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Modeling the impacts of climate change on wheat yields in Northwestern Turkey

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ABSTRACT

This study investigated the impacts of elevated atmospheric CO_2 concentrations and associated changes in climate on winter wheat yields in northwestern Turkey. The analysis was based on climate change predictions of four global circulation models (GCMs) for three greenhouse gas emission scenarios during three time periods in the 21st century. Climate change predictions by most GCMs used in this study suggested a consistent pattern of increase in the mean growing season air temperature and this increase is more pronounced under the aggressive emission scenario. Growing season precipitation experienced various levels of reduction, although with more variability than air temperature, depending on the model used and the scenario considered. Using these inputs, a mechanistic wheat crop model that successfully simulated contemporary wheat yields as well as the timing of critical growth stages indicated that increased atmospheric CO_2 concentrations in the absence of changing climatic conditions had a slightly positive effect on yields. This was due to both the stimulating function of CO_2 for photosynthesis and the regulatory function of CO_2 that increases water use efficiency. However, these positive effects failed to counteract the significant decline in yields when temperature and precipitation were allowed to vary with increased atmospheric CO_2 concentrations. Under these conditions, winter wheat yields were predicted to decline between 5 and 35 percent, depending on the GCM input used. When multi-model ensemble GCM inputs were considered to reduce inter-model variation, wheat yields were predicted to decline in excess of 20 percent across all emission scenarios and time periods. Further investigation of crop model outputs suggested that the main drivers of reduced yields were a shorter grain filling period caused by rapid plant development and increased water loss through transpiration, exacerbated by a significant decline in precipitation. The combined effects of reduced precipitation and enhanced transpiration in a future climate are particularly important in this semi-arid region, which is already at the limit of rain-fed winter wheat production. This study also points to the urgent need for controlled field- and laboratory-based experiments for temperature, water, and greenhouse gas effects on cereal yields as well as development of cultivars with longer grain filling periods in Turkish environments.

1. Introduction

It is widely accepted that projected climate changes associated with increasing atmospheric concentrations of greenhouse gases will fundamentally alter the magnitude and the seasonal variations of temperature and precipitation patterns in many parts of the globe (IPCC, 2007). What is less known, however, are the impacts this change may have on social and economic sectors that are important to human well-being, such as agricultural production, water availability, and public health (Rosenzweig and Parry, 1994; Tubiello and Ewert, 2002; Tubiello et al., 2007). In particular, climate change impacts on agricultural productivity, defined as the amount of food production over a unit of land area, are critically important as global population increase coincides with diminishing productive land area and water resources.

While a vast amount of research in recent decades has focused on crop productivity under changing climates (e.g. Rosenzweig and Parry, 1994; Ruttan et al., 1994; Fischer et al., 1994; Ortiz et al., 2008), a great deal is still unknown about many regions (Reilly, 1999). It is likely that climate change will improve crop yields in some areas and negatively affect yields in others. These effects will depend on current climatic and soil conditions, the direction of change, and the adaptation strategies used to cope with these changes.

Turkey, with its large agricultural output, is projected to experience a range of climate changes. The country is the world's eighth largest producer of wheat, which is cultivated in diverse physical and climatic regions (FAO, 2010). Climate change is also expected to have varying effects on agriculture, from increased drought

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conditions to warmer temperatures (Ortiz et al., 2008). Modeling studies report generally decreasing trends in crop yields in Turkey (e.g. Özkan and Akçaöz, 2002; Çaldağ and Saylan, 2005). However, despite its significance in the global wheat market, a fast-rising population, and strongly wheat-based diets, the impact of climate change on production has not been extensively studied in Turkey. The research presented here investigates the impact of projected climatic changes on cereal yields in northwestern Turkey, using a dynamic crop model capable of accurately simulating yields. This study is a comprehensive assessment that uses 36 climate change scenario realizations (four models, three emission scenarios, and three time periods).

A number of researchers have examined climate change impacts on wheat production, both in terms of climatic variables and CO_2 effects (see, for example, Fuhrer, 2003 for a comprehensive review). In a series of laboratory experiments, Wheeler et al. (1996) subjected winter wheat to elevated temperatures in heat tunnels along with increased CO_2 concentrations. Their results suggest that grain yield is reduced by warmer temperatures due to shortening of the grain-filling period, but increased by CO_2 enrichment at all temperatures, thanks in part to a change in the partitioning of assimilates to the grain. In a simulation study, El-Shaer et al. (1997) reported potential decreases in yield and water use efficiency for wheat as a result of future climatic variation in Egypt's main agricultural regions. Although the beneficial effects of increased CO_2 and no-cost on-farm adaptation techniques were taken into account, yield losses with a warmer climate were not compensated. Ferris et al. (1998) tested the effects of high temperature on spring wheat under laboratory conditions and concluded that grain fertilization and grain set were most sensitive to the maximum temperature at mid-anthesis. These results confirm that yields would be reduced considerably if high temperature extremes become more frequent, which is a feature of projected climate change in the region. Jamieson et al. (2000) evaluated the predictions of three wheat simulation models, namely AFRCWHEAT2, FASSET, and Sirius, against data from field experiments in which the amount of applied N and the atmospheric CO_2 concentration were both varied. Comparison of simulated and observed results from all models showed that CO_2 affected light use efficiency, whereas N caused variations in green plant area. Amthor (2001), in a comprehensive study, evaluated the effects of CO_2 concentration on wheat yield in various exposure schemes. On average, doubling of CO_2 from 350 ppm to 700 ppm increased yields across all exposure methods. Amthor's results also suggest that modest warming (1–4 °C) generally counteracts the positive effects of CO_2, but the combined effects appear to be highly uncertain. Long et al. (2004) reported on Free-Air CO_2 Enrichment (FACE) experiments, which grow plants subjected to elevated CO_2 under fully open-air field conditions. In general, observed trends in CO_2 effects agreed with similar studies in enclosed environments. However, quantitative differences also emerged that may have important implications for both predicting the future terrestrial biosphere and understanding how crops may need to adapt.

Studies in Turkey have resulted in similar findings as those described above. For example, Özkan and Akçaöz (2002) reported on the importance of temperature at planting, flowering, and harvesting phases for three crops (including wheat) in southern Turkey. Considering the potential impacts of climate change on shifting temperature at these times, this study points to the need for improved climate information delivery to farmers in the region. Çaldağ and Saylan (2005) investigated the effects of climate change on plant growth in Turkey using the Crop Environment Resource Synthesis (CERES) wheat crop growth simulation model. Results indicate that biomass and grain yield showed upward trends due to the combined effects of increased solar radiation, air temperature and CO_2. However, variations in precipitation were negatively correlated with crop yields and biomass accumulation. Kobata (2007) reported generally increasing yields in a changing climate, in the Adana region of Turkey although that study underscores the importance of increased instances of drought as a key factor reducing the potential production. Thus it concludes that the estimation accuracy for precipitation and evaporative demand is critical for the wheat yield more than temperature. Also in Adana, Nakagawa et al. (2007) concluded that a decrease in precipitation by global warming would potentially reduce and destabilize wheat yields, although CO_2 fertilization effects would partly compensate for the negative effect of global warming. Yano et al. (2007), using the results from three general circulation models forced with a single emission scenario, predicted increased wheat yields in Turkey due to: (a) accelerated crop development and shortened growing period that led to reduced biomass accumulation regardless of CO_2-fertilization effect and (b) decreased evaporative demand.

In light of these previous studies, this research focuses on testing the following hypotheses: wheat yields will positively respond to increases in CO_2 but may negatively or positively correlate with decreases in precipitation and increases in air temperature, depending on the timing and amount of change. Moreover, the main reason for yield reduction, if any, under various climate change scenarios will be due to: (1) shortening of vegetation duration through acceleration of the developmental processes and (2) augmentation of respiration rates and assimilate partitioning.

2. Materials and methods

2.1. Study area

The study area is located in northwestern Turkey (centered at 41.5 N and 27.25 E), in a region commonly referred to as *Thrace*, and covers approximately 20,000 km^2 within the Ergene river basin (Fig. 1). The area is surrounded by bodies of water on three sides and is characterized by rolling hills and a broad fertile plateau covered by rainfed cultivation, orchards, grasslands, and forests. The average elevation is 350 m. Since the area is in the transitional zone between the Mediterranean and Black Sea climates, it exhibits the major climatic features of both, with a strong continental influence. Average temperatures range from 3 °C in February to 24 °C in July with a mean annual precipitation of 600 mm and an average of 100 rainy days. There is significant seasonal variation in both precipita-

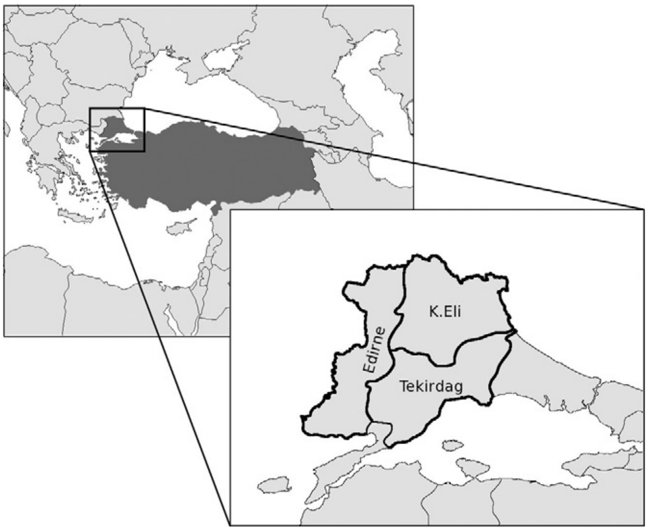

Fig. 1. The location of the study area in NW Turkey. The names of three provinces are provided for reference. K.Eli stands for Kirklareli.

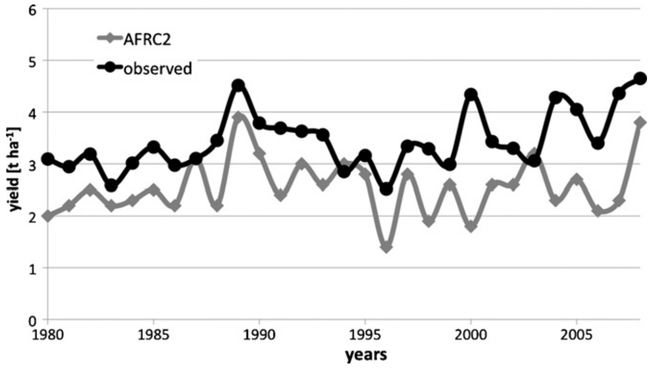

Fig. 2. Comparison between modeled (gray) and observed (black) wheat yields in NW Turkey in the form of a time series plot. The observed data reflects the average yields in the Tekirdag province where the NKU experimental site is located.

tion and temperature, with most precipitation occurring between October and April.

The study area is one of the most productive agricultural regions in Turkey; it accounts for more than 15 percent of the country's annual wheat production on only five percent of Turkey's total arable land. Gentle topography, fertile soils, temperate climate, and moisture availability allow significant production, providing the greatest yields of any region in the country (4.7 ± 0.6 t ha^{-1} [2000–2008 average]). Winter wheat is sown in October/November without irrigation and harvested in June/July, covering a total area of 5400 km^2. Wheat yields show significant year-to-year variability associated with the amount and timing of precipitation and cold or warm stress in critical growth stages. The fields are fertilized at least three times during the growing period.

2.2. Data

2.2.1. Crop yield data

Winter wheat (*Triticum aestivum* L.) crop yield data for the 1981–2008 period were obtained from the Turkish Statistical Institute (TSI) Annual Agricultural Structure and Production Book series (TSI, 2008). Yield data were computed from the ratio of annual production (in metric tons) to the area sown (in hectares) for three provinces, namely Edirne, Kırklareli, and Tekirdağ. For this research, yield data were averaged from all three provinces that had significant climatic overlap and similar soil resources (Fig. 1).

2.2.2. Observed climatic data

Climate data were obtained from the National Climatic Data Center (NCDC, 2010) global summary of day reports for five major meteorological stations located in the study area. Extracted variables included precipitation (mm), air temperature (°C), humidity (hPa), wind speed (m s^{-1}), and solar radiation (W m^{-2}). Missing observations were replaced with data from the National Centers for Environmental Prediction (NCEP) Reanalysis (Kalnay et al., 1996) using the grid box that covered the study region. Except for precipitation, a strong correlation was observed between the NCDC station-level observations and the NCEP gridded data (correlation coefficient of 0.84). The correlation for precipitation was less than for other variables and also displayed a 100 mm positive bias in the NCEP Reanalysis data. Nevertheless, the missing observations amounted to less than five percent of the total, so the results were not significantly affected by this bias.

Twenty-eight years [1981–2008] of daily observations from the augmented NDCD dataset, averaged over the entire study area, were used to drive the wheat simulation model for calibration (Fig. 2). A longer time series of daily observations [1961–2008] from the same dataset were additionally used to generate the parameters for the scenario files to be used in the LARS-WG weather generator. The purpose of this simulation experiment was to characterize the variation in local weather conditions (mean and standard deviation for temperature, precipitation, and radiation) that is essential to generate future weather projections.

2.2.3. Climate change scenarios

The climate change scenarios were constructed from the output of four models obtained from the World Climate Research Program's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) (Meehl et al., 2007). The models included: CSIRO Mk3.5 [192 × 96 grids] (Gordon et al., 2002); NCAR CCSM3 [256 × 128 grids] (Collins et al., 2006); UKMO HadCM3 [96 × 73 grids] (Pope et al., 2000); and GFDL CM2.1 [144 × 90 grids] (Delworth et al., 2006). These models were chosen because their response to greenhouse forcing in the region were divergent thus providing the opportunity to capture inherent model-based variation. Variables required by the wheat simulation model were extracted from each model for the grid box most closely aligned with the study area without spatial downscaling. Note that the selected grid boxes occupied slightly different areas and locations across models due to different projection characteristics of each model's grid layout. However, both the control and future climate scenario simulations were compared at the same spatial resolution and location for each model without any spatial downscaling (Arnell et al., 2003). Monthly data from the control and future integrations of each model run were used to calculate the parameters of scenario files to be used in a probabilistic weather generator (see below). These included monthly changes in precipitation intensities (in relative units), changes in duration of wet and dry spells, changes in monthly temperature means (in absolute terms), and changes in monthly mean radiation (in absolute terms). These changes were then applied to the site parameters previously calculated from the observed daily data at each site using LARS-WG (Semenov and Barrow, 1997). The purpose of this weather generator-based approach was to obtain daily values of weather variables required by the wheat model in a future climate, while at the same time, preserving the statistical structure of each variable.

The LARS-WG stochastic weather generator produces a suite of climate variables conditioned on whether the day is wet or dry (i.e. precipitation). The simulation of precipitation occurrence is based on distributions of the length of the series of wet and dry days. Consideration of prolonged dry series is particularly attractive in agricultural studies since long droughts significantly affect crop growth and can dramatically decrease yields (Semenov and Barrow, 1997). The distributions of the other weather variables, e.g. maximum and minimum temperature and solar radiation, are considered to be stochastic processes with daily means and standard deviations conditioned on the wet and dry series (Semenov et al., 1998).

Using monthly deviations from baseline observations, LARS-WG generated 100 years of synthetic daily weather data under a series of future climate scenarios by perturbing historical climate data based on the parameters obtained from the historical observations. For the climate change impact assessment, four time periods were considered: 1961–1990 (baseline), 2021–2040 (2030s), 2041–2060 (2050s), and 2061–2080 (2070s). Note that while the wheat model input data for the baseline period remained the same across all periods and all experiments, new weather data series were generated for each run in each time period as well as for each emission scenario.

For emission scenarios, three storylines (IPCC, 2000) were selected from the Special Report on Emission Scenarios (SRES). Each storyline describes a different world evolving through the 21st century, with different demographic, economic, technological, and land-use forces leading to different greenhouse gas emission

Table 1
Atmospheric CO_2 concentrations under different IPCC SRES storylines (climate change scenarios) across a range of model years. The values in the table are parts per million (ppm) equivalent and were obtained from IPCC (2007).

	1995	2030	2050	2070
Baseline	380	–	–	–
B1	–	435	485	520
A1B	–	460	535	615
A2	–	460	535	635

trajectories. The story lines included in this research range from *low-impact* (B1) to *medium-impact* (A1B) to *high-impact* (A2) development. The B1 scenario describes a convergent world (where developing and developed nations converge) with rapid changes in economic structures, reductions in the intensity of material usage, and introduction of clean technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improving equity, but without additional climate change policies. The A1B storyline occurs in a world with very rapid economic growth, a global population that peaks at mid-century, and rapid introduction of new and more efficient technologies along with an energy system balanced across all sources. The A2 storyline, in contrast, describes a differentiated world. Economic development is primarily regional, and technological changes are more fragmented in a world of self-reliance and continuously increasing population. These SRES scenarios and their associated atmospheric CO_2 concentrations are provided in Table 1.

2.3. AFRC2 model and parameters

2.3.1. Model description

The purpose of this research was to estimate the potential impacts of climate change on wheat yields. Dynamic process-based crop models are ideal tools for this task, as they allow evaluation of agronomic processes such as water stress and crop phenology in detail. Crop models are also useful for assessing potential adaptation strategies to climate change (Rosenzweig and Parry, 1994). In this research, a computer model (AFRC2) for wheat crop development was used to evaluate the effect of changes in climatic variability on crop yields. The AFRC2 model simulates the phenological development of wheat by splitting the crop's lifecycle into eight phases (Porter, 1983; Porter, 1993; Weir et al., 1984). The weather variables required to drive the model are the daily minimum and maximum air temperature, daily averaged wet- and dry-bulb temperatures, daily precipitation, and daily net short-wave radiation. Given a specific location and daily weather inputs, the model calculates the dates of crop developmental stages including emergence, floral initiation, anthesis, and the grain-filling period. These estimates are based on total thermal time (in °C), modified by factors that affect the response to photoperiod and vernalization requirements of different varieties (Porter and Gawith, 1999; Miglietta and Porter, 1992). The phenological development module simulates tiller and leaf production, sequentially building a canopy made up of photosynthesizing leaves and ear-bearing shoots. The modeled cycle of leaf production, growth, and senescence continues until the expansion of flag leaves, after which the green leaf area declines steadily (Hay and Porter, 2006). The AFRC2 model has been extensively validated in the UK and other countries and is often used in simulating effects of climate change on wheat (Laurila, 1995; Ewert et al., 2002).

An important feature of the AFRC2 model is its population-based approach to tillering and canopy development that results in vertically-stratified age structure with associated physiological properties, such as rates of photosynthesis (Porter, 1984). In other words, at any given time, the canopy is composed of a population of leaves and shoots that have different birth, duration, and senescence times as cohorts.

Table 2
The timing of observed and modeled critical growth stages of wheat in NW Turkey. The numbers indicate the day of year when each critical phase occurs. The observed data comes from the NKU experimental site [located at 40.98 N, 27.55 E] for both years. For this comparison, the AFRC2 model was run with meteorological conditions observed at a closest station (approximately 10 km away).

	2007		2008	
	Observed	Modeled	Observed	Modeled
Sowing	324	324	311	311
Emergence	333	335	315	323
Double ridges	97	98	87	89
Begin ear growth	130	125	122	115
Anthesis	135	134	129	130
Begin grain fill	138	137	133	136
End grain fill	156	164	159	164
Maturity	167	168	176	170

The water limitation to growth in AFRC2 is modeled by a water stress factor estimated from the ratio of soil water supply to plant water demand. The stress factor begins to reduce the potential rates of leaf expansion and biomass accumulation when evapotranspiration demand exceeds twice the amount of root extractable soil water. At more severe levels of water stress, other processes such as the rate of CO_2 assimilation and partitioning are also affected.

The effects of nitrogen limitation occur as soon as crop nitrogen concentration per unit dry matter produced falls below a specified upper limit (Hay and Porter, 2006). The demand for crop nitrogen is calculated from the difference between the concentration levels at the current crop development stage and their maximum value (Hay and Porter, 2006). For example, the maximum value of demand for nitrogen by grain is set at 1.7 mg N grain^{-1} °C day (Vos, 1981). Note that neither water nor nitrogen limitation affects phenological stage development (Hay and Porter, 2006).

2.3.2. Model calibration

The AFRC2 model was calibrated for a generic variety of winter wheat cultivated in northwestern Turkey using multi-year yield observations from the region. The model was run at a research site located in the middle of the Tekirdag province, close to the experimental wheat plot located at the Namik Kemal University (NKU) (located at 40.98 N, 27.55 E). For the rest of this paper, this research site is considered to be representative of the conditions of the entire study domain, including the other two provinces. While phenological data from the NKU experimental farm was used to assess the model performance in Table 2, there was no weather data available from this particular location. Therefore, the model was run with climate data obtained from the closest meteorological station, approximately 10 km away.

Reported grain yield (in t ha^{-1}) was used as an aggregate measure of model performance. The adaptation of the AFRC2 model for simulating a generic wheat variety from Turkey was achieved by adjusting the thermal time requirements between different development stages as well as vernalization and optimum photoperiod requirements (e.g. Weir et al., 1984) while keeping the sowing date constant (November 6 or day 310). A constant sowing date was used represent average sowing time for wheat in the region. These adjustments were conducted on a trial and error basis until the best match between modeled and observed grain yields was achieved.

Another form of model calibration was made with the help of timing of critical phases in wheat plant's growth cycle. To test the ability of the AFRC2 model to simulate the growth stages critical for determining final grain yield, modeled date of occurrence of several growth phases were compared to those obtained from the NKU experimental wheat farm. The observed growth stages

Table 3
Comparison of observed wheat yield to estimates from the AFRC2 model under contemporary climate conditions. The variables used in comparison and their description and formulas are also provided.

Statistic	Value	Description
N	29	Number of samples
$\overline{\text{mod}}$	2.59	Mean modeled wheat yield [t ha^{-1}]
$\overline{obs}$	3.19	Mean observed wheat yield [t ha^{-1}]
S_{mod}	0.55	Standard deviation of modeled wheat yield [t ha^{-1}]
S_{obs}	0.52	Standard deviation of observed wheat yield [t ha^{-1}]
MAE	0.74	Mean absolute error $\frac{1}{N}\sum_{i=1}^{n}\left\lvert \text{mod}_i - obs_i \right\rvert$
$RMSE$	0.87	Root mean squared error $\left[N^{-1}\sum_{i=1}^{n}(\text{mod}_i - obs_i)^2\right]^{0.5}$
$RMSE_S$	0.83	Systematic RMSE $\left[N^{-1}\sum_{i=1}^{n}(\overline{\text{mod}}_i - obs_i)^2\right]^{0.5}$
$RMSE_U$	0.52	Unsystematic RMSE $\left[N^{-1}\sum_{i=1}^{n}(\text{mod}_i - \overline{\text{mod}}_i)^2\right]^{0.5}$
d	0.54	Index of agreement $d = 1.0 - \left[\frac{\sum_{i=1}^{n}(\text{mod}_i - obs_i)^2}{\sum_{i=1}^{n}\left(\left\lvert \text{mod}_i - \overline{obs}\right\rvert + \left\lvert obs_i - \overline{obs}\right\rvert\right)^2}\right]$

included emergence, double ridges, beginning of ear growth, anthesis, beginning of grain filling period, end of grain filling period, and physiological maturity. Observations were available for both 2007 and 2008.

2.3.3. Experiments

Multiple experiments were conducted using both observed and future climate data. For each experiment, the generic variety, sowing date, and sowing density (300 seeds m^{-2}) were kept constant. The first experiment was designed to simulate contemporary winter wheat yields using 28-year (1981–2008) weather observations. The results of this experiment were used to assess AFRC2 model performance and to determine the baseline wheat yield from which any increases or decreases due to climate change could be estimated. For quantitative comparison between simulated and observed values, the correlation coefficient (r), mean absolute error (MAE), root mean square error ($RMSE$), and the index of agreement (d) were estimated (Willmott, 1981). These statistics are provided in Table 3 along with the equations used. The index of agreement is a measure of relative error in model estimates. It is a dimensionless number between 0.0 and 1.0, where 0.0 describes complete disagreement between estimated and observed values, and 1.0 indicates that the simulated and observed values are identical. The index of agreement is included because the correlation coefficient (r) cannot account for additive differences or differences in proportionality (Willmott, 1981). Nevertheless, r (measure of covariability between observed and modeled values) and $RMSE$ (measure of average difference between observed and modeled values) statistics are also included because they describe different components of model error indicated by d. Note that while the contemporary climate experiments were initially conducted for 28 years, the baseline wheat yield value from which future change was determined was estimated from the last ten years only [1998–2007].

In future climate scenarios, the effects of CO_2 increases were isolated from predicted changes in climate variables, mainly precipitation and temperature with the help of two separate experiments: CO_2 only scenario *and* CO_2 + climate change scenario. The effects of CO_2 increases were separated from those of climate because a number of previous studies have shown the opposing effects of these two agents (e.g. Batts et al., 1997; Jamieson et al., 2000; Amthor, 2001). For the CO_2-only experiment, the ambient atmospheric CO_2 was changed to the values predicted under the three SRES climate change scenarios (Table 1). For this experiment, the AFRC2 model was run with ten years (1998–2007) of observed climate data twice, first using contemporary CO_2 concentrations set to 385 ppm and then using future CO_2 concentrations. Note that the CO_2-only experiment does not necessarily represent a possible future outcome because the SRES scenarios inherently include changes in atmospheric CO_2 concentrations in association with changes in climatic variables. However, this experiment was conducted to isolate the often-reported opposing effects of CO_2 increases and climatic change.

For the CO_2+climate change experiments, the AFRC2 model was run with 36 inputs (four climate models, three emission scenarios, and three time periods) but this time, the climatic variables important for wheat growth were allowed to vary the ambient atmospheric CO_2 concentration values predicted by the IPCC (2007). For each of the 36 inputs, the AFRC2 model was run 100 times with 100 different realizations of future climatic conditions as predicted by the LARS-WG weather generator. The wheat yield results were then averaged for these runs and compared to baseline conditions in the form of relative deviation.

3. Results

3.1. Model validation

The first set of results concerns the ability of the AFRC2 model to simulate wheat growth in northwestern Turkey. To this end, a comparison was made between observed and modeled yields in the form of a time-series plot between 1981 and 2008 (Fig. 2). This plot compares average observed wheat yields from all three provinces to the AFRC2 model results obtained at the NKU site using closest climatic inputs. For most years, the modeled yield representing the entire study area compared well to the province-averaged observed yields. However, there is a large year-to-year variation in how well modeled yields match observations; in certain years (e.g. 1989 and 1996) the predicted wheat yields are well-matched with reported yields, while in other years (e.g. 1994, 2000, and 2004), there is a large mismatch (greater than 100 percent difference) between modeled and observed values. Quantitatively, the fit between observed and modeled values is intermediate, as indicated by a large *MAE* [0.74] and *RMSE* [0.87], and intermediate *d* [0.54] and *r* [0.7 after removing two outliers to improve correlation] (Table 3). To further assess whether the bias of modeled yields versus observed yields was statistically significant, the model outputs were analyzed for lack of fit with the observed data. The strength of this approach over more traditional goodness-of-fit statistics such as the r and RMSE is that it considers multiple observed values and differing numbers of observed values in a temporal series. The calculated F value (4.95), which was not significant, suggests that there is no statistical evidence statistical similarity between modeled and observed wheat yields.

Another important observation from Fig. 2 concerns the differences in inter-annual variability. The AFRC2 model predicts large swings in yields on an inter-annual basis, associated with different climatic conditions each year. The observed yields, on the other hand, show much less year-to-year variation, and in some cases (e.g. year 2000) an opposite direction of change.

While these limitations and the results of the goodness-of-fit tests suggest that the AFRC2 model did not always perform well (and further adjustments of thermal time requirements of the model did not improve these results), the current model was retained and used to predict yield response to climate change since it was the best available tool to predict wheat yields under NW

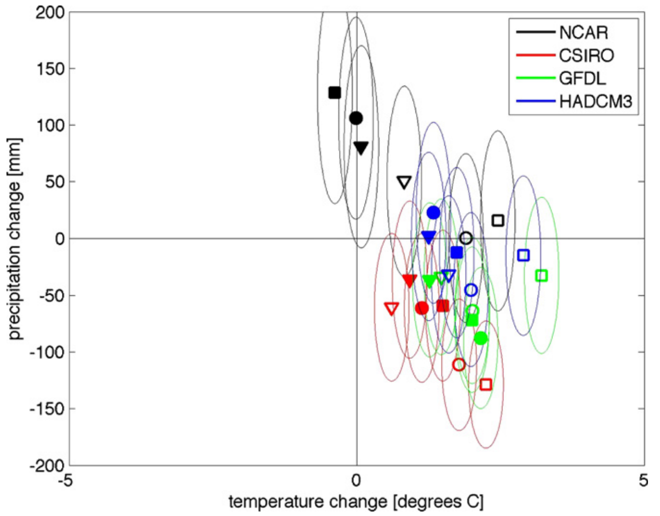

Fig. 3. Changes in growing season (October 15–June 15) temperature and precipitation predicted by four global circulation models in three time periods for the B1 (filled markers) and A2 (open markers) SRES emission scenarios. The time periods are 2030 (triangles), 2050 (circles), and 2070 (squares). Both the temperature and precipitation change was computed as the difference between future (climate change) and baseline (1961–1990) conditions. Positive values indicate increases in both variables from the baseline while negative numbers indicate reduction. The ellipse around each marker represents the variation in the form of one standard deviation.

Turkey conditions. Furthermore, this study was mainly concerned with understanding relative changes in yields under climate change from baseline conditions, and thus erroneous model results from these calibration experiments may not be important. A similar amount of error was expected in the climate change experiments, which may cancel out any model uncertainty.

3.2. Simulation of key phenological stages

Accurate prediction of key physiological stages of a wheat crop throughout the growing season are essential to model yields at the end of the season. To test the ability of the AFRC2 model to simulate the critical growth phases that affect final grain yield, modeled date of occurrence of several key growth stages were compared to the NKU dataset (Table 2). In general, there is a strong agreement between modeled and observed dates of various growth stages, including double ridges, anthesis, and maturity. For example, the day of anthesis, as an important predictor of green leaf area development, was modeled to be on day 134 compared to the observed anthesis day of 135 in 2007. Similar one-day difference was also observed in 2008.

3.3. Expected changes in climatic variables

The deviations from average climatic conditions of the 20th century (1961–1990) predicted by the four climate models under two climate change scenarios (B1 and A2) for three time periods are provided as a temperature-precipitation cross-plot in Fig. 3. Each marker in the figure represents averaged conditions for the growing season (October 15th–May 31st). Both the temperature and precipitation changes were computed as absolute differences (in °C for temperature and in mm season^{-1} for precipitation, respectively) between climate change and baseline (1961–1990) conditions. Positive values indicate increases from the baseline while negative numbers indicate reduction from baseline conditions for both variables.

The mean growing season air temperatures show a consistent pattern of change. Except for the NCAR model under the 2070 conditions, all models predict a 1–4 °C warming across all time periods. All models also suggest consistent increases from year 2030 to 2070, regardless of the emission scenario. In contrast to other models, the NCAR model predicts no net change or cooler temperatures (by as much as 0.5 °C) under the B1 scenario, but shifts to warming under the A2 scenario.

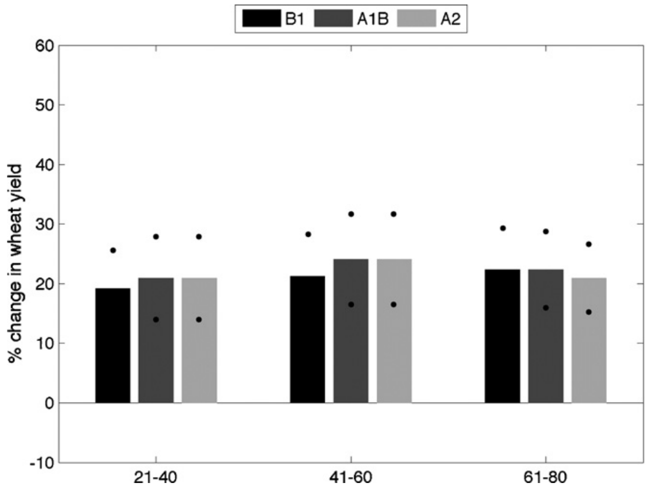

Fig. 4. Relative changes in winter wheat yields in three time periods as a result of increases in atmospheric CO_2 concentrations. The time periods are 2030 (21–40), 2050 (41–60), and 2070 (61–80). For each time period, each bar represents a different CO_2 concentration under different IPCC SRES emission scenarios that are provided in Table 1. The dots represent the variation in yield change in the form of one standard deviation as a result of changes in CO_2 concentrations across multiple iterations of the wheat model.

With respect to precipitation, all models except the NCAR model suggest various levels of reduction, under all scenarios and all time periods. The NCAR model predicts a 0–20 percent increase in precipitation when compared to the baseline conditions; this increase is larger under the B1 scenario but much smaller or negligible under the A2 scenario. In general, precipitation change from the baseline conditions is larger, by as much as 25 percent, under the A2 scenario than the B1 scenario across all models.

3.4. Wheat yield results under the CO_2-only scenario

Experiments that considered only the increases in CO_2 concentrations revealed moderate increases under all scenarios for all time periods (Fig. 4). For example, wheat yields in the year 2030 are expected to increase eight to nine percent depending on the emission scenario. Under the low-impact (B1) emissions, yield increases are lower than those under the A1B and the A2 scenario-related CO_2 concentrations. In year 2050, the discrepancy is larger, ranging from 10 to 13 percent between the low CO_2 (B1) and moderate to high CO_2 scenarios. This linear increase, however, breaks down as atmospheric CO_2 concentrations are pushed above 615 ppm (as would be in the case of the A1B and the A2 in 2070). For the B1 scenario, this decline in wheat yield increase was not observed, indicating a possible threshold for CO_2-related increases, at least as modeled by the AFRC2 model. Based on this observation, it is possible that further increases in atmospheric CO_2 concentrations beyond year 2070 as predicted by the A1B and the A2 emission scenarios would likely have a positive – albeit reduced – effect, or possibly a negative effect on wheat yields.

Results reveal that crop water loss through transpiration is negatively affected by increased CO_2 concentrations (Fig. 5). However, transpiration results do not follow the same pattern of yield increases in an elevated CO_2 world. For example, there is an inverse relationship between ambient CO_2 concentrations and transpiration. The largest gains in water use efficiency (as much as 3

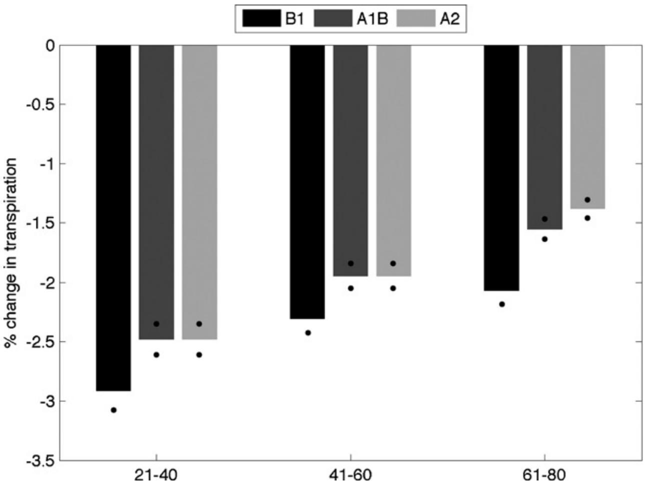

Fig. 5. Relative changes in growing season transpiration in three time periods as a result of increases in atmospheric CO_2 concentrations. The time periods are 2030 (21–40), 2050 (41–60), and 2070 (61–80). For each time period, each bar represents a different CO_2 concentration under different IPCC SRES emission scenarios that are provided in Table 1. The dots represent the variation in transpiration change in the form of one standard deviation as a result of changes in CO_2 concentrations across multiple iterations of the wheat model.

percent) occur under the B1, low-impact scenario ca. 2030, but in all subsequent periods (2050 and 2070), the relative decrease in transpiration amounts is lower. There is less of a decline in transpiration rates across different CO_2 concentrations, with the lowest gains occurring in 2070 under A2.

3.5. Wheat yield results under the CO_2 + climate change scenario

When changes in ambient CO_2 concentrations are combined with associated changes in climatic variables, the modeled wheat yields across all models, emission scenarios, and time periods are consistently lower than the baseline values. However, these reductions occur differently across models and time periods (Fig. 6). For example, the AFRC2 model results using the GFDL GCM output (upper left panel, Fig. 6) suggest the smallest decline (less than 5 percent) in yields, but this decrease occurs more frequently under the B1 scenario in 2030. The results in 2050 show a similar trend under the same low impact scenario. In 2070, however, the reduction in yield is very small across all climate change scenarios.

When the CSIRO-derived climate variables are used in the AFRC2 model, yields show a considerable decline, as much as 28 percent, from the baseline (upper right panel, Fig. 6). There appears to be an equivalent decline in both 2030 and 2050 (about 20 percent) across all emission scenarios. In 2070 the largest decline occurs under the medium-impact (A1B) scenario, but not under B1 and A2. With the HADCM3 outputs, yields show similar reductions to the CSIRO-derived estimates, but at a lower rate across all scenarios ca. 2050.

The largest decline in winter wheat yields occurs when the AFRC2 model is forced with variables from the NCAR climate model (lower right panel, Fig. 6). The reduction is considerable (as much as 25 percent) but also consistent across all years, and there are no major differences across emission scenarios.

These results suggest that the effect of changing temperature and precipitation patterns coupled with CO_2 increases have important consequences for wheat production in northwestern Turkey. One mechanism through which climate change, and temperature in particular, affect grain yields is by changing the number of growing degree days required for specific plant development phases. When modeled days of anthesis under future climate were compared to the baseline conditions, there was evidence for accelerated development, manifested by anthesis occurring up to two weeks earlier (Fig. 7). This earlier development is consistent across all models and shows a linear increase with increased emission scenarios, from less than five days under B1 to as many as 15 days under A2. Assuming that this earlier anthesis is paralleled by a shorter grain-filling period, the accelerated development of wheat plants due to climate change partially explains the reduction in yields in the study area.

Average yields of cereal crops under water-limited conditions, such as in northwestern Turkey, are also determined by crop water use and water-use efficiency. All climate models under all scenarios suggest dramatic increases in temperatures, coupled with a steady decline in precipitation in the region, especially later in the 21st century. Analysis using all models and emissions scenarios suggests that crop transpiration (as well as soil evaporation) could increase by as much as 10 percent in a future climate (Fig. 8). While there are significant differences across models and emissions scenarios, the results indicate increased growing season evapotranspiration, suggesting lower water use efficiency in the future. When viewed in parallel with modeled reduction in wheat yields, this decline in water use efficiency coupled with increasingly limited interception losses is likely to drive the changes predicted here.

Given model-derived variability in predicting climate variables important for crop production studies, the question arises as to which models or strategies should be used to distill information to be of use to stakeholders. Clearly, the magnitude of the change depends to a large extent on the model and the scenario used, due to the substantial differences in predicted climatic variables between the individual models and scenarios. One common approach to account for inter-model differences is to average all models. This approach, commonly referred to as a multi-model ensemble, is suggested because the procedure weights models that provide poor outcomes with those that provide better results in simulating a region. Using this approach, the changes in yields as well as the changes in the anthesis day and growing season transpiration were re-examined. A multi-model ensemble climate forcing dataset was generated as an input to the AFRC2 model using averaged results across all climate models in this study, Ensemble results suggest a significant reduction in yields, as much as 20 percent under all emission scenarios in both the 2030 and 2050 time periods. In 2070, the magnitude of the decline is similar to earlier periods. But the decline is positively correlated with the emission scenarios considered (Fig. 9 left panel).

As with individual model outcomes, predicted changes in anthesis day and growing season transpiration from the ensemble approach reveal a linear but opposite direction of change for both variables (Fig. 9 center and right panels). As the climate warms in the 21st century, the day of anthesis occurs earlier in response to rapid plant development, showing small changes (about 5 days) under the B1 scenario and larger changes (up to 12 days earlier) under both the A1B and A2 scenarios. Growing season transpiration increases, because of the expected increases in evaporation in a warmer (and drier) climate.

4. Discussion

In this research, the effects of climate change on future wheat yields in northwestern Turkey were assessed using the AFRC2 wheat simulation model. Inevitably, the approach adapted in this study linking a crop model with climate model results has several limitations. For example, with respect to the climate change predictions, this study only considered the means of the regional climate system, but did not assess changes in its variability. While the LARS-WG framework allows for some random variation in day-to-day weather events, the true variability, including climatic extremes, is not captured. Work on the sensitivity of crop models to changes

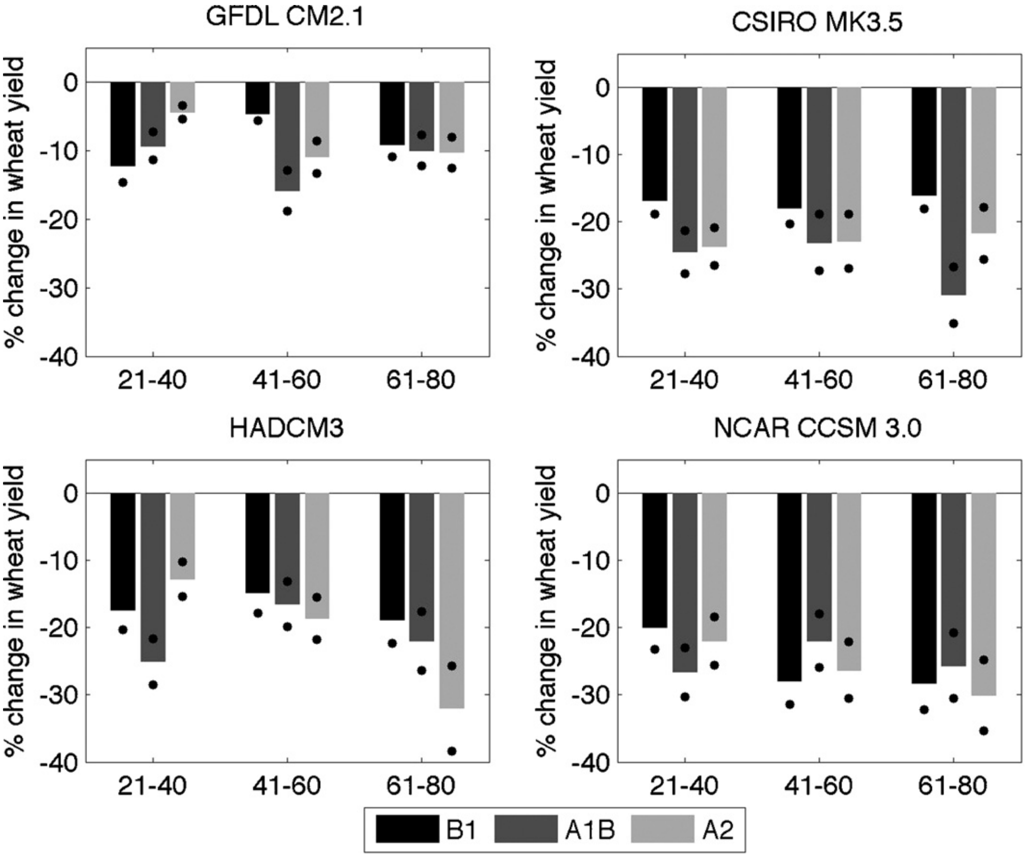

Fig. 6. Relative changes in wheat yields under three different climate change scenarios predicted by four different climate models for the 2021–2040, 2041–2060, and 2061–2080 periods. The name of the climate model in question is provided on top of each panel. The dots represent the variation in relative yield change in the form of one standard deviation as a result of changes in climate across multiple iterations of the wheat model.

in the frequency and magnitude of extreme weather events suggests that droughts and hot or cold spells can have important consequences for crop production (e.g. Porter and Semenov, 1999; Rosenzweig et al., 2001; Collier et al., 2008). The "average" predicted changes in future yields presented in this study are thus likely to significantly under- or over-estimate future cereal yields. For this reason, improved representation of climate variability may answer important questions about the implications of extreme weather events. Additionally, studies such as this could further benefit from probabilistic modeling of uncertainty associated with climate.

Another climate model-related limitation of this study was to apply the GCM-predicted changes to observed temperature and precipitation. It is possible to downscale large GCM grids using statistical tools or regional climate models so that the spatial variability across a study area could be examined. In this study, this was not done. Arnell et al. (2003) suggested that it was preferable to apply modeled changes in climate to observed data to construct climate scenarios (as used in this study) rather than derive these directly from the regional climate model simulations.

The comparison of future climatic conditions from four global circulation models points to several important conclusions. First, there is significant variation of future conditions among different models, although all models were forced with the same emission scenarios. Second, the models responded differently to atmospheric forcing time periods. For example, the GFDL model predicts a four degree increase in temperature in 2070 while the NCAR model suggests only a two degree increase under the same emission scenario (although both models predict a change in the same direction). In other cases, different models suggest opposite directions of change during the same time period. Third, the variability in precipitation estimates is much larger than the variability of estimates for temperature. Precipitation declines by more than 20 percent in the CSIRO model, but less than 10 percent using the NCAR model under the same conditions. Temperature, on the other hand, has an expected pattern of change, generally increasing into the 21st century across three successive periods. This variation among models is one reason for using the multi-model ensemble approach adopted here. This type of multi-model ensemble approach is already in use in global studies that examine the mean state of a given climate and has been found to be superior to any individual model output in regional scale studies (Pierce et al., 2009). Research suggests that this occurs a result of errors in the individual models cancelling out one another. This study utilizes both the individual model and the multi-model ensemble average approach, unlike previous studies that investigated the effects of climate change on crop yields in Turkey. In the fourth assessment report, IPCC points out the discrepancy among models and suggests the use of multiple models for any impact assessment (IPCC, 2007).

An additional limitation of the current study is that other yield-limiting conditions – such as increased frequency of plant pests as a consequence of climate – change were not considered. Unfortunately biotic factors such as weeds and pest effects are difficult to model with current crop simulation tools. Depending on the inter-annual variation in precipitation patterns, weed infestations are already a major constraint on wheat yields in northwestern Turkey. Under a changing climate, increasing atmospheric CO_2 concentrations may favor weed growth and alter weed-crop competition dynamics (Patterson, 1995). Unfortunately, very little is known about the determinants of current weed-crop

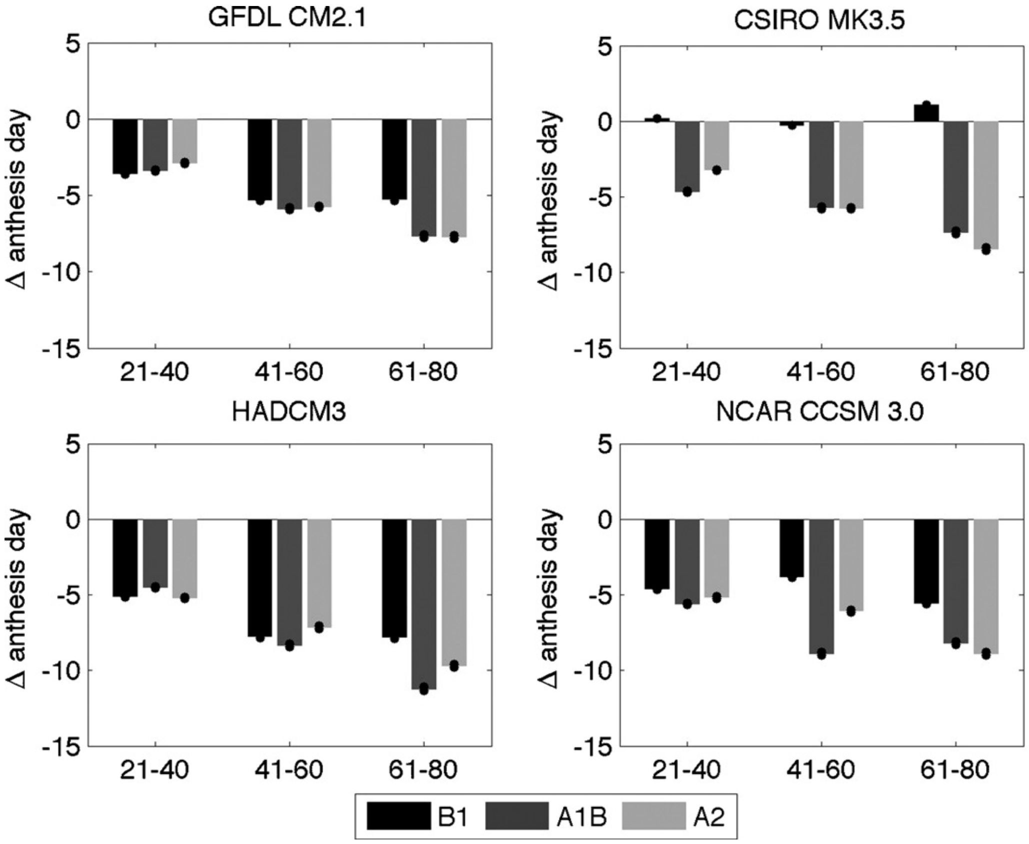

Fig. 7. Changes in day of anthesis under three climate change scenarios predicted by four climate models for the 2021–2040, 2041–2060, and 2061–2080 periods. The dots represent the variation in change in anthesis date in the form of one standard deviation as a result of changes in climate across multiple iterations of the wheat model. The units are in days.

dynamics in the study region, let alone expected changes in the future.

Perhaps the biggest limitation of the current study is the less-than-ideal fit between the modeled and observed wheat yields in the study area. While crop simulation models are important tools for testing whether predicted global atmospheric changes are likely to have an impact on crop yields, any confidence in model predictions is directly related to their ability to reliably and accurately characterize crop growing cycles and yields. In early yield comparisons, the AFRC2 model did not always perform well (as suggested by the goodness-of-fit tests) and further adjustments of thermal time requirements of the model did not improve the results. Three possible reasons may account for this. First, the AFRC2 model is constructed to respond to environmental conditions. In other words, if there is excess precipitation in a given year, the AFRC2 model responds by removing all moisture stress and by boosting wheat yields. In reality, however, excess precipitation (especially if it occurs early in the growing season) is responsible for excessive weed growth, substantially reducing yields in the field (Köklü, 2004). The second reason for the mismatch between observed and modeled yields is related to soil tilling practices in northwestern Turkey. Conventional tillage with complete soil overturn prior to sowing is common in the region and studies have found that these tillage practices affect yields (e.g. Young et al., 1994; Korucu and Merdun, 2009). In AFRC2 modeling however, these tillage practices are not captured, and even if they were captured, they would be manifested only in the form of changes in top-soil moisture.

One solution to these issues may be to adapt a specific model for the conditions of the study area. However, research shows that, of the available crop simulation models that would allow significant adaptation to a new site, nearly all predict the same direction/magnitude of change in yields. In other words, previous studies that compared several wheat growth models in the context of climate change studies found that many models produce similar results when forced with the same climate inputs (e.g. Jamieson et al., 2000). This is because in general all models are designed to temperature, water, radiation, and nutrient limitation in similar ways. The AFRC2 model used here simulates canopy development in more detail than several other models, namely LINTULC2 and Sirius by calculating leaf and tiller emergence, expansion, and senescence (Porter, 1984; Porter, 1993; Weir et al., 1984), while operating with less detail in simulating light interception and photosynthesis and the effects of drought. Moreover, none of the other current mechanistic crop growth models have the ability to simulate stress due to pests and weeds.

In sum, the AFRC2 model may not necessarily provide the best fit but in the context of available tools for simulation, it is likely the best choice. Moreover, the lack of fit between modeled and observed yields can also be attributed to other yield limiting factors that are not well modeled by this or any other model. Finally, this study was mainly concerned with understanding relative changes in yields under climate change from baseline conditions, and thus erroneous model results from the crop model calibration may not be as important as errors from the climate change experiments.

This study also revealed some beneficial effects of increased ambient CO_2 concentrations. Previous studies suggest that the mechanism through which yield increases occur under elevated ambient CO_2 concentrations is related to the regulatory function of CO_2, which causes fewer and less frequent stomatal openings. This reduces transpiration thereby leading to higher water use efficiency (Lawlor and Mitchell, 1991; Rosenzweig and Hillel, 1998; Amthor, 2001; Kang et al., 2002).

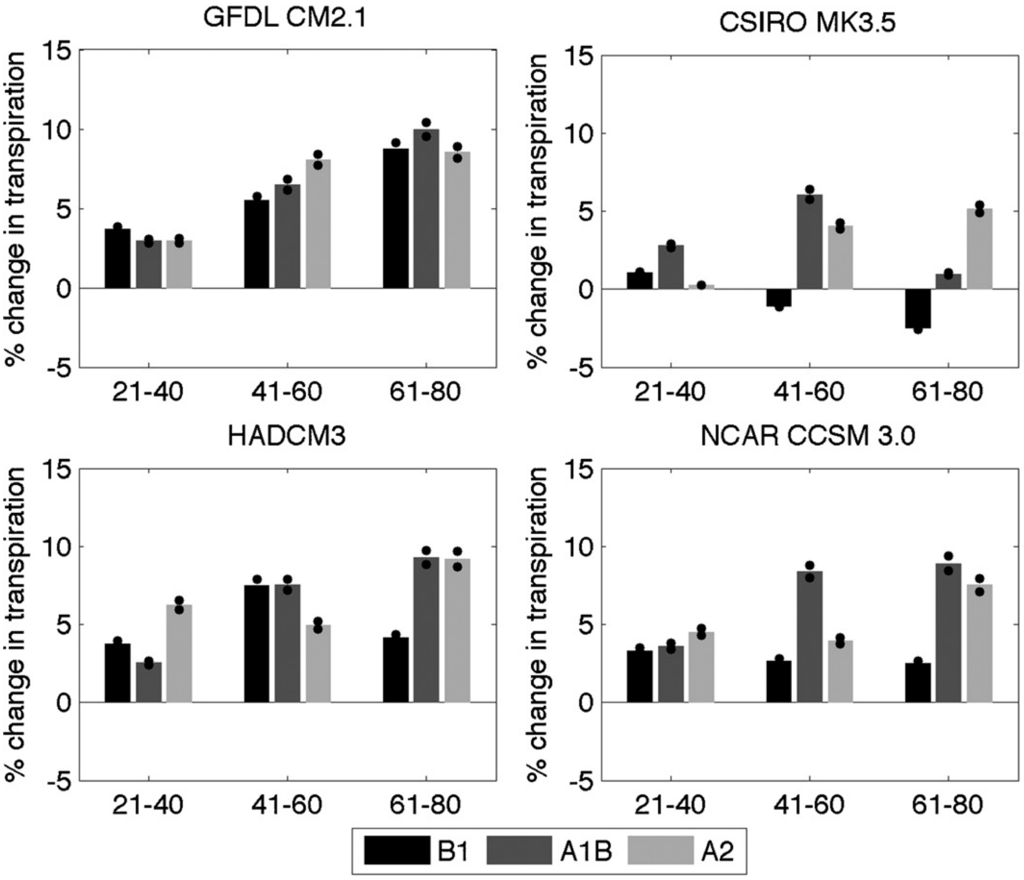

Fig. 8. Relative changes in growing season transpiration under three climate change scenarios predicted by four climate models for 2021–2040, 2041–2060, and 2061–2080 periods. The dots represent the variation in changes in transpiration in the form of one standard deviation as a result of changes in climate across multiple iterations of the wheat model.

The findings presented here are inline with the previous studies on crop productivity under a changing climate. At the same time, the present study goes beyond existing studies by providing a more comprehensive assessment involving four GCMs, two emission scenarios and three time periods. Considering the variability between models and emission scenarios, a more complete assessment, such as this study, is needed to provide improved information to stakeholders and policy makers in the region (Lambert and Boer, 2001).

The results presented in the research have important implications for the future of the Turkish wheat sector and potential adaption. A significant decline in yields could depress overall production volumes, affecting both market conditions and livelihoods, unless adaptation strategies are put in place. In a country where agriculture contributes roughly 10 percent of the gross domestic product and employs about 35 percent of the economically active population (TSI, 2008), such a reduction could have unprecedented social implications and pose serious risks to economic growth. In addition, the projected changes in environmental conditions may also affect grain quality (i.e. gluten and protein content) for derived products such as flour and pasta that are important for the export market (Bilgin and Korkut, 2005). This in turn could put pressure on domestic food production and Turkish export markets.

Given the current uncertainty about location-specific effects of climate change, one of the contributions of this study was to localize these effects in an important wheat-growing area of Turkey. If the drop in wheat yield due to climate change (as predicted by this study) is realized, it will require prioritization of adaptation strategies. There are a number of possible adaptation strategies, including development of drought- and heat-resistant crop varieties, earlier planting to avoid heat stress during summer, development and adoption of slower-maturing varieties to increase the grain filling period, and investments to boost agricultural productivity. The potential for adapting wheat systems to climate change by introducing cultivars with new traits is well documented in the literature.

Another form of adaptation is development of irrigation, although this strategy is often controversial. If precipitation amounts are reduced as predicted by the GCMs considered in this study, the inter-annual storage of excess precipitation and the use of resource-efficient irrigation could be an important means of maintaining cropping intensities in the region. While technological capacity is available in Turkey for developing irrigation infrastructure, the lack of water availability in the study area may impede this strategy. There is a river system west of the study area with the potential for storage and delivery of irrigation water, but resource management of this river basin and associated aquifers – which themselves are transboundary in nature – would be forced to become more agile and adaptive, as variability in river flows and aquifer recharge become apparent. Moreover, if irrigation is brought to this area, it would make it difficult to allocate water to other competing sectors such as fast growing industries and urban areas.

Finally, the findings of this study are in line with previous findings in Turkey, although it is one of the more comprehensive assessments involving multiple GCMs, scenarios and time periods. As an important contributor to the local and global demand for wheat grain and associated products, more studies are needed to

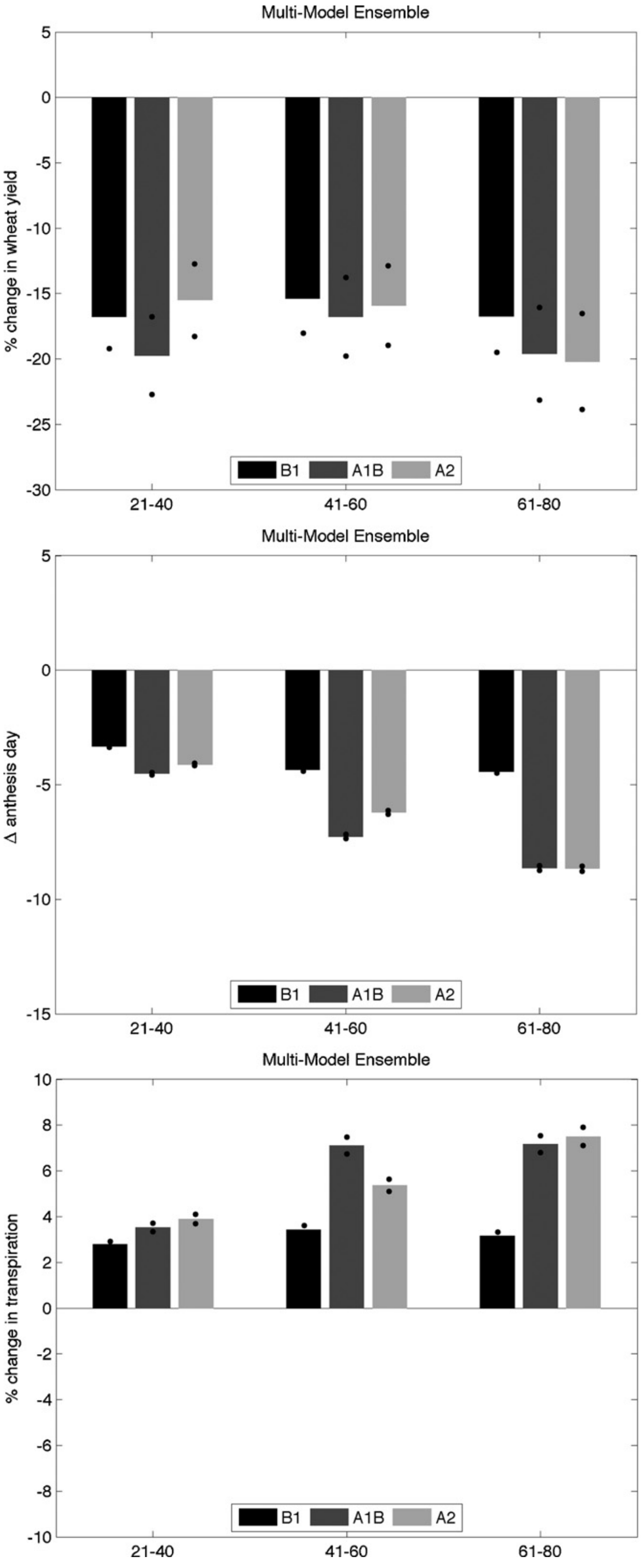

Fig. 9. Changes in wheat yield (left), day of anthesis (center), and transpiration (right) computed from climate change predictions based on multi-model ensemble runs. The ensemble run includes climate change predictions averaged across all four models to account for inter-model variability. The dots represent the variation of change in each variable in the form of one standard deviation as a result of changes in climate across multiple iterations of the wheat model using the ensemble inputs. The yield and transpiration changes are in relative unit while the change in the day of anthesis is in units of days.

determine various aspects of climate change on crop productivity in Turkey.

5. Conclusions

This study investigated the impacts of elevated atmospheric CO_2 concentrations and associated changes in climate on winter wheat yields in northwestern Turkey in the 21st century. This was achieved using three greenhouse gas emission scenarios, four global climate model outputs at three time periods and a fairly sophisticated mechanistic crop growth model. The first set of results involving GCM output point to a consistent pattern of change in the mean growing season air temperature that is more pronounced under the aggressive emission scenario. With respect to growing season precipitation, GCMs considered here predict various levels of reduction, although with more variability than air temperature, depending on the model used and the scenario considered.

With variations only in atmospheric CO_2 compositions, the crop model predicted positive changes in wheat yields across all scenarios and all time periods. However, these positive effects failed to counteract the significant decline in wheat yields when temperature and precipitation patterns were changed in association with increased atmospheric CO_2 concentrations. Under the new warmer and drier climatic conditions, winter wheat yields were predicted to decline between 5 and 35 percent, depending on the GCM input used. With the results of a multi-model ensemble developed to reduce inter-model variation, wheat yields are found to decline in excess of 20 percent from the baseline conditions. The main reason for the yield reduction appears to be temperature increase that not only shortens the vegetative duration, and more importantly the grain filling period, through speeding up the developmental processes, but also enhances plant water loss through transpiration as well as assimilate partitioning. All of these changes are further exacerbated by a significant decline in precipitation. More specifically, the generally lower amount of precipitation during the critical months is not sufficient to cover the increased evapotranspiration demand.

These results combined with the effects of reduced precipitation and enhanced transpiration in a future climate are particularly important in this semi-arid region, which is already at the limit of rain-fed winter wheat production. The results also suggest prioritization of adaptation strategies in the region, including development of local cultivars of drought- and heat-resistant crop varieties, earlier planting to avoid heat stress during summer, development and adoption of slower-maturing varieties to increase the grain filling period, and further investments to boost agricultural productivity.

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References

Amthor, J.S., 2001. Effects of atmospheric CO_2 concentration on wheat yield: review of results from experiments using various approaches to control CO_2 concentration. Field Crops Res. 73, 1–34.

Arnell, N.W., Hudson, D.A., Jones, R.G., 2003. Climate change scenarios from a regional climate model: estimating change in runoff in southern Africa. J. Geophys. Res. 108, 4519.

Batts, G.R., Morison, J.I.L., Ellis, R.H., Hadley, P., Wheeler, T.R., 1997. Effects of CO_2 and temperature on growth and yield of crops of winter wheat over several seasons. Eur. J. Agron. 7, 43–52.

Bilgin, O., Korkut, K.Z., 2005. Determination of some bread quality and grain yield characters in bread wheat (*Triticum aestivum* L.). Int. J. Agric. Biol. 7, 125–128.

Çaldağ, B., Saylan, L., 2005. Sensitivity analysis of the CERES-Wheat model for variations in CO_2 and meteorological factors in northwest of Turkey. Int. J. Environ. Pollut. 23, 300–313.

Collier, R., Fellows, J., Adams, S., Semenov, M., Thomas, B., 2008. Vulnerability of horticultural crop production to extreme weather events. Aspects Appl. Biol. 88, 3–14.

Collins, W.D., Bitz, C.M., Blackmon, M.L., Bonan, G.B., Bretherton, C.S., Carton, J.A., Chang, P., Doney, S.C., Hack, J.J., Henderson, T.B., 2006. The community climate system model version 3 (CCSM3). J. Climate 19, 2122–2143.

Delworth, T.L., Broccoli, A.J., Rosati, A., Stouffer, R.J., Balaji, V., Beesley, J.A., Cooke, W.F., Dixon, K.W., Dunne, J., Dunne, K.A., Durachta, J.W., Findell, K.L., Ginoux, P., Gnanadesikan, A., Gordon, C.T., Griffies, S.M., Gudgel, R., Harrison, M.J., Held, I.M., Hemler, R.S., Horowitz, L.W., Klein, S.A., Knutson, T.R., Kushner, P.J., Langenhorst, A.R., Lee, H.-C., Lin, S.-J., Lu, J., Malyshev, S.L., Milly, P.C.D., Ramaswamy, V., Russell, J., Schwarzkopf, M.D., Shevliakova, E., Sirutis, J.J., Spelman, M.J., Stern, W.F., Winton, M., Wittenberg, A.T., Wyman, B., Zeng, F., Zhang, R., 2006. GFDL's CM2 global coupled climate models—Part 1: formulation and simulation characteristics. J. Climate 19, 643–674.

El-Shaer, M.H., Rosenzweig, C., Iglesias, A., Eid, H.M., Hillel, D., 1997. Possible scenarios for Egyptian agriculture in the future. Mitig.Adaptat.Strategies Global Change 1, 233–250.

Ewert, F., Rodrigez, D., Jamieson, P., Semenov, M.A., Mitchell, R.A.C., Goudriaan, J., Porter, J.R., Kimball, B.A., Pinter Jr., B.A., Manderscheid, R., Weigel, H.J., Fangmeier, A., Fereres, E., Villalobos, F., 2002. Effects of elevated CO_2 and drought on wheat: testing crop simulation models for different experimental and climatic conditions. Agric. Ecosyst. Environ. 93, 249–266.

FAO, 2010. UN Food and Agricultural Organization online statistical database [FAOSTAT]. Available from: http://faostat.fao.org/site/339/default.aspx (accessed 17.01.11).

Ferris, R., Ellis, R.H., Wheeler, T.R., Hadley, P., 1998. Effect of high temperature stress at anthesis on grain yield and biomass of field-grown crops of wheat. Ann. Bot. 82, 631–639.

Fischer, G., Frohberg, K., Parry, M.L., Rosenzweig, C., 1994. Climate change and world food supply, demand and trade: who benefits, who loses? Global Environ. Change 4, 7–23.

Fuhrer, J., 2003. Agroecosystem responses to combinations of elevated CO_2, ozone, and global climate change. Agric. Ecosyst. Environ. 97, 1–20.

Gordon, H.B., Rotstayn, L.D., McGregor, J.L., Dix, M.R., Kowalczyk, E.A., O'Farrell, S.P., Waterman, L.J., Hirst, A.C., Wilson, S.G., Collier, M.A., Watterson, I.G., Elliott, T.I., 2002. The CSIRO Mk3 Climate System Model [Electronic publication]. Aspendale: CSIRO Atmospheric Research (CSIRO Atmospheric Research technical paper; no. 60), 130 pp.

Hay, R., Porter, J.R., 2006. The Physiology of Crop Yield, 2nd edition. Blackwell Publishing, Oxford, United Kingdom.

IPCC, 2000. In: Nebojsa, N., Rob, S. (Eds.), Special Report on Emission Scenarios. Cambridge University Press, UK, p. 570.

IPCC, 2007. Climate change 2007: the physical science basis. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jamieson, P.D., Berntsen, J., Ewert, F., Kimball, B.A., Olesen, J.E., Pinter Jr., P.J., Porter, J.R., Semenov, M.A., 2000. Modelling CO_2 effects on wheat with varying nitrogen supplies. Agric. Ecosyst. Environ. 82, 27–37.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Jenne, R., Joseph, D., 1996. The NCEP/NCAR 40-year reanalysis project. Bull. Am. Meteorol. Soc. 77, 437–471.

Kang, S.Z., Zhang, F.C., Hu, X.T., Zhang, J.H., 2002. Benefits of CO_2 enrichment on crop plants are modified by soil water status. Plant Soil 238, 69–77.

Kobata, T., 2007. Estimation of crop production by the future climate changes in surrounding areas of the Seyhan River in Turkey, The ICCAP (impact of climate changes on agricultural production system in arid areas) project final report, 4 pp. Available from: http://www.chikyu.ac.jp/iccap/finalreport.htm.

Korucu, T., Merdun, H., 2009. Effects of tillage systems on wheat yield and residue in Turkey. J. Anim. Vet. Adv. 8, 1973–1978.

Köklü, G., 2004. Occurrence of cereal viruses on wheat in Tekirdag, Turkey. Phytoprotection 85, 19–25.

Lambert, S.J., Boer, G.J., 2001. CMIP1 evaluation and inter-comparison of coupled climate models. Clim. Dyn. 17, 83–106.

Laurila, H.A., 1995. Modelling the effects of elevated CO_2 and temperature on Swedish and German spring wheat varieties with CERES-wheat and AFRC-wheat crop models. J. Biogeogr. 22, 591–595.

Lawlor, D.W., Mitchell, R.A.C., 1991. The effects of increasing CO_2 on crop photosynthesis and productivity: a review of field studies. Plant Cell Environ. 14, 807–818.

Long, S.P., Ainsworth, E.A., Rogers, A., Ort, D.R., 2004. Rising atmospheric carbon dioxide: plants face the future. Annu. Rev. Plant Biol. 55, 591–628.

Meehl, G.A., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J.F.B., Stouffer, R.J., Taylor, K.E., 2007. The WCRP CMIP3 multi-model dataset: a new era in climate change research. Bull. Am. Meteorol. Soc. 88, 1383–1394.

Miglietta, F., Porter, J.R., 1992. The effects of climate change on development in wheat: analysis and modeling. J. Exp. Bot. 43, 1147–1158.

Nakagawa, H., Kobata, T., Yano, T., Barutçular, C., Koç, M., Tanaka, K., Nagano, T., Fujihara, Y., Hoshikawa, K., Kume, T., Watanabe, T., 2007. Predicting the impact of global warming on wheat production in Adana, The ICCAP (impact of climate changes on agricultural production system in arid areas) project final report, 6 pp. Available from: http://www.chikyu.ac.jp/iccap/finalreport.htm.

NCDC, 2010. Global Summary of day data product. Available from: http://www.ncdc.noaa.gov/cgi-bin/res40.pl?page=gsod.html (accessed 17.01.11).

Ortiz, R., Sayre, K.D., Govaerts, B., Gupta, R., Subbarao, G.V., Ban, T., Hodson, D., Dixon, J.M., Ortiz-Monasterio, J.I., Reynolds, M., 2008. Climate change: can wheat beat the heat? Agric. Ecosyst. Environ. 126, 46–58.

Özkan, B., Akçaöz, H., 2002. Impacts of climate factors on yields for selected crops in the Southern Turkey. Mitig. Adaptat. Strategies Global Change 7, 367–380.

Patterson, D.T., 1995. Weeds in a changing climate. Weed Sci. 43, 685–701.

Pierce, D.W., Barnett, T.P., Santer, B.D., Gleckler, P.J., 2009. Selecting global climate models for regional climate change studies. Proc. Natl. Acad. Sci. 106, 8441–8446.

Pope, V.D., Gallani, M.L., Rowntree, P.R., Stratton, R.A., 2000. The impact of new physical parameterization in the Hadley Centre climate model-HadAM3. Clim. Dyn. 16, 123–146.

Porter, J.R., 1983. Modeling stage development in winter wheat. In influence of environmental factors on herbicide performance and crop and weed biology. Aspects Appl. Biol. 4, 449–455.

Porter, J.R., 1984. A model of canopy development in winter wheat. J. Agric. Sci. 102, 383–392.

Porter, J.R., 1993. AFRCWHEAT2: a model of the growth and development of wheat incorporating responses to water and nitrogen. Eur. J. Agron. 2, 69–82.

Porter, J.R., Gawith, M., 1999. Temperatures and the growth and development of wheat: a review. Eur. J. Agron. 10, 23–26.

Porter, J.R., Semenov, M.A., 1999. Climatic variability and modeling of crop yield in Europe. Nature 400, 724.

Reilly, J., 1999. What does climate change mean for agriculture in developing countries? A comment on Mendelsohn and Dinar. World Bank Res. Obs. 14, 295–305.

Rosenzweig, C., Parry, M.L., 1994. Potential impact of climate-change on world food-supply. Nature 367, 133–138.

Rosenzweig, C., Hillel, D., 1998. Climate Change and the Global Harvest: Potential Impacts of the Greenhouse Effect on Agriculture. Oxford University Press, Oxford, United Kingdom.

Rosenzweig, C., Iglesias, A., Yang, X.B., Epstein, P.R., Chivian, E., 2001. Climate change and extreme weather events; implications for food production, plant diseases, and pests. Global Change Hum. Health 2, 90–104.

Ruttan, V.W., Bell, D.E., Clark, W.C., 1994. Climate change and food security: agriculture, health and environmental research. Global Environ. Change 4, 63–77.

Semenov, M.A., Barrow, E.M., 1997. Use of a stochastic weather generator in the development of climate change scenarios. Climate Change 35, 397–414.

Semenov, M.A., Brooks, R.J., Barrow, E.M., Richardson, C.W., 1998. Comparison of the WGEN and LARS-WG stochastic weather generators for diverse climates. Climate Res. 10, 95–107.

Turkish Statistical Institute (TSI), 2008. Agriculture Structure, Production, Price, and Value. Turkish Statistical Press, Ankara, Turkey.

Tubiello, F.N., Ewert, F., 2002. Simulating the effects of elevated CO_2 on crops: approaches and applications for climate change. Eur. J. Agron. 18, 57–74.

Tubiello, F.N., Soussana, J.-F., Howden, S.M., 2007. Climate change and food security special feature: crop and pasture response to climate change. Proc. Natl. Aca. Sci. 104, 19686–19690.

Vos, J., 1981. Effects of Temperature and Nitrogen Supply on Post-floral Growth of Wheat: Measurements and Simulations. Pudoc, Wageningen, The Netherlands.

Weir, A.H., Bragg, P.L., Porter, J.R., Rayner, J.H., 1984. A winter wheat crop simulation model without water or nutrient limitations. J. Agr. Sci. Camb. 102, 371–382.

Wheeler, T.R., Hong, T.D., Ellis, R.H., Batts, G.R., Morison, J.I.L., Hadley, P., 1996. The duration and rate of grain growth, and harvest index, of wheat (*Triticum aestivum* L.) in response to temperature and CO_2. J. Exp. Bot. 47, 623–630.

Willmott, C.J., 1981. On the validation of models. Phys. Geogr. 2, 184–194.

Yano, T., Koriyama, M., Haraguchi, T., Aydin, M., 2007. Simulation of crop productivity for evaluating climate change effects, The ICCAP (impact of climate changes on agricultural production system in arid areas) project final report, 4 pp. Available from: http://www.chikyu.ac.jp/iccap/finalreport.htm.

Young, F.L., Ogg, A.G., Papendick, R.I., Thill, D.C., Alldredge, J.R., 1994. Tillage and weed management affects winter wheat yield in an integrated pest management system. Agron. J. 86, 147–154.