by about a month to utilize the excess rainfall in March, however issues such as temperature, day length and harvest condition would need to be considered. At the national level, the government can plan and implement anticipatory adaptive measures. Increases in dam capacities and numbers will enhance the availability of water in the future. Construction of these dams allows policy makers to establish irrigation projects, which facilitate a shift from subsistence agriculture to a more sustainable agriculture state. Technology of irrigation has to improve as well in order to minimize water costs. Government policy and support for research and development considerably influences the agricultural production sector. Strategic research planning and a well-directed research programs are needed to study crops, and livestock that are more drought tolerant and disease resistant. Sustained research on short-season, high-yield crop varieties and livestock breeds is of paramount importance to adaptation.

In the future, cropland will have to be expanded and agriculture will have to be further intensified on existing cropland, which poses crucial questions on tradeoffs between future land use for agriculture, natural ecosystems and bio-energy plantations (Gerten et al., 2010). Adaptive measures

must be planned and implemented in agricultural infrastructure development and further research on mitigatory measures for the climate change impact for the study region is needed.

5. Methodological limitations

Predicting global climatic change impacts accurately on the study area remains largely uncertain. One limitation is that HadCM3 model provides a bigger scale to a much smaller scale baseline and interpolation distortions are inevitable. Another limitation is that since change factors are used, range and variability remain unchanged. One can note that even when considering only one driving emission scenario, for almost every region in Africa there is at least one climate model that projects an increase in precipitation and at least one that projects a decrease (Muller, 2009).

Despite climate being a stochastic process and having a predictable component, the random component could magnify the impact of global climate change in this particular region. Rainfall in southern Africa is strongly influenced by the Inter-Tropical Convergence Zone (ITCZ) and in recent years by the El Niño Southern Oscillation (ENSO). The southern African region has high inter-annual climate variability and hence suffers more from water scarcity than comparable regions with a more even climate (Doll, 2002).

Even though direct CO_2 effects on plant physiology were not accounted for in this analysis, corn is a C4 plant, so the elevated CO_2 effects are indirect to irrigation water requirements due to increased stomatal resistance and reduced transpiration but could interact with yield.

IV. CONCLUSION

Impacts of climate change on net irrigation water requirements on corn in Zimbabwe have been presented. Proportional changes in precipitation available to plants were projected to vary from － 15 % to ＋ 7 % depending on the time slice. Temperature was projected to increase by 1.6 to 5.3 ℃. The overwhelming impact of increased temperatures especially when coupled with decreases in precipitation will cause net irrigation water requirements to increase by 28 to 115 % mainly in November to Feburary. With such increases in the net irrigation demand, additional environmental problems may arise as freshwater resources on current agricultural land may not suffice to sustain a rising national food demand. The high temperatures could

affect crop development stages such as grain filling. This implies that cropland will have to be expanded in the future and that agriculture will have to be further intensified on existing cropland, which poses crucial questions on tradeoffs between future land use for agriculture, natural ecosystems, bio-energy plantations, agricultural infrastructural development and research. Anticipatory adaptive measures must be planned and implemented in agricultural infrastructure development and further research on mitigatory measures for the climate change impact for the study region is needed.

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