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Impacts of climate change as a function of global mean temperature: maize productivity and water use in China

Fulu Tao · Zhao Zhang

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Abstract Projections of future climate change are plagued with uncertainties from global climate models and emission scenarios, causing difficulties for impact assessments and for planners taking decisions on adaptation measure. Here, we developed an approach to deal with the uncertainties and to project the changes of maize productivity and water use in China using a process-based crop model, against a global mean temperature (GMT) increase scale relative to 1961–1990 values. From 20 climate scenarios output from the Intergovernmental Panel on Climate Change Data Distribution Centre, we adopted the median values of projected changes in monthly mean climate variables for representative stations and driven the CERES-Maize model to simulate maize production under baseline and future climate scenarios. Adaptation options such as automatic planting, automatic application of irrigation and fertilization were considered, although cultivars were assumed constant over the baseline and future. After assessing representative stations across China, we projected changes in maize yield, growing period, evapotranspiration, and irrigation-water use for GMT changes of 1°C, 2°C, and 3°C, respectively. Results indicated that median values of projected decreases in the yields of irrigated maize without (with) consideration of CO_2-fertilization effects ranged from 1.4% to 10.9% (1.6% to 7.8%), 9.8% to 21.7% (10.2% to 16.4%), and 4.3% to 32.1% (3.9% to 26.6%) for GMT changes of 1°C, 2°C, and 3°C, respectively. Median values of projected changes in irrigation-water use without (with) consideration of CO_2-fertilization effects ranged from −1.3% to 2.5% (−18.8% to 0.0%), −43.6% to 2.4% (−56.1% to

F. Tao (✉)
Institute of Geographical Sciences and Natural Resources Research,
Chinese Academy of Sciences, Beijing 100101, China
e-mail: taofl@igsnrr.ac.cn

Z. Zhang
State Key Laboratory of Earth Surface Processes and Resource Ecology,
Beijing Normal University, Beijing 100875, China
e-mail: zhangzhao@bnu.edu.cn

−18.9%), and −19.6% to 2.2% (−50.6% to −34.3%), which were ascribed to rising CO_2 concentration, increased precipitation, as well as reduced growing period with GMT increasing. For rainfed maize, median values of projected changes in yields without (with) consideration of CO_2-fertilization effects ranged from −22.2% to −1.0% (−10.8% to 0.7%), −27.6% to −7.9% (−18.1% to −5.6%), and −33.7% to −4.6% (−25.9% to −1.6%). Approximate comparisons showed that projected maize yield losses were larger than previous estimates, particularly for rainfed maize. Our study presents an approach to project maize productivity and water use with GMT increases using process-based crop models and multiple climate scenarios. The resultant impact function is fundamental for identifying which climate change level is dangerous for food security.

1 Introduction

There are increasing attempts (IPCC 2001a, 2007) to define the measures of 'dangerous anthropogenic inference with the climate system' in context of Article 2 of the Framework Convention on Climate Change, due to its linkage to goals for stabilising greenhouse gas concentrations. The criteria for identifying dangerous anthropogenic interference may be characterized in terms of the consequences (or impacts) of climate change (Patwardhan et al. 2003). Although these impacts and a precise definition of "dangerous anthropogenic interference" are subject to considerable uncertainty, a plausible uncertainty range can be quantified from current scientific knowledge (IPCC 2001a). Therefore, interest has increased (e.g. IPCC 2001a, 2007; Hitz and Smith 2004; Leemans and Eickhout 2004; Smith et al. 2005; Hare 2006; Warren 2006; Tao et al. 2008a) in determining the general shape of the damage curve expressed as a function of global mean temperature (GMT), one of the most feasible measures of the magnitude of future climate change. However, most of our knowledge on the damage function is based on the sparse literatures with different assumptions, experimental designs and purposes or just roughly transferred from the impacts against time scale (e.g. IPCC 2001a, 2007; Hitz and Smith 2004; Hare 2006; Warren 2006). The agricultural system has complex interactions with climate system, an approach to project crop productivity and water use with GMT increases using process-based crop models is needed.

Furthermore, projections of future climate change are plagued with uncertainties from global climate models (GCMs) and emission scenarios, causing difficulties for impacts assessment and for planners taking decisions on adaptation measure (Lobell and Burke 2008; Tao et al. 2008a, 2009; Tebaldi and Lobell 2008). Although uncertainty about climate change has received growing attention in recent years, much of this has focused on the description of scientific uncertainties in the climate system (Carter et al. 1999) and to a lesser extent in climate change impact assessments (Jones 2000). Recent progresses in the climate model diagnosis and intercomparison and multi-model ensembles weather and climate predictions provide an excellent opportunity to explore climate impacts and adaption using probabilistic methods (Cantelaube and Terres 2005; Challinor et al. 2005; Marletto et al. 2005; Tao et al. 2008a, 2009; Tebaldi and Lobell 2008). More comprehensive assessments of impacts are needed, which use probabilistic output from ensembles of climate models to better represent uncertainties, and which clearly communicate what we know and do not know about how regional climate may change and how it may affect (Lobell and Burke 2008; Tao et al. 2008a, 2009).

We try to develop an approach to present a picture of how regional climate and impacts would change against a GMT increase scale using process-based impact model and multiple climate scenarios. Here, we focus on maize productivity and water use in China. Maize is one of staple crops, also the most vulnerable crop to both seasonal climate variability (Tao et al. 2004) and long-term climate trend (Tao et al. 2008b) among the staple crops in China. The objectives of the study are (1) to assess the uncertainties in regional climate projections at different GMT increases, on basis of different GCMs and emission scenarios; (2) to develop an approach to project how maize productivity and water use would change with GMT increasing by 1°C, 2°C, and 3°C, respectively, using process-based crop model and multiple climate scenarios.

2 Methods and data

2.1 Study stations

We selected study stations that: (1) were located in the primary maize production areas, (2) represented the typical cropping system for maize cultivation, (3) were geographically and climatologically representative, and (4) have good experimental

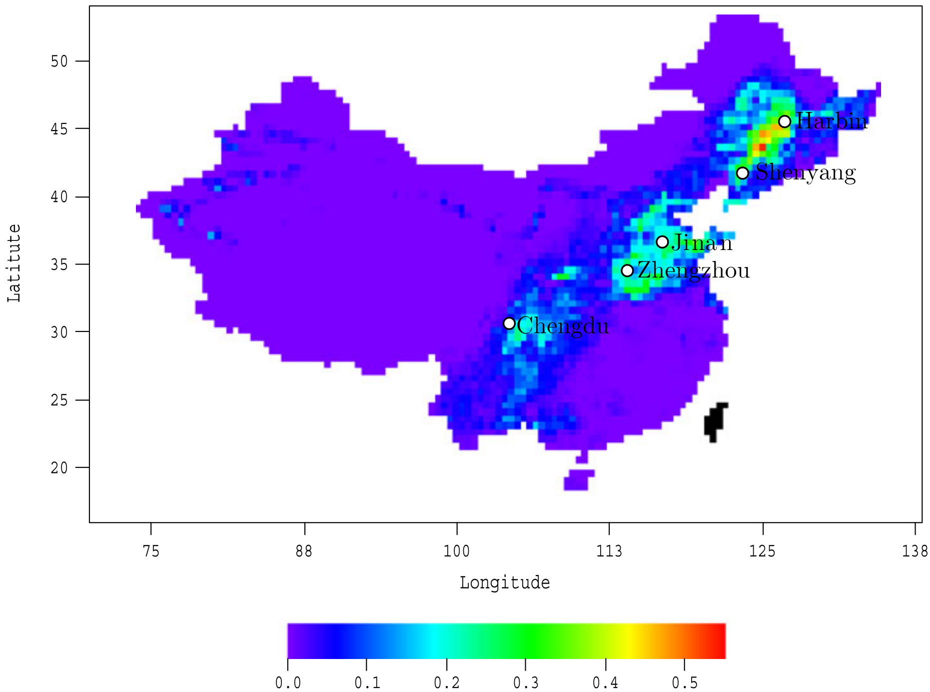


Fig. 1 Maize cultivation fraction and the selected study stations

observation records on both crop and weather for at least 3 years. Finally, we selected five stations for study: Harbin (HB) in Heilongjiang province, Shenyang (SY) in Liaoning province, Jinan (JN) in Shandong province, Zhengzhou (ZZ) in Henan province, and Chengdu (CD) in Sichuan province (Fig. 1). Geographically, HB and SY are located in the Northeast China Plain; JN and ZZ are located in the North China Plain; and CD is located in the Sichuan Basin. All of them are the major food production areas in China, with various climates. The general information on, for example, maize cultivation fraction, climate, cropping system, and soils for the selected stations is showed in Fig. 1 and Table 1.

2.2 Calibration and validation of CERES-Maize model

2.2.1 CERES-Maize model

The CERES-Maize model embedded in DSSAT 4.0 (Jones and Kiniry 1986; Jones et al. 2003) was chosen because it has been calibrated and validated in different regions of the world (e.g. Carberry et al. 1989; Jones et al. 2003; Lopez-Cedron et al. 2005), and used for studying impacts of climate variability and change in broad regions (e.g., Hansen and Indeje 2004; Xiong et al. 2007). The model requires inputs including daily weather data (minimum (*Tmin*) and maximum temperature (*Tmax*), precipitation and solar radiation (*Srd*)), soil properties, cultivar characteristics, planting date, and N fertilizer management, etc. In the version of CERES-Maize, photosynthetic reduction factor follows a different four-point temperature function: a linear function of average temperature during the daylight hours with the following cardinal temperatures (a base temperature of 6.2°C, a first optimum of 16.5°C, a second optimum of 33°C and a maximum of 44.0°C). This model employs constant multipliers for daily total crop biomass under elevated CO_2, equally applied to either stressed or unstressed growth conditions. For C4 crops, the assumed response ratios

Table 1 General information for climate, soils, cropping system, etc. for selected study stations

	Station				
	Harbin	Shenyang	Jinan	Zhengzhou	Chengdu
Latitude, longitude	45°45′ N, 126°46′ E	41°44′ N, 123°27′ E	36°41′ N, 116°59′ E	34°43′N, 113°39′ E	30°40′ N, 104°01′ E
Typical cropping system	Single maize or rice	Single maize or rice	Rotation between winter wheat and maize	Rotation between winter wheat and maize	Rotation between winter wheat and maize
Annual mean temperature (°C)	4.6	8.9	15.3	14.4	16.7
Annual total precipitation (mm)	555	689	651	623	862
Soil texture	Clay loam	Silty clay loam	Silty clay loam	Clay loam	Clay loam
Soil depth (cm)	150	140	127	100	82
Agricultural experimental data used[a]	1996–2000	1998–2000	1998–2000	1994–2000	1998–2000

[a]The experiment in 1998 was used for crop model calibration at all stations

change almost linearly with CO_2 level from 330 to about 660 ppm, but diminish at higher levels, reaching a plateau of 1.10 beyond 990 ppm. The model calculates daily soil water balance using the methods of Ritchie (1985). Evapotranspiration (ET) was calculated using the Priestley–Taylor equation as modified by Ritchie (1985).

2.2.2 Experiment establishment, model calibration, and validation

For each study station, we used experimental records from 1 year for model parameters calibration, and the records of several other years for model validation (Table 1). The experimental records included detailed information on crop phenology, management practices (e.g. irrigation, fertilization, and pesticide use), and crop yield and yield components. For each maize growing season, we set up an experiment with three treatments, one following exactly the experimental records (hereafter "R-treatment"), one accounting for irrigation maize with adaptation ("I-A-treatment"), and another accounting for rainfed maize with adaptation ("R-A-treatment"). The R-treatment represented current local traditional management, with planting and management on the reported dates. The I-A-treatment generally had the same settings as the R-treatment, although planting and management, such as irrigation and fertilization applications, were set automatically. The R-A-treatment had the same settings as the I-A-treatment but no irrigation. Automatic planting was defined as planting once soil temperature and moisture conditions were satisfactory during a station-specific planting window or the final date of the planting window. Automatic irrigation applications were defined as the refilling of the soil water profile whenever soil water content fell below 50% of capacity at 30-cm depth. Automatic fertilizer applications were defined as the application of fertilizer at 30-cm depth whenever the nitrogen stress factor reached 50% of threshold. Soil profiles were station specific and represented typical regional soils for maize cultivation. Soil profile data for each station were extracted from the Soil Species of China (National Soil Survey Office 1993). The maize cultivar was season specific and represented the cultivar most widely planted in the region at that time. We used the R-treatment in the experiment to calibrate genetic coefficients for each cultivar. The I-A-treatment and R-A-treatment were used to evaluate maize productivity and irrigation-water use under both baseline climate conditions and future climate scenarios, because the treatments were likely to be more similar to the actual situation. We evaluate the accuracy of models by calculating the root mean square error (RMSE) between the observed and simulated value:

$$RMSE = \left[\left(\sum_{i=1}^{n} (Simulated_i - Observed_i)^2 \right) \Big/ n \right]^{0.5}, \qquad (1)$$

where n is the number of comparison.

2.3 Develop an approach to project maize productivity and water use change against a GMT increase scale using process-based crop model and multiple climate scenarios

The general framework of the study is given in Fig. 2. For each station, we first used historical daily weather data from 1961 to 1990 to parameterize a weather

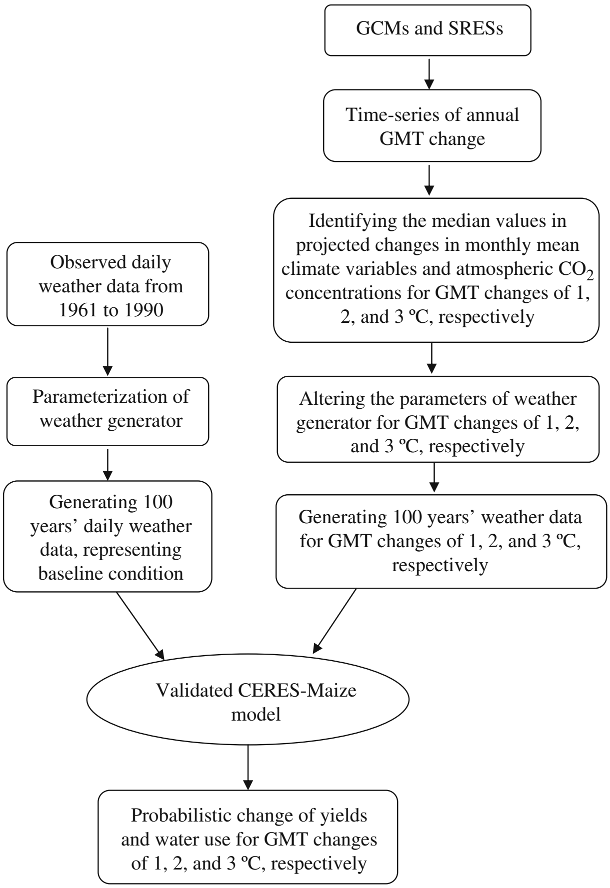


Fig. 2 The general framework of the study

generator and to generate 100 years of daily weather data, which represented the baseline climate conditions. Then we identified the projected climate changes and atmospheric CO_2 concentrations at the station for GMT changes of 1°C, 2°C, and 3°C, respectively, on basis of GCMs and SRESs and their projected time series of annual GMT change (IPCC 2001b). Next, we identified the median values in the projected changes in monthly mean of climate variables (*Tmin*, *Tmax*, precipitation and *Srd*), further used them to alter the parameters in the weather generator, and to generate 100 years of daily weather data for GMT changes of 1°C, 2°C, and 3°C, respectively. Finally, we ran the validated CERES-Maize model by using both the baseline climate conditions and the climate-change scenarios for GMT changes of 1°C, 2°C, and 3°C for 100 years, respectively. We calculated the changes in growing period, maize yield, evapotranspiration (ET), and irrigation-water use between the future climate-change scenarios and the baseline climate conditions and further investigated the probability distribution of the resultant changes for GMT changes of 1°C, 2°C, and 3°C, respectively. More details are provided in the following sections.

2.3.1 Baseline climate

LARS-WG is a stochastic weather generator to simulate time-series of a suite of climate variables at a single site (Semenov et al. 1998). LARS-WG has been tested and able to reproduce most of the characteristics of the observed data well in diverse climates around the world (Semenov et al. 1998). It has also been used to develop daily site-specific climate change scenarios for climate change impact study (Semenov 2007). Here, for each station, we used the observed daily data on *Tmin*, *Tmax*, precipitation and *Srd* from 1961 to 1990, obtained from China Meteorological Administration, to parameterize LARS-WG and further generate 100 years' daily weather data on the same climate variables, which represented baseline climate conditions.

2.3.2 Climate change scenario and uncertainties

The 20 scenarios for monthly fields of mean temperature (*Tmean*), diurnal temperature range (*DTR*), precipitation on a 0.5°grid from 2001 to 2100 were taken from the Climatic Research Unit, University of East Anglia (Mitchell et al. 2004). The scenarios comprise all 20 combinations of four SRESs (A1FI, A2, B1, B2) and five GCMs (HadCM3, PCM, CGCM2, CSIRO2, ECHAM4), using GCM outputs from the IPCC Data Distribution Centre. More detailed information on the GCMs can be found at http://www.ipcc-data.org/. The complete method of dataset construction was described in Mitchell et al. (2004). Twenty different futures were used to represent the uncertainty in climate impacts arising from two distinct uncertainty sources: uncertainty in the future emissions of greenhouse gases and uncertainty in climate modeling. Each of the 20 permutations should be treated as equally likely (Mitchell et al. 2004). The 20 alternative future climates represent >93% of the range of possible global warming presented by the IPCC (2001b).

Because the crop model requires input data of *Tmax*, *Tmin*, precipitation, and *Srd*, we derived the corresponding changes in *Tmax* and *Tmin* through changes in *Tmean* and *DTR* using the following equations (e.g. Tao et al. 2008a):

$$T_{\max} = T_{mean} + \frac{DTR}{2} \tag{2}$$

$$T_{\min} = T_{mean} - \frac{DTR}{2} \tag{3}$$

We also derived solar radiation by a self-calibrating method through monthly average daily *Tmax* and *Tmin* (Hargreaves et al. 1985; Allen 1997):

$$\frac{H}{H_0} = a(T_{\max} - T_{\min})^{0.5} + b\,, \tag{4}$$

where H is the monthly average daily solar radiation, H_o is the monthly average daily extraterrestrial radiation, a and b are parameters.

Before using Eq. 4, for each station, we used the observed records of H, *Tmax*, and *Tmin* from 1961 to 1980 to parameterize and the records from 1981 to 1993 to validate the equation. The observed records of H, *Tmax*, and *Tmin* were obtained from the China Meteorological Administration. The equation generally simulated

H well, with RMSE ranging from 1.18 MJ m^{-2} day^{-1} at ZZ to 2.14 MJ m^{-2} day^{-1} at HB.

For each station, to identify the projected changes in monthly means of climate variables for GMT changes of 1,°C 2°C, and 3°C, respectively, for the grid cell that covers the station, we first extracted the 20 climate scenarios for the period 2001–2100. Then, for each scenario, together with its projected time-series of annual GMT change, we identified its projected changes in monthly means of the four climatic variables—*Tmax*, *Tmin*, precipitation, and *Srd*—for GMT changes of 1°C, 2°C, and 3°C, respectively, until 2100.

The four SRESs (A1FI, A2, B1, B2) led to substantial differences in projected CO_2 concentration trajectories. According to the time series of global warming as projected by the 20 climate scenarios and the projected CO_2 concentration trajectories across scenarios (IPCC 2001b), the CO_2 concentration ranges would be 396–490, 473–635, and 552–856 ppmv for GMT changes of 1°C, 2°C, and 3°C, respectively.

2.3.3 Construction of daily climate scenarios using weather generator

For each station, for GMT changes of 1°C, 2°C, and 3°C, respectively, the median values of the projected changes in monthly means of climate variables, on basis of the 20 climate scenarios, were used to alter the parameters of LARS-WG describing baseline climate condition. The new set of LARS-WG parameters, which was specific to the station and the scenario for GMT changes of 1°C, 2°C, and 3°C, respectively, was calculated following Semenov (2007). Specifically, in the LARS-WG scenario file, the absolute changes in daily *Tmax* and *Tmin*, and the relative changes in monthly mean precipitation and *Srd* between the climate change scenario and baseline climate, were calculated and renewed. However the duration of monthly mean dry and wet series were assumed to be same as the baseline climate because they required daily precipitation output from the climate scenarios that are not robust enough. The assumption may underestimate the impacts of extreme precipitation events, however may not affect the results much in this study because we focus on the mean changes in maize productivity and water use with GMT increasing. Using the new set of parameters, LARS-WG was applied to generate 100 years' daily station-specific weather time series consistent with the scenario for GMT changes of 1°C, 2°C, and 3°C, respectively.

2.3.4 Simulation and analysis

For each station, the generated 100 years' daily weather for baseline climate condition, and for GMT changes of 1°C, 2°C, and 3°C, respectively, was input to the validated CERES-Maize model to simulate maize productivity and water use, respectively. Then for each simulation treatment, we investigated the simulated changes in the growing period, maize yield, ET, and irrigation water use for GMT changes of 1°C, 2°C, and 3°C, respectively, compared with the corresponding simulation under baseline climate conditions. We also investigated the probabilistic distribution of the resultant 100 changes in these variables for GMT changes of 1°C, 2°C, and 3°C, respectively, in comparison with the baseline climate conditions. We used box plots and cumulative distribution functions (CDFs) to describe their statistics and probability distributions.

3 Results

3.1 Validation of the CERES-Maize model

We validated the CERES-Maize model by using available agricultural experiment records ranging from 2 to 6 years (Table 1). The model was able to simulate maize phenology and yield reasonably well for most experiments (Fig. 3). Across the

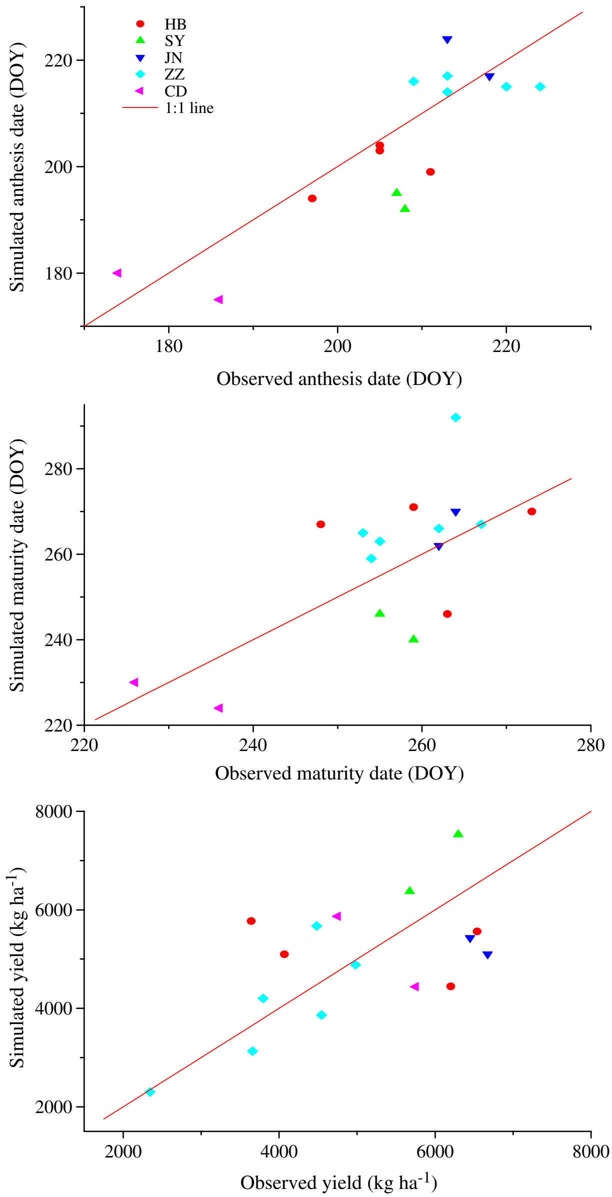


Fig. 3 Observed and simulated maize yield, anthesis date and maturity date at selected stations

stations, the RMSE of simulated anthesis and maturity dates was 8.9 and 12.4 days, respectively, with average error of 3.5% for anthesis date and 3.8% for maturity date. The RMSE of simulated maize yields were 1,347.6 kg ha^{-1}, with errors generally less than 20.0%. Considering that the simulations did not take into account the impacts of insects and diseases, we believe the validated model can be employed to investigate the potential impacts of climate change.

3.2 Regional climate change scenarios and uncertainties

The uncertainties in the projected regional climate change on basis of the 20 climate scenarios were considerable. As an example, at JN station with GMT increase of 2°C, in comparison with the period of 1961–1990, the projected changes in monthly mean *Tmax* ranged from −3.0°C to 5.7°C for February and from 0.8°C to 4.0°C for July (Fig. 4), across the 20 climate scenarios. Changes in monthly mean of *Tmin* ranged from −0.3°C to 7.3°C for February and from 1.5°C to 4.9°C for July; relative changes in monthly mean precipitation ranged from 0.1 to 4.2 for February and from 0.6 to 2.0 for July; relative changes in monthly mean *Srd* ranged from 0.8 to 1.2 for February and from 0.9 to 1.0 for July (Fig. 4).

Regional and seasonal variations in projected climate change on basis of the 20 climate scenarios were also considerable. For all the stations, the median values of the projected changes in monthly mean *Tmax*, *Tmin*, precipitation and *Srd*, for GMT changes of 1°C, 2°C, and 3°C, respectively, were showed in Fig. 5. At all the stations, the mean changes in annual mean temperature were higher than the corresponding global mean temperature. *Tmin* would increase more than *Tmax;* the temperature at the stations in high latitude region such as HB and SY would increase more in comparison with the stations in low latitude region such as CD. Temperature in winter and spring would increase more than in summer. Such characteristic is consistent with the general feature of observed and projected climate change (IPCC 2001b). The relative changes in precipitation and *Srd* were not so dependent on the changes in GMT, compared with *Tmax* and *Tmin* (Fig. 5).

3.3 Changes in growing period, yield, ET, and irrigation water use with increases in GMT

3.3.1 Irrigated maize

We simulated maize growth and productivity with and without consideration of CO_2-fertilization effects. When CO_2-fertilization effects were not considered, across all the stations, the median values of projected decreases in growing period ranged from 4.2% at CD to 13.0% at HB, 10.8% at CD to 22.5% at HB, and 12.3% at CD to 30.3% at HB for GMT changes of 1°C, 2°C, and 3°C, respectively (Fig. 6). The changes in maize growing period remained almost same when CO_2-fertilization effects were considered (Fig. 7).

Maize yields would also decrease, and the degree of the reduction would increase with increasing GMT (except at CD station). The median values of projected decreases in yields ranged from 1.4% at CD to 10.9% at JN, 9.8% at CD to 21.7% at ZZ, and 4.3% at CD to 32.1% at HB for GMT changes of 1°C, 2°C, and 3°C, respectively (Fig. 6). When CO_2-fertilization effects were considered, the corresponding values

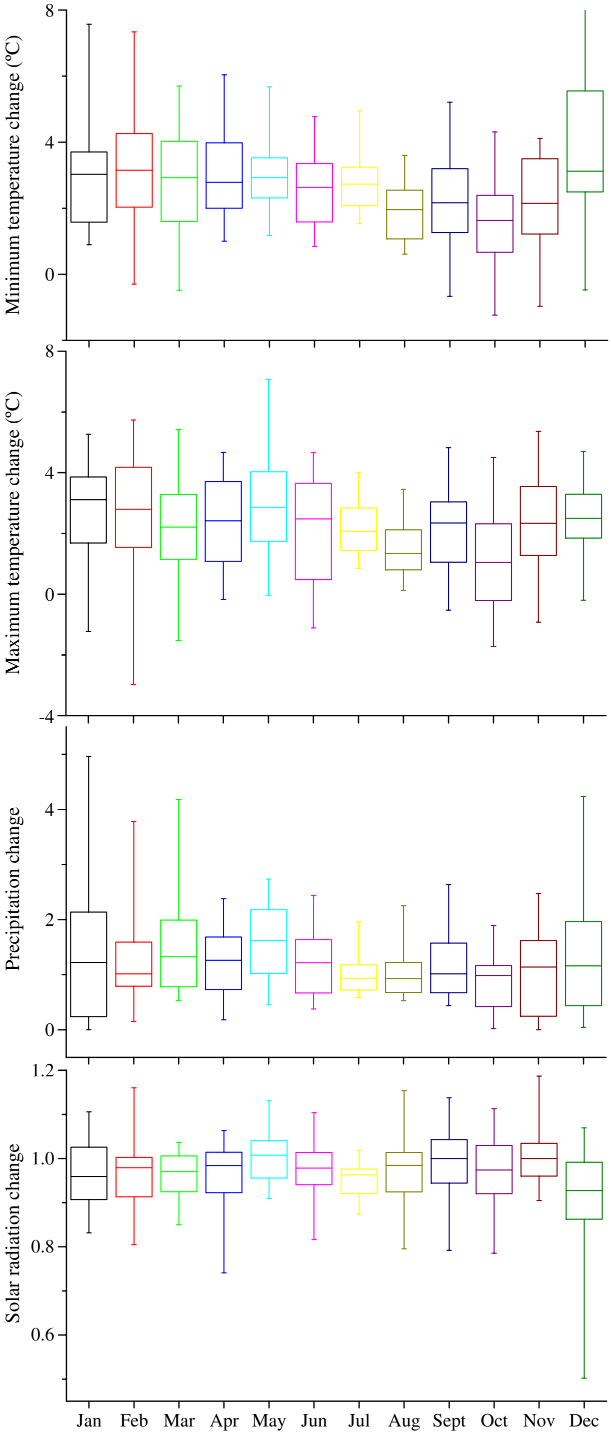


Fig. 4 Projected absolute changes in monthly mean *Tmax*, *Tmin*, and relative changes in monthly mean precipitation and *Srd* at JN station for GMT increase of 2°C on basis of the 20 climate change scenarios, relative to the period of 1961–1990

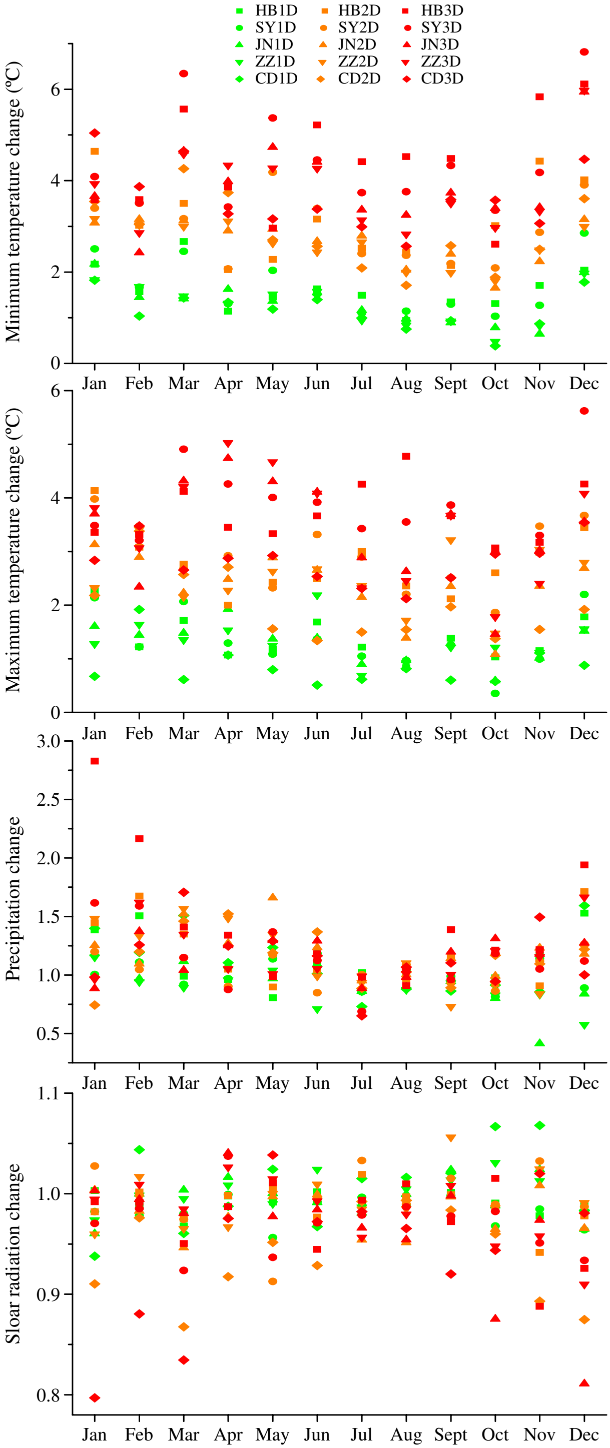


Fig. 5 Median values of projected absolute changes in monthly mean *Tmax*, *Tmin*, and relative changes in monthly mean precipitation and *Srd*, for GMT changes of 1°C (1D), 2°C (2D), and 3°C (3D), respectively, at all the stations, on basis of the 20 climate change scenarios, relative to the period of 1961–1990

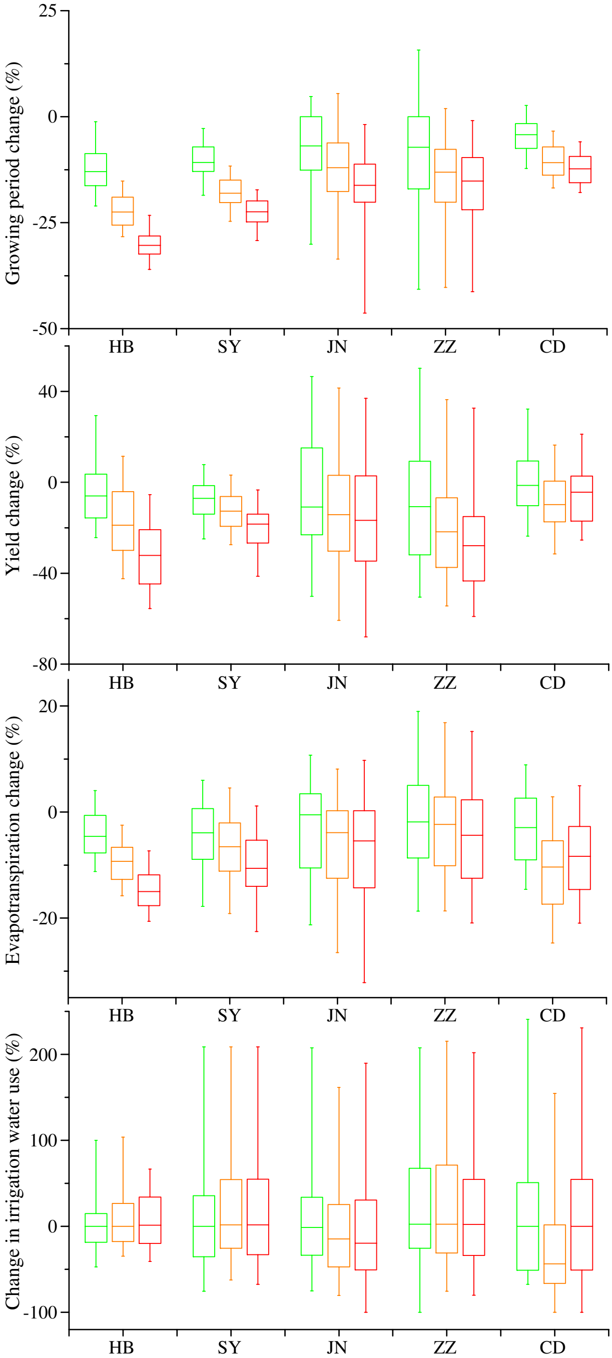


Fig. 6 Box plot of projected changes in growing period, yield, ET, and irrigation water use for irrigated maize at each study station for GMT changes of 1°C (*green*), 2°C (*orange*), and 3°C (*red*), without consideration of CO_2 fertilization effects. The *upper* and *lower hinge of the box* indicates the 75th percentile and 25th percentile of the dataset, respectively. The *line in the box* indicates the median value of the data

were from 1.6% at CD to 7.8% at SY, 10.2% at CD to 16.4% at ZZ, and 3.9% at CD to 26.6% at HB (Fig. 7). CO_2-fertilization effects could offset maize yield decrease to some extent. At CD station, the *Tmin* and *Tmax* at key growing stage (June and

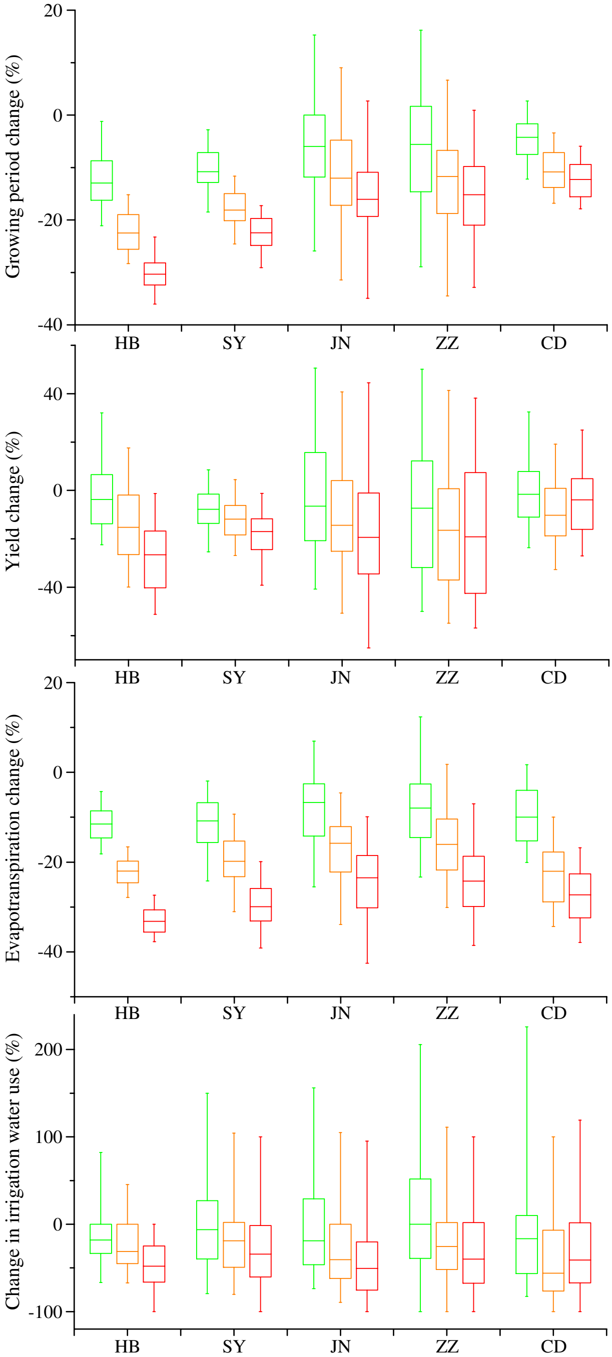


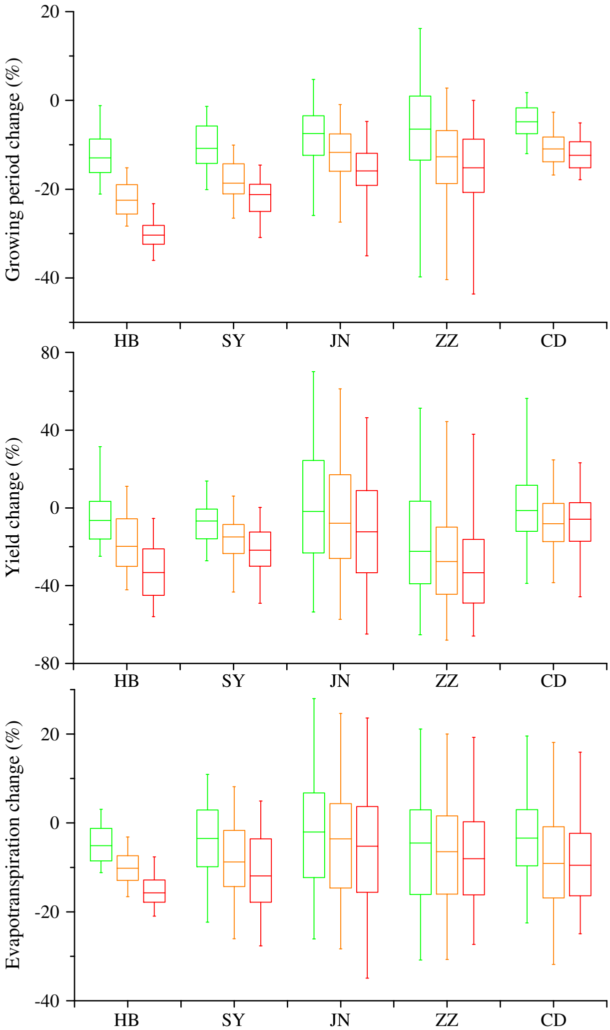
Fig. 7 As for Fig. 6 except with consideration of CO_2 fertilization effects

July) for GMT changes of 3°C were only 0.86°C and 1.01°C higher than those for GMT changes of 2°C, however precipitation was 20% less, the reason why yield could decrease more for GMT changes of 2°C.

The median values of projected decreases in ET ranged from 0.5% at JN to 4.6% at HB, 2.3% at ZZ to 10.4% at CD, and 4.4% at ZZ to 15.0% at HB for GMT changes of 1°C, 2°C, and 3°C, respectively (Fig. 6). When CO_2-fertilization effects were considered, the corresponding values were from 6.7% at JN to 11.5% at HB, 15.8% at JN to 22.0% at CD, and 23.5% at JN to 33.2% at HB (Fig. 7). Thus, rising CO_2 concentration could reduce ET greatly.

The median values of projected changes in irrigation water use ranged from −1.3% at JN to 2.5% at ZZ, −43.6% at CD to 2.4% at ZZ, and −19.6% at JN to 2.2% at ZZ for GMT changes of 1°C, 2°C, and 3°C, respectively (Fig. 6). When CO_2-fertilization effects were considered, the corresponding values were from −18.8% at JN to 0.0% at ZZ, −56.1% at CD to −18.9% at SY, and −50.6% at JN to −34.3% at SY (Fig. 7). Rising CO_2 concentration could reduce irrigation water use greatly by reducing ET.

Fig. 8 Box plot of projected changes in growing period, yield, and ET for rainfed maize at each study station for GMT changes of 1°C (*green*), 2°C (*orange*), and 3°C (*red*), without consideration of CO_2 fertilization effects. The *upper and lower hinge of the box* indicates the 75th percentile and 25th percentile of the dataset, respectively. The *line in the box* indicates the median value of the data



3.3.2 Rainfed maize

When CO_2-fertilization effects were not considered, across all the stations, the median values of projected decreases in growing period of rainfed maize ranged from 4.8% at CD to 13.1% at HB, 10.9% at CD to 22.5% at HB, and 12.3% at CD to 30.3% at HB for GMT changes of 1°C, 2°C, and 3°C, respectively (Fig. 8). The corresponding values were almost same when CO_2-fertilization effects were considered (Fig. 9). The values were also almost same as those for irrigated maize.

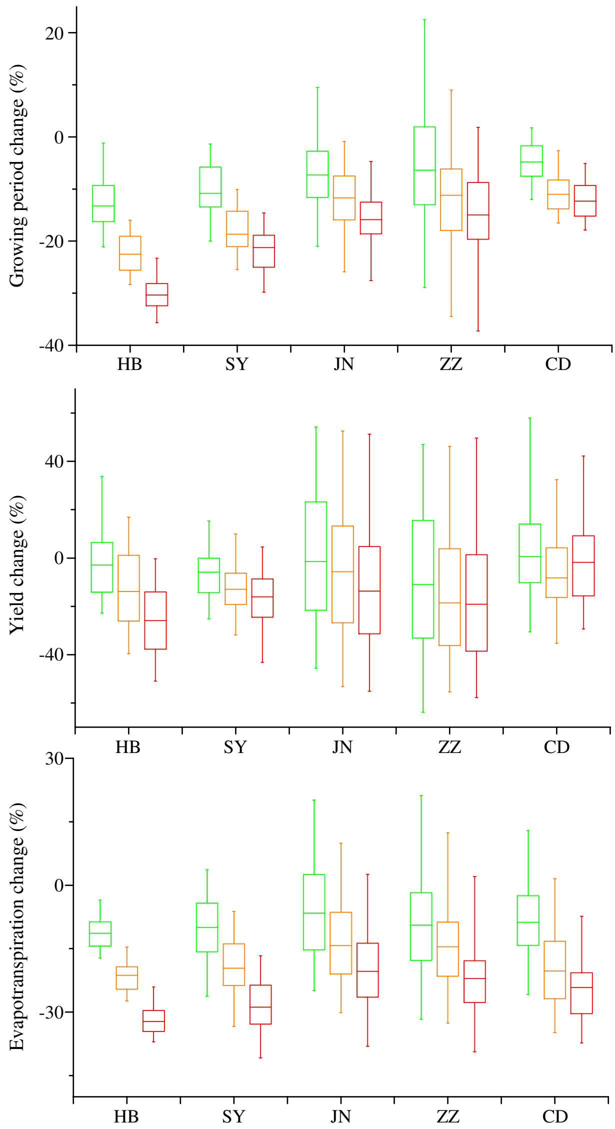


Fig. 9 As for Fig. 8 except with consideration of CO_2 fertilization effects

The yields of rainfed maize would also decrease and the degree of the reduction would increase with increasing GMT. The median values of projected decreases in yields ranged from 1.0% at CD to 22.2% at ZZ, 7.9% at CD to 27.6% at ZZ, and 4.6% at CD to 33.7% at ZZ for GMT changes of 1°C, 2°C, and 3°C, respectively (Fig. 8). When CO_2-fertilization effects were considered, the corresponding values ranged from −10.8% at ZZ to 0.7% at CD, −18.1% at ZZ to −5.6% at JN, and −25.9% at HB to −1.6% at CD (Fig. 9). CO_2-fertilization effects could increase the yield of rainfed maize more than that of irrigated maize.

The median values of projected decreases in ET ranged from 2.0% at JN to 5.1% at HB, 3.7% at JN to 10.1% at HB, and 5.2% at JN to 15.7% at HB for GMT changes of 1°C, 2°C, and 3°C, respectively (Fig. 8). When CO_2-fertilization effects were considered, the corresponding values were from 6.5% at JN to 11.3% at HB, 14.2% at JN to 21.3% at HB, and 20.2% at JN to 32.1% at HB (Fig. 9). CO_2-fertilization effects also reduced ET greatly for rainfed maize.

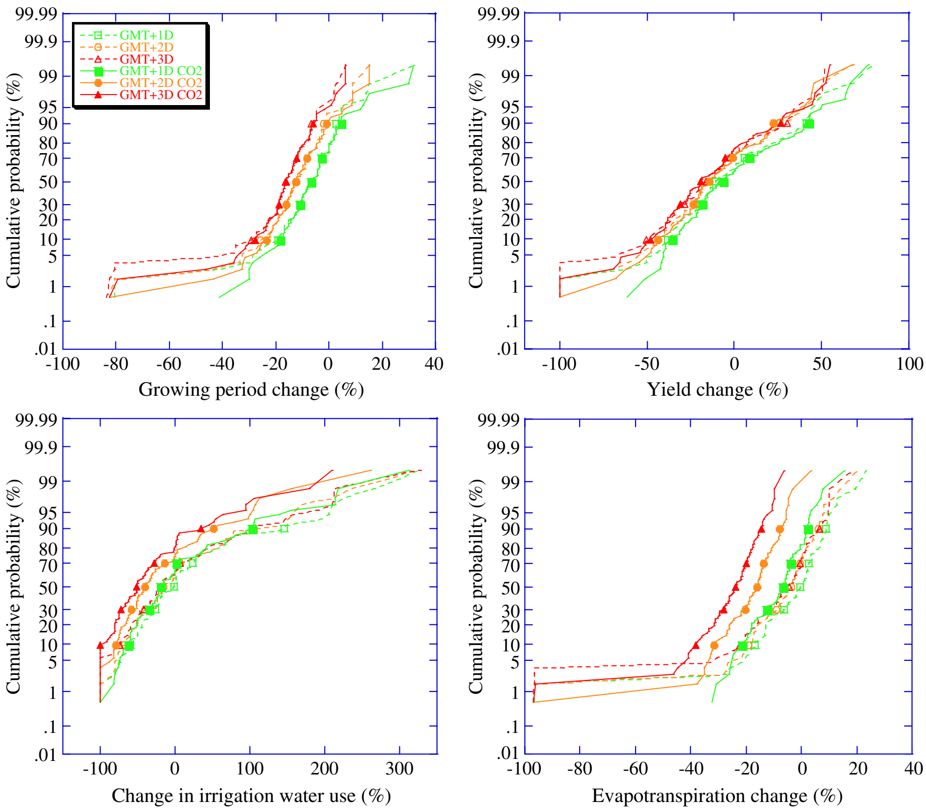


Fig. 10 Cumulative probability distribution for projected changes in growing period, yield, ET, and irrigation water use for irrigated maize at JN station for GMT changes of 1°C, 2°C, and 3°C. GMT+1D, GMT+2D, and GMT+3D represent GMT increases of 1°C, 2°C, and 3°C, respectively, without consideration of CO_2 fertilization effects. GMT+1D CO2, GMT+2D CO2, and GMT+3D CO2 represent GMT increases of 1°C, 2°C, and 3°C, respectively, with consideration of CO2 fertilization effects

3.4 Probabilistic changes in maize productivity and water use

The resultant changes could be presented in CDFs to investigate the probabilistic changes in maize productivity and water use. As an example, at JN station, for

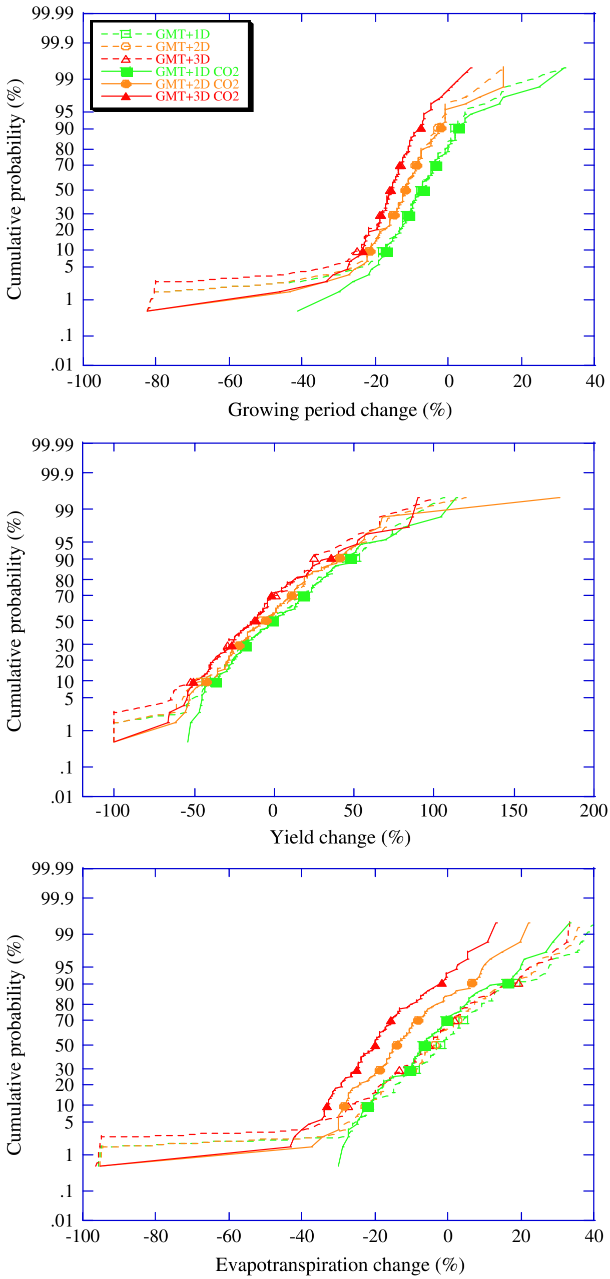


Fig. 11 Cumulative probability distribution for projected changes in growing period, yield, and ET for rainfed maize at JN station for GMT changes of 1°C, 2°C, and 3°C, respectively. The legends are as for Fig. 10

GMT changes of 1°C, 2°C, and 3°C, respectively, maize growing period would decrease with a probability of 75%, 93%, and 97%, respectively (Fig. 10); the yield of irrigated maize without (with) consideration of CO_2 fertilization effects would decrease with a probability of 61% (58%), 70% (69%), and 73% (74%), respectively (Figs. 10 and 11); the ET of irrigated maize without (with) consideration of CO_2 fertilization effects would decrease with a probability of 54% (80%), 74% (96%), and 71% (97%), respectively; the irrigation water use without (with) consideration of CO_2 fertilization effects would decrease with a probability of 53% (61%), 60% (73%), and 60% (79%), respectively. For rainfed maize at JN, the yield without (with) consideration of CO_2 fertilization effects would decrease with a probability of 52% (51%), 56% (55%), and 70% (77%), respectively; the ET without (with) consideration of CO_2 fertilization effects would decrease with a probability of 55% (71%), 64% (84%), and 66% (92%), respectively (Figs. 10 and 11).

4 Discussion

4.1 Changes in maize productivity and water use as a function of GMT

Most of previous studies derive climate change impacts against time scale (e.g. Lin et al. 2005; Lobell 2007; Xiong et al. 2007). The general shape of the damage curve expressed as a function of GMT is fundamental to derive the dangerous climate change level. Some researchers have also tried to derive such kind of impact function, however based on the sparse literatures with different assumptions, experimental designs and purposes or just roughly transferred from the impacts against time scale (e.g. IPCC 2001a; Hitz and Smith 2004; Hare 2006; Warren 2006; IPCC 2007). Increases in GMT would result in quite a large regional change in all the climate variables, although the uncertainties in climate change scenarios were considerable. Our study presents an approach to derive climate change impacts as a function of GMT using process-based crop models and multiple climate scenarios. Generally, the yields of both rainfed and irrigated maize would decrease, and the degree of the reduction would increase with increasing GMT (except at CD station). When CO_2-fertilization effects were not considered, rainfed (irrigated) maize yield would decrease averagely by 5.0% (5.3%), 13.5% (14.0%) and 19.9% (19.6%) for GMT changes of 1°C, 2°C, and 3°C, respectively. One of main reasons could be ascribed to the reduction of growing period with GMT increasing. For rainfed (irrigated) maize, the CO_2 fertilization effects could offset yield decrease averagely by 3.3% (1.9%), 4.6% (2.0%) and 6.5% (3.4%) for GMT changes of 1°C, 2°C, and 3°C, respectively. Recent re-analyses of Free-Air Carbon Dioxide Enrichment studies indicate that, at 550 ppm atmospheric CO_2 concentration, yields increase under unstressed conditions by 10–25% for C3 crops, and by 0–10% for C4 crops (IPCC 2007). For C4 crops such as maize, ribulose-1,5-bisphosphate carboxylase-oxygenase (RuBisCO) is localized to bundle sheath cells in which CO_2 is concentrated to three to six times atmospheric CO_2 (von Caemmerer and Furbank 2003). This concentration is sufficient to saturate RuBisCO and in theory would prevent any increase in CO_2 uptake with rising CO_2. Although C4 crops may not show a direct response in photosynthetic activity, an indirect increase in the efficiency of water use via reduction in stomatal conductance may still increase yield (Long et al. 2004). For both rainfed and irrigated maize, ET would also decrease, and the degree of the reduction would generally increase with increasing GMT. When CO_2-fertilization effects were not considered, the ET of rainfed (irrigated) maize could decrease averagely by 4.1% (3.8%), 7.7% (7.5%), and 10.0% (9.6%) for GMT changes of 1°C, 2°C, and 3°C, respectively. Rising CO_2 could reduce stomatal conductance and subsequently reduce ET of rainfed (irrigated) maize by 4.8% (6.1%), 10.0% (12.2%), and 15.4% (18.5%) for GMT changes of 1°C, 2°C, and 3°C, respectively. The average changes in irrigation water use with CO_2 fertilization effects were 1.9%, −20.3%, and −30.8% for GMT changes of 1°C, 2°C, and 3°C, respectively. The decrease in ET could be one of main reasons for decrease in irrigation water use. In addition, the decrease in ET and irrigation water use could also be ascribed to the reduction of growing period and increased precipitation.

4.2 Assessing the impacts of climate change in a probabilistic framework

Previous projections on maize productivity in China have quite a wide range, depending on the crop models, GCMs and emission scenarios used. As examples, Wang and Lin (1996), using CERES-Maize model and there climate scenarios from doubled CO_2 simulations of three GCMs (i.e., GFDL, MPI and UKMO), showed that across 35 investigated sites in China, maize yields would change from −19% to 5% without CO_2 fertilization effects, primarily because of increases in temperature, which could reduce maize growing period, particularly the grain-filling period. Based on CERES-Maize model and three climate scenarios from doubled CO_2 simulations of three GCMs (i.e., GISS, GFDL and UKMO), Fischer et al. (1996) showed that maize yield could decline much in many countries with direct CO_2 effects, probably due to its lower response to the physiological effects of CO_2 on crop growth. Using CERES-Maize model and the A2-based and B2-based climate scenarios from a regional climate model, previous studies, Lin et al. (2005) showed that average rainfed maize yield would change by 1.1–9.8% (−11.3% to −10.3%), 8.5–18.4% (−14.5% to −22.8%), and 10.4–20.3% (−26.9% to −36.4%) during 2020s, 2050s, and 2080s, respectively, with (without) CO_2 fertilization effects. For irrigated maize, average yield would change by −0.1% to −0.6% (0.2% to −5.3%), −1.3% to −2.2% (−0.4% to −11.9%), and −2.2% to −2.8% (−3.8% to −14.4%) during 2020s, 2050s, and 2080s, respectively, with (without) CO_2 fertilization effects. Using the same model and climate scenarios, Xiong et al. (2007) showed that maize productivity in the North China Plain would decrease by up to 25% under irrigation condition; however rainfed maize productivity would increase by up to ≥50% during 2080s because of CO_2 fertilization effects. The CO_2 fertilization effects posed a 9–15% production increase compared to those without CO_2 effects in their study (Xiong et al. 2007). Using regression model at national scale, Lobell (2007) showed that maize yield in China would change from about −6% to about 10% during 2046–2065. Tao et al. (2009), using crop model MCWLA and 10 climate scenarios, indicated expected rainfed maize yield changes of −9.7% to −9.1%, −15.7% to −19.0%, and −24.7% to −25.5% in North China Plain during 2020s, 2050s and 2080s, respectively, in percent of 1961–1990 yields. The uncertainties mentioned above warrant the necessity of probabilistic projections using multiple climate scenarios and/or crop models. Approximate comparisons showed that projected maize yield losses in the study were larger than previous estimates, particularly for rainfed maize. Although based on the same CERES-Maize crop model, the final results can be different due to the use of different climate scenarios, modeling scales, inputs data such as soil properties and experiment settings. The resultant range of changes in the study encompassed a wide range of the previous estimations; moreover, the probabilistic assessment provided not only the range of changes but also the probabilistic information.

To address the uncertainties from GCMs and emission scenarios, previous studies driven impact assessment model using number of climate scenarios (e.g. Lobell 2007; Tao et al. 2009), estimated probabilities of climate variables changes (e.g. Tao et al. 2008a; Tebaldi and Lobell 2008) or using multi-model based ensemble prediction (e.g., Cantelaube and Terres 2005; Challinor et al. 2005; Marletto et al. 2005). In the study, we adopted the median values of projected changes in monthly mean *Tmax*, *Tmin*, precipitation and *Srd* on basis of 20 alternative future climates, which should be the most likely scenario because each of the 20 climate scenarios is treated as equally likely (Mitchell et al. 2004). This is an effective and simple way to deal with the uncertainties in climate change scenarios and to feed process-based impact models, although the most likely scenario does not cover the full range of projections by all the GCMs.

4.3 Uncertainties of the study

In the present study, the climate-change scenarios were assumed to be equally reliable, despite recent efforts to provide probability density functions for multiple models (e.g., Giorgi and Mearns 2003; Murphy et al. 2004). Although the ranges of projected changes in climate variables were investigated, only the median values have been applied, as a result, the impacts of some extreme climate events may not be included. The climate scenarios used were downscaled into 0.5° grids from GCM outputs with relatively coarse resolutions. And climate change was assumed to be homogenous within a 0.5° grid. The possible future changes in multi-decadal or interannual variability were not included in the scenarios. The uncertainties can also stem from the crop model and its parameterizations. Furthermore, adaptation is a key factor that will shape the future severity of climate change impacts on food production (IPCC 2007). The biggest benefits will result from the development of new crop varieties. In the present study, some adaptation options, including shifts in planting dates and automatic application of irrigation and fertilization, were considered, although the cultivars were assumed to be constant over the baseline and future. In fact, the adoption of more temperature-tolerant cultivars and later-maturing cultivars to take advantage of longer growing seasons can be feasible in future, which, to some extent, can reduce yield loss due to climate change. The results of the study can be constrained by these uncertainties.

5 Conclusion

We developed an approach to derive climate change impacts as a function of GMT using process-based crop models and multiple climate scenarios. The resultant impacts function is fundamental to define the criteria of ‘dangerous anthropogenic inference with the climate system’ in terms of food security.

The median values of projected decreases in the yields of irrigated maize without (with) consideration of CO_2-fertilization effects ranged from 1.4% to 10.9% (1.6% to 7.8%), 9.8% to 21.7% (10.2% to 16.4%), and 4.3% to 32.1% (3.9% to 26.6%) for GMT changes of 1°C, 2°C, and 3°C, respectively; the median values of projected changes in irrigation-water use without (with) consideration of CO_2-fertilization effects ranged from −1.3% to 2.5% (−18.8% to 0.0%), −43.6% to 2.4% (−56.1% to −18.9%), and −19.6% to 2.2% (−50.6% to −34.3%); the median values of projected changes in the yields of rainfed maize without (with) consideration of CO_2-fertilization effects ranged from −22.2% to −1.0% (−10.8% to 0.7%), −27.6% to −7.9% (−18.1% to −5.6%), and −33.7% to −4.6% (−25.9% to −1.6%). As a C4 crop, for rainfed (irrigated) maize, the CO_2 fertilization effects offset yield decrease averagely by 3.3% (1.9%), 4.6% (2.0%) and 6.5% (3.4%) for GMT changes of 1°C, 2°C, and 3°C, respectively; in contrast, rising CO_2 could reduce ET by 4.8% (6.1%), 10.0% (12.2%), and 15.4% (18.5%). Approximate comparisons showed that projected maize yield losses were larger than previous estimates, particularly for rainfed maize.

Changes in crop productivity and water use as a function of GMT may be crop- and region- specific, which, among other things, depends the regional climate change associated with GMT changes. The methods developed in the study are widely applicable. The study can be further improved by inputting multi-model ensemble-based probabilistic climate change scenarios and including all the potential adaptation options.

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