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Simulating impacts of climate change on cotton yield and water requirement using RZWQM2

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A R T I C L E I N F O

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A B S T R A C T

Assessing the potential impacts of climate change on cotton (*Gossypium hirsutum* L.) yield and water demand is crucial in allocating water resources. In this study, cotton yield and water requirement under future climate scenarios was evaluated in Qira oasis, China. Six general circulation models (GCMs), under moderate and high representative concentration pathway (RCP) scenarios (4.5 and 8.5) and elevated CO_2 (eCO_2) concentration (218–502ppm), were used to project climate for near (2041–2060) and far future (2061–2080) periods. With current management practices, the impacts of climate change on cotton yield and water requirement were simulated using the Root Zone Water Quality Model (RZWQM2), which was calibrated with experimental data (2007–2014) in a previous study. For the study region, the GCMs predicted an increase of 2.38°C and 3.24°C in temperature and 3.5% and 5.3% mm in precipitation during the growing seasons (April–October) for 2041–2060 and 2061–2080, respectively. For 2041–2060, seed cotton yield was projected to increase by 0.24Mg ha^{-1} (5.6%) under RCP4.5 and 0.19Mg ha^{-1} (4.5%) under RCP8.5 comparing to the baseline yield of 4.23Mg ha-1; however, for 2061–2080, the model predicted a 0.32Mg ha^{-1} (7.6%) yield increase under RCP4.5 but a 0.28Mg ha^{-1} (6.5%) decrease under RCP8.5. The increased cotton yield was mainly attributable to the fertilization effect of eCO_2 dominating the detrimental effects of shorter growing seasons (8.0–9.5 days). Alleviated low temperature stress also slightly promoted cotton yield. Averaged across the RCP4.5 and RCP8.5 scenarios, simulated cropping season water requirement for the 2041–2060 and 2061–2080 were 728mm and 706mm, respectively, an decrease by 7.5% and 10.3% relative to the present day baseline (786mm), respectively. This decrease was attributed to shorter growing seasons and eCO_2. These results suggest that the region's agricultural water crisis may be alleviated in the future.

1. Introduction

According to the 5th Assessment Report of the Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change (IPCC, 2014), global warming has occurred in the recent past and will continue during the 21st century. Associated with the accumulation of greenhouse gases, climate change is expected to decisively affect agricultural production. Cotton (*Gossypium hirsutum* L.) is a major irrigated cash crop in China's Xinjiang province, which accounts for 70% and 80%, respectively, in terms of national cotton production and acreage (National Bureau of Statistic of China, 2018). With the steep rise in the cost of irrigation water in 2016, farmers' enthusiasm for planting corn (*Zea mays* L.), wheat (*Triticum æstivum* L.) and vegetable crops declined. In contrast, as a drought-tolerant crop, cotton is suitable for growing in regions with high soil salinity and/or low irrigation availability. Accordingly, a potential increase in cotton acreage is expected in Xinjiang. In a comprehensive assessment of agriculture and water management in the Upper Tarim River basin, which took into account irrigation and

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river transmission losses, Huang et al. (2018) warned of the risk of decreasing river discharge by the end of the 21st century if the area devoted to agricultural continued to expand. Using Ricardian method, Wang et al. (2009) analyzed the effects of temperature and precipitation on net crop revenues (wheat, maize, and rice) in China, and showed that global warming and the projected increase in precipitation were likely to benefit irrigated farms, as it would be profitable for farmers to switch from irrigation to rain-fed agriculture and thereby save on irrigation costs. However, depending on regional conditions and crop cultivars, climate change may have a negative impact on crop production, although cereal production is projected to increase with the fertilizing effect of eCO_2 in Northwest, China (Piao et al., 2010).

The impact of increased temperature and eCO_2 on crop development has also extensively studied. Changes in temperature and eCO_2 have modified crop phenology (Badeck et al., 2004; Tao et al., 2006; Doi and Katano, 2008). Current cotton cultivars' growth period has shortened due to rising temperatures (Wang et al., 2008; Gérardeaux et al., 2013; Wang et al., 2017). Phenological changes lead to changes in cotton water requirement, yields and water use efficiency, especially in semi-arid and arid regions. The results of several investigators (Chun et al., 2011; Bassu et al., 2014; Liu et al., 2019), covering a wide range of crops and regions, indicated that eCO_2 could increase the crop dry matter accumulation and enhance crop yield due to increasing photosynthesis and reduce crop water requirement by decreasing stomatal conductance and transpiration. In C_3 plants, an increase in the CO_2/O_2 ratio at the chloroplast caused by eCO_2 improve the efficiency of net carbon gain through acceleration of the carboxylation reaction and inhibition of the oxygenation reaction (Ogren, 2003). In C_4 plants, significant enhancement of photosynthesis and growth by eCO_2 occurs only under water stress conditions (Morgan et al., 2011). The fertilization effect of eCO_2 on C_3 crop (*e.g.*, wheat, soybeans, cotton) was more significant than C_4 crop (*e.g.*, corn, sorghum). However, photosynthetic rate would decrease when the air temperature exceeded a maximum temperature (Erice et al., 2011). Li and Zhou (2015) reported that within Xinjiang province water requirement for cotton would decrease in the future. Attavanich and McCarl (2014) also predicted that a 65% to 96% increase in cotton yields would occur due to the overriding effect of CO_2 fertilisation. Similarly, Williams et al. (2015) reported that by 2030 the effects of CO_2 fertilisation would counteract the effect of decreased water availability and yield would increase by 5.9% (*vs.* the present); however, by 2050 cotton yield would decrease by 3.6%, as the change in climatic parameters would then outweigh the benefits of CO_2 fertilisation. In contrast, other studies have revealed that increased temperature and changes in precipitation would offset the positive impacts of CO_2 fertilisation on crop yield (Hatfield et al., 2011; Paz et al., 2012; Hatfield and Prueger, 2015), especially under extreme heat. Studying the impact of climate change on cotton production in three major cotton-producing regions of China between 1961 and 2010, Chen et al. (2015) found that increase in average temperature by 1°C increased cotton yields by 0–13.7% in both the northwest region and the Yellow River valley, where greater precipitation was expected. However, a decrease in diurnal temperature range would reduce cotton yield in some provinces. Using the Infocrop model to simulate the impact of climate change on cotton production in India under different emission scenarios (A2, B2 and A1B), Hebbar et al. (2013) found that the projected higher temperature and lower precipitation might decrease cotton yield in northern India, while eCO_2 would have no significant effects on cotton production. The uncertainties in current studies arise from the wide range of climatic and agricultural systems models, scenarios, and sites used.

The effects of climate change on crop production have been studied through laboratory control experiment, field CO_2 enrichment trials, long-term on-site observation, and model simulation. Compared with laboratory or field studies, models have the advantage of being low cost, high efficiency, and affording an easy control of variables. Agricultural systems models are vital tools for evaluating the impact of climate change on crop water demand and yield as they comprehensively consider various environmental factors, which are difficult to control in the field (Webber et al., 2017; Shelia et al., 2019). One of the crop simulation models used for assessing climate change effects on cotton water requirement and yield is the Agricultural Production Systems Simulator (APSIM) model. Yang et al. (2014) used the APSIM-OzCot crop growth model to evaluate the response of cotton phenology, yield and water use to climate change under the HadCM3 Global Climate Model at Alaer and Shihezi, Xinjiang, China. Their results showed shorter growing seasons and higher yield before 2070 due to the fertilization effect of eCO_2. However, a decline in yield was simulated in the late 21st century due to a severe shortening of growth periods. Compared to single-model approaches, multiple climate models were found to provide a more representative range of climate change impacts (Tao et al., 2009; Kassie et al., 2015; Araya et al., 2015). In addition, DSSAT model appeared to be the most appropriate as it combines an acceptable set of physiological bases (Gérardeaux et al., 2013). Rahman et al. (2018), integrating 29 GCMs under RCP4.5 and RCP8.5 scenarios, used the DSSAT model to evaluate the potential impacts of climate variability on cotton production in Pakistan. Under RCP4.5 and RCP8.5, the simulated cotton seed yield decreased by 8% and 12%, respectively, for year 2039, and 20% and 30% for year 2069, relative to the baseline (1980–2010). Others (Voloudakis et al., 2015; Gérardeaux et al., 2013; Adhikari et al., 2016) reported climate change impacts on cotton production using the AquaCrop crop simulation model and the CSM-CROPGRO-Cotton model.

Another system model used to project climate change effects on crop production is the Root Zone Water Quality Model (RZWQM2) (Ko et al., 2012). Wang et al. (2015) assessed the potential effects of climate change and eCO_2 on NO_3^-N losses and crop production using the RZWQM2 model. Using the RZWQM2 model to simulate climate change effects on corn production under current management practices including full or deficit irrigation regimes, Ma et al. (2017) showed that by the end of the 21st century maize yield and biomass would decrease. However, studies evaluating the RZWQM2 model's ability to simulate cotton phenology, yield and water requirement in response to future climate change are sparse. In addition, the stomatal resistance parameter in the Shuttleworth-Wallace equation that computes potential crop transpiration, as well as the photosynthetic rate of C_3 crops, are both affected by atmospheric CO_2 concentration ($[CO_2]_{atm}$). Therefore, it possesses an advantage to assess the effects of climate change on evapotranspiration and biomass accumulation as simulated by RZWQM2 model.

Agricultural water use accounts for the largest proportion (97.7%) of total water requirement in the Qira oasis. Approximately a quarter of irrigation water is extracted from groundwater (Hotan Water Resources Planning, 2013), which is directly pumped into water channels to flood-irrigate the farmlands. Given such unsustainable farmland irrigation and water management strategies, the annual average water shortage in the Qira oasis ranges from 5.2 to $11.5 \times 10^6 m^3$. Agricultural production contributes over 80% of the region's total Gross Domestic Product (GDP). Water demand for cotton, one of the main agricultural crops in the region, is mainly concentrated from April to August. However, there is lack of structures to store seasonal snowmelt water in early spring to meet the demand of local irrigation water demand in summer. To maintain agricultural production, farmers have intensified their exploitation of groundwater. Quantification of projected climate change impacts on cotton yield becomes particularly important for arid regions with a wide distributed planting acreage (Bange et al., 2010). To sustain the production of cotton in arid regions, it is imperative to understand the impacts of changes in temperature, precipitation, and $[CO_2]_{atm}$ on cotton yield and cotton crop water requirement. In this paper, we used the calibrated and validated RZWQM2 model which provided readily available crop and soil parameters (Liu et al., 2017), coupled with future climate change projections drawn from six GCMs under RCP4.5 and RCP8.5 scenarios and eCO_2. Six GCMs climate projections

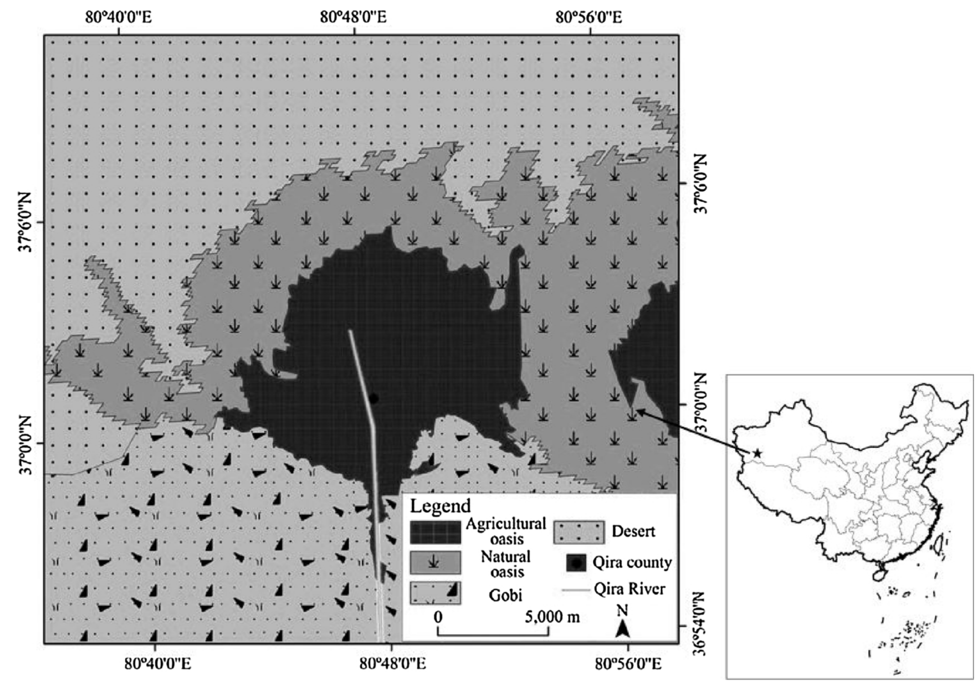

Fig. 1. Location of the Qira agricultural oasis (Xue et al., 2017a).

simulated temperature and rainfall well in China were selected in this paper (Wu et al., 2013; Jiang and Wu, 2013; Chen and Frauenfeld, 2014). The six GCMs includes BCC-CSM1-1 (BC), CCSM4 (CC), CNRM-CM5 (CN), MIROC5 (MC), MRI-CGCM3 (MG), and MPI-ESM-LR (MP). Therefore, the objectives of the study was (*i*) to quantify the effects of climate change on cotton production and crop water requirement; and (*ii*) to assess climate change impacts and propose adaptation strategy in extremely arid regions.

2. Materials and methods

2.1. Study region

Located on the southern rim of the Taklimakan Desert, Xinjiang, Northwest China, and extending over an area of 274km^2, the Qira oasis (36°54'N-3709'N, 8037'E-8059'E; Fig. 1) was selected to represent an extremely arid region, for which changes in cotton yield and water requirement under a projected future climate could be assessed. The annual mean temperature and precipitation are 15.85°C and 42.62mm (1955–2000), respectively, and the free water surface evaporation is 2700mm. The soil texture is a fine sand. The water supply to the Qira oasis region depends strictly on endorheic river discharge, which comes from a high altitude valley in the Kunlun Mountains (Xue et al., 2017a,b). Average annual runoff of Qira River is approximately 1.23×10^8m^3 (1957–2008). Compounded by the extension of farmlands, the Qira River's 0.285×10^6m^3 decline in annual runoff between 1957 and 2008 has incited enormous challenges to agricultural water management in this region. Increased agricultural water demand causes the lower reaches of the Qira River to frequent dry up.

2.2. RZWQM2 model description

In the present study, the RZWQM2 model (a hybrid model between RZWQM and DSSAT4.0) was used to evaluate the effect of climate change on cotton water requirement and production. As a process-oriented agricultural system model, RZWQM2 can simulate long-term effects of management and climate change on carbon/nitrogen cycles and soil-water-plant processes (Ahuja et al., 2000). Management practices simulated in the model mainly includes crop variety selection, planting and harvesting operations, fertilizer, tillage, and irrigation. Cotton yield was simulated based on photothermal unit accumulation from planting to harvest using the CSM-CROPGRO-COTTON model (DSSAT v4.5) incorporated into RZWQM2 (Tsuji et al., 1998). Crop yield is calculated from biomass allocated to growing organs, which is affected by the amount of light intercepted by plants growing within an optimum temperature range. The effect of CO_2 on cotton photosynthesis follows the Michaelis-Menten equation (Islam et al., 2012a). Optimal upper limited air temperature for cotton growth is 35°C. The cardinal base and optimum temperatures for cotton development and reproduction are 16.5°C (after emergence) and 33°C, respectively. The temperature stress factor (F_T) in CSM-CROPGRO-COTTON model is given in Boote et al. (1998). The formula of F_T is given as:

$$F_T = \begin{cases} \dfrac{T - T_B}{T_{o1} - T_B} & T < T_{O1} \\ 1 & T_{O1} \le T \le T_{O2} \\ 1 - \dfrac{T - T_{o2}}{T_M - T_{o2}} & T > T_{O2} \end{cases} \tag{1}$$

Where T is the ambient temperature; T_B is the base temperature; T_{O1} is the lowest temperature at which maximum rate is attained; T_{O2} is the upper temperature at which maximum rate is sustained; T_M is the maximum air temperature.

The RZWQM2 model was calibrated and validated using 2007 to 2014 crop and soil parameters from a previous field experiment in Cele National Station of Observation & Research for Desert-Grassland Ecosystems, Chinese Academy of Sciences (37°01'N, 80°43'E) located in the Qira Oasis. In this study, the parameters used in the RZWQM2 model are consistent with those in Liu et al. (2017) which presented details in the calibration and validation of RZWQM2 for the Qira Oasis. The experimental field plot, characterized by a fine sand, measured 150m (north-south) ×140m (east-west). Cotton (cv. 'Ceke No. 1') was planted at a 0.3m interrow spacing at an average rate of 40 plants m^{-2}. With the exception of climate variables (T°_{max}, T°_{min}, and precipitation) and $[CO_2]_{atm}$, all other parameters and agricultural management practices for the projected future climate scenarios were identical to those implemented during the baseline period. Planting date was set at Apr. 11 each year, the average planting date of the 2006–2015 field experiments. Harvest date was set as the date of maturity (100% open

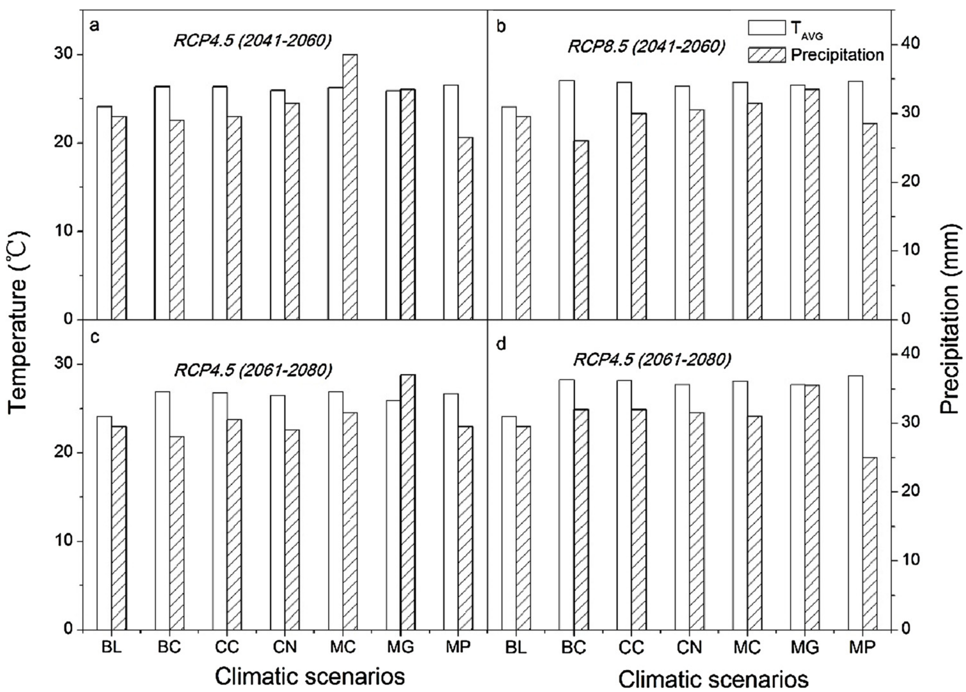

Fig. 2. Growing season (Apr.-Oct) average temperature and overall precipitation projected for 2041–2060 (a, b) and 2061–2080 (c, d) derived from future climate models under the RCP4.5 and RCP8.5 scenarios. T_{AVG}, average temperature; BL, baseline; BC, BCC-CSM1-1; CC, CCSM4; CN, CNRM-CM3; MC, MIROC5; MG, MRI-CGCM3; MP, MPI-ESM-LR.

bolls).

The crop water requirement was assumed to be equivalent to ET_{pot}, which in this case was computed using RZWQM2 by assuming no water and no nitrogen stresses, thereby precluding its interaction with climate change for both historical and future climate scenarios. In the RZWQM2 model, the Shuttleworth-Wallace equation, a modified Penman-Monteith equation, is used to calculate the ET_{pot}. Increased $[CO_2]_{atm}$ reduces transpiration due to an increase in stomatal resistance and increases yield due to an increased photosynthetic rate for cotton (Islam et al., 2012a). Decreased potential transpiration demand caused by eCO_2 was considered in RZWQM2 model. The decrease in potential transpiration decreases root water uptake and actual transpiration, and reduces plant water stress (Islam et al., 2012b). Cotton (early maturity) was planted at a 0.3m interrow spacing and 0.04m planting depth.

2.3. Meteorological data

Observed historical meteorological data, including daily T°_{max}, T°_{min}, shortwave (or 'solar') radiation (R_s), wind speed (v), relative humidity (RH) and precipitation (P) from 1970 to 2000, were downloaded from the China Meteorological Data Sharing Services System (CMDSSS, http://data.cma.cn/). The Brock method (Brock, 1981) was used to convert sunshine hours (n) into R_s (MJ m^{-2}). Changes in weather variables were calculated by subtracting the monthly averages of simulated historical weather data from the monthly average of simulated future climate data. Subsequently, those monthly changes of each GCMs were superimposed to the observed historical weather data to generate future weather data. The monthly observed historical weather parameters during 1970–2000 (April 1 to Oct 31) were listed in Supplemental material Table A1.

Monthly T°_{max}, T°_{min}, and$P$ of future climate under RCP4.5 and RCP8.5 scenarios with a 5' longitude/latitude degree spatial resolution was obtained from the World ClimGlobal climate dataset (http://worldclim.org/), which houses bias-corrected global gridded layers (Hijmans et al., 2005). The data available are the most recent GCMs climate projections used in the Fifth Assessment IPCC report for four RCPs. In contrast with the Special Report on Emission Scenarios (SRES), the RCPs considered the impact of human responses to climate change in response to future emission scenarios. Among the RCP2.6, RCP4.5, RCP6.0 and RCP8.5 scenarios, the RCP2.6 scenario represents low emissions, the RCP4.5 and RCP6.0 scenarios represent medium emissions, and the RCP8.5 represents high emissions (van Vuuren et al., 2011); accordingly, the RCP4.5 and RCP8.5 scenarios were selected for this study. The increase in projected monthly T°_{max} and T°_{min} and P were superimposed onto the daily baseline (1970–2000) to serve as future climate variables. Absolute/relative (percentage) changes in R_s, v, and RH of projected future climate scenarios were small to negligible (Wang et al., 2015), so these meteorological parameters were assumed to remain unchanged. Each climate scenario model was run separately using the RZWQM2 model to simulate cotton growth and production. The $[CO_2]_{atm}$ was set to 330ppm for the baseline period. Under RCP4.5 and RCP8.5 scenarios, the $[CO_2]_{atm}$ was set to 548ppm and 628ppm for the 2041–2060 period, and 631ppm and 832ppm for 2061–2080 period, respectively. More details about future climate data used in RZWQM2 are given in Supplemental material Tables A2-A3.

2.4. Management practices for adaptation strategy

Various cotton cultivars and planting dates were fed into RZWQM2 model to optimize cotton yield under future climate in this region. Six cotton cultivars in the DSSAT-CSM-cotton model database were tested using default parameters in the database, which were listed in Supplemental material Table A4. Planting dates of 10, 20, 30, 40 days before, or 10, 20 days after the original planting date (April 11th) were selected when running the RZWQM2 model.

2.5. Statistical analysis

The PROC ANOVA procedure of SAS 9.2 software was used to determine the significance of mean difference in seed cotton yield, ET_{pot}, and water use efficiency (WUE) as affected by climate change. Difference was considered significant at $P < 0.05$ level using Duncan's Multiple Range Test. For this purpose, we assumed that year to year values of seed cotton yield, ET_{pot}, and WUE were statistically independent, as we simulated each climatic scenarios separately.

3. Results

3.1. Projected future climate scenarios

The predicted future climates showed increasing trends for both air temperature and precipitation. The baseline average T°_{max} and T°_{min} during the growing season (April 1 to Oct 31) were 27.67°C and 20.58°C, respectively, and precipitation was 29.5mm. For 2041–2060, the mean temperature during the growing season increased by 1.78–2.24°C and 2.46–2.94°C under the RCP4.5 and RCP8.5 scenarios, respectively (Fig. 2a and b). In contrast, for 2061–2080, the mean projected temperature increased by 1.82–2.81°C and 3.56–4.55°C under RCP4.5 and RCP8.5 scenarios, respectively (Fig. 2c and d). Precipitation was projected to increase by 6.5% and 1.7% for 2041–2060 under RCP4.5 and RCP8.5 scenarios, respectively, whilst for 2061–2080, the increase in precipitation was 4.8% and 5.7%, respectively.

3.2. Climate change impact on cotton phenology

The RZWQM2 model simulated cotton maturity was 8 days earlier than the baseline scenario for 2041–2060 and 9.5 days earlier for 2061–2080, when averaged across all climatic models and RCP scenarios. A plot of cotton post-sowing development stages for 2041–2060 and 2061–2080 (Fig. 3a-d), shows that for both these future periods, mean cotton emergence occurred 2 and 3 days earlier under the RCP4.5 and RCP8.5 scenarios, respectively. Likewise, under the RCP4.5 and RCP8.5 scenarios, the mean flowering stage was shortened by 5 and 6 days for 2041–2060, respectively, and the time to flowering for 2061–2080 was shortened by 6 and 8 days, respectively (Fig. 3e-h). The simulated mean boll cracking stage was shortened by 7 and 9 days for 2041–2060, and 8 and 11 days for 2061–2080 under RCP4.5 and RCP8.5 scenarios, respectively (Fig. 3i-l).

3.3. Seed cotton yield response to future climate change

The RZWQM2 predicted a future increase in cotton yield, except for the 2061–2080 period under the RCP8.5 scenario. The simulated average seed cotton yield under the baseline was 4.23Mg ha^{-1}. An increases (*vs.* baseline) of 0.24Mg ha^{-1} (5.6%) and 0.19Mg ha^{-1} (4.5%) were found for the average seed cotton yield for the 2041–2060 period under RCP4.5 and RCP8.5 scenarios, respectively (Fig. 4a, b). For the 2041–2060 period, the simulated average seed cotton yield under CN and MC climatic models were significantly higher than other climatic scenarios. However, simulated average seed cotton yield for 2061–2080 increased by 0.32Mg ha^{-1} (7.6%) under the RCP4.5 scenario (Fig. 4c), but decreased by 0.28Mg ha^{-1} (6.5%) under the RCP8.5 scenario, with a maximum reduction of 0.73Mg ha^{-1} (17.3%) for the MP climate model (Fig. 4d). For the 2061–2080 period under the RCP4.5 scenario, the simulated average seed cotton yield under BC and MG climatic models was significantly higher than other climatic scenarios. The simulated average seed cotton yield under MP climatic model was significantly lower than other climatic scenarios for 2061–2080 under RCP8.5.

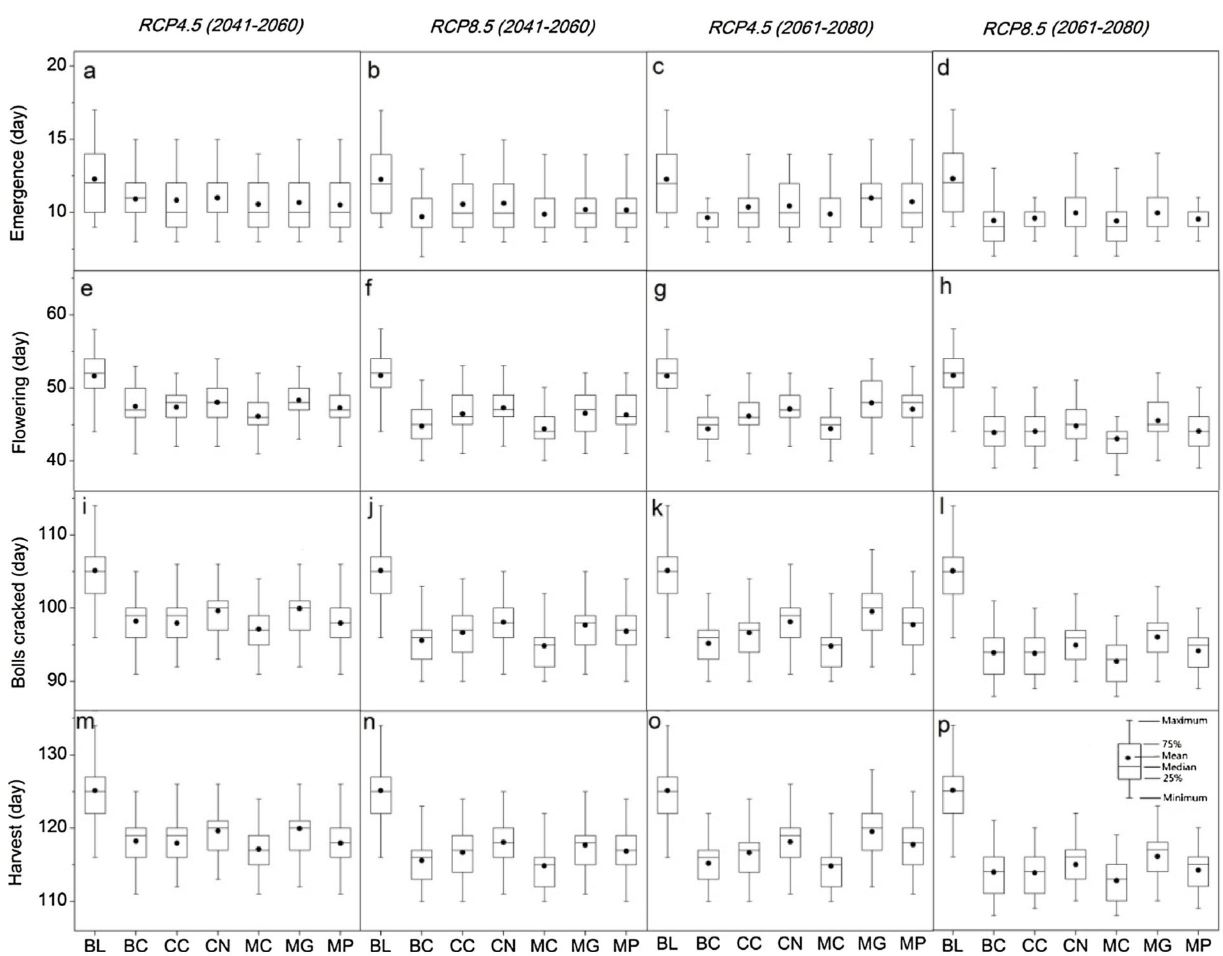

Fig. 3. Projected attainment of cotton phenological stages under future climates, using the RCP4.5 and RCP8.5 scenarios. BL, baseline; BC, BCC-CSM1-1; CC, CCSM4; CN, CNRM-CM3; MC, MIROC5; MG, MRI-CGCM3; MP, MPI-ESM-LR.

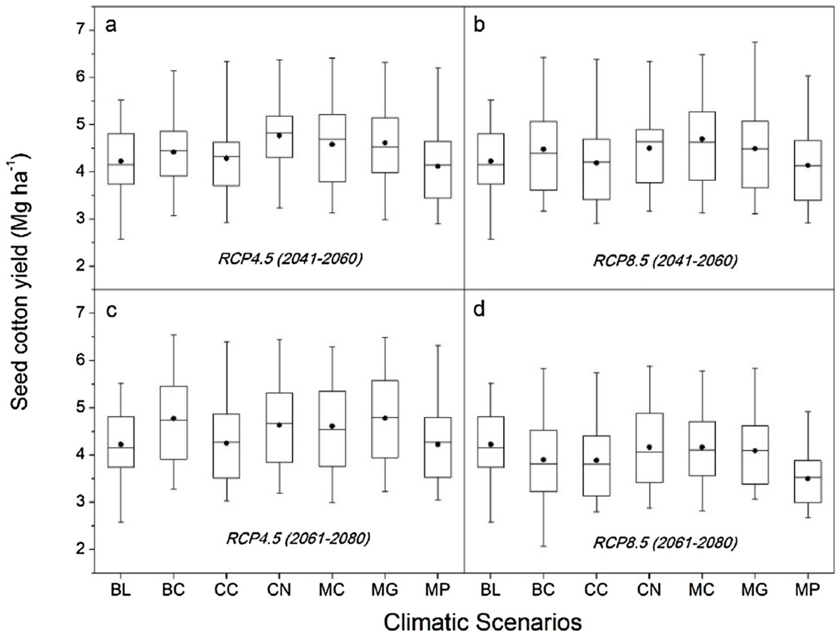

Fig. 4. Seed cotton yield projected for 2041–2060 (a, b) and 2061–2080 (c, d) by different climatic scenarios. BL, baseline; BC, BCC-CSM1-1; CC, CCSM4; CN, CNRM-CM3; MC, MIROC5; MG, MRI-CGCM3; MP, MPI-ESM-LR.

3.4. Simulated crop water requirement under future climate change scenarios

The simulated average cotton water requirement from sowing to maturity (Table 1) declined from 786mm at baseline, to 735mm in 2041–2060 and 693mm in 2061–2080. Compared to the baseline, the simulated ET_{pot} for 2041–2060 decreased by 51mm (7%) under the RCP4.5 scenario, and 65mm (8%) under the RCP8.5 scenarios when averaged six GCMs. Relative to the baseline, the simulated ET_{pot} for 2061–2080 decreased by 68mm (9%), and 93mm (12%) under the RCP4.5 and RCP8.5 scenarios when averaged six GCMs, respectively. The differences for all climatic scenarios were insignificant, except for 2061–2080 under RCP8.5 scenario. The simulated WUE increased by 0.7kg/ha mm (13%) and 0.75kg/ha mm (14%) for 2041–2060 and 0.96kg/ha mm (17.8%) and 0.33kg/ha mm (6%) for 2061–2080 under RCP4.5 and RCP8.5 scenarios comparing to baseline water use efficiency (WUE) of 5.38kg/ha mm, respectively. The WUE under CN and MC climatic models for 2041–2060 was significantly higher than other climatic scenarios under RCP4.5 and RCP8.5 due to significant increase in cotton yield. Compared to the baseline, the simulated WUE under CN, MC, and MG climatic models significant increased for 2061–2080 under RCP4.5 scenario. However, a significant decrease in WUE was simulated under MP climatic scenario for 2061–2080 under RCP8.5, comparing to other climatic scenarios.

3.5. Adaptation strategy by cultivar and planting date selection

The largest reduction in cotton yield predicted by the six GCMs was with the MPI-ESM-LR (MP) for 2061–2080 under the RCP8.5 scenario. Therefore, an adaptation strategy to mitigate the impact of climate

Table 1
Simulated cotton evapotranspiration and WUE (or percentage) from sowing to maturity, for 2041-2060 and 2061-2080 under RCP4.5 and RCP8.5 scenarios.

Scenarios	RCP4.5				RCP8.5			
	Yield (Mg/ha)	AET (mm)	ET_{pot} (mm)	WUE (kg/ha mm)	Yield (Mg/ha)	AET (mm)	ET_{pot} (mm)	WUE (kg/ha mm)
BL	4.23	665	786	5.38	4.23	665	786	5.38
2041-2060								
BC	4.42 (5%)	619 (-7%)	735 (-7%)	6 (11%)	4.48 (6%)	611 (-8 %)	722 (-8%)	6.2 (15%)
CC	4.28 (1%)	621 (-7%)	738 (-6%)	5.81 (8%)	4.19 (-1%)	608 (-9%)	722 (-8%)	5.81 (8%)
CN	4.77 (13%)	615 (-8%)	730 (-7%)	6.53 (21%)	4.5 (6%)	604 (-9%)	718 (-9%)	6.27 (17%)
MC	4.58 (8%)	620 (-7%)	735 (-7%)	6.23 (16%)	4.7 (11%)	607 (-9%)	720 (-8%)	6.52 (21%)
MG	4.61 (9%)	615 (-8%)	730 (-7%)	6.32 (18%)	4.49 (6%)	606 (-9%)	719 (-9%)	6.25 (16%)
MP	4.12 (-3%)	625 (-6%)	740 (-6%)	5.56 (3%)	4.14 (-2%)	610 (-8%)	724 (-8%)	5.72 (6%)
AVG	4.46 (5%)	619 (-7%)	735 (-7%)	6.08 (13%)	4.42 (5%)	608 (-9%)	721 (-8%)	6.13 (14%)
2061-2080								
BC	4.77 (13%)	608 (-9%)	717 (-9%)	6.65 (24%)	3.9 (-8%)	582(-13%)	692(-12%)	5.64(5%)
CC	4.25 (1%)	607 (-9%)	721 (-8%)	5.89 (10%)	3.89 (-8%)	585(-12%)	694(-12%)	5.6(4%)
CN	4.64 (10%)	602 (-10%)	715 (-10%)	6.48 (20%)	4.16 (-2%)	581(-13%)	688(-13%)	6.05(13%)
MC	4.61 (9%)	607 (-9%)	719 (-9%)	6.41 (19%)	4.17 (-1%)	580(-13%)	689(-12%)	6.04(12%)
MG	4.78 (13%)	601 (-10%)	712 (-9%)	6.72 (25%)	4.09 (-3%)	582(-13%)	689(-12%)	5.94(10%)
MP	4.22 (0%)	607 (-9%)	721 (-8%)	5.86 (9%)	3.5 (-17%)	594(-10%)	704(-10%)	4.96(-8%)
AVG	4.55 (8%)	606 (-8%)	718 (-9%)	6.33 (18%)	3.95 (-7%)	584(-12%)	693(-12%)	5.7(6%)

Note: AET, cumulative actual evapotranspiration; ET_{pot}, cumulative potential evapotranspiration; WUE = Yield/ ET_{pot}; AVG, averaged over 6 scenarios; BL, baseline; BC, BCC-CSM1-1; CC, CCSM4; CN, CNRM-CM3; MC, MIROC5; MG, MRI-CGCM3; MP, MPI-ESM-LR.

Table 2
Simulated effects of cotton cultivars and planting date (with cv 'Ceke No. 1') on mean annual yield, ET_{pot} and WUE for 2061–2080 by MP climate model under RCP8.5 scenario.

	Yield(Mg/ha)	E_{pot} (mm)	T_{pot} (mm)	ET_{pot} (mm)	WUE (kg/ha mm)
Cotton cultivars					
Ceke No. 1	3.50	204	500	704	4.96
GA0001 Georgia king	4.55 (30%)	225 (10%)	691 (38%)	916 (30%)	4.97 (0%)
IB0001 DP 77	6.60 (89%)	236 (16%)	610 (22%)	846 (20%)	7.81 (57%)
IB0002 DP 458	4.71 (35%)	204 (0%)	632 (26%)	836 (19%)	5.64 (14%)
IB0003 DP 555	4.58 (31%)	222 (9%)	656 (31%)	878 (25%)	5.22 (5%)
IB0004 DP 555 BG/RR	5.12 (46%)	224 (10%)	627 (25%)	851 (21%)	6.02 (21%)
TX0003 GP 3774	3.17 (-9%)	228 (12%)	612 (22%)	840 (19%)	3.78 (-24%)
Planting date					
PD-40	4.37 (25%)	221 (8%)	495 (-1%)	716 (2%)	6.11 (23%)
PD-30	4.38 (25%)	219 (7%)	495 (-1%)	714 (1%)	6.13 (24%)
PD-20	4.15 (19%)	216 (6%)	494 (-1%)	710 (1%)	5.85 (18%)
PD-10	3.79 (8%)	211 (3%)	497 (-1%)	708 (1%)	5.36 (8%)
PD + 0	3.50	204	500	704	4.96
PD0 + 010	2.97 (-15%)	207 (1%)	501 (0%)	708 (1%)	4.19 (-16%)
PD0 + 020	2.36 (-33%)	206 (1%)	501 (0%)	707 (0%)	3.34 (-33%)

Note: E_{pot}, cumulative potential evaporation; T_{pot}, cumulative potential transpiration; ET_{pot}, cumulative potential evapotranspiration; WUE = Yield/ ET_{pot}, water use efficiency; PD-40, PD-30, PD-20, PD-10, PD-0, PD + 10, PD + 20, change planting date to -40, -30, -20, -10, 0, + 10, and + 20 before(-) /after (+) original planting date.

Table 3
Parameters for top cotton cultivars of IB0001 DP 77 and Ceke No.1.

Parameter	Description	IB0001 DP 77	Ceke No. 1
EM-FL	Time between plant emergence and flower appearance (days)	34	36
FL-SH	Time between first flower and first pod (days)	8	5
FL-SD	Time between first flower and first seed (days)	15	10
SD-PM	Time between first seed and physiological maturity (days)	30	30
FL-LF	Time between first flower and end of leaf expansion (days)	49	47
LFMAX	Maximum leaf photosynthesis rate at 30°C, 350 vpm CO_2, and highlight (mg $CO_2 m^{-2}$ s-1)	1.1	1.2
SLAVR	Specific leaf area of cultivar under standard growth conditions ($cm^2 g^{-1}$)	170	200
SIZLF	Maximum size of full leaf (cm^2)	280	240
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell	0.9	0.67
WTPSD	Maximum weight per seed (g)	0.18	0.2
SFDUR	Seed filling duration for pod cohort at standard growth conditions (days)	35	18
SDPDV	Average seeds per pod under standard growing conditions (seeds pod^{-1})	27	15
PODUR	Time required for cultivar to reach final pod load under optimal conditions (days)	8	8

change on cotton yield is proposed based on MP climate model. The simulated effect of different cultivars and planting dates on seed cotton yield was evaluated under the MP climate model for 2061–2080 under the RCP8.5 scenario (Table 2). Compared to the baseline cultivar 'Ceke No. 1', the simulated seed cotton yield and WUE were projected to increase for all cultivars, except for 'TX0003 GP 3774'. With a seed filling duration for pod cohort at standard growth conditions (SFDUR) and average seeds per pod under standard growing conditions (SDPDV) of 35 and 27, respectively, cultivar 'IB0001 DP 77' showed the greatest yield (6.60Mg ha^{-1}), greater than the baseline cultivar ‘Ceke No. 1’ (3.50 Mg ha^{-1}), with a SFDUR and SDPDV of 18 and 15, respectively. The various model parameters for cotton cultivars 'IB0001 DP 77' and 'Ceke No.1' are shown in Table 3. The simulated seed cotton yield increased from 3.79 Mg ha^{-1} to 4.38 Mg ha^{-1} as the planting date varied from 10 to 40 days before the baseline, but decreased from 2.36 Mg ha^{-1} to 2.97 Mg ha^{-1} as the planting date advanced from 10 to 20 days after the baseline. The simulated effect of planting date on ET_{pot} was less affected.

4. Discussion

4.1. Changes in temperature and precipitation

Huang et al. (2018) projected increases of 2.18–3.03°C for 2041–2070 and of 2.69–4.99°C for 2071–2099 under the RCP4.5 and RCP8.5 scenarios, compared to a 1970–2000 baseline, for a site in Hotan, on the southern rim of the Taklimakan Desert, Xinjiang. The changes in mean *P* in the present study were much smaller than those reported by Huang et al. (2018), who found projected increases of 28–43% for 2041–2070, and 34–66% for 2071–2099 under the RCP4.5 and RCP8.5 scenarios, respectively. However, slight changes in rainfall would have little effect on simulating cotton growth owing to the baseline rainfall being quite small (29.5mm).

4.2. Cotton phenology and water requirement

Under all future climate scenarios, the days to emergence, flowering, boll cracking, and maturity for 2041–2060 and 2061–2080 were shorter than those for the baseline period (Fig. 3). Using the COSIM cotton model associated with the Centre regional climate model-PRECIS for a site in the Shiyang River Basin of Northwestern China, Chen et al. (2011) noted that simulated flowering and boll opening stages of cotton were significantly advanced by 5 and 17 days for 2071–2100, respectively, when averaged across the A2 and B2 emission scenarios. This shortening of the cotton's development also concurred with the results of Yang et al. (2014), who found that the cotton growing season in Alaer, Xinjiang, would be shortened by about 13 days in 2050 and 16 days in 2070 for a late maturity variety and about 22 days in 2050 and 26 days in 2070 for medium maturity variety. The differences in projected cotton phenology may be caused by the selected crop cultivars,

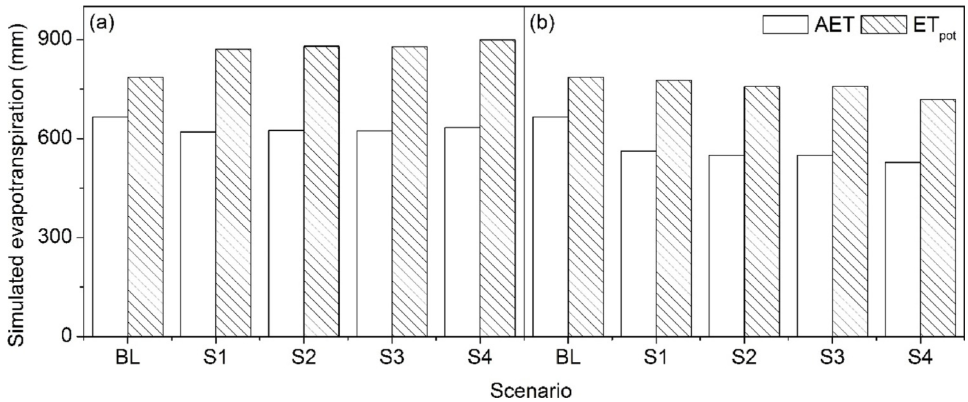

Fig. 5. Simulated evapotranspiration from sowing to maturity in response to increased temperature but without eCO_2 under BC climatic model (a) and eCO_2 in the absence of increased temperature (b). AET, cumulative actual evapotranspiration; ET_{pot}, cumulative potential evapotranspiration; BL, baseline; S1, 2041–2060 under RCP4.5; S2, 2041–2060 under RCP8.5; S3, 2061–2080 under RCP4.5; S4, 2061–2080 under RCP8.5.

crop model, and regional conditions.

Simulated crop water requirement agrees with those in Luo et al. (2015) which reported a decrease in cotton water use as simulated by O_ZCOT model at Moree, Goondiwindi, and Warren, Australia under irrigated condition in 2030's (both eCO_2 and future climate were considered). The effects of eCO_2 and shorter growth period on cotton water use offset the negative impacts of increased temperatures. Increases in simulated ET_{pot} ranged from 85mm to 113mm (10.8-14.4%) when only temperature increases without CO_2 fertilization effect (Fig. 5a). The decrease in AET was due to simulated shorter growth period. Decreased in simulated ET_{pot} ranged from 9mm to 67mm (1.2-8.5%) when eCO_2 in the absence of increased temperature (Fig. 5b). However, Yang et al. (2014) reported that irrigation water increased by 35mm for 2050 and 32mm for 2070 with late maturity cultivar in Alar, Xinjiang. This may be caused by the selected different sites, climatic scenarios, cultivars and models. The simulated low cotton water requirements in our study would probably alleviate the annual maximum environmental flow requirement (0.75×10^8 m^3), which accounts for 58.8% of the natural river runoff in this region (Xue et al., 2015).

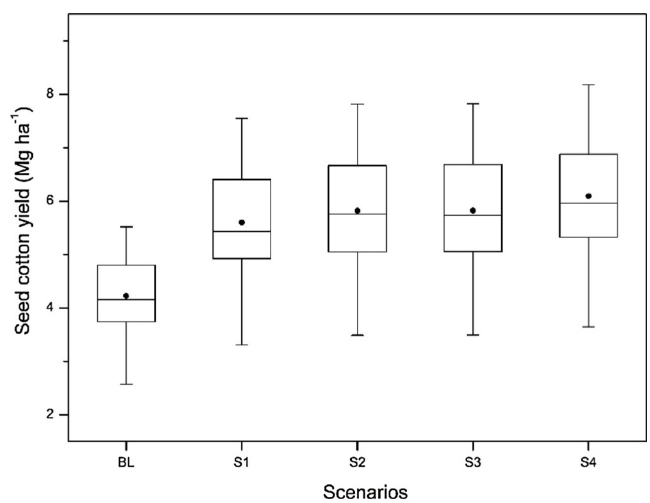

Fig. 6. Simulated seed cotton yield under eCO_2 without changes in temperature conditions. BL, baseline; S1, 2041–2060 under RCP4.5; S2, 2041–2060 under RCP8.5; S3, 2061–2080 under RCP4.5; S4, 2061–2080 under RCP8.5.

4.3. Seed cotton yield

The simulated increase in seed cotton yield in the present study was mainly attributable to the enhancement of $[CO_2]_{atm}$ from 330 to 832ppm. Under eCO_2 without temperature increases, seed cotton yield for 2041–2060 and 2061–2080 increased by 35.1% and 41% across RCP4.5 and RCP8.5 scenarios, respectively (Fig. 6), which was consistent with Reddy and Zhao (2005), who found a 35% of increase in cotton yield projected by the GOSSYM model when only an increase in $[CO_2]_{atm}$ was considered. Luo et al. (2015) reported that under irrigation conditions in Australia, increased cotton lint yield benefits from interactive effects of eCO_2 and future climate for 2020–2039 when compared with baseline climate (1980–1999). Using the GOSSYM model, Reddy et al. (2002) indicated that a 10% of increase in cotton yields was simulated when the $[CO_2]_{atm}$ increased to 540ppm, but a 9% decrease was ensued when both the climatic (T°_{max} and T°_{min}, precipitation, radiation and wind speed) and $[CO_2]_{atm}$ were changed. Our simulation results also showed that seed cotton yield would decrease by 22.4% and 28.6% for 2041–2060 and 2061–2080, respectively, with baseline $[CO_2]_{atm}$ (330ppm) and projected temperature increases (Fig. 7). Using the APSIM model, Williams et al. (2015) showed declines in simulated cotton yields of 3% for 2030 and 17.8% for 2050, when the effect of CO_2 fertilisation was not considered. Using the DSSAT model, Adhikari et al. (2016) found a 4-17% of decrease in seed cotton yield when $[CO_2]_{atm}$ was assumed to be remain at 380ppm. Due to no water stress and slight changes in rainfall, the impact of rainfall on cotton yield were small to negligible in the present paper.

However, high temperature appeared to have a rather negative effect on yields (Voloudakis et al., 2015). In the present paper, a 3.56–4.55°C increase in temperature was projected under RCP8.5 that resulted in decrease in seed cotton yield by 6.5% for 2061–2080, which was similar to other studies involving C_3 species in the literature. Using DSSAT model, Lal et al. (1998) demonstrated that the positive effect of eCO_2 on wheat yield was nearly cancelled out when air temperature was increased by 3°C, and wheat yield was decreased by 32% with a 5°C increase in air temperature and doubling of $[CO_2]_{atm}$. In addition, the shorter growth period caused by higher temperature resulted in the severe decreases in seed cotton yield for 2061–2080 under the RCP8.5 scenarios in the present paper. Using RZWQM2 model, Saseendran et al. (2016) showed seed cotton yield loss of 10% for 2080 under RCP8.5 due to the adverse effect of temperature superseded the fertilization effect of CO_2 in cotton growth.

When the ambient air temperature exceed 35°C, cotton was subjected to high temperature stress. In contrast, low temperature stress occured when the ambient air temperature was below 15°C. Our simulation study suggested that the effects of potential low temperature stress on cotton growth might be alleviated in this region, which in turn slightly increased cotton yield. Although heat temperature stress was aggravated under the increased air temperatures of future scenarios, cold temperature stress was alleviated in cool days. Singh et al. (2007) and Luo (2011) indicated that there was a significant reduction in flower and boll retention at temperatures above 36°C. Luo et al. (2014)

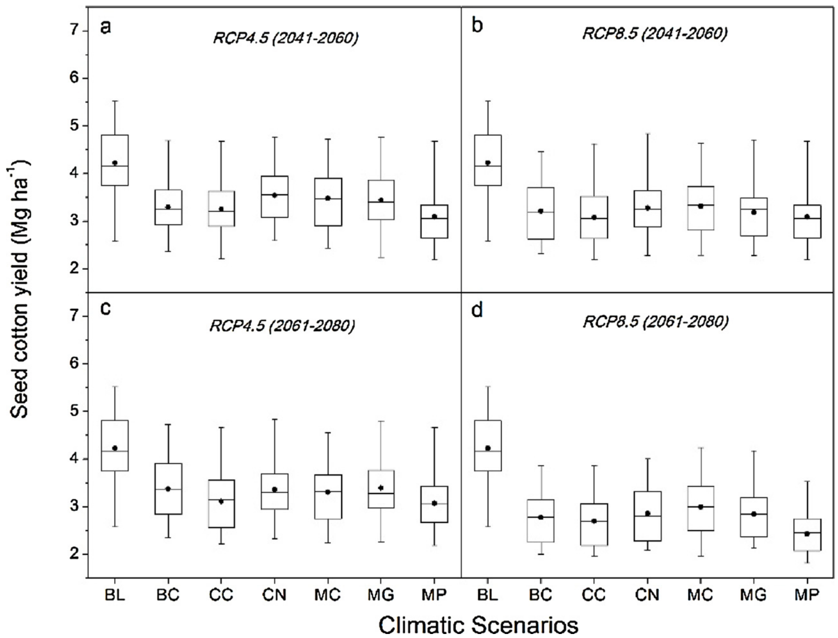

Fig. 7. Changes in simulated seed cotton yield in response to increased temperatures, but in the absence of higher $[CO_2]_{atm}$ levels. BL, baseline; BC, BCC-CSM1-1; CC, CCSM4; CN, CNRM-CM3; MC, MIROC5; MG, MRI-CGCM3; MP, MPI-ESM-LR.

Table 4
Simulated average temperature stress factor for 2041–2060 and 2061–2080 under RCP4.5 and RCP8.5 scenarios.

Scenarios	2041-2060				2061-2080			
	RCP4.5		RCP8.5		RCP4.5		RCP8.5	
	T < 15°C	T > 36°C	T < 15°C	T > 36°C	T < 15°C	T > 36°C	T < 15°C	T > 36°C
BL	0.89	0.96	0.89	0.96	0.89	0.96	0.89	0.96
BC	0.92	0.94	0.93	0.94	0.92	0.94	0.94	0.91
CC	0.92	0.94	0.92	0.94	0.91	0.95	0.93	0.92
CN	0.91	0.95	0.92	0.94	0.93	0.94	0.94	0.93
MC	0.92	0.95	0.94	0.94	0.91	0.95	0.92	0.92
MG	0.91	0.95	0.92	0.94	0.92	0.93	0.93	0.91
MP	0.91	0.94	0.92	0.93	0.92	0.94	0.93	0.89
AVG	0.92	0.95	0.93	0.94	0.92	0.94	0.93	0.91

Note: Temperature stress factor = 1 indicates that there is no temperature stress; Temperature stress factor < 1 indicates some temperature stress; Temperature stress factor = 0 indicates maximum temperature stress; T, average air temperature; AVG, averaged over 6 combined scenarios; BL, baseline; BC, BCC-CSM1-1; CC, CCSM4; CN, CNRM-CM3; MC, MIROC5; MG, MRI-CGCM3; MP, MPI-ESM-LR.

also found that there would be more heat stress events when daily maximum temperature exceeded 35°C. However, most studies did not consider the effect of low temperature stress on crop growth. The simulated average temperature stress factors for 2041–2060 and 2061–2080 under RCP4.5 and RCP8.5 according to different climate model scenarios are shown in Table 4. Compared to the baseline, the average variability of decreased low temperature stress factor (T < 15°C) is greater than the increased high temperature stress (T > 36°C) for all scenarios, except for 2061–2080 under the RCP8.5 scenario. As cotton is a warm season crop, high temperatures may be more conducive to crop growth if there is no water stress.

4.4. Adaptation strategy by cultivar and planting date selection

Seed cotton yield in the future increased when current cotton cultivars were replaced by cotton cultivars with longer growth period. Yang et al. (2014) indicated that replacing faster-maturing cotton cultivars by slower-maturing cultivars might increase seed cotton yield. Moreover, an early planting date was proven to be a relatively easy adaptation strategy to mitigate the impact of climate change on cotton yield in an extremely arid region. Sowing cotton one month earlier than the current planting date (11-April) was found to be effective for seed cotton yield production in the future in this region. These simulation results were similar to those of Saseendran et al. (2016) and Rahman et al. (2018), who reported that an earlier planting date (five weeks or six weeks) than the current planting date could enhance seed cotton yield in Pakistan and Lower Mississippi Delta Region, respectively. The potential increase in water use should be taken into account when planting cotton cultivars with longer growth stages and sowing cotton earlier in this region. However, a too early planting date might increase the chances of cold stress (Luo et al., 2016). Selecting suitable cotton cultivars and planting date in combination with water-saving irrigation technology may be a good choice for the local producers in the future.

4.5. Uncertainty of simulation

Significant differences in simulated average seed cotton yield under different climatic models were probably caused by the variation in maximum and minimum temperature under different climatic models (Supplemental material Tables A2-A3), which suggested that the inclusion of multiple future climate models may reduce the uncertainty in climate change effect projection. For example, Yang et al. (2014)

indicated that, under the A2 scenarios, cotton yield would increase by 0.43Mg ha^{-1} by 2050. However, they only used the HadCM3 Global Climate Model to simulate cotton yield response to climate change in Northwest China. In the case of the DSSAT model, limitations in crop growth were based largely on air temperature, the model being less sensitive to eCO_2 than to elevated temperatures (Thorp et al., 2014; Rahman et al., 2018). This may then have affected simulation accuracy in the present paper as DSSAT crop model was used in RZWQM2. In addition, there are important considerations with respect to present crop models' prediction of the effects of eCO_2 and high temperatures on crop yield · these models may be too simplistic to provide realistic predictions of yield (Boote et al., 2013). Improving experimental studies on crop growth response to CO_2 fertilization and extremely high temperatures and incorporated data into crop models may help improve simulation accuracy.

5. Conclusions

In this study, through the aid of a well calibrated RZWQM2 model, the effects of climate change on cotton yield and crop water requirement in an extremely arid region (precipitation ≈ 40 mm y^{-1}) were analyzed. The simulated days to emergence, flowering, boll cracking, and harvest stages for 2041–2060 and 2061–2080 were shorter for all of future climatic scenarios. The model projected that seed cotton yield would increase for 2041–2060 with current management practices. However, an increase in seed cotton yield under RCP4.5 but a decrease under RCP8.5 for 2061-2080 were predicted in this region. The increase in temperature alleviated low temperature stress, which in turn slightly increased cotton yield. Simulated cotton water requirement decreased by 7.5% and 10.3% in 2041–2060 and 2061–2080 when averaged over RCP4.5 and RCP8.5 scenarios, respectively. In addition, increases in average WUE were simulated in this region for all future GCMs. Significant differences in seed cotton yield, water requirement, and WUE were found under different climatic scenarios. This study suggested that climate change might alleviate agricultural water crisis in this area in the future. However, for the RCP8.5 scenario in 2061–2080, replacing cotton cultivars and earlier planting could mitigate the reduction of cotton yield due to future temperature increase.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agwat.2019.05.030.

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