

Full Research Paper

Impact of Climate Change on Irrigation Demand and Crop Growth in a Mediterranean Environment of Turkey

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Received: 25 September 2007 / Accepted: 15 October 2007 / Published: 16 October 2007

Abstract: A simulation study was carried out to describe effects of climate change on crop growth and irrigation water demand for a wheat-maize cropping sequence in a Mediterranean environment of Turkey. Climate change scenarios were projected using data of the three general circulation models—GCMs (CGCM2, ECHAM4 and MRI)—for the period of 1990 to 2100 and one regional climate model—RCM—for the period of 2070 to 2079. Potential impacts of climate change based on GCMs data were estimated for the A2 scenario in the Special Report on Emission Scenarios (SRES). The forcing data for the boundary condition of the RCM were given by the MRI model. Daily CGCM2 and RCM data were used for computations of water balance and crop development. Predictions derived from the models about changes in irrigation and crop growth in this study covered the period of 2070 to 2079 relative to the baseline period of 1994 to 2003. The effects of climate change on water demand and on wheat and maize yields were predicted using the detailed crop growth subroutine of the SWAP (Soil-Water-Atmosphere-Plant) model.

Precipitation was projected to decrease by about 163, 163 and 105 mm during the period of 1990 to 2100 under the A2 scenario of the CGCM2, ECHAM4 and MRI models, respectively. The CGCM2, ECHAM4 and MRI models projected a temperature rise of 4.3, 5.3 and 3.1 °C, respectively by 2100. An increase in temperature may result in a higher evaporative demand of the atmosphere. However, actual evapotranspiration (ET_a) from wheat cropland under a doubling CO₂ concentration for the period of 2070 to 2079 was

predicted to decrease by about 28 and 8% relative to the baseline period based on the CGCM2 and RCM data, respectively. According to these models, irrigation demand by wheat would be higher for the same period due to a decrease in precipitation. Both ETa and irrigation water for maize cropland were projected to decrease by 24 and 15% according to the CGCM2, and 28 and 22% according to the RCM, respectively. The temperature rise accelerated crop development but shortened the growing period by 24 days for wheat and 9 days for maize according to the CGCM2 data. The shortened growth duration with a higher temperature reduced the biomass accumulation of both crops regardless of CO₂-fertilization effect. With the combined effect of CO₂-fertilization and increased temperature, the CGCM2 and RCM projections resulted in an increase by 16 and 36% in grain yield of wheat and a decrease by about 25% and an increase by 3% in maize yield, respectively.

Keywords: Climate change; Mediterranean region; SWAP model; Wheat; Maize; Irrigation demand.

1. Introduction

Global climate change may have serious impacts on water resources and agriculture in the future. Therefore, numerous studies have been undertaken in the last decades to evaluate the impacts of climate change on agriculture in various parts of the world [1-10]. The use of general circulation model (GCM) projections has been at the core of climate change assessments for agriculture and water resources over the past decades [11, 12]. Assessments of climate change impacts on agricultural production often use outputs of more than one GCM to drive agro-ecosystem models [12-16]. Therefore, adequate downscaling of GCM projections is necessary to study most impacts of climate change at local to regional scales, although many aspects of climate change are still uncertain, particularly, at the local and regional scales [17, 18]. In addition, there is a need to make extensive use of regional climate models (RCMs) (<http://prudence.dmi.dk/>).

Based on a range of several current climate models, the mean annual global surface temperature is projected to increase by 1.4 to 5.8 °C over the period of 1990 to 2100 [19], with changes in the spatial and temporal patterns of precipitation [20, 21]. (Semi-) arid areas already suffering from limited availability of water under current conditions are likely to be most sensitive to climate change, while (sub-)humid areas may be less adversely affected [22, 23]. Though different in socio-economic development, technological possibilities, and climatic regimes, the semi-arid regions that appear to have relatively ample water supplies for agriculture under the current climate are all most likely to be adversely affected due to an increase in water demand for irrigation projected under a warmer climate [7, 24-26].

Water deficit stress can occur as precipitation does not adequately compensate for an increased evaporative demand due to a temperature rise. This stress could cause a decline in yield or require more irrigation to maintain yields [27]. This negative effect of increased temperature may be counteracted by effects of elevated CO₂ on crop tolerance to water stress [23, 28, 29]. Increased

atmospheric CO₂ levels have important physiological effects on crop plants such as an increase in photosynthetic rate. Depending on the inclusion and exclusion of CO₂-fertilization effect, an increase, or a decrease is reported to occur in crop yields [27]. In the Mediterranean environment of Western Australia, the impact of increased CO₂ and temperature on grain yield of wheat was, on average, positive, but varied with a seasonal rainfall distribution [30]. Alexandrov and Hoogenboom [6] reported that the GCM scenarios resulted in a decrease in winter wheat yield, and especially, in maize in Bulgaria, caused by a shorter crop growing season due to higher temperatures and precipitation deficit. When the CO₂-fertilization effect was included in the study above, all the GCM scenarios resulted in an increase in winter wheat yield. According to Richter and Semenov [31], scenarios simulated for the 2020s and 2050s showed that wheat yields in England are likely to increase more by the 2020s than in the following 30 years in spite of increasing CO₂ and temperature.

In the Mediterranean countries including Turkey, cereal yields are limited by low water availability, restricted rainfall, high evapotranspiration, heat stress and the short duration of the grain-filling period which makes irrigation important for crop production [6, 7]. Changes in water demand and supply for irrigation in Çukurova plain, one of the most productive regions of Turkey, as a consequence of climate change may have serious implications for the country's food security and economy. The studies under the model projections of both global and regional climate change are needed to assess the full range of climate change impacts and adaptation strategies.

The purposes of this study were, therefore, to (1) generate future climate data for the Çukurova plain using GCMs, (2) explore local impacts of climate change projected by GCM and RCM on water demand for irrigation using the SWAP (Soil-Water-Atmosphere-Plant) model, and (3) predict changes in crop growth for a wheat and maize rotation in the study area.

2. Materials and Methods

2.1 Study area

Study site (Adana) (36°59'N, 35°18'E) is located in the Çukurova plain of *ca.* 38 500 km² at the eastern Mediterranean coast of Turkey (Figure 1). The agricultural region chosen for this study is the major growing belt of field crops (cotton, maize, wheat and soybean) and permanent crops (citrus, fruit trees and grape). A typical Mediterranean climate prevails in the study region with the long term (1975-2006) mean annual temperature, precipitation and potential evapotranspiration of 19.0 °C, 650 mm and 1320 mm, respectively. The temperature extremes are -6.4 °C in February and 44.0 °C in July. About 87% of precipitation occurs during the winter (November to May) (<http://meteor.gov.tr/>). The region soils with different proportions of sand, silt, and clay fractions are predominantly fine-textured soils. The soil at the study location is a Vertic Luvisol.



Figure 1. Location of the study site in the Çukurova region.

2.2 Climate change scenarios

The climate change data were obtained from the outputs of the three GCMs: the second version of the Canadian Global Coupled Model—CGCM2—[32], the model developed from the atmospheric model of European Center for medium range weather forecasting, and parameterized at Hamburg—ECHAM4—[33], and the general circulation model developed at the Meteorological Research Institute of Japan—MRI—[34, 35]. The impacts of climate change based on GCMs data were estimated for the A2 scenario in the Special Report on Emission Scenarios (SRES). The A2 scenario describes a very heterogeneous world of high population growth, slow economic development and strong regional cultural identities. Scenario A2 is one of the emission scenarios with the highest projected CO₂ increase (up to 800 ppm) by the end of the 21st century [36]. The GCM-based climate change data are available with seven climate models at the IPCC web-site (<http://ipcc-ddc.cru.uea.ac.uk/>). Monthly temperature and precipitation values projected by CGCM2 and ECHAM4 were obtained from the IPCC database. The MRI model can be used to explore climate change associated with anthropogenic forcings [34], however, its data are not available at the IPCC web-site. The MRI control run simulates the current climate condition, while the MRI global warming run is performed based on the A2 scenario of the SRES. The MRI data were computed for Adana from the projected values at the four nearest grid points. It is unreasonable to expect that a large GCM grid box completely represents climate for any particular point. In order to move from the coarse grid scale of the GCMs outputs to the specific location, the following procedure was used: GCMs data from the four nearest grid points were used to compute climatic data for the specific site. The actual values were calculated using the inverse distance weighted method between the specific site and the GCMs grid points [6, 37].

Daily climatic values necessary for calculations of water balance and crop growth were obtained from CGCM2 since the data of the other IPCC models are monthly. In addition, climate change data obtained by a regional climate model with a grid distance of 25 km (hereafter RCM) developed in Japan [38] were used for computations of water balance and crop growth for further comparisons. The forcing data for the boundary condition of the RCM are given by the MRI. To create climate data, the GCMs were used for the period of 1990 to 2100, while RCM was used for 1994 to 2003 (the baseline period of 10 years) and 2070 to 2079. The CGCM2, ECHAM4 and RCM projections were compared to 10-year average observations provided by the Turkish State Meteorological Service (DMI).

One limitation of this type of study is that GCMs may not provide accurate results for the specific site due to downscaling using the data from surrounding grid points. Climate change scenarios were created by superimposing projected anomalies on observed climate data of the baseline period. Temperature changes between the future projections and the control runs were added as absolute changes to the observational data; the other climate parameters were adapted according to their relative changes [39, 40].

2.3 Water demand for irrigation

The impacts of generated climate data on evapotranspiration (ET) and irrigation water demand for wheat and second crop maize were simulated using the SWAP model [41] for the periods of 1994 to 2003 and 2070 to 2079. The model can simulate water, solute and heat transport in relation to plant growth at the field scale for the entire growing seasons. The SWAP model integrates soil-water balance and crop growth, and requires input data for soil, crop and climate for its calibration and validation in different environments. Climate (solar radiation, maximum and minimum temperatures, relative humidity, wind speed and rainfall), soil (soil water retention and hydraulic functions) and crop management data (e.g., crop calendar, some growth parameters, and irrigation) were obtained for the study location. Accurate simulation of water transport with the SWAP depends on the use of hydraulic parameters and functions which adequately represent soil hydraulic behavior [42].

The daily soil-water balance was calculated during the growing period of the studied crops. Irrigation amount was calculated for the optimal irrigation conditions. When soil moisture was depleted to 100% of the readily available water, the calculated amount of water was added by irrigation to bring the soil back up to field capacity. The available amount of soil water in the root zone is calculated from the water balance. This balance includes precipitation, irrigation, losses by runoff, soil evaporation, crop transpiration, and percolation from the root zone. The model simulates evaporation from soil water and plant transpiration separately, thus facilitating a differential crop development and yield under varying temperatures as well as rainfall conditions. Partitioning of potential evapotranspiration into potential rates of soil evaporation and crop transpiration is calculated based on the leaf area index (LAI). In this study, reductions in transpiration by 17 and 26% were used for wheat and maize, respectively [43] in the calculations for the period of 2070-2079. Evapotranspiration from grass as a reference crop (E_{Tr}) was calculated using the Penman-Monteith equation to represent evaporative demand of the atmosphere. Instead of plant height, crop coefficients (K_c) were used with E_{Tr} to estimate evapotranspiration from actual crops.

2.4 Crop growth model

Crop growth was simulated using the detailed crop growth sub-model of the SWAP with a daily time step from sowing to maturity, based on eco-physiological processes that describe daily phenological development and growth in response to environmental factors such as soil and climate, and crop management. This sub-model of the SWAP is a version of the WOFOST (WORLD FOOD STUDIES) which requires the input of daily climate data as well as information on soil properties, and crop-specific growth parameters. In principle, the WOFOST model can simulate the growth and production of annual field crops on the scale of a single farm field. The major processes for crop growth are phenological development, CO₂-assimilation, transpiration, respiration, partitioning of assimilates to the various organs, and dry matter accumulation. Plant development is quantified according to the plant physiological stages. The model simulates grain yields from biomass accumulation until anthesis and during grain filling. The simulation of anthesis date, growth rate and the decline of green leaf area during grain fill is therefore important for model accuracy. The model is particularly suited to quantify the combined effect of changes in CO₂, temperature, rainfall and solar radiation on crop development and growth, and crop water use, as all the relevant processes are simulated separately while taking into account of their interactions. More detailed information on the crop model was given by Boogaard et al. [44].

The model was parameterized for wheat and maize and calibrated with the crop growth (for example, LAI and biomass) measured during two growing years and one growing year, respectively. Simulations were implemented for wheat and maize (the second crop). The growth of the crops was simulated in single stands of each crop. In calculations, the percent changes in acclimatized photosynthesis rate were assumed to be +27 and +4% for wheat and maize, respectively, as suggested by Cure and Acock [43]. Changes in yield (stated as percentage) were evaluated by comparing the future crop yields to the current yields, as also described by Southworth et al. [20].

3. Results and Discussion

3.1 Projection of air temperature and precipitation

Variations of mean annual temperature and precipitation for 111 years from 1990 to 2100 in Adana are shown in Figure 2. These data were computed for Adana with the projected values of CGCM2, ECHAM4 and MRI models. Annual temperature increases gradually, and the CGCM2 projects generally moderate temperature rises compared to the other two GCMs. Averaged surface temperature is estimated to increase by 4.3, 5.3 and 3.1 °C by 2100 for the CGCM2, ECHAM4 and MRI models, respectively. Although annual precipitation denotes noticeable inter-annual variations, the CGCM2 and ECHAM4 models show consistent results for the study area. Precipitation is projected to decrease by about 163, 163 and 105 mm over the period of 1990 to 2100 under the A2 scenario of the CGCM2, ECHAM4 and MRI models, respectively. Decreasing rainfall trends in Turkey have already been observed during the 20th century [45].

Further comparisons have been conducted with the CGCM2 and ECHAM4 models. Instead of MRI which is forcing the RCM [38], the projected RCM data were used for further impact studies. A comparison of the GCMs-and RCM-projected and observed monthly temperature and precipitation for

the baseline period in Adana is given in Figure 3. The RCM model compares well with particularly the observed data as the RCM data were corrected based on observational data to avoid bias in the original data. Temperature projections of the ECHAM4 are higher and lower than those of the other models during summer and winter, respectively. Precipitation amount predicted and observed are comparable although some considerable deviations are evident for ECHAM4.

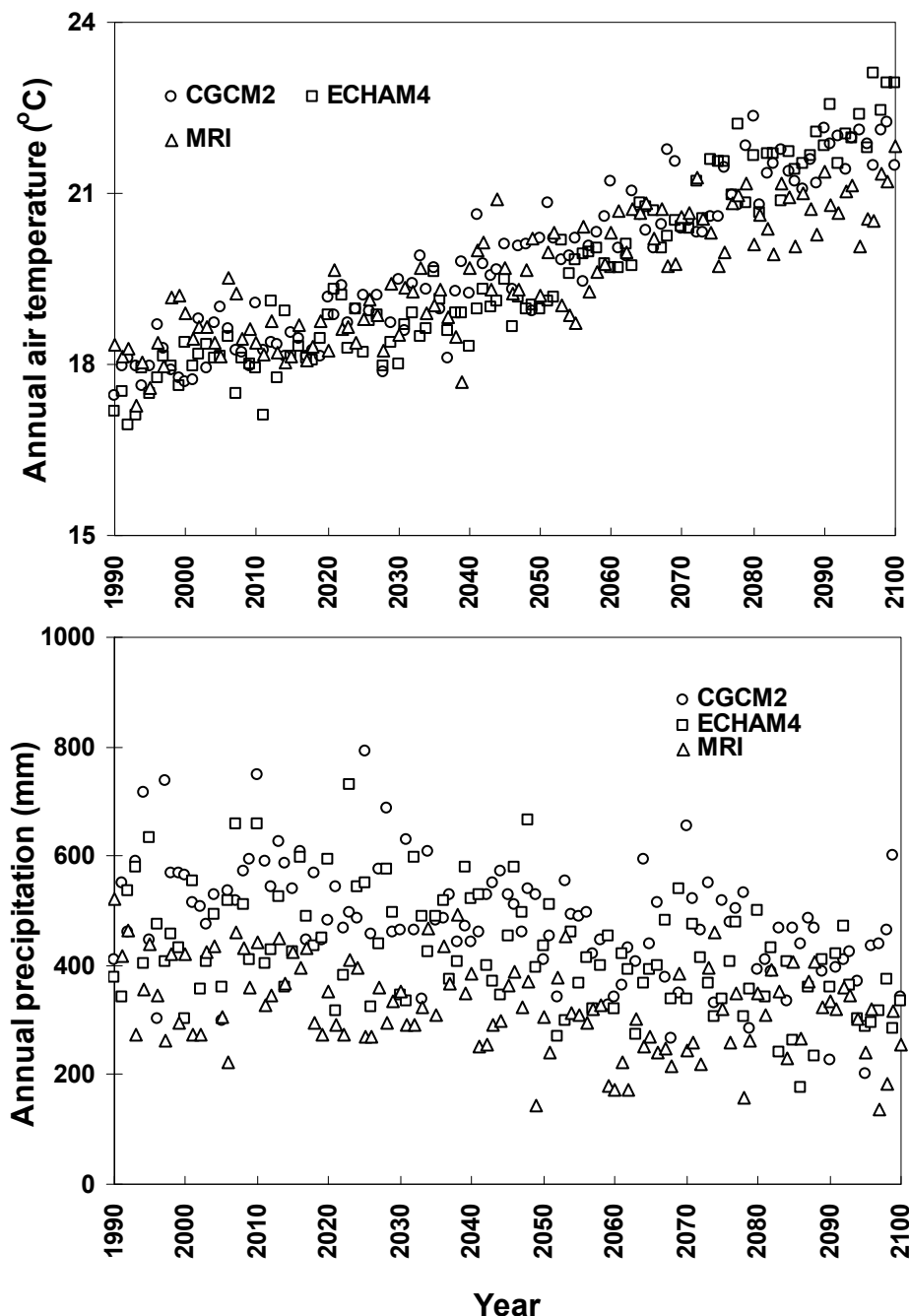


Figure 2. Variations of annual air temperature and precipitation from 1990 to 2100 downscaled for Adana with the CGCM2, ECHAM4 and MRI models.

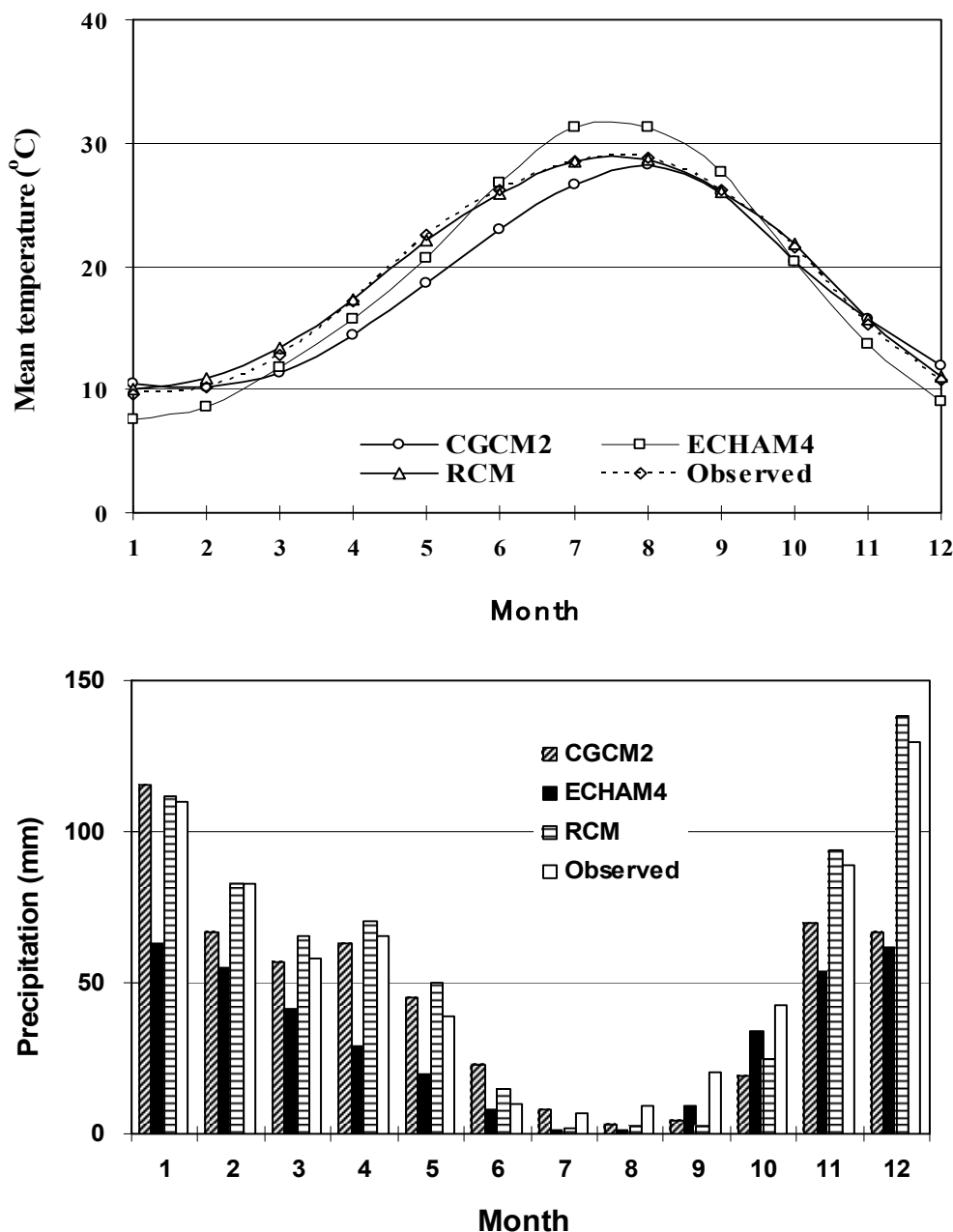


Figure 3. Comparison of monthly mean air temperature / precipitation predicted with the CGCM2, ECHAM4 and RCM models, and observed data for a period of 10 years from 1994.

Monthly air temperature and precipitation predictions for Adana for the future period (2070 to 2079) based on the CGCM2, ECHAM4 and RCM models are depicted in Figure 4. As can be seen, air temperatures predicted by the models are in agreement for most of the months except for the summer months. Generally, precipitation projections of the RCM were lower than those of CGCM2 for the future period. For the A2 scenario of both GCMs, the future projections of temperature rise over the region are 2.7 °C higher than the baseline period. The increase in temperature is projected to be 1.4 °C by the RCM for the same period. Projected mean annual precipitation would decrease by 133, 56, and

306 mm (equivalent to 25, 12 and 46% decrease) according to the CGCM2, ECHAM4 and RCM models, respectively. The discrepancies between the RCM and GCM results can be attributed to the spatial resolutions of the models.

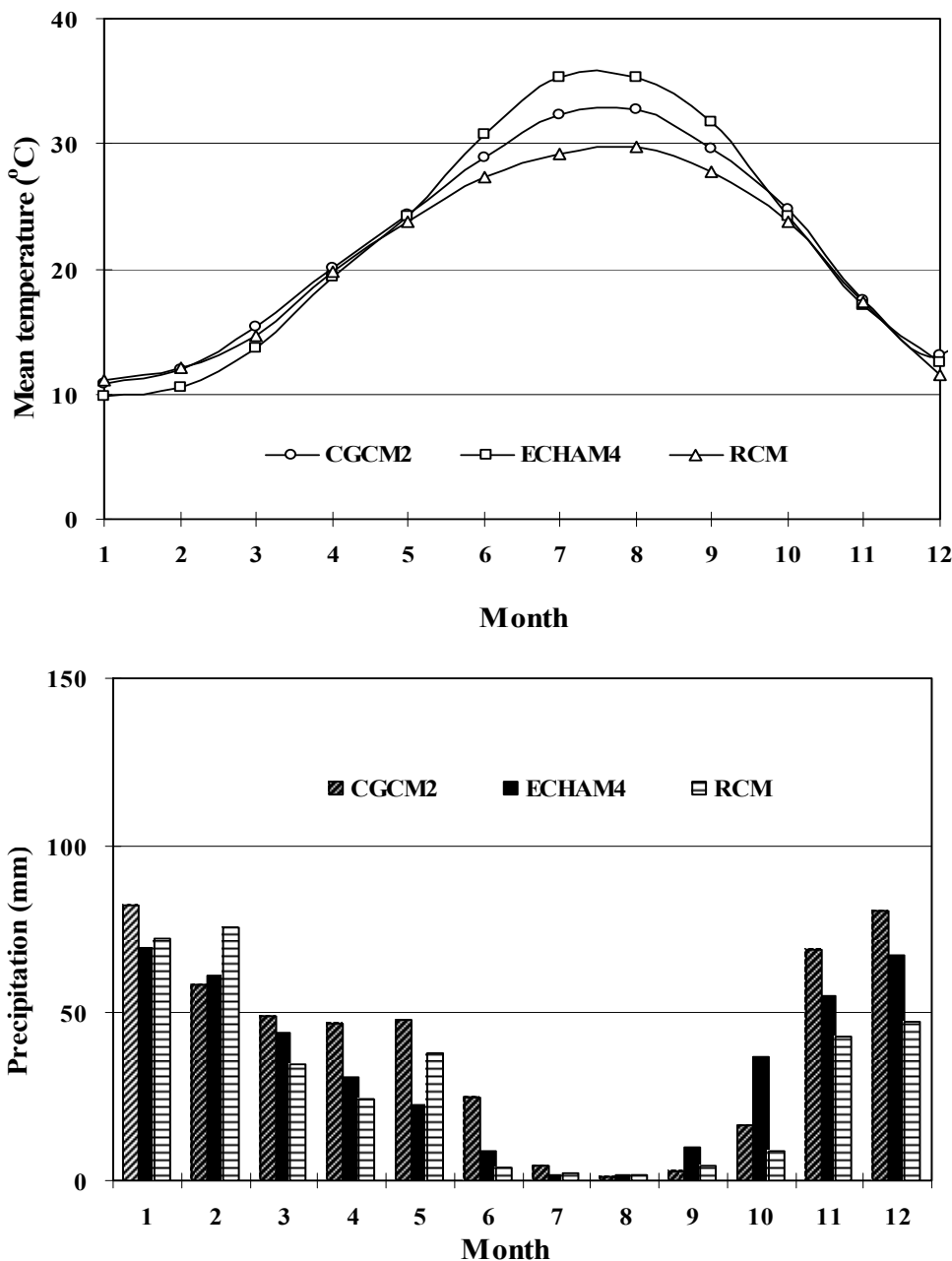


Figure 4. Comparison of monthly air temperature / precipitation created from the CGCM2, ECHAM4 and RCM models for a period of 10 years from 2070.

3.2. Water balance and crop growth

Monthly variations of ETr calculated based on the CGCM2 and RCM data and the observed data are shown in Figure 5. Potential ETr calculated from the different climatic data shows similar monthly variations with air temperature variations. In addition, ETr values predicted from the data of both models are close to those calculated from the observed climate data. Calculated and measured (LAI) as

well as biomass for wheat and maize are compared in Figures 6 and 7, respectively. The biomass values in these Figures are total above-ground biomass. The simulated LAI values of wheat are in agreement with the measured ones although some discrepancies were recognized. However, crop biomass was simulated very well with the SWAP. It is well known that biomass growth is related to LAI and intercepted radiation [30, 46]. LAI and biomass simulations for maize reflected the measurements sufficiently.

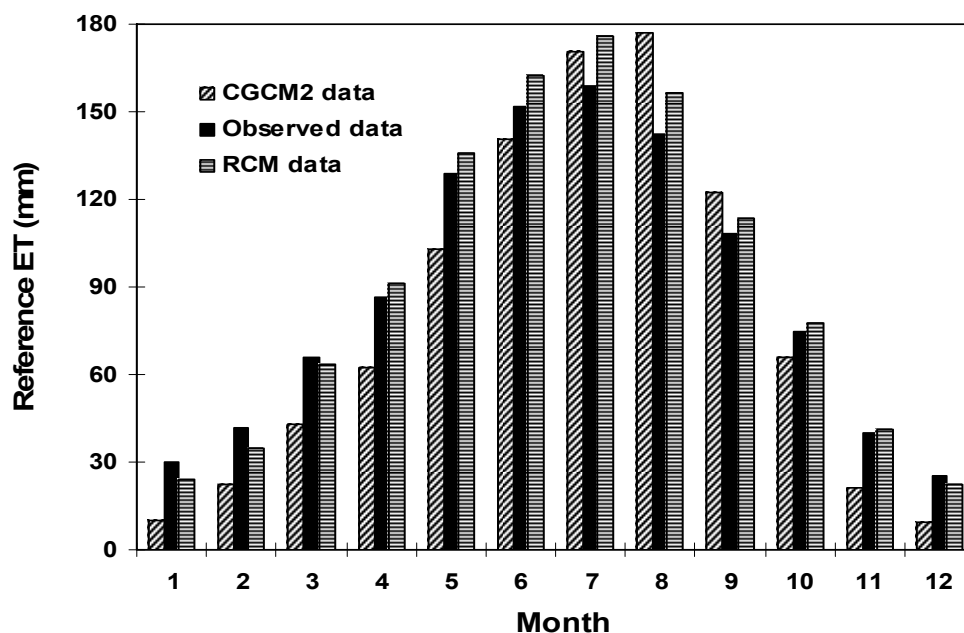


Figure 5. Monthly reference evapotranspiration (ET_r) calculated from CGCM2, RCM and observed climatic data for a period of 10 years from 1994.

The average values and standard deviations of the water balance components for the periods of 1994-2003 and 2070-2079 together with biomass and growing days for wheat and the second crop of maize are given in Tables 1 and 2, respectively. Since the atmospheric CO₂ concentration is supposed to double (even up to 800 ppm) in the late 21st century, calculations were also performed using CGCM2 as well as RCM data for the period of 1994-2003 under a doubling CO₂ concentration (2xCO₂) for comparisons. Also, data produced by Yano et al. [47] using the RCM/CCSR-NIES model are included in both Tables for comparison.

Differences in evapotranspiration from actual crops (ET_a) values under the current CO₂ and 2xCO₂ concentrations over the period of 1994-2003 are negligible for both wheat and maize according to each of the models regardless of higher biomass accumulations. ET_a for the future (2070-2079) decreases compared with the baseline period due to a shorter growing duration following the future temperature rise. Comparison of ET_a values between the current climatic conditions and the future for the CGCM2 and the RCM data shows 28 and 8% decreases for wheat, and 24 and 28% decreases for maize, respectively. Discrepancies in ET_a from wheat between the two climate models may have resulted from changes (24 and 7 days for CGCM2 and RCM, respectively) in the growing duration predicted for the future.

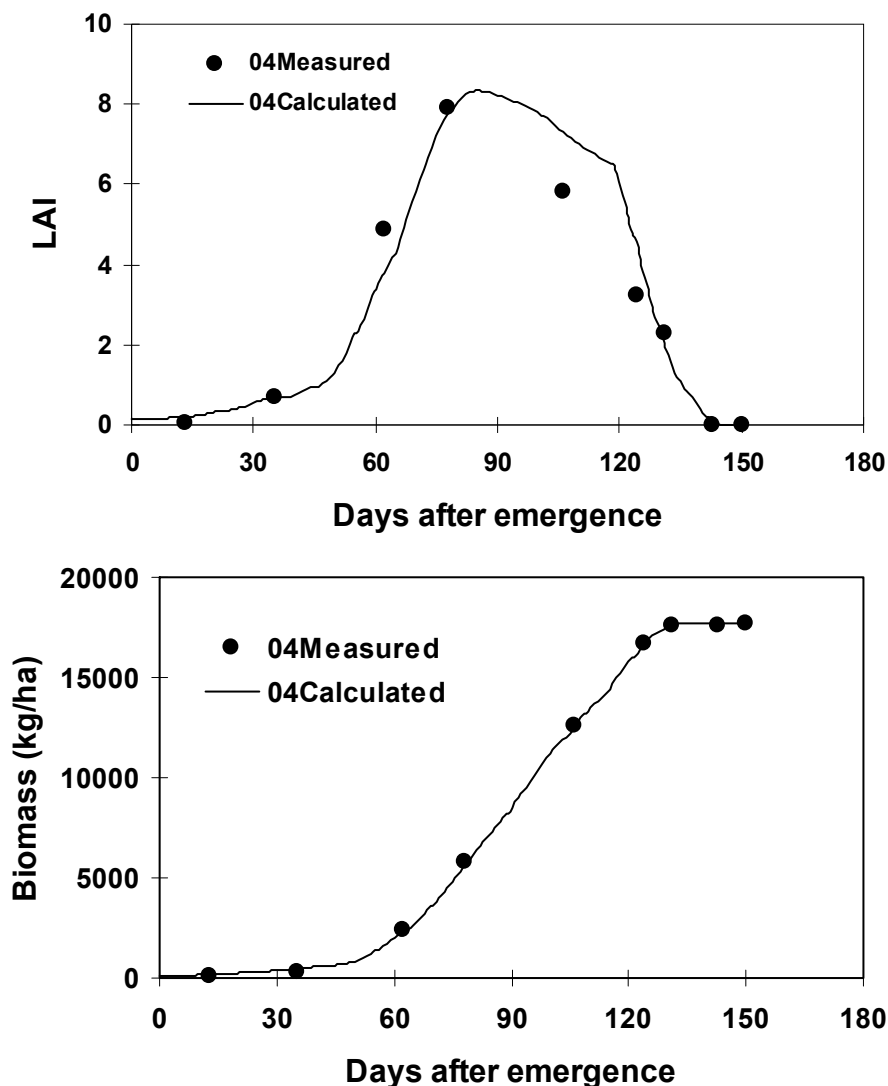


Figure 6. Comparison of calculated and measured leaf area index (LAI), and biomass of wheat.

Air temperature rise results in an increase in evaporative demand of the atmosphere. However, as mentioned above, the decreases in ET_a for both wheat and maize can be attributed to decreases in growing days and LAI due to temperature rise and in transpiration due to stomatal closure regardless of increased evaporative demand. Experimental findings indicating considerable decreases in actual ET due to stomatal closure under elevated CO_2 concentration have received a wide recognition [48]. Elevated atmospheric CO_2 concentration reduces evapotranspiration from both crops in the future due to reduced stomatal conductance, thereby their improving water use efficiency. The interactive effects of the increased temperature and CO_2 concentration on ET_a of the crops differed significantly due to transpiration suppression caused by stomatal closure. With stomatal closure (WSC), ET_a would decrease by 11 and 24% for wheat and maize, respectively, compared to without stomatal closure (NSC) (see NSC and WSC lines in Tables 1 and 2). The outcomes of Yano et al. [47] in both Tables 1 and 2 show similar trends for the combined effects of $2 \times CO_2$ and the increased temperature with stomatal closure on ET_a .

Irrigation water requirements resulted from the CGCM2 and RCM data for wheat in the future are higher compared to the present due to decreases in precipitation. On the contrary, the amount of water for irrigation of the second crop maize is projected to decrease by 15 and 22% according to CGCM2 and RCM, respectively. This finding is opposite to that found by Yano et al. [49] who ignored the effects of transpiration reduction following elevated CO₂ concentration in a study for maize with the MRI projections. Although comparison of climate simulations with site-specific climate data is quite difficult [6, 18], the approach used in this study to predict the future change in water demand is necessary under the present situation.

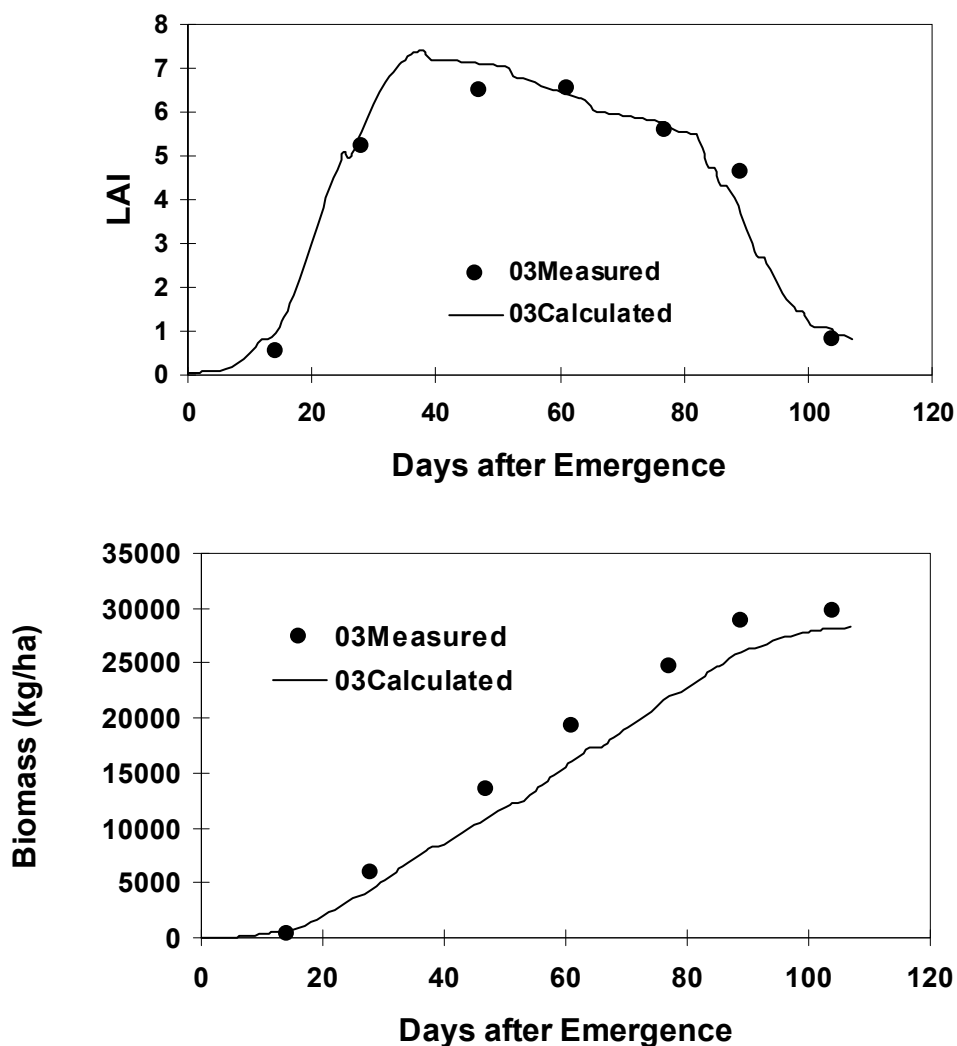


Figure 7. Comparison of calculated and measured leaf area index (LAI), and biomass of maize.

Climate change data of the CGCM2 resulted in a shorter growing season for wheat and maize during the period of 2070-2079 compared to 1994-2003 (see Tables 1 and 2). The duration of the regular growing season for wheat would be 24 days shorter in the future. This change is caused by the projected temperature rise of 2.2 °C during a growing period in the 2070s with the CGCM2 scenario. Duration of growing period becomes shorter by about 9 days for maize, and results in lower biomass and yield in the future with the same model data. The CGCM2 climate change scenario predicted that harvest maturity for winter wheat would be approximately 3 weeks earlier in the 2070s. In other

words, high temperatures accelerate the phenological development of plants, thus resulting in a faster maturation. This may cause a shift in harvest maturity dates for wheat from May to April in nearly three-quarters of this century. In the case of the RCM data, growth duration is 7 and 3 days shorter for wheat and maize, respectively, in the future.

Percent changes in biomass (or grain yield) of wheat and maize predicted by the CGCM2 scenario were less and higher than those predicted by the RCM, respectively. Both models projected higher mean annual temperatures (2.8 and 1.4 °C for the CGCM2 and RCM, respectively) in the future than those in the baseline climate. Thus, the different temperature increases result in different effects on the growing duration and yields. On the other hand, elevated atmospheric CO₂ concentration increases photosynthetic rate. Different changes in photosynthesis rates for wheat and maize also cause different yields. However, in determinate crops such as cereals, grain yield not only depends on photosynthesis but also on the length of the active phase of leaf photosynthesis, and the sink capacity of the grains, as reported by Fuhrer [23].

Wheat biomass and grain yield increase by 17 and 14% for the CGCM2 and by 24 and 27% for the RCM under the conditions of 2xCO₂ concentration and current climate, respectively. When the current CO₂ level is assumed, wheat biomass and grain yield decrease by 24 and 12% due to the effects of the temperature rise of 2.2 °C projected by the CGCM2 for growing period in the future. Similar trends were also found for the RCM (data not shown). The combined effects of 2xCO₂ concentration and increased temperature resulted in a decrease in biomass by 4% and an increase in grain yield by 16% for the CGCM2 in the 2070s. However, biomass and grain yield increased by 38 and 36% for the RCM data, respectively. Air temperature rise for growing period was 1.6 °C according to the latter model data, and the increase in temperature did not have a significant counteracting effect on wheat growth under elevated CO₂. Alexandrov and Hoogenboom [6] reported that all transient GCM climate change scenarios for the 21st century projected a reduction in winter wheat yields across Bulgaria. They also emphasized that when the direct effect of higher CO₂ levels was assumed, all the GCM climate change scenarios projected an increase in winter wheat yield.

Maize biomass and grain yield decreased by 17 and 25% under the CGCM2 scenario and all increased by 3% according to the RCM model, respectively. The opposite findings for the two climate model results are due to the same reason as previously mentioned. Alexandrov and Hoogenboom [6] also found a decrease in simulated maize yield by the end of this century primarily caused by a shorter growing season duration and reduced precipitation in Bulgaria. They reported that the increased CO₂ level alone had a significant impact neither on crop growth nor on development or final yield of maize as a C4 crop.

Brown and Rosenberg [15] simulated the impacts of climate change on the potential productivity of maize and winter wheat in the US. Regardless of the GCM scenarios used, elevated atmospheric CO₂ increased winter wheat yields but maize yields. Although wheat as a C3 crop is positively affected by CO₂- fertilization in terms of photosynthesis, increased temperature may partially compensate it with stomatal closure. In their study, the crops were negatively influenced by the increasing temperature, and yields decreased by as much as 70% below the baseline (1961-1990), when global mean temperatures increased by 5 °C.

Table 1. Predictions by SWAP model for the impacts of projected climate change with risen air temperature (T) and doubling CO₂ concentration (2xCO₂) on water balance and crop growth for wheat.

Climate Model	Period	Factor	Precipitation (mm)	ETa (mm)	Irrigation water demand (mm)	Biomass (ton/ha)	Grain yield (ton/ha)	Growing duration (days)
CGCM2	1994-2003	Control	535.0 ± 186.3	349.2 ± 35.2	0 ± 0	17.5 ± 1.8	5.0 ± 0.9	198.5 ± 7.8
		2xCO ₂	535.0 ± 186.3	331.3 ± 35.0	24.1 ± 47.2	20.5 ± 1.9	5.7 ± 1.0	195.7 ± 8.4
	2070-2079	T	503.6 ± 211.8	280.5 ± 24.2	16.7 ± 37.0	13.2 ± 2.0	4.4 ± 0.6	174.1 ± 6.6
		T+2xCO ₂ (NSC)	503.6 ± 211.8	282.6 ± 24.4	16.6 ± 36.9	16.9 ± 2.0	5.8 ± 0.8	164.4 ± 6.0
		T+2xCO ₂ (WSC)	503.6 ± 211.8	250.9 ± 32.1	16.8 ± 20.0	16.8 ± 2.0	5.8 ± 0.8	174.1 ± 6.6
RCM	1994-2003	Control	597.9 ± 190.1	301.8 ± 30.1	24.8 ± 45.3	16.9 ± 1.7	4.5 ± 0.9	188.1 ± 5.8
		2xCO ₂	597.9 ± 190.1	301.6 ± 29.8	24.1 ± 47.2	20.9 ± 1.8	5.7 ± 1.2	188.3 ± 5.8
	2070-2079	T+2xCO ₂ (NSC)	313.9 ± 82.5	276.6 ± 20.9	68.9 ± 56.8	23.3 ± 0.9	6.1 ± 1.3	181.3 ± 4.1
		T+2xCO ₂ (WSC)	308.0 ± 88.1(§)	252.5 ± 26.7(§)	79.2 ± 88.1(§)	19.0 ± 2.1 (§)	5.6 ± 0.9 (§)	167.6 ± 4.5(§)

(NSC): No Stomatal Closure; (WSC): With Stomatal Closure; (§): Taken from Yano et al. [47] using the data of RCM/CCSR-NIES (with an increase of 2.3 °C in air temperature) for the same area.

Future cereal crop production will depend not only on climate change effects, but also on further developments in technology and crop management [7, 9, 40]. For example, Alexandrov and Hoogenboom [6] suggested that the sowing dates of spring crops could shift under the climate change scenarios in order to reduce yield losses caused by an increase in temperature. Thus, the selection of an earlier sowing date for maize will probably be the appropriate response to offset the negative effect of a potential increase in temperature.

Like most studies on climate change effects on agriculture using crop models [5, 50], this study suffers from several limitations. For instance, the crop model used assumes that nutrients are not limiting. Also, pests are assumed to pose no limitation to crop growth under the climate scenarios. On the other hand, the research and plant breeding studies may mitigate many of the detrimental effects. Due to decadal time studies, limited field experiment, and the large possible range of factorial interactions not tested, simulated quantitative effects with the model should be interpreted cautiously. However, the results would meet our expectations if farmers could continue to grow the same varieties in the same way in the same locations.

Table 2. Predictions by SWAP model for the impacts of projected climate change with risen air temperature (T) and doubling CO₂ concentration (2xCO₂) on water balance and crop growth for maize.

Climate Model	Period	Factor	Precipitation (mm)	ETa (mm)	Irrigation water demand (mm)	Biomass (ton/ha)	Grain yield (ton/ha)	Growing duration (days)
CGCM2	1994 - 2003	Control	47.5 ± 23.8	414.1 ± 26.1	375.5 ± 51.7	27.3 ± 1.5	15.1 ± 1.3	115.9 ± 3.8
		2xCO ₂	47.5 ± 23.8	413.6 ± 28.1	374.1 ± 50.0	28.7 ± 1.6	15.8 ± 1.4	116.0 ± 3.7
	2070- 2079	T	24.9 ± 18.0	393.1 ± 33.9	383.3 ± 44.2	20.4 ± 1.6	10.4 ± 1.1	106.7 ± 0.7
		T+2xCO ₂ (NSC)	24.9 ± 18.0	412.1 ± 30.1	391.0 ± 37.7	21.5 ± 1.4	10.9 ± 1.1	106.7 ± 0.7
		T+2xCO ₂ (WSC)	24.9 ± 18.0	314.0 ± 23.7	318.4 ± 27.6	22.6 ± 1.6	11.4 ± 1.2	106.7 ± 0.7
RCM	1994- 2003	Control	9.8 ± 6.0	439.8 ± 5.8	423.1 ± 7.8	30.1 ± 1.0	16.4 ± 0.9	118.8 ± 2.9
		2xCO ₂	9.8 ± 6.0	442.3 ± 7.1	425.0 ± 23.6	31.6 ± 1.0	17.2 ± 0.9	118.8 ± 2.9
	2070 - 2079	T+2xCO ₂ (WSC)	8.5 ± 8.0	317.6 ± 5.9	331.4 ± 36.0	31.0 ± 1.0	16.9 ± 0.8	115.8 ± 2.8
			10.7 ± 17.1(§)	326.6 ± 5.2(§)	328.2 ± 24.8(§)	29.2 ± 0.8(§)	15.5 ± 0.7(§)	109.8 ± 1.3(§)

(NSC): No Stomatal Closure; (WSC): With Stomatal Closure; (§): Taken from Yano et al. [47] using the data of RCM/CCSR-NIES (with an increase of 2.3 °C in air temperature) for the same area.

4. Conclusions

Precipitation is projected to decrease during the studied periods under the A2 scenario of the three GCMs (CGCM2, ECHAM4 and MRI), and the RCM. All the GCMs projected a temperature increase by 2100 in Çukurova plain of Turkey although the models were slightly inconsistent in their predictions of the seasonal cycles of temperature and precipitation (albeit not ETr) for both control run and scenario simulations. Though the results are clearly not conclusive, they are certainly suggestive for potential impacts of climate change on crop production in Çukurova plain.

In the future, water demand for irrigation of wheat in the Mediterranean environment will increase due to decreasing precipitation. Changes in climatic conditions and CO₂ concentration would result in changes in crop yields. The results show that when the effect of the increases in CO₂ concentration and temperature was considered, both CGCM2 and RCM data projected an increase in wheat grain yield. It is likely that wheat would behave tolerantly under climate change. On the contrary, the CGCM2 data projected a decrease in maize grain yield, and the RCM data a slight increase under the future climate. The future of crop production in the region is vulnerable to changes in air temperature, precipitation

and other climatic variables, and further studies with projections of global and regional climate change models are needed to assess the full range of climate change impacts and adaptation strategies.

The detailed crop growth subroutine of the SWAP model is able to simulate a crop-specific growth pattern and its interaction with environmental conditions. The parameterized crop model should be validated under the different climatic conditions. Elaborate experimental datasets from wheat and second crop maize under a range of environmental conditions are rare but essential for further studies to refine our findings. The combined effects of the increases in CO₂ concentration and air temperature on crop growth response should also be clarified for the other major crops.

Acknowledgements

The research was funded by the Project – Impact of Climate Changes on Agricultural System in the Arid Areas (ICCAP), administered by the Research Institute for Humanity and Nature (RIHN) of Japan, and the Scientific and Technological Research Council of Turkey (TUBITAK). We are grateful to Drs. M. Koc, M. Unlu and C. Barutcular for providing crop and meteorological data.

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