Consideration of Climate Variability and Change in Agricultural Water Resources Planning

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Abstract

While agriculture and its use of water resources are obviously sensitive to climatic conditions, past research has seldom identified the effects of climate variability and climate change on the fully developed relationship between crop yield and irrigation. There is potentially great value in understanding the role of climatic uncertainty on this relationship because of the dependence of agriculture on irrigation and the scale of water consumption for irrigation. Probability distributions of crop-water production functions (CWPF-PD's) are demonstrated as being useful encapsulations of the climate-yield-irrigation relationship for decisions at various levels of time and space. Combined with reliable climate teleconnections or climate forecasts, CWPF-PD's can be a central decision support tool for questions of risk and reliability. For long planning horizons, potential climate change predicted by multiple general circulation models (GCM's) can be assessed in the context of agricultural water resources. By analysis of changes in the CWPF-PD's, conclusions regarding the efficacy and sustainability of water resources and agricultural policies can be made. A semi-hypothetical case study for the Lake Victoria basin in East Africa is used to illustrate these methodologies, and potential future climate impacts as predicted by the CGCM1, ECHAM3, and HadCM2 GCM's are discussed.

SUBJECT HEADINGS: Water resource management, Climatic changes, Variability, Irrigation, Regional planning, Africa, Crop response

Introduction

Agricultural systems are obviously sensitive to climatic conditions. This sensitivity is perhaps greater than for other water resources systems due to the common lack of buffering capability in agricultural response to climatic events. For example, a single month of extremely low rainfall may affect a reservoir by decreasing storage over the course of a few months, but the reservoir system might be able to recover quickly with a single large rainfall. The same dry month may cause the death of a region's crops with no hope of growing new crops until the next growing season twelve months later. Consequently, agricultural water resources planning must consider the variability of agricultural systems over time and the primary cause for temporal variation, climatic variability. Irrigation is a principal adaptation mechanism to climatic variability, and econometric studies have shown that climatic variability, both measured and perceived, can be a factor determining private investment in irrigation infrastructure more important than many others including credit availability, governmental price policies, and local violence (Dinar and Keck 1997). However, climatic changes may alter the cost-benefit structure of these irrigation infrastructure investments. There is great value in understanding the responses of agricultural water resources systems to both climate variability and climate change.

Climate variability – the inter-annual oscillations of flood and drought about an assumed constant mean – and its effects on agricultural water resources has been investigated in a variety of ways (Wigley and Qipu 1983, Venema et al. 1997, Evers et al. 1998, Hook 1994, and Hook and Thomas 1995, among others). However, quantification of climate variability impacts on yield-irrigation relationships has not often been included in past assessments. Recent research has also been concerned with systems responses to non-stationary climate and the possibility of global climate warming and change, and a significant body of literature has been produced on the subject. Generally speaking, this literature has used two approaches to simulate potential climate change. The first group of studies has used sensitivity analysis whereby selected climate and atmospheric variables (e.g., temperature, precipitation, humidity, CO_2) and plant physiological variables (e.g., stomatal resistance) are incrementally varied from historical norms both independently and in various combinations with each other (e.g., Peterson and Keller 1990, McCabe and Wolock 1992, Brown and Rosenberg 1999). The second assessment philosophy has been to use climate scenarios produced by general circulation models (GCM's) in systems assessment. The advantage to this approach over sensitivity analysis is that GCM scenarios are climatically consistent from year to year, which allows for the derivation of frequency distributions for several years of analysis. The disadvantage to the use of GCM scenarios is that they have uncertain prediction skill over very long time scales. Crop yield assessments have been performed using GCM scenarios by Rosenzweig and Parry (1994), Singh et al. (1998), and Karim et al. (1999), among others. Brumbelow and Georgakakos (2001) assessed both irrigation requirements and crop yields for the coterminous U.S. using GCM scenarios along with regional soil moisture predictions.

This article presents a set of techniques for the assessment of climate variability and climate change impacts on agricultural water resources planning. The principal difference between this study and previous ones is that the full crop yield versus irrigation relationship is explicitly quantified at various scales and is available as an assessment tool. Knowledge of this "crop-water production function" (CWPF) is a powerful tool for irrigation planning purposes, but it has not often been included in past investigations due to the difficulty in determining the function for specific locations (Hexem and Heady 1978, Clumpner and Solomon 1987). However, ignorance of the CWPF has often implicitly involved the assumption that either local crop production is non-irrigated or irrigation water is freely available and all crop water needs will be met without limit. For many locations neither of these assumptions is valid, and current trends indicate that they will be increasingly irrelevant in the future. It is reasonable to anticipate that future planning decisions must include assessment of risk and reliability within the deficit irrigation regime. Brumbelow (2001) presents techniques for determining CWPF's at the single-site, single-season scale, and Brumbelow and Georgakakos (2005) present techniques for determining regional CWPF's (i.e., for multiple growing sites) for a single growing season under various policy options. They use physiologically based numerical models of crop growth (Tsuji et al. 1994) in concert with optimization techniques for CWPF determination. This article extends those techniques in the temporal scale. Ensemble predictions will allow for determination of probabilistic CWPF information. The case study for the techniques of this article is a semi-hypothetical irrigation development of 25 sites in the Lake Victoria Basin of East Africa (Figure 1). The region is bisected by the equator and experiences two rainy seasons and two consequent growing seasons per year: the "long rains" (approximately March to May, here abbreviated "LR") and the "short rains" (approximately October to December, here abbreviated "SR"). Maize is used as a single representative food crop; thus, crop mix issues are not presently included in the analysis. Geographic and historical climatic data for the region were taken from the Lake Victoria Basin Database (FAO 1999). Further details of the case study system are provided by Brumbelow and Georgakakos (2005).

Quantification of climatic variability for agricultural systems

Variability of the yield-irrigation relationship will be quantified here using techniques of non-parameteric statistics. These methods do not require an assumption of appropriate probability distribution functions, yet the familiar framework of probability analysis can be used for various questions of risk and reliability. Figure 2 presents the SR seasonal CWPF's for the nine years of climatic data available in the Lake Victoria basin database for Musoma, Tanzania; these functions were determined using the "simple yield-irrigation gradient (YIG)" algorithm (Brumbelow 2001). All parameters except meteorology and initial soil moisture profile are constant between the individual CWPF's. The variability of yield response to irrigation is readily evident in the graph. Rainfed yield ranges from about 400 kg/ha (year 1975) to over 6,400 kg/ha (year 1973). Fully irrigated yield varies between approximately 7,100 and 10,000 kg/ha (years 1971 and 1984, respectively), and the seasonal irrigation necessary for full yield is as low as 100 mm (year 1973) and as high as 280 mm (year 1975). Adding to the complexity of the situation, the various yield-irrigation functions cross each other frequently so that no function is obviously a "low," "high," or "average" case throughout the yield-irrigation domain. That is, no one year could be chosen as having the "average" response allowing it to be an appropriate surrogate for the full set of functions, and no one year is an obvious "poor" year for irrigation response.

The variability and complexity of this system's response necessitates consideration of the actual policy decisions that are directly affected by the system uncertainty. At the individual farm level, a typical decision is, "Given production costs and knowing a fixed yield level at which net profits become positive, what is the irrigation necessary to meet or exceed the 'break-even' production level?" The converse of this decision is, "If there exists a fixed water volume available for irrigation, what production level should be assumed to be realizable in determining expected profit?" (Expansion of these questions to larger scales is not difficult; the particulars only change to regional, national, etc., values such as aggregate production, basinwide withdrawal, and so on). Addressing the information contained in Figure 2 to these decisions, it becomes evident that the trajectory of each function throughout the yield-irrigation domain is not necessarily important for these planning-level questions. Rather, what is useful is the ordering of crop-water response at specific values of seasonal irrigation or crop yield. Thus, a vertical or horizontal section could be made through the ensemble of CWPF's, and a probability distribution could be determined of irrigation needed to produce a specific yield (horizontal section) or yield expected for a fixed irrigation amount (vertical section). By taking multiple sections through the available CWPF's, a crop-water production function probability distribution (CWPF-PD) can be determined as shown in Figure 3. This "quartile graph" replaces the ensemble of yield-irrigation functions with five lines representing the minimum, 25th percentile, median, 75th percentile, and maximum values, respectively, for any fixed irrigation or yield value. Viewing the quartile graph, it is seen that rainfed yields are highly variable from the lowest to highest values, but the central range between the 25th and 75th percentiles is not nearly so wide. Between irrigation values of 50 mm and 150 mm, total yield variability is significantly diminished, and the central region is tightly grouped about the median. At fully irrigated yield, total variability increases somewhat, but the trend of lower variability in the central half of values remains. This information could of course be ascertained from the original ensemble in Figure 2, but it is presented somewhat more clearly in the quartile graph. Moreover, as the number of ensemble members grows, the quartile graph will become more valuable in clarifying the CWPF-PD.

The determination of a CWPF-PD disregards the individual trajectories of the annual crop-water production functions. This omission is a reasonable one at the planning level and is reflective of the difference between deterministic and uncertain systems. Each individual yield-irrigation relationship was determined with perfect knowledge of that season's various conditions including weather. In operational circumstances, the conditions of future growing seasons are unknown. Hence, the need to evaluate the multiple functions as an ensemble representative of the uncertain behavior of the agricultural system as forced by variable weather. If processes exist whereby the nature of climatic inputs can be narrowed to include a specific sub-set of variability (e.g., correlation with El Nino Southern Oscillation events, Indeje et al. 2000, Mutai et al. 1998, Phillips and McIntyre 2000), the behavior of individual seasons' yield-irrigation functions may be considered.

The quartile graph has many uses for planning-level decisions. It is especially useful for evaluating system reliability and policy risk. For example, if a farm had available water for 100 mm of total seasonal application, the farmer can be assured of a minimum crop yield of 6,000 kg/ha. If the farm sets a yield goal of 7,500 kg/ha, the probability of meeting this target is less than 25%. However, if available water could be doubled to 200 mm, the probability of meeting this target increases to approximately 90%. Obviously, the conclusions drawn from these quartile graphs are dependent upon the number of years of analysis available and the quality of input data used to derive the original crop-water production functions.

The quartile graph is a generally applicable method for understanding variability in yield-irrigation response. Data from field observations or simulation model results can be used. If model results are used, it should be remembered that models generally tend to predict outputs with lower variability than exists in reality (Hansen and Jones 2000). Thus, the quartile plots produced from simulated data potentially include underestimations of total system variability. However, the variability in crop yields and irrigation needs induced by climate variability is expected to be of sufficiently larger magnitude compared to model estimation error to make the derived quartile plots useful analytical tools. Additional sources of variability beyond climate (e.g., groundwater fluctuations, changing application efficiencies, etc.) could also be included in the construction of CWPF quartile plots.

Climate change

Potential future climate scenarios and methodology for assessment

The efficacy of long-range plans for agricultural and water resources systems may be altered if the climatic forcings on those systems are altered during the planning horizon. That is, if policies have been formulated assuming stationary climate, any intervening climate change may modify the final outcomes of the policies for better or worse. The effects of climate change on crop yield-irrigation relationships will be demonstrated here by investigating how CWPF-PD's change from their current state to new ones under climate change scenarios.

The potential future climate scenarios predicted by three different GCM's will be used in this assessment: the Canadian Centre for Climate Modeling and Analysis Global Coupled Model 1 ("CGCM1," CCCMA 1997), the Deutsches Klimarechenzentrum and Max-Planck-Institut für Meteorologie "ECHAM3" model (DKRZ 1993), and the U.K. Meteorological Office Hadley Climate Model version 2 ("HadCM2," UKMO 2000). Data for all GCM scenarios was obtained on-line at the DKRZ internet site (DKRZ 1999) for runs assuming 1% annual CO_2 increase and sulphate aerosol increase (named "GHG+A"). In any assessment of future climate change impacts, it is important to use multiple climate scenarios due to the uncertainty inherent in any GCM predictions. By definition, it is impossible to verify any model's simulation of future climate trajectory; thus, the best that can be done is to assess values of interest under multiple scenarios, look for consistent predictions among scenarios, and appreciate inconsistencies as indicative of uncertainty at the present state of the science. The horizon of available data ended at year 2049 for the ECHAM3, and this year was chosen as the end point for all analyses. Example grid cells overlying the Lake Victoria basin are shown for each of the three GCM's in Figure 1. Several cells from each model were used in the spatial downscaling process for each model as described below. Changes in precipitation and daily maximum temperature are shown for the climate scenarios in Figures 4 and 5, respectively, for the cell in each model's grid most centered on the basin (the cells shown in Figure 1). The data shown are 48-month moving averages of GHG+A values compared to a control run where greenhouse gases and sulphate aerosols were unchanged; the comparisons are ratios for precipitation ($P_{GHG+A}/P_{Control}$) and deltas for temperature ($T_{GHG+A} – T_{Control}$). Trends in precipitation changes differ among the models with a slight decrease in the CGCM1, generally steady values in the ECHAM3, and a slight increase in the HadCM2. All three models predict significant warming by 2.5º to 3.0º C over the analysis period.

The crop models used to derive CWPF's require six input meteorological parameters: precipitation, daily maximum temperature, daily minimum temperature, humidity, wind speed, and solar radiation. The CGCM1 and ECHAM3 model data included the first five of these parameters, and the HadCM2 included the first four. Parameters not included in the GCM runs were based upon historical climatology.

The methodology for assessing potential climate scenario effects on agricultural water resources systems consisted of four principal steps: spatial downscaling of climate scenario parameters, temporal downscaling of climate scenario parameters, establishment of points of comparison for present and future climate, and determination of parameters to cite as indicative of system response to potential climate change. A flowchart of the assessment methodology is given in Figure 6.

As can be seen in the maps of GCM grid cells overlying the Lake Victoria basin (Figure 1), the spatial resolution of GCM computations is much larger than relevant scales of many agricultural systems and local scales of variation (e.g., microclimates, major topographic features, etc.). The spatial downscaling method of Taylor and Felzer (1999) was used to translate large cell values into localized ones. Briefly described, this method computes for each model cell deviations in monthly climate variables in the GHG+A scenarios versus climatological norms computed in model "control" runs. Then, the deviations are interpolated to point locations by inverse distance weighting from cells surrounding the site. The monthly deviation values are added to (or multiplied by, in the case of rainfall) the observed climatological means determined at each site from actual historical data. By defining future climate values as observed climatology plus deviation of GHG+A from control climate, the assessment is grounded in potential deviations from present conditions, not wholesale circumstances as determined exclusively by the model.

Temporal downscaling follows spatial downscaling to convert monthly parameter values to the daily values needed by the physiologically-based crop models. The WGEN stochastic weather generator (Richardson 1981) was used for this purpose. For each site, observed meteorological data were used to derive daily climatologies and matrices of auto-correlation and cross-correlation among all six parameters necessary for input to the crop models. Once base parameters were known, GCM daily weather was generated by producing daily values for each month in the assessment horizon, aggregating daily values in each month, and adjusting the daily values as necessary so that the monthly aggregates matched the GCM monthly values determined in the spatial downscaling.

The two points of comparison for this assessment were the periods 1965-1984, representing “current climate,” and 2031-2049, representing “future climate,” with the continuous GHG+A scenario model runs being used for both periods. The logic for using these two periods in the GCM scenarios is motivated by the fact that the GCM’s are not totally accurate replications of climatic state. It would be incorrect to compare agricultural system response from the historically observed climate to that from GHG+A GCM runs far in the future. Rather, the best alternative is to compare points along the time trajectory of a single consistent model run. In this way, changes in system response are correctly understood as effects of changes in a consistent climate scenario.

System response to climate scenarios was diagnosed by observing changes in CWPF-PD’s from “present” to “future” climate periods. In order to determine if statistically significant changes in CWPF-PD’s occur, the Kolmogorov-Smirnov test (hereafter “K-S”) was used. This test is a non-parametric technique to reject a null hypothesis of equivalent probability distributions at various confidence levels. So that system response at various scales and under various management policies could be analyzed, trends were assessed at single site scale and basinwide scale.

Assessment results

Single site scale

One particular site will be discussed as an example of assessment results at the scale of a single site. Eldoret, Kenya, is located in the northeast corner of the Lake Victoria basin (0.57º N, 35.30º E, elevation 2148 m; see Figure 1). Eldoret assessment results for the LR season are shown in Table 1. Distributions of rainfed yields did not significantly change under any of the future climate scenarios. The mid-irrigation portion of the ECHAM3 CWPF-PD's (at roughly 120 mm) did have a future climate lowering and an increase in variability that were statistically significant at 90% confidence. All three future climate scenarios had lower fully irrigated yield distributions, although they were statistically significant only for the CGCM1 (90% confidence) and HadCM2 (99% confidence) scenarios. SR seasonal results for Eldoret are shown in Figure 7 and Table 2. Changes in rainfed yield distributions were significant only for the HadCM2 scenario, but the increase in yield in the future climate did not fundamentally change the character of the overall yield-irrigation response in this case. The ECHAM3 scenario did have a mid-irrigation (roughly 150 mm) increase in variability of future climate yield distribution, while the other scenarios had similar CWPF-PD's in the mid-irrigation region. Two scenarios had lowering of fully irrigated yields in the future climate, significant at 95% confidence for the CGCM1 and 90% confidence for the ECHAM3.

While this site is only a sample of the twenty-five in the basin, it exhibits some of the consistent trends in the assessment results for all the individual sites. First, rainfed yields appear mostly unchanged in the future climate scenarios. Second, fully irrigated yields are lower in the future climate scenarios in all cases with almost all cases having statistically significant differences in probability distributions of those yields. Obviously, this phenomenon is not due to moisture stress at the fully irrigated level. It is likely that the reduced yields are due to two factors. First, temperature stresses may be occurring under the warmer climate scenarios. The maize crop model includes daily determination of a temperature stress factor affecting carbohydrate production (Jones and Kiniry 1986), where a daily weighted average temperature is compared to the "optimal" temperature of 26˚ C. The current climate temperature values in the Lake Victoria basin are very close to this optimal value. The GCM predicted increases in temperature (approximately 2.5˚ to 3.0˚ C) are sufficient to induce temperature stress, reducing photosynthetic efficiency and eventual crop yield. Second, the warmer temperatures of the future climate induce more rapid phenological development as thermal-time accumulates faster. As the plant is “rushed to maturity,” fewer days exist for photosynthesis and grain filling leading to reduced yield.

Multi-site scale

Potential criteria for spatial allocation of water-sharing among multiple irrigation sites are discussed by Brumbelow and Georgakakos (2005). That article applies five water-sharing scenarios to the Lake Victoria basin: full system optimization, equal national water shares, equal national benefits, equal national production, and food supply security. In order to understand the effect of potential climate change scenarios on a large agricultural water resources system, the water–sharing process was conducted for all five criteria for the three GCM scenarios’ current and future climate periods. Effects on system performance are discussed generally as changes in CWPF-PD’s under each GCM scenario. The food supply security criterion is the one exception to this diagnostic; maximum irrigation requirements under various scenarios of population growth and post-harvest losses were used instead.

Changes in CWPF-PD’s for the full system optimization criterion (i.e., crop production maximized without regard for national boundaries) are presented in Figure 8 for the LR season. The three climate scenarios had similar results. Rainfed yields had very similar distributions in the current and future climates. Fully irrigated yields were reduced in the future climate, and the change in CWPF-PD at this level was statistically significant with very high confidence (Table 3). The reduction in median fully irrigated yield was between 200,000 and 280,000 tonnes, which represented 11% to 23% of production gains from irrigation. Changes in variability of fully irrigated yields ranged from negligible change to moderate increases in variability. Trends in relative distribution of water among the three lacustrine nations were largely unchanged in the future climate scenarios.

The changes in CWPF-PD's for full system optimization in the SR season are presented in Figure 9. In contrast to the LR season, the SR season did have statistically significant changes in rainfed yield distributions for two of the three scenarios (Table 4). However, the aggregate meaning of these changes is uncertain; the CGCM1 scenario predicted a future climate decrease in rainfed yields, and the HadCM2 scenario predicted an increase in yields. Changes in variability of rainfed yields were also mixed among the three GCM scenarios. In keeping with the trends in the LR season, SR fully irrigated yields had decreased distributions in all cases. These decreases were varied at the median from 6% to 22% of gains from irrigation. The comparison of spatial distribution of irrigation shares for roughly median years produced no major changes in distribution patterns from the current to future climate scenarios.

Thus, the consistent trends seen in the future climate scenarios were a strong indication of decreases in fully irrigated yields and decreases in irrigation necessary to reach fully irrigated yield levels. The decrease in fully irrigated yields is likely a result of faster phenological development and increased temperature stresses as discussed above. The decrease in irrigation requirements to produce optimum yields is also likely related to increased temperatures. As yield reductions for the Lake Victoria sites are often caused by rain failures at the end of growing seasons, a shortening of the life cycle of the plant to avoid these riskier periods leads to a decrease in irrigation requirements. Assessment of aggregate system performance and distributional trends for the “equal national water shares”, “equal national benefits”, and “equal national production” water-sharing criteria all produced similar results (Brumbelow 2001).

Changes to water allocation for the food supply security objective were for population as projected to the year 2040. To include uncertainties arising from variable population growth rates and rates of crop production lost between the farm and table, three scenarios of population growth and farm-to-table losses were all included: low, medium, and high population growth and farm-to-table losses (Brumbelow and Georgakakos 2005). The “low growth and losses” (LGL) scenario is a best case, where population growth rates are 50% of current values and farm-to-table losses are reduced to 20% of crop production; “medium growth and losses” (MGL) assumes future population growth and farm-to-table loss rates at current values; and “high growth and losses” (HGL) is a worst case with population growth rates at 150% of current values and farm-to-table losses of 60%. Irrigation requirements for food supply were determined for all years in both the current climate and future climate periods for each GCM scenario. Then, the highest irrigation requirement for each growth and losses scenario in each period was assumed as being indicative of the system requirement for food supply security.

The changes in food supply security irrigation requirements are shown in Table 5. In the LR season for all three GCM scenarios there appears to be a decrease in irrigation requirements for each growth and losses scenario. (The one exception is the low growth and losses, “LGL,” scenario under the ECHAM3). The magnitude of these decreases is somewhat variable, however. The LGL irrigation requirement is virtually eliminated for the HadCM2 future climate scenario, but the MGL requirement is reduced by only about 11% in the ECHAM3 scenario. The consistency of these changes is likely caused by the consistency of precipitation increases for the LR season under all GCM scenarios, especially in the southwestern corner of the basin.

Food supply security is the criterion most heavily influenced by rainfed yield levels, and LR rainfall increases in the critical southwestern corner resulting in higher rainfed crop yields should lead to lower irrigation needs for food supply. SR seasonal changes in food supply security irrigation requirements were mixed among the three GCM scenarios. The CGCM1 predicts slight increases in irrigation needs for the MGL and HGL cases and a large decrease for the LGL case. The ECHAM3 and HadCM2 future climate scenarios lead to substantial decreases in irrigation requirements for all population growth and post-harvest losses cases. Again, these trends are in agreement with general rainfall trends for the SR season among the three GCM scenarios and associated changes in rainfed yield.

Conclusion

This article has presented a set of methods by which to quantify and understand temporal-climatic variability of agricultural water resources systems in historical and potential future climates. It should be reiterated that the Lake Victoria basin system of irrigation sites is a virtual system proposed for the purposes of this study. This point helps to underscore the value of the information gained by the methods in this chapter. For decision-makers contemplating such a large irrigation system, it is useful to know among other things the susceptibility of the system's performance to climatic phenomena, the system's ability to mitigate adverse circumstances, and the potential changes in system performance in the future. All of these questions can be answered by the methods demonstrated here. The case study has shown consistent forecasts of decreased returns from irrigation under several future climate scenarios. This information may be considered at long-term planning levels in deciding if investment in irrigation will produce the greatest return on capital, social good, and other desired objectives.

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Table 1. Results of Kolmogorov-Smirnov tests of equivalence of CWPF-PD's for current and future climates, LR season at Eldoret, Kenya.

Model	Zero Irrigation	Fully Irrigated	Notes
CGCM1	Not different at 90% c.l.*	*Different at 90% c.l.*	Future climate has lower yields at fully irrigated level
ECHAM3	Not different at 90% c.l.	Not different at 90% c.l.	For irrigation of 120 mm, CWPF-PD's different at 90% c.l.; future climate yield lower and more variable
HadCM2	Not different at 90% c.l.	*Different at 99% c.l.*	Future climate has lower yields at fully irrigated level

* c.l. = confidence level

Table 2. Results of Kolmogorov-Smirnov tests of equivalence of CWPF-PD's for current and future climates, SR season at Eldoret, Kenya.

Model	Zero Irrigation	Fully Irrigated	Notes
CGCM1	Not different at 90% c.l.	*Different at 95% c.l.*	Future climate has lower yields at fully irrigated level
ECHAM3	Not different at 90% c.l.	*Different at 90% c.l.*	Future climate has lower yields at fully irrigated level; At 150 mm, CWPF-PD's different at 95% c.l.; future climate yield lower and more variable
HadCM2	*Different at 95% c.l.*	Not different at 90% c.l.	Future climate has higher yields at rainfed level

Table 3. Results of Kolmogorov-Smirnov tests of equivalence of CWPF-PD's for current and future climates, LR season for full Lake Victoria system.

Model	**Zero Irrigation**	**Fully Irrigated**	**Notes**
CGCM1	Not different at 90% c.l.	*Different at 99% c.l.*	Future climate fully irrigated yields are lower and reached at lower irrigation levels
ECHAM3	Not different at 90% c.l.	*Different at 99% c.l.*	Future climate fully irrigated yields are lower
HadCM2	Not different at 90% c.l.	*Different at 99% c.l.*	Future climate fully irrigated yields are lower and reached at lower irrigation levels

Table 4. Results of Kolmogorov-Smirnov tests of equivalence of CWPF-PD's for current and future climates, SR season for full Lake Victoria system.

Model	**Zero Irrigation**	**Fully Irrigated**	**Notes**
CGCM1	*Different at 90% c.l.*	*Different at 99% c.l.*	Future climate has lower yields at both rainfed and fully irrigated levels
ECHAM3	Not different at 90% c.l.	*Different at 99% c.l.*	Future climate fully irrigated yields are lower
HadCM2	*Different at 95% c.l.*	*Different at 95% c.l.*	Future climate has slightly higher yields and reduced variability at rainfed level; Future climate fully irrigated yields are lower

Table 5. Irrigation requirements in million cubic meters to meet food supply security needs in the Lake Victoria basin for the two local growing seasons. Requirements are shown for current and future climate scenarios for three general circulation models and for three population growth and farm-to-table losses scenarios.

	Long Rains Season			Short Rains Season		
	LGL	MGL	HGL	LGL	MGL	HGL
CGCM1 Current	77	429	527	135	488	812
CGCM1 Future	40	208	423	35	574	821
ECHAM3 Current	721	990	1119	515	812	991
ECHAM3 Future	785	875	890	53	379	638
HadCM2 Current	152	604	789	389	771	886
HadCM2 Future	12	431	690	171	404	601

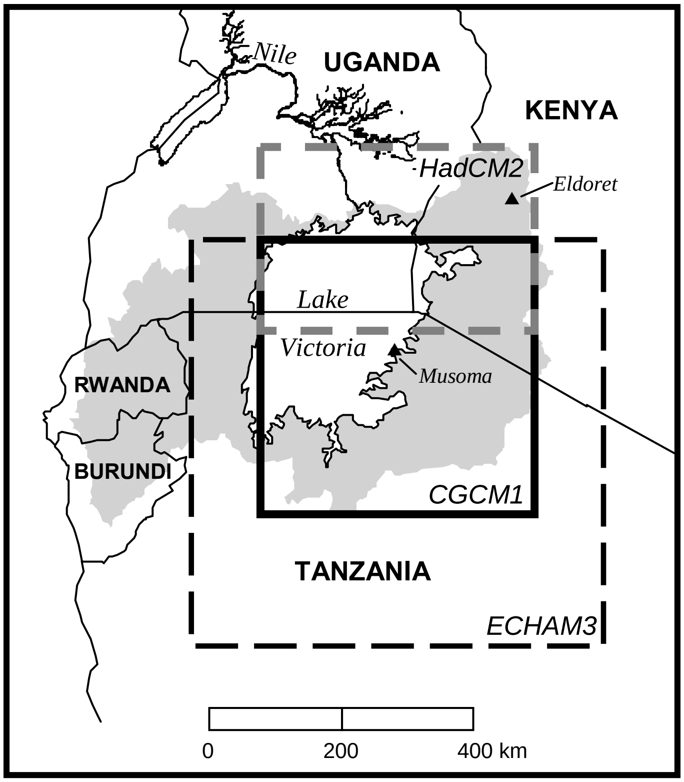

Figure 1. Map of the Lake Victoria Basin (shown in gray), the cities of Musoma, Tanzania, and Eldoret, Kenya, and selected cells from the three general circulation models used for future climate scenarios.

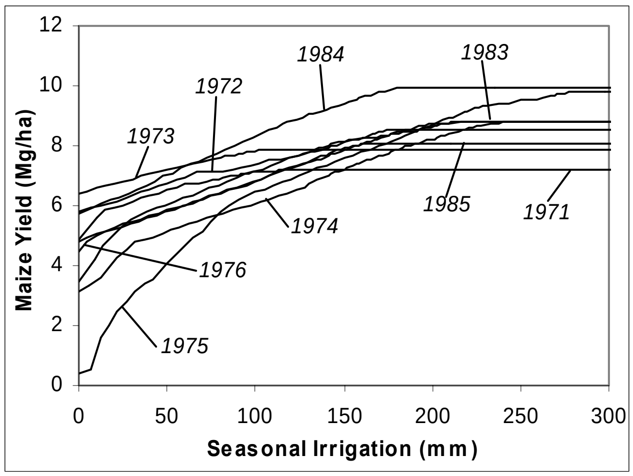

Figure 2. Maize crop-water production functions for the “Short Rains” (SR) growing season at Musoma, Tanzania, for nine different years.

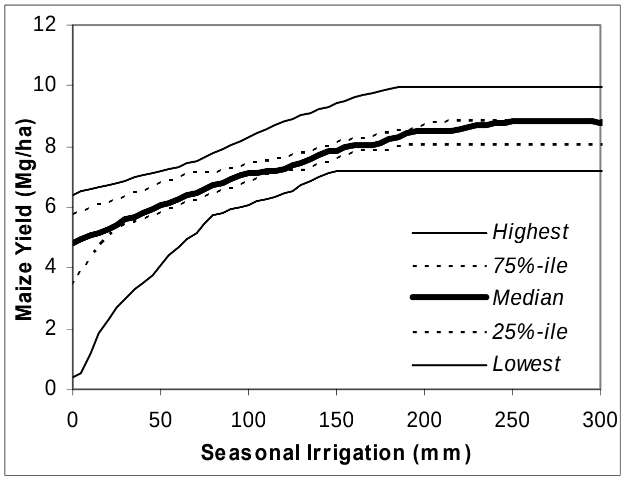

Figure 3. CWPF-PD quartile graph for SR seasons at Musoma, Tanzania.

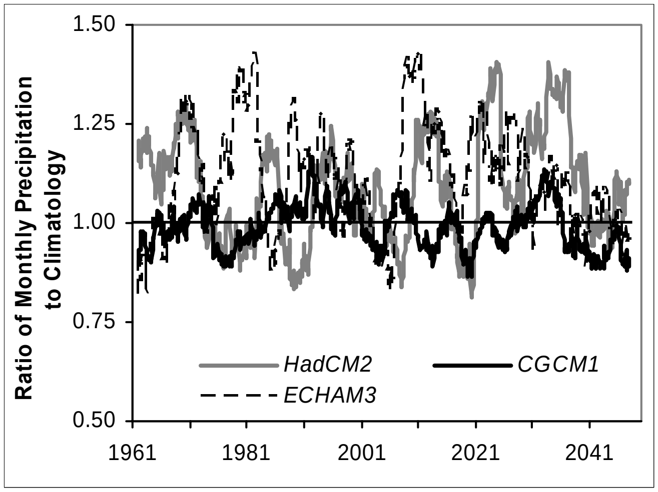

Figure 4. Time-series of precipitation scaling ratios (i.e., relative changes in precipitation) for the three future climate scenarios assessed. Values shown are 48-month moving averages.

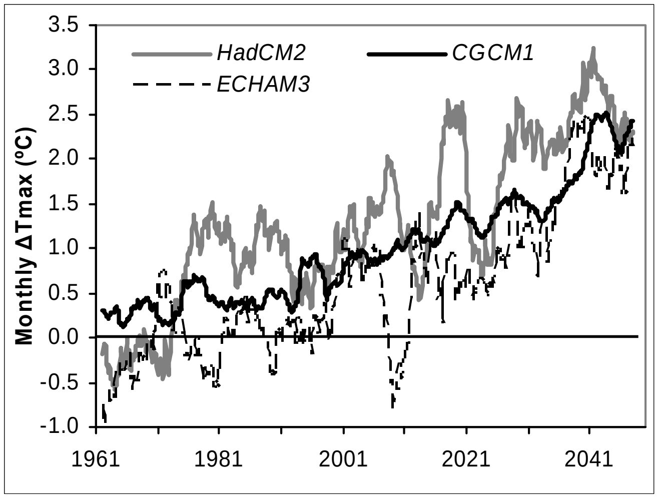

Figure 5. Time-series of ΔT_{max} (i.e., relative changes in daily maximum temperature) for the three future climate scenarios assessed. Values shown are 48-month moving averages.

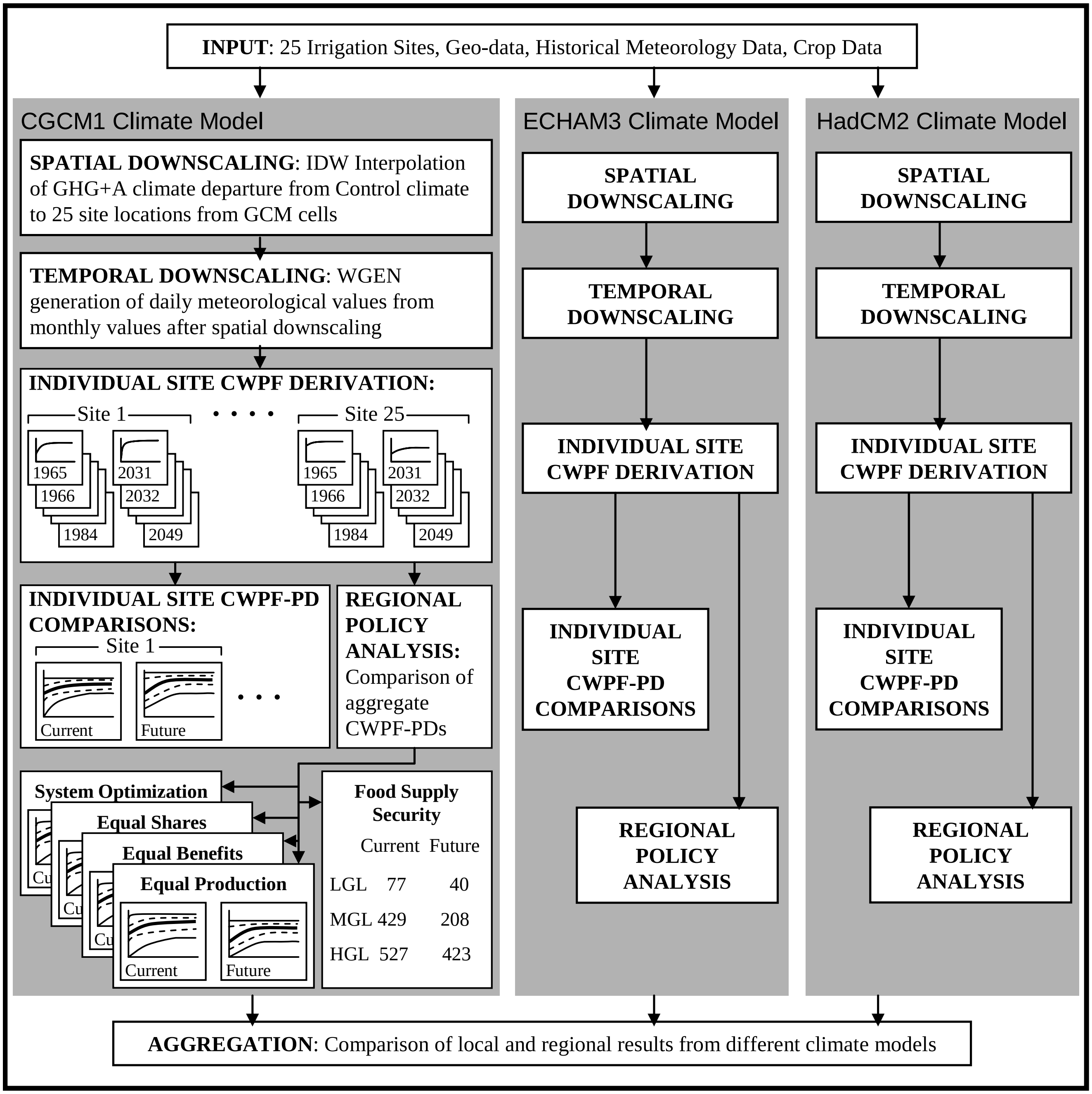

Figure 6. Flowchart of the future climate scenarios assessment methodology. An identical process was used for all three climate models; details are shown only for CGCM1.

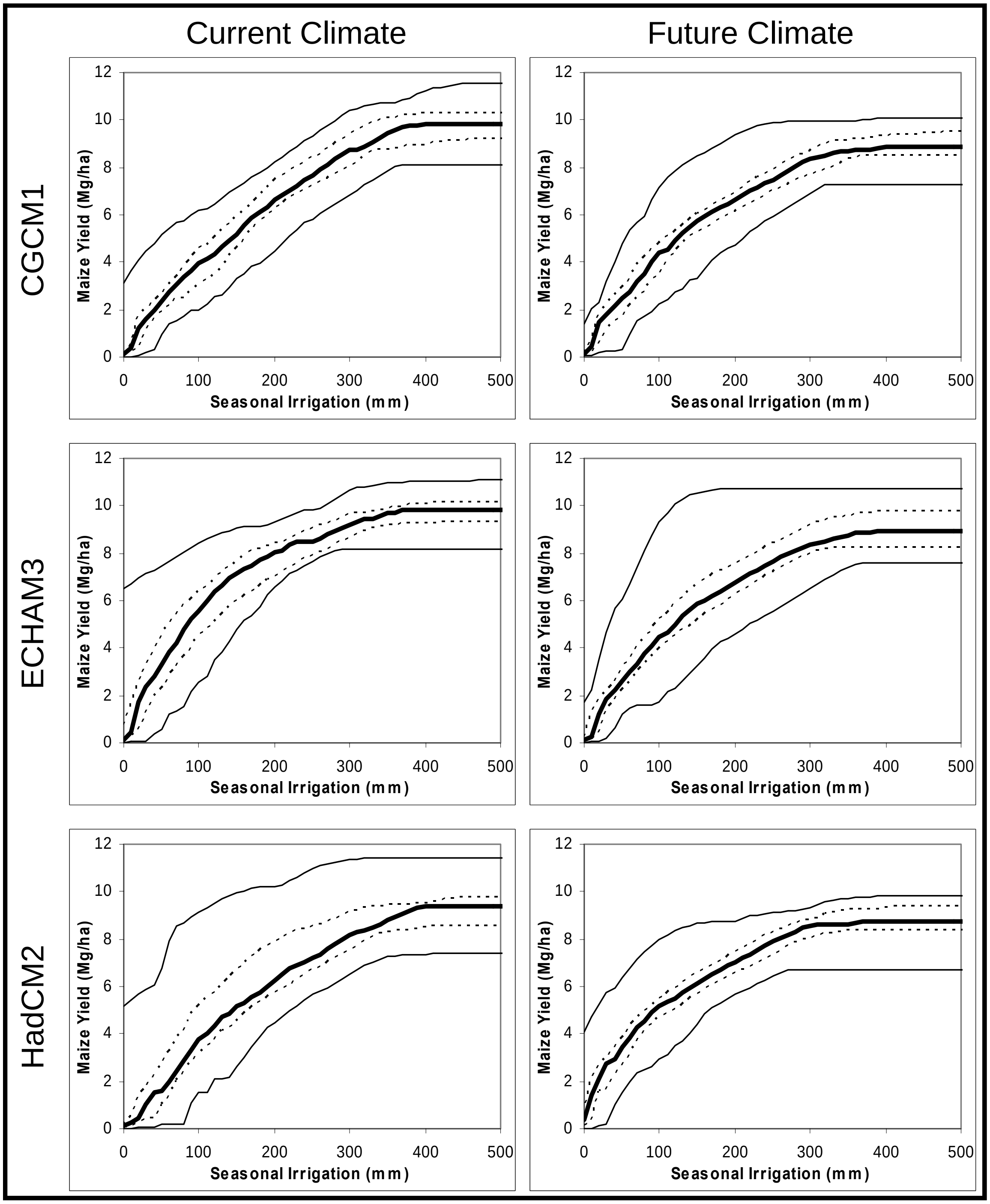

Figure 7. Quartile plots of SR seasonal CWPF-PD's at Eldoret, Kenya, for current climate and future climate scenarios according to the CGCM1, ECHAM3, and HadCM2 general circulation models.

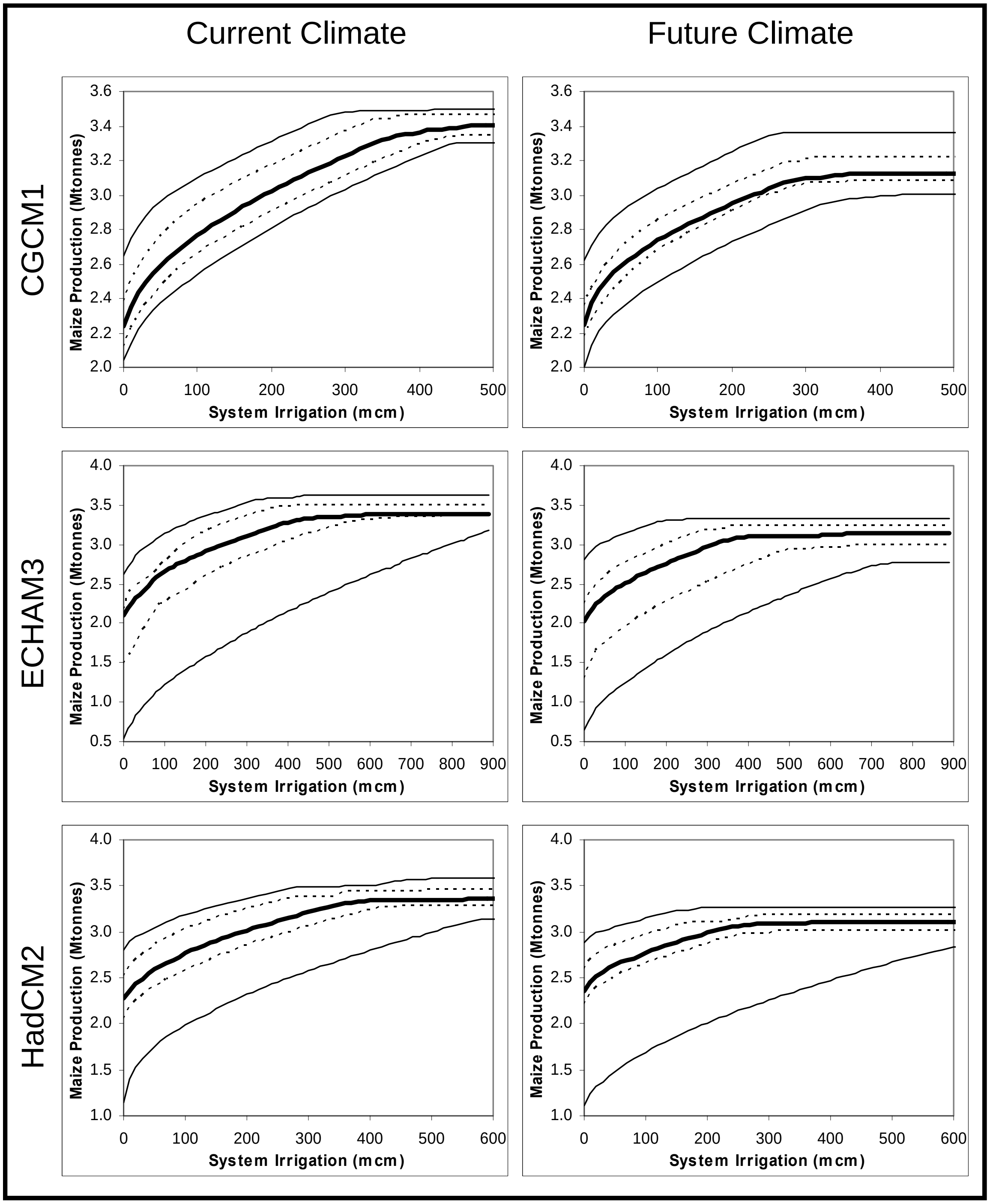

Figure 8. Quartile plots of LR seasonal CWPF-PD's for full system optimization of basinwide system for current climate and future climate scenarios according to the CGCM1, ECHAM3, and HadCM2 general circulation models.

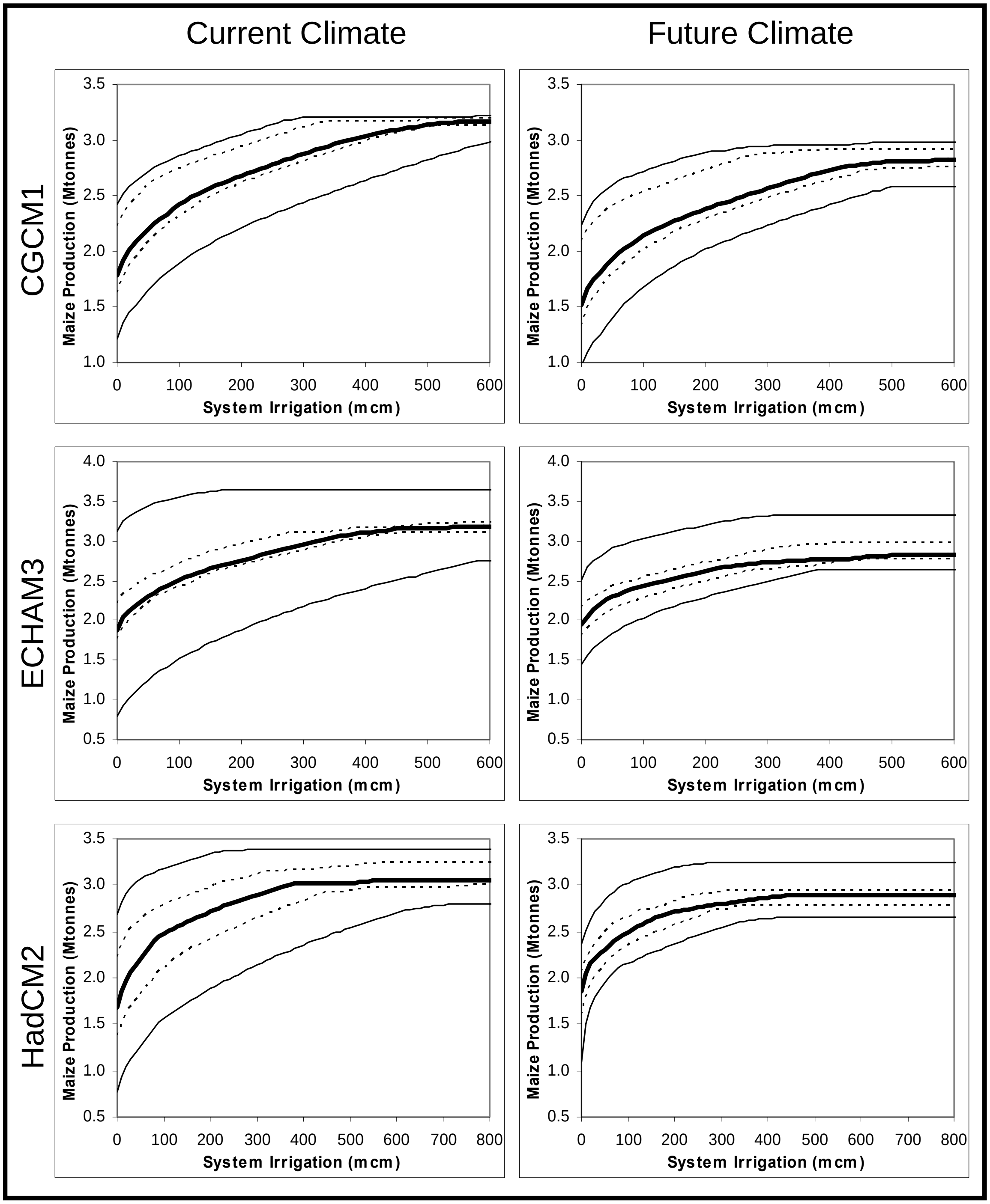

Figure 9. Same as Figure 8 for the SR season.