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RESEARCH

Evaluating Climate Change Impacts on Cotton Phenology and Yield Under Full and Deficit Irrigation Conditions in an Extremely Arid Oasis

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Abstract

Sustaining cotton (*Gossypium hirsutum* L.) production under limited water availability and climate change in an extremely arid oasis is a key challenge for the stakeholders. This study was conducted to quantify the climate change impacts on cotton phenology and seed yield under full (638 mm) and deficit (478 mm) irrigation regimes in an extremely arid oasis in China. The Root Zone Water Quality (RZWQM2) model with the integration of six global circulation models (GCMs) under two representative concentration pathways (RCP 4.5 and 8.5) was used to determine the potential impacts of climate change on cotton for future periods (2022–2047, 2048–2073, and 2073–2099) compared to baseline (1975–2000). The results revealed that number of days to anthesis and maturity was expected to be reduced under RCP 4.5 and RCP 8.5 with full and deficit irrigation for future periods compared to baseline. However, this reduction was maximum under RCP 8.5 for 2074–2099 with full irrigation treatment. Seed cotton yield was also expected to decrease by 13–18% (RCP4.5) and 14–18% (RCP 8.5) with full irrigation, while decline in yield was 10–14% (RCP 4.5) and 11-19.6% (RCP 8.5) under deficit irrigation for future periods. The maximum decline in yield appeared with deficit irrigation under RCP 8.5 for 2074–2099. This reduction in seed cotton yield is primarily attributed to elevated temperature in the future climate. A 25% deficit of irrigation compared to normal irrigation has also ensured a reasonable seed yield in future climate, therefore it could be considered as an irrigation management strategy in future for cotton production in extremely arid regions. Findings of this study will provide a better guidance to cotton growers for applying deficit irrigation to sustain cotton production under changing climate with limited water availability in XUAR and other similar agro-climatic regions.

Keywords Arid region · Cotton · Climate change · GCM · Deficit irrigation · RCP · RZWQM2

Introduction

Global climate change, characterized by global warming resulting from rising atmospheric carbon dioxide (CO_2) concentration, has become a critical issue in agricultural systems (Tilman et al., 2011, IPCC, 2014, 2021). This warming is expected to induce substantial changes in the climate system mainly due to the projected rise in temperature, which will alter the rainfall pattern and enhance the occurence of extreme events such as drought and heat (Li et al., 2021). Such climate shifts and shocks will affect the crop growth, phenology, irrigation demand, crop cultivation area and especially crop yield (Babel et al., 2019; Rahman et al., 2018; Arshad et al., 2021) thereby impacting the sustainable agricultural development. Cotton (*Gossypium hirsutum* L.) is cultivated on 5.53 million hm^2 annually in China, which is about 15% of the world's cotton cultivated area (Yu et al., 2015). The Xinjiang Uygur Autonomous Region (XUAR) is

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home to 80% of China's cotton growing area, with 5.16 Tg y^{-1} cotton production, accounting for 87% of the nation's cotton production (Chen et al., 2022). A quarter of the total agricultural water used in the region is devoted to irrigate cotton in the XUAR, which utilizes about 12.4 billion m^3 of water annually. The XUAR uses about11.8 billion m^3y^{-1} of groundwater, surpassing the fixed limit of use (57%), thus significantly decreasing the groundwater table (Chen et al., 2019). Such rapid depletion of groundwater levels is constraining the irrigation water supply for continuously expanding cotton cultivation in this region. Additionally, extreme weather events such as heat waves and severe droughts are expected to increase irrigation demand for cotton in future (Olesen & Bindi, 2002). Therefore to ensure sustainable cotton production and mitigate negative effects of future climate change in water scarce arid regions, it is crucial to implement suitable irrigation management strategies for efficient utilization of limited water resources.

Limited water availability seriously impacts the cotton production in arid regions due to high dependence on irrigation. Water stress significantly affects the biomass accumulation in cotton, node and boll development, and crop maturity (Ritchie et al., 2009). The amount and timing of irrigation critically influences the size and number of bolls in cotton. Some studies revealed a higher decrease in cotton seed yield when water stress occurred at flowering stage compared to earlier or later stages during the growing season. Therefore under conditions of limited water availability deficit irrigation could be a viable option for sustainable cotton production. A plethora of studies demonstrated that deficit irrigation can improve crop water productivity in cotton without causing a serious large reduction in yield. For instance, Zhang et al. (2016) revealed that irrigation with 70% crop evapotranspiration (ETc) could save significant amount of irrigation water regardless of nitrogen rate. Wu et al., (2014) reported the highest gains in water productivity with 5% reduction in seed cotton yield at 80% (ETc) compared to 100% (ETc) irrigation. Hussein et al. (2014) demonstrated the highest irrigation water use efficiency with 80% of the soil water depletion in drip irrigated cotton. These studies suggest that deficit irrigation could be a valuable irrigation strategy in water scarce regions but it needs proper evaluation under specific agro-climatic conditions particularly under changing climate.

On the other hand weather conditions such as increasing temperatures and changing rainfall patterns negatively affect growth and productivity in cotton (Iqbal et al., 2016). Whereas increasing concentration of atmospheric CO_2 contributed positively towards cotton growth and yield through increases in photosynthesis and by reducing transpiration for improved water use efficiency (Rahman et al., 2018), recent research revealed that temperature escalation and variation in rainfall under future climate scenarios can substantially counterbalance the positive outcomes of higher atmospheric CO_2 (Nasim et al., 2016). The growth period of existing cotton cultivars has reduced due to increasing temperatures. Changes in crop phenology alter the cotton nutrient and water demands, and water use efficiency which leads to yield reduction particularly in arid and semi-arid regions. The optimum temperature range for normal physiological and metabolic processes in cotton is 23–32 °C (Cottee et al., 2010). Efficient growth in cotton is observed to be occurred at 33 °C while temperature above 36 °C induced a drastic decrease in flower and boll retention (Luo, 2011; Rahman et al., 2018). Prevalence of high temperature shortens the boll growth period that results in smaller bolls and yield reduction. Similarly higher variations in the frequency of rainfall from mean values have negative impacts on cotton productivity (Rahman et al., 2018). Such climatic variations with substantial effects on growth, phenology and yield can be a potential threat for sustainable cotton production in future. Assessment of cotton seed yield responses under changing climate is highly important particularly to develop better adaptation plans by taking in to account those factors influencing the crop phenology and yield (Ruane et al., 2015). In this context crop simulation models can be used to assess climate change impacts on cotton growth and yield, and developing efficient irrigation strategies for productive water use.

In recent days model simulations with integration of GCMs, which can project the future climate have been employed to evaluate the percussion of climate variation on crop phenological stages and yield (Adhikari et al., 2016; Abbas et al., 2017; Rahman et al., 2018; Ding et al., 2019; Ahmed et al., 2022). The RZWQM2 model, integrated with DSSAT4.0, showed good simulation performance for growth and yield responses under deficit irrigation strategies in cotton and maize crops (Fang et al., 2017; Li et al., 2020). Similarly, RZWQM2 model reasonably simulated the sunflower growth and yield responses under deficit irrigation conditions for future climates (Zhang et al., 2021). In another study, RZWQM2 successfully simulated the crop yield responses under long-term management practices (Cheng et al., 2021). Chen et al., (2022) reported that RZWQM2 accurately simulated the growth and yield responses of under deficit and normal irrigation treatments. Several other studies simulated the growth and yield responses of cotton against different factors using different crop models in XUAR (Tan et al., 2018; Li et al., 2019, 2021; Wang et al., 2020). However, studies regarding the impact of future climate warming on cotton production in an extremely arid climate of XUAR under deficit and full irrigation are scarce. Therefore, studying the impact of different irrigation regimes on cotton yield under current and

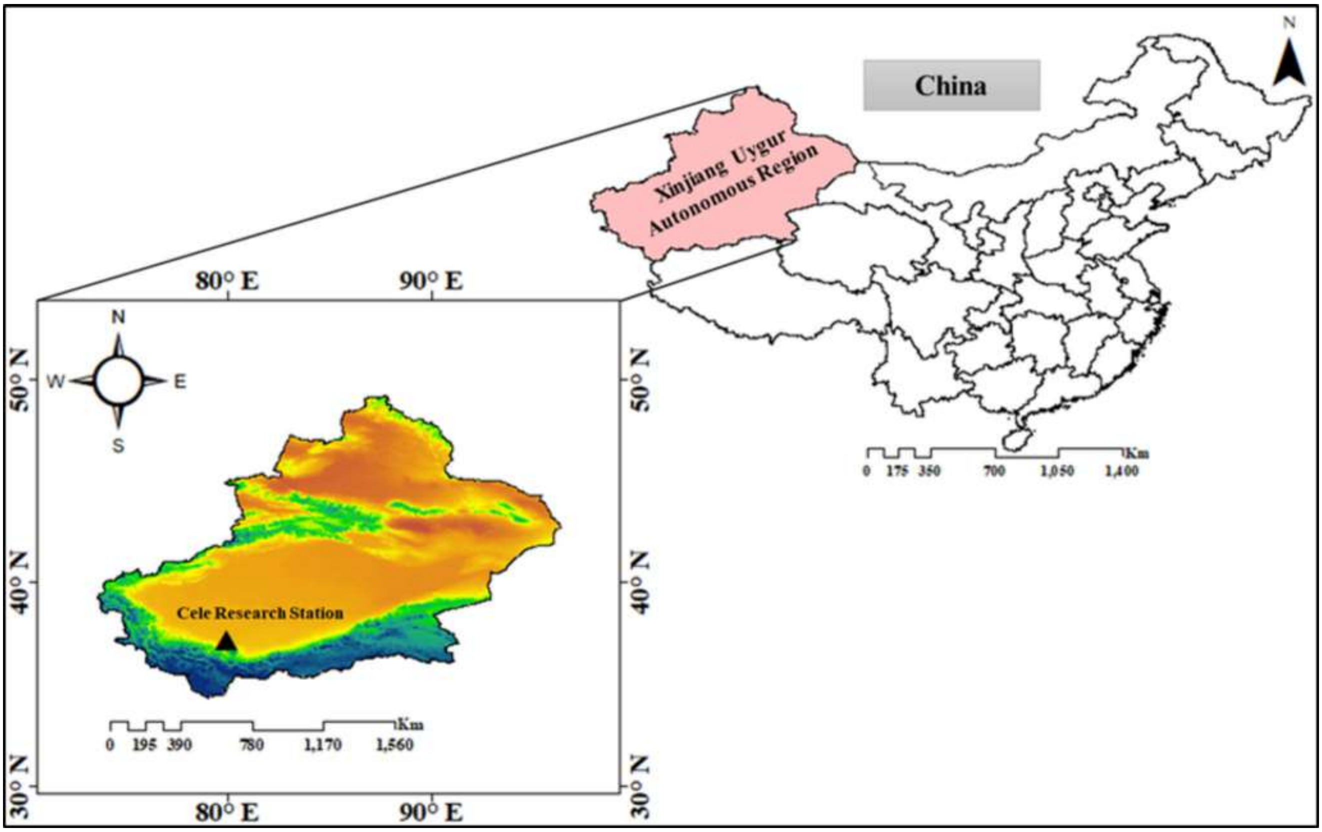

Fig. 1 Location of the study area

future climates could assist cotton growers in the XUAR and similar agro-climatic regions in the world in optimizing irrigation water use for cotton production in the future. The specific objectives of this study include the following;

(i) Evaluate the applicability and performance of RZWQM2 to simulate cotton phenology and seed yield with full and deficit irrigation regimes in an extremely arid oasis.
(ii) Quantify the impact of changing climate on cotton phenology and seed yield under RCP 4.5 and RCP 8.5 for the current period (2022–2047), mid-century (2048–2073), and late-century (2074–2099) with full and deficit irrigation regimes using RZWQM2 model.
(iii) To establish suitable irrigation strategy for sustainable cotton production in arid oasis pertaining to future climate change.

Materials and Methods

Study Region

This study was conducted in Qira Oasis (36°54'N-3709'N, 8037'E-8059'E) situated on the southern rim of the Taklimakan Desert of the Xinjiang province in Northwest China (Fig. 1). The Qira Oasis extended over an area of 274 km^2 and has extremely arid conditions. The long term annual mean precipitation is 42.62 mm and mean temperature is 15.85ºC (1955–2000) respectively, and surface evaporation is 2700 mm (Chen et al., 2019).

Field Experiment

A two-year field study (2017 and 2018) was conducted at Cele Research Station (37°01′06′′N, 80°43′48″E) of the Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences located in the Qira Oasis. The experiment was performed by using the randomized complete block design with four replications. Each plot has a size of 10 m×6 m. Plant-plant distance was 10 cm with a row spacing of 50 cm and cotton cultivar Xinluzao No. 779 was planted on April 19, 2017 and April 23, 2018 under a plastic mulch with drip irrigation system. There were two irrigation treatments including full irrigation (100%) and deficit irrigation (75% of full irrigation). There were a total 11 irrigation events which supplied 638.7 mm and 479 mm water in 2017 and 602.5 mm and 451 mm water in 2018 for full and deficit irrigation treatments respectively, through drip irrigation system. From sowing to harvest, the volumetric

Table 1 Date and amount of irrigation applied during the field experiment

2017			2018		
Date	Full irrigation (mm)	Deficit irrigation (mm)	Date	Full irrigation (mm)	Deficit irrigation (mm)
19 April	140	105	23 April	120	90
14 May	47	32.25	16 May	46	34.5
2 June	50	37.5	5 June	48	36
20 June	48	36	22June	47	35.25
3 July	49.3	36.97	7 July	48	36
16 July	50	37.5	19 July	50	37.5
27 July	48.4	36.3	31 July	47.5	35.62
8 August	50	37.5	10 August	46	34.5
17 August	52	39	21 August	48	36
30 August	50	37.5	31 August	50	37.5
19 September	54	4.5	12 September	52	39
Total	638.70	479.02	Total	602.5	451.9

Table 2 Crop management practices during the field experiment

Crop Management Practices	2017	2018
Planting time	19 April	23 April
Planting density (ha^{-1})	200,000	200,000
Harvest time	7 October	13 October
Fertilizer (Kg ha^{-1})	240 kg N (granular urea) 120 kg P_2O_5 ha^{-1} 60 kg K_2O	240 kg N ha^{-1} (granular urea) 120 kg P_2O_5 ha^{-1} 60 kg K_2O
Irrigation Irrigation start date Irrigation end date	11 irrigations (full irrigation = 638 mm, Deficit irrigation 479 mm), 19 April 19 September	11 irrigations (full irrigation = 602 mm, deficit irrigation = 451 mm) 23 April 12 September
Tillage	Conventional	Conventional

soil moisture content at soil profile depths of 0-0.15 m, 0.15–0.25 m, 0.25–0.40 m, 0.40–0.65 m and 0.65-1.00 m soil layers was measured weekly by the oven-dry method. The irrigation was applied when soil moisture dropped to 50% of the plant available water content at 50 cm soil depth in the full irrigation treatment. The full irrigation treatment was then irrigated up to 100% field capacity level and deficit irrigation treatment was replenished with 75% of the volume of the water applied to full irrigation treatment (Table 1). Nitrogen fertilizer (granular urea) was applied at the rate of 240 kg N ha^{-1}. All plots received 120 kg P_2O_5 ha^{-1} as calcium phosphate and 60 kg K_2O as potassium sulphate before planting. Soil parameters from a previous study (Liu et al., 2017) were used in this study. Crop management data (Table 2) were used to establish the management file of the model. To get data about cotton phenological stages, five plants were randomly tagged in each plot and calendar time (photothermal days) between different phenological stages until cotton harvesting was recorded. Days for anthesis (flowering), physiological maturity and final seed cotton yield were used to create the model input files.

Climate Data

Historical climate data including rainfall, daily air temperature (minimum and maximum), solar radiation, wind speed, relative humidity, and vapor pressure during 1970–2000 was downloaded using the China Meteorological Data Sharing Services System (CMDSSS, http://data.cma.cn/). The daily meteorological data during experimentation was collected from the weather station installed 20 meter away from the experimental field. Future climate data for rainfall and air temperature (maximum and minimum) under RCP 4.5 and RCP 8.5 scenarios with a 5' longitude/latitude degree spatial resolution was obtained from the World ClimGlobal climate dataset (http://worldclim.org/), containing bias-corrected global data (Hijmans et al., 2005). The weather data projected by six GCMs is used in this study. These six GCMs are CCSM4 (CM4), CNRMCM5 (CN), MIROC5 (MC), MRI-CGCM3 (MG), MIROC-ESM (ME), and MPI-ESM-LR (MP) (Table 3).

Table 3 Summary of six global climate models (GCMs) used in this study

GCM	Modeling Group	Reference
CCSM4 (CC)	National Center for Atmospheric Research, U.S.	Gent et al. (2011)
CNRM-CM5 (CN)	National Centre of Meteorological Research, France	Voldoire et al. (2013)
MIROC5 (MC)	Atmosphere and Ocean Research Institute, University of Tokyo,	Japan Watanabe et al. (2010)
MIROC-ESM (ME)	Atmosphere and Ocean Research Institute, University of Tokyo	Kamworapan & Surussavadee 2019
MPI-ESM-LR (MP)	Max Planck Institute for Meteorology, Germany	
MRI-CGCM3 (MG)	Meteorological Research Institute, Japan	Yukimoto et al., (2012)

RZWQM2 Model

The RZWQM2 model was employed to evaluate the effects of climate variation on cotton growth and yield. RZWQM2 is a one-dimensional process-based model which contains modules for hydrology, energy balance, water quality, and crop growth processes (Ahuja et al., 2000). This model can develop and evaluate different management practices (Ma et al., 2012). The Main management practices which can be simulated through this model include the selection of crop cultivar, sowing date, tillage, planting and harvesting operations, and irrigation and fertilizer applications. The RZWQM2 model requires daily data, and minimum input data required for simulation include daily weather data, soil physical and chemical properties, soil hydraulic properties, soil and crop management information (tillage operations, sowing date, plant density, amount and ways of fertilizer and irrigation applications), and initial soil parameters (soil carbon, nitrogen and water contents in the profile) (Anapalli et al., 2016). Despite having a generic crop model which can be parametrized for the simulation of crops, RZWQM2 is also equipped with the crop modules of DSSAT Cropping System Models (CSM, v4.5 for specific crop simulations (Jones et al., 2003; Ma et al., 2009). Cotton yield was simulated via CSM-CROPGRO-Cotton model (DSSAT v4.5) based on photo-thermal units accumulated from sowing to harvest (Tsuji et al., 1998). Seed cotton yield was determined on the basis of biomass allocation to developing organs, and it is mainly influenced by the quantity of light captured by plants growing at an optimal temperature. The influence of CO_2 on photosynthesis of cotton plant was estimated with the equation of Michaelis-Menten (Islam et al., 2012).

Model Calibration and Validation

Model calibration was done by using the data from the field experiment conducted in 2017 (Table 2), while data from the 2018 experiment was used for model validation (Table 3). Two steps were involved in the evaluation of the model. In first step, simulated cotton phenological stages (anthesis and maturity), plant height, and LAI were compared with field observed data. Later, model-simulated seed cotton yield was compared with observed yield. The model was initialized with in-situ meteorological, crop and soil management parameters with default genotype traits. The base growing period for cotton crop was considered from April to October. The initial soil moisture condition was at field capacity. The genetic coefficients of cotton cultivar used for simulation was determined from the cultivar parameters in the model. The CSMCROPGRO-Cotton model simulates cotton growth and developmental stages (emergence, first leaf, first flower, first seed, first cracked boll (physiological maturity) and 90% open boll) based on photo thermal time (Thorp et al., 2014). Each cotton cultivar genetic coefficients were obtained (against planted cultivar) successively during this process; starting with phenological parameters including photo thermal time between plant emergence and flower appearance (EM-FL), photo thermal time between first flower and first boll (FL-SH), photo thermal time between first flower and first seed (FL-SD), photo thermal time between first seed and physiological maturity (SD-PM), photo thermal time between first flower and end of leaf expansion (FL-LF). Growth parameters consisted of LFMAX [maximum leaf photosynthesis rate at 30 °C, 350 ppm CO_2, and high light (mg $CO_2 m^{-2} S^{-1}$)], specific leaf area of cultivar under standard growth conditions (SLAVR), maximum size of full leaf (SIZLF) and cotton seed yield and its components parameters include seed size (WTPSD), maximum fraction of daily growth that is partitioned to seed plus shell (XFRT), seed filling duration for pod cohort at standard growth conditions (SFDUR), average seed per boll under standard growing conditions (SDPDV), time required for cultivar to reach final boll load under optimal conditions (PODUR). A manual calibration technique (iterative approach; trial and error method) was followed once suitable combination of genetic coefficients was obtained (Rahman et al., 2018). Parameters were adjusted within the studied range and the effect of each genetic coefficient on the modeled process was studied by comparing measured versus simulated development, growth, and cotton seed yield. The TX003 GP3774 cultivar was best suited as a reference cultivar (Table 4). The CROPGRO-Cotton model does not include the mulch module, therefore the model is unable to simulate the effects of plastic film mulch on soil-plant system. Due to this limitation of model, we modified

Table 4 Crop cultivar parameters adjusted during model calibration

Parameter	Description	Calibrated value	Default value
EM-FL	Time between emergence and flower appearance (days)	33	35
FL-SH	Time between first flower and first pod (days)	10	10
FL-SD	Time between first flower and first seed (days)	17	18
SD-PM	Time between first seed and physiological maturity (days)	25	45
FL-LF	Time between first flower and end of leaf expansion (days)	51	75
LFMAX	Maximum leaf photosynthesis rate at 30 °C, 350 ppm CO_2, and highlight (mg CO_2 m^{-2} s^{-1})	1.05	1.10
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm^2 g^{-1})	150	175
SIZLF	Maximum size of full leaf (cm^2)	286	250
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell	0.85	0.55
WTPSD	Maximum weight per seed (g)	0.20	0.18
SFDUR	Seed filling duration for pod cohort at standard growth conditions (days)	18	22
SDPDV	Average seeds per pod under standard growing conditions (seeds pod^{-1})	20	20
PODUR	Time required for cultivar to reach final pod load under optimal conditions (days)	8	8

Table 5 Calibration (2017) of RZWQM2 model using cotton cultivar TX003 GP3774 for anthesis, maturity, seed yield and average soil water content (at 40–65 cm soil depth) under full and deficit irrigation treatments

Full Irrigation					Deficit Irrigation			
Crop parameters	Observed	Simulated	RMSE	PE	Observed	Simulated	RMSE	PE
Anthesis (days)	80	78	2	2.5	80	72	8	10
Maturity (days)	155	148	7	4.5	150	139	11	7.3
Seed yield (kg/ha)	4272	3810	462	10.8	3577	3589	12	0.33
Soil water content (cm^3 cm^{-3})	0.14	0.12	0.02	-14	0.12	0.13	0.01	-6.6

Where RMSE is root mean square error and PE is percent error (%)

the potential evapotranspiration model and extinction coefficient of evaporation process following the method adopted by Li et al. (2019) and Wang et al. (2020).

After completing optimization, the RZWQM2 model was run by replacing the GCMs simulations (temperature and rainfall) for historical period (1970–2000) and for each year of three future periods [(2022–2047), (2048–2073) and (2074–2099)] under RCP 4.5 and RCP 8.5. Statistical indices such as root mean square error (RMSE) and percent error (PE) were used to evaluate the performance of model (Wallach & Goffinet, 1987):

$$\mathrm{RMSE} = \sqrt{\left(\frac{1}{n}\sum_{i=1}^{n}(Y_{pi} - Y_{Oi})^2\right)} \quad (1)$$

$$\mathrm{PE} = \left(\frac{P_i - O_i}{O_i}\right) \times 100 \quad (2)$$

Where, RMSE indicates the magnitude of error between predicted (P) and observed (O) values. The PE represents the size of error in percent between the observed and predicted values. Performance of model will be good if RMSE and PE have lower values.

Results

Model Evaluation

The CSM- CROPGRO-Cotton model predicted the anthesis, maturity stages and seed cotton yield very well during the calibration by using the 2017 experimental data as indicated by good fit between the observed and simulated values (Table 5). RMSE values for observed and simulated anthesis, maturity stages and seed cotton yield were 2, 7, and 462 under full irrigation and 8, 11, and 12 under deficit irrigation, respectively The PE values for observed and simulated anthesis, maturity stages and seed cotton yield were 2.5%, 4.5% and 10.8% under full irrigation and 10%, 7% and 0.33% under deficit irrigation, respectively (Table 5). The model has also well predicted the soil water content (SWC) values against the observed values for both irrigation treatments during calibration phase (Fig. 2). The RMSE and PE values for observed and simulated SWC were 0.02 and −14% under full irrigation while 0.01 and −6% for deficit irrigation, respectively (Table 5; Fig. 2).

Model verification using the 2018 experimental data reflected good agreement between observed and simulated crop parameters (Table 6). The RMSE values for observed and simulated anthesis, maturity stages and seed cotton yield in case of full irrigation were 11, 12 and 375, while under deficit irrigation these values were 9, 11, and 392,

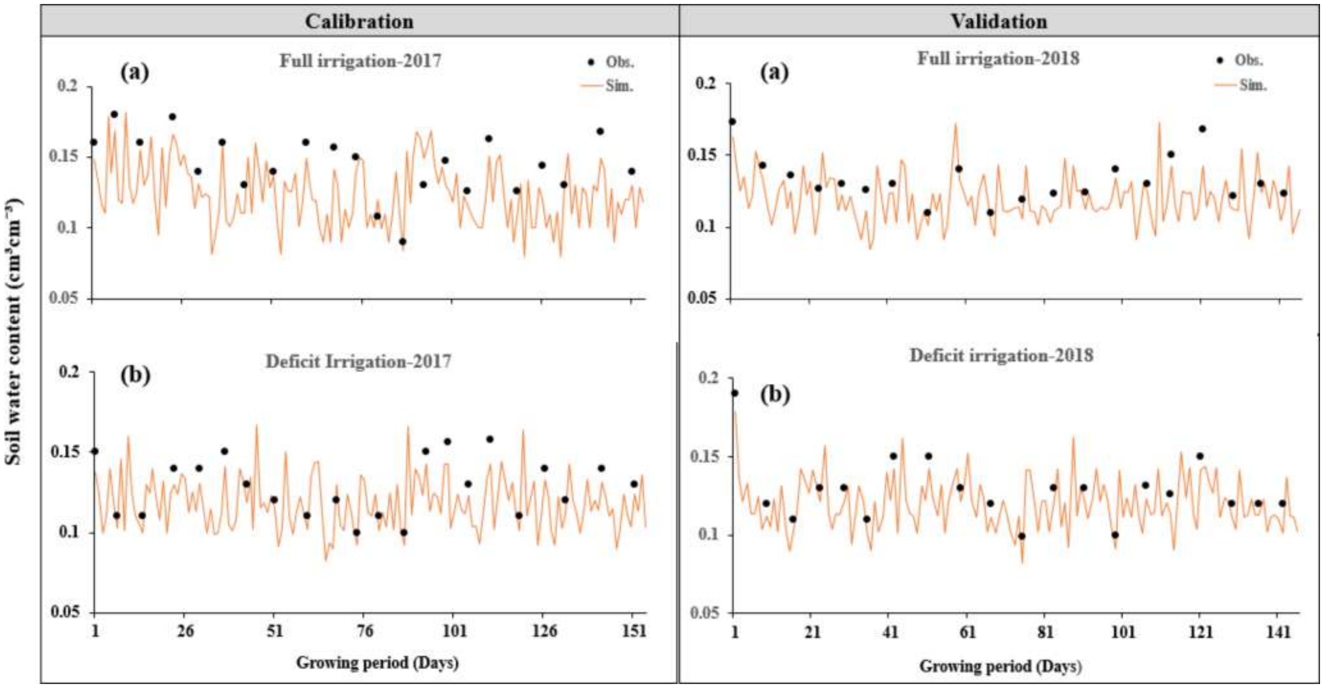

Fig. 2 Measured and simulated soil water contents at 40–65 cm soil depth for full and deficit irrigation treatments during 2017 and 2018

Table 6 Validation (2018) of RZWQM2 model using cotton cultivar TX003 GP3774 for anthesis, maturity, seed yield and average soil water content (at 40–65 cm soil depth) under full and deficit irrigation treatments

Full Irrigation					Deficit Irrigation			
Crop parameters	Observed	Simulated	RMSE	PE	Observed	Simulated	RMSE	PE
Anthesis (days)	89	78	11	12.35	88	79	9	10.22
Maturity (days)	156	144	12	7.69	157	146	11	7
Seed yield (kg/ha)	4015	3640	375	9.33	3248	3640	392	12.06
Soil water content (cm^3 cm^{-3})	0.12	0.13	0.01	-6.6	0.13	0.11	0.02	-15

Where RMSE is root mean square error and PE is percent error (%)

respectively. The observed and simulated anthesis, maturity stages and seed cotton yield exhibited PE values of 12.3, 7.6 and 9.3 under full irrigation, while under deficit irrigation PE values were 10%, 7% and 12%, respectively (Table 6). During validation phase RMSE and PE values for SWC were 0.01 and −6.6% under full irrigation, whereas under deficit irrigation these values were 0.02 and −15%, respectively (Table 6; Fig. 2). Overall, the comparison between observed and simulated cotton phenology, seed cotton yield and SWC under different irrigation levels indicated a good model performance based on the criteria suggested by Bannayan and Hoogenboom, (2009).

Climate Change Projections

Climate change projections revealed increasing trends for both precipitation and air temperature over 2022–2047, 2048–2073 and 2074–2099 in the study region (Fig. 3). The baseline (BL) average minimum and maximum temperatures from April 1 to October 30 (cotton growing season) were 20.58 and 27.67 °C, respectively and rainfall was 29.5 mm. The predicted rise in mean temperature for 2022–2047 during the cotton growth period was 0.49 °C (RCP 4.5) and 0.59 °C (RCP 8.5) (Fig. 3a and b). In 2048–2073, mean temperature was increased by 0.92 and 1.38 °C under RCP 4.5 and 8.5, respectively (Fig. 3c and d). In case of 2074–2099, the rise in mean temperature was 1.19 and 2.35 °C under RCP4.5 and 8.5 respectively (Fig. 3e and f). Climate projections revealed an increase of 31–47% (2022–2047), 33-49% (2048–2073) and 37-52% (2074–2099) in precipitation under both RCP scenarios 4.5 and 8.5 respectively (Fig. 3).

Climate Change Impact on Cotton Growth, Phenology and Seed Yield Under Full and Deficit Irrigation

The results of this study revealed a decrease in mean anthesis length simulated by all GCMs under full irrigation treatment. The decrease in mean anthesis length was 9, 11, and

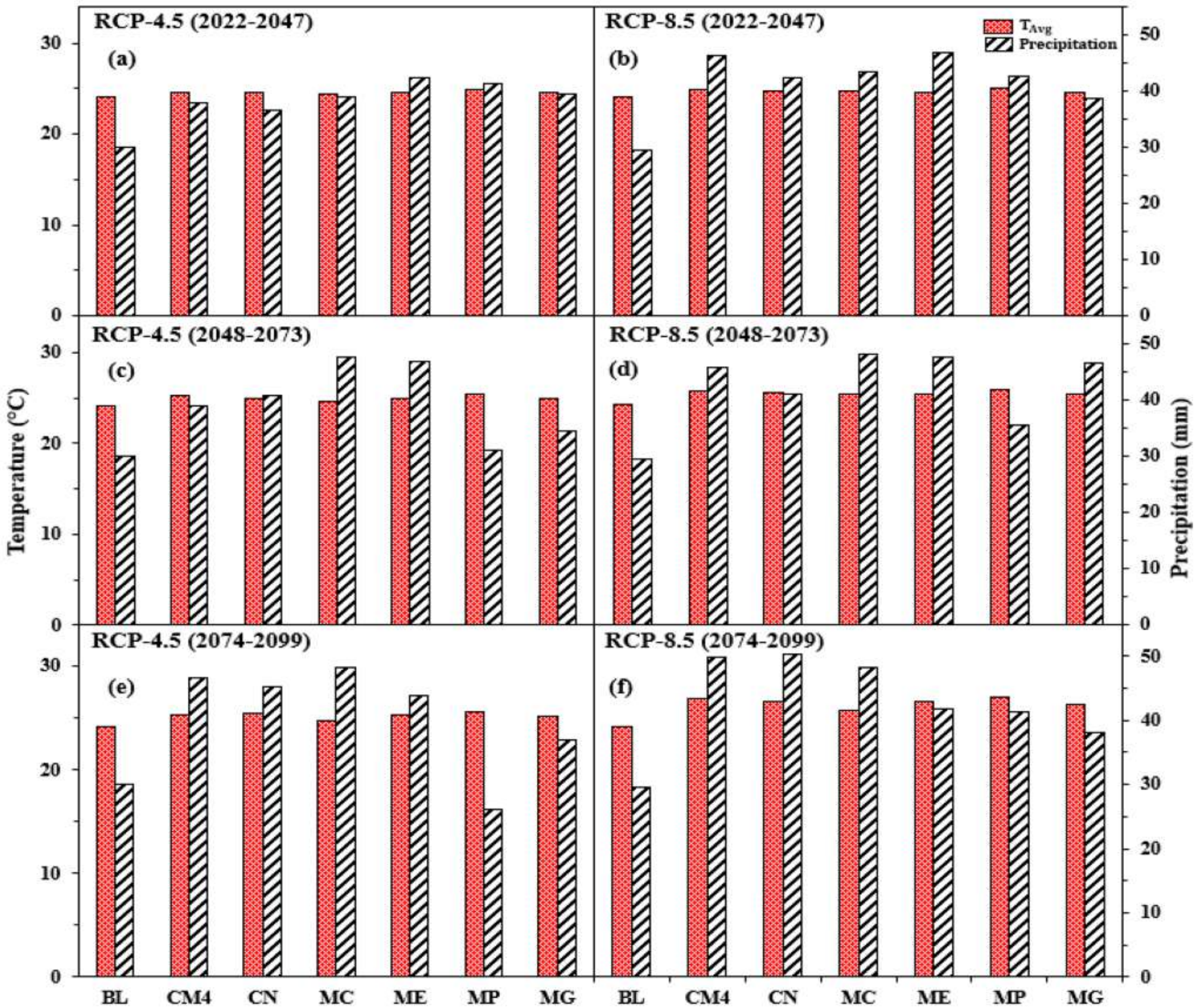

Fig. 3 Projected average temperature and precipitation during the growing season (April-October) for 2022–2047 (a,b), 2048–2073 (c, d) and 2074–2099 (e, f) under RCP 4.5 and 8.5 from climate models. T_{ave}, average temperature; BL, baseline; CM4, CCSM4; CN, CNRMCM5; MC, MIROC5; ME, MIROC-ESM; MP, MPI-ESM-LR; MG, MRI-CGCM3

13 days under RCP 4.5, while under RCP 8.5 this reduction was 9, 12, and 15 days for 2022–2047, 2048–2073 and 2074–2099 (Fig. 4), respectively as compared to the baseline period. The maximum decrease in mean anthesis length (15 days) was noted in future period of 2074–2099 under RCP 8.5 while minimum decrease (9 days) was recorded in 2022–2047 under both RCPs compare to BL. The overall reduction in mean anthesis length was higher in mid (2048–2073) and late (2074–2099) periods under both RCPs (8.5 and 4.5) compared to 2022–2047. This could be attributed to projected rise in mean temperature in mid and late periods. The simulated mean maturity length manifested a substantial decrease under full irrigation for future scenarios. The mean maturity length was decreased by 8 days (2022–2047), 12 days (2048–2073), and 14 days (2074–2099) under RCP 4.5 (Fig. 4). Under RCP 8.5, the reduction in mean maturity length was 9, 13 and 16 days during 2022–2047, 2048–2073, and 2074–2099, respectively as compared to the baseline period (Fig. 4). The maximum reduction of 16 days in mean maturity length was recorded under RCP 8.5 in the future period of 2074–2099 (Fig. 4). The reduction in mean maturity length was slightly higher under RCP 8.5 compared to RCP 4.5 particularly in mid and late periods than 2022–2047. The RZWQM2 predicted a substantial decline in average seed cotton yield for the future under both RCP scenarios. The mean seed cotton yield was declined by 13%, 15%, and 16% under RCP 4.5 (Fig. 5), and this reduction was 15%, 16%, and 18% under RCP 8.5

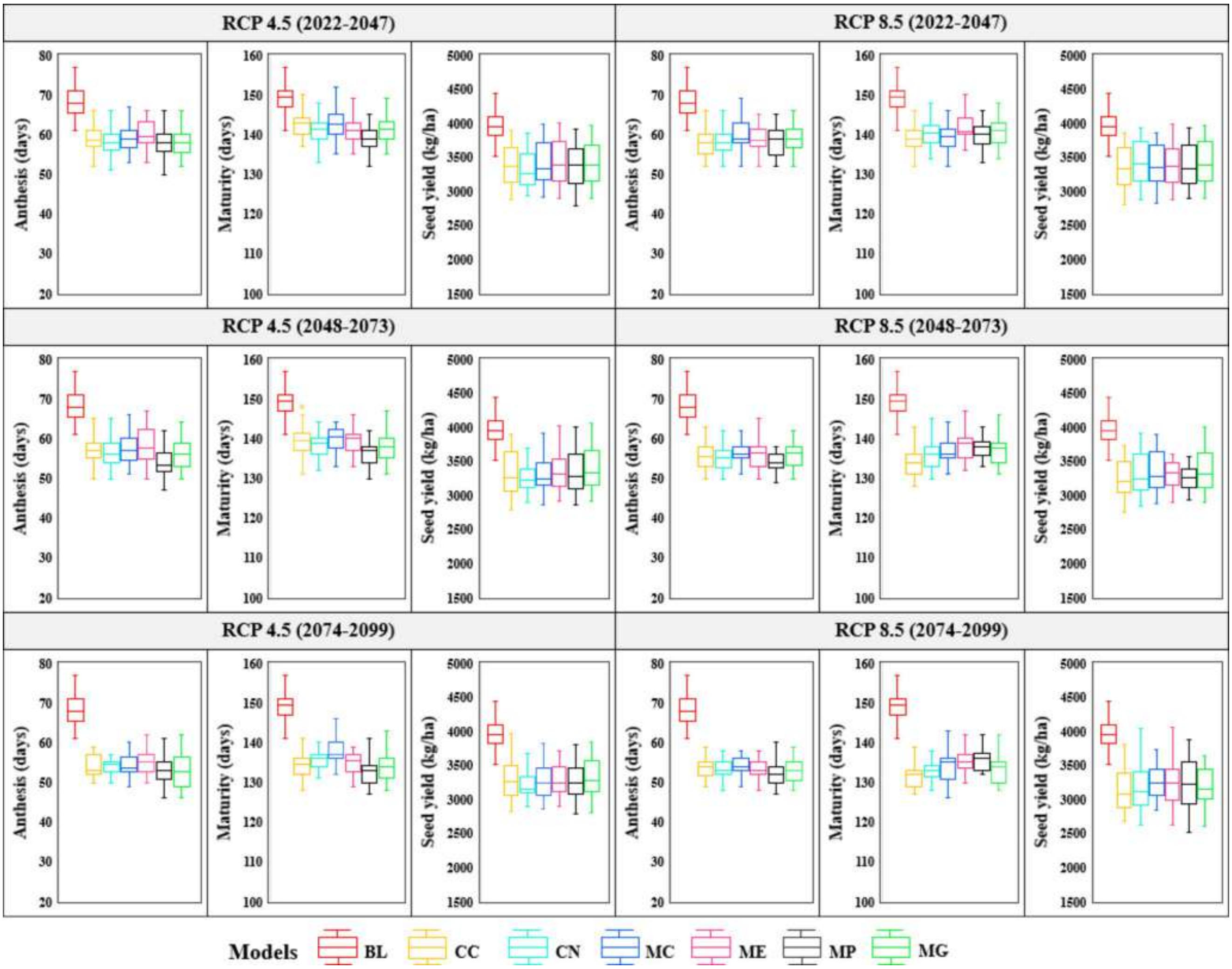

Fig. 4 Model predicted days for anthesis and maturity length (days), and seed cotton yield (kg/ha) with full irrigation under RCP 4.5 for 2022–2047, 2048–2073, and 2074–2099 compared to baseline

for 2022–2047, 2048–2073, and 2074–2099, respectively as compared to BL (Fig. 5). The maximum decrease (18%) in average seed cotton yield was recorded under RCP8.5 for the future period of 2074–2099. Overall, decline in average seed cotton yield was higher in 2048–2073 and 2074–2099 than 2022–2073 under both RCPs.

Under deficit irrigation, the GCM predicted mean days to anthesis were reduced by 7, 9, and 10 days under RCP 4.5 and 7, 9, and 13 days under RCP 8.5 for future periods 2022–2047, 2048–2073, 2074–2099, respectively, as compared to baseline (Fig. 6). The days to anthesis were substantially decreased under RCP 8.5 compared to RCP 4.5 in 2074–2099 than other periods. Similarly, days to maturity fell shorter for 9, 11, and 11 days under RCP 4.5, while under RCP 8.5, this reduction was 9, 12, and 14 days for 2022–2047, 2048–2073, 2074–2099, respectively, as compared to BL (Fig. 6). However, the maximum reduction in the number of days for maturity (14 days) was noted for 2074–2099 under RCP 8.5. The average seed cotton yield simulated by six GCMs showed a 10%, 12%, and 13.8% decline under RCP 4.5, but under RCP 8.5, yield reduction was 11%, 14%, and 19.6% for 2022–2047, 2048–2073, 2074–2099, respectively as compared to the BL (Fig. 7). The maximum yield reduction appeared in 2074–2099 under RCP 8.5 however, least reduction (10%) in seed cotton yield was observed in 2022–2047 under RCP4.5. Overall, the reduction in average seed cotton yield was slightly higher under RCP 8.5 compared to RCP 4.5 especially in mid and late periods.

Discussion

The GCMs projected an increase in temperature and rainfall in this study. The expected increase in temperature in current study is in line with the findings of Huang et al. (2018) and Chen et al. (2018). Huang et al., 2018 predicted

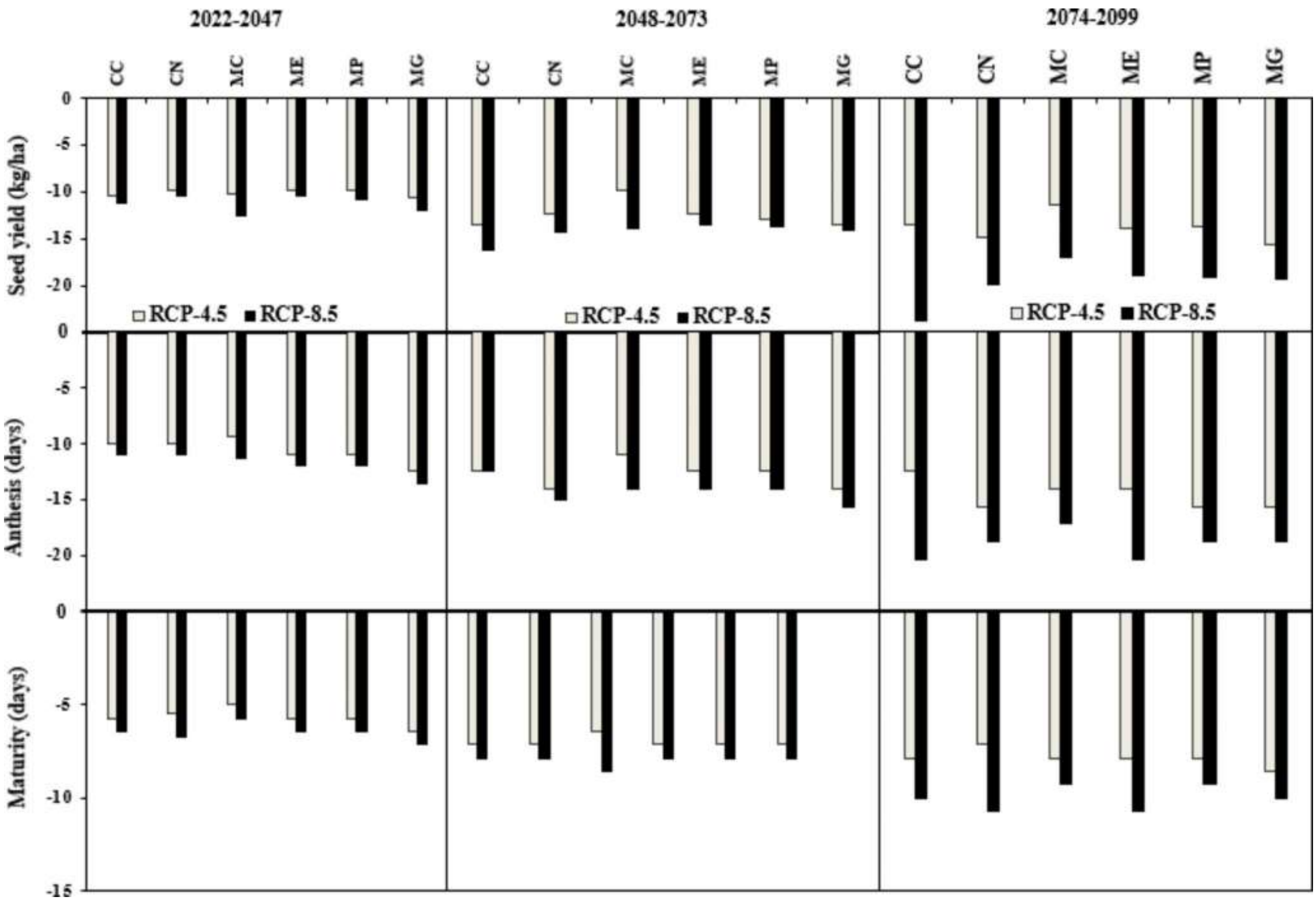

Fig. 5 Percent (%) change in model predicted values for anthesis, maturity, and seed cotton yield compared with full irrigation to baseline under 4.5 for 2022–2047, 2048–2073 and 2074–2099

an increase of 2.18–3.03 °C and 2.69–4.99 °C in temperature, whereas 28–43% and 34–66% increase in precipitation for 2041–2070 and 2071–2099 under both RCPs (4.5 and 8.5) respectively as compared to the baseline (1970–2000). Likewise Chen et al. (2019) also predicted a temperature rise of 2.38 and 3.24 °C and precipitation increase of 3.5% and 5.3% mm during cotton growing season for 2041–2060 and 2061–2080 respectively in the same study area. However, in the current study, predicted rise in temperature is less compared to the previous studies (Huang et al., 2018; Chen et al., 2019) but increase in precipitation is in close agreement with Huang et al. (2018). The projected increase in precipitation might be due to the fact that high temperature rapidly evaporates the moisture from the surface. The warmer air then becomes moist as high temperature warms the earth and causes more precipitation (Trenberth, 2011). The climate warming significantly impacts the cotton phenology and seed cotton yield. In present study reduced number of days to anthesis and maturity has been predicted with full and deficit irrigation for 2022–2047, 2048–2073 and 2074–2099 under both emission scenarios (RCP 4.5 and 8.5) compared to BL. Our findings are in line with Yang et al. (2014) who predicted a shortening of cotton growing season by 13 days for 2050 and 16 days in 2070 for a late maturing variety but for a medium maturity variety this shortening was 22 days in 2050 and 26 days in 2070. Earliness in cotton anthesis and maturity under climate warming has also been reported by Ahmad et al., (2017).

The shortening of the anthesis and maturity period could be attributed to the elevated temperature which caused a rapid cotton development providing short time interval between cotton development phases (Adhikari et al., 2016). Reddy et al. (2002) demonstrated a positive correlation between increasing temperature and cotton development. The rising temperature shortens the reproductive phase of cotton by increasing its metabolic and carbon utilization rates, which accelerate the production of flowers and buds during the growth process (Li et al., 2021). Wang (2015) studied the impact of future climate change and reported earliness in emergence, squaring, flowering and boll opening phases of cotton compared to baseline. Furthermore, variation in simulated phenology might be induced by the designated cultivar, crop model and existing regional conditions (Chen et al., 2019). Some researchers suggested that

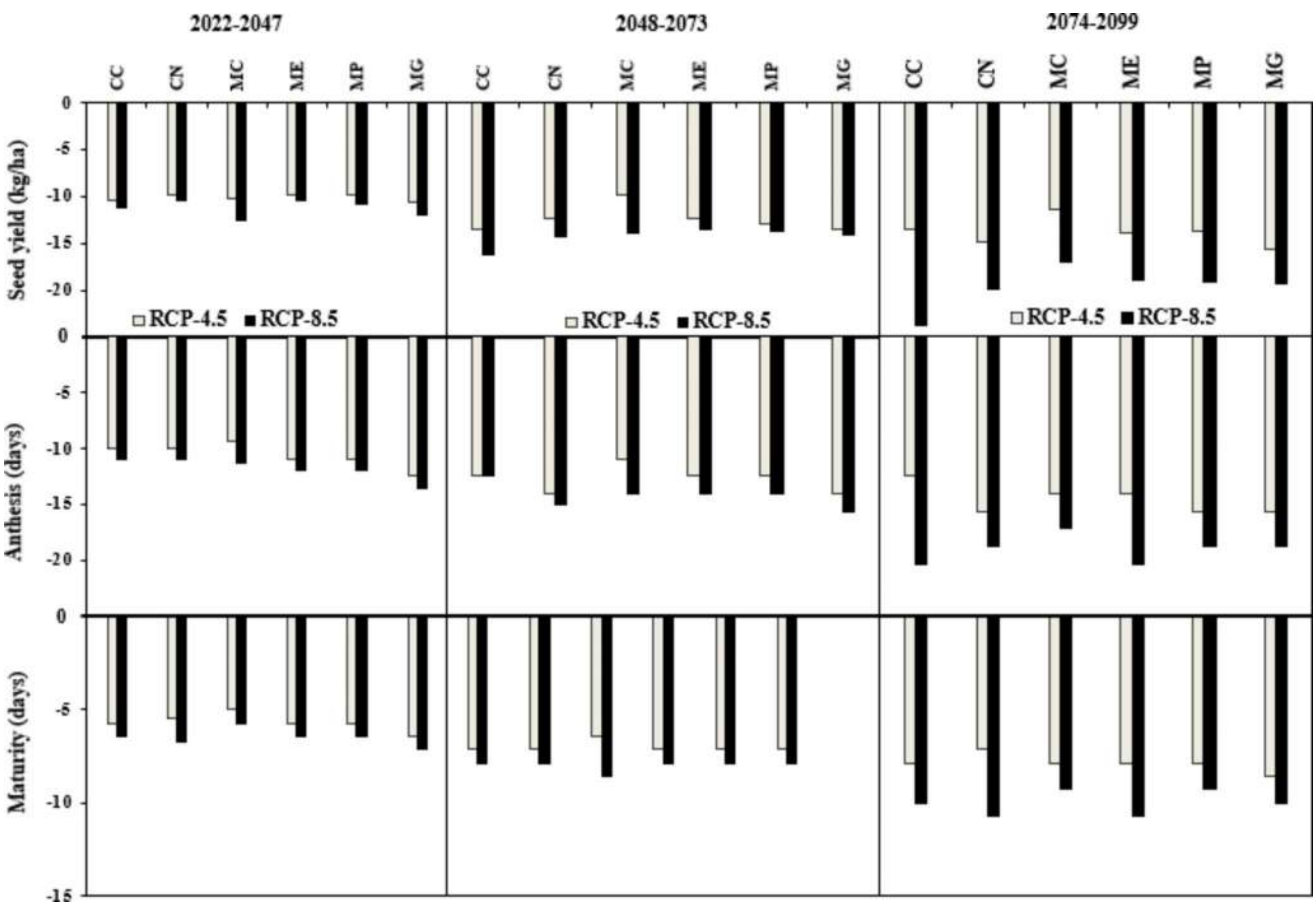

Fig. 6 Model predicted days for anthesis and maturity length (days), and seed cotton yield (kg/ha) with deficit irrigation under RCP 4.5 for 2022–2047, 2048–2073, and 2074–2099 compared to baseline

cotton genotypes with early flowering and longer reproductive periods can prove beneficial under future climate change (Loison et al., 2017; Gerardeaux et al., 2018).

A reduction in seed cotton yield is predicted in future periods (2022–2047; 2047–2073 and 2074–2099) under RCP 4.5 and RCP 8.5 with full and deficit irrigation. The decrease in yield was more pronounced (19.6%) with deficit irrigation than full irrigation under RCP 8.5 in 2074–2099. This reduction in seed cotton yield could be the result of projected rise in mean temperatures which were 0.49 -1.19 °C (RCP 4.5) and 0.59-2.35 °C (RCP 8.5) higher than BL temperature. Apparently seed cotton yield reflected a negative relationship with rising temperature, and it varies according to the crop growth stage (Rahman et al., 2018). Ayankojo et al. (2020) reported significant reduction (40–51%) in seed cotton yield (irrigated cotton) under projected future climate conditions and this reduction was attributed to rise in daily maximum and minimum air temperatures. Increasing temperature causes faster growth of crop and shorten the time to obtain adequate resources like nutrients, water and radiation, which are harmful to crop productivity under warm conditions (Craufurd & Wheeler, 2009). Chen et al. (2019) reported 22.4% and 28.6% decrease in seed cotton yield for 2041–2060 and 2061–2080, respectively against projected temperature increases. Furthermore, reproductive phase of cotton crop found to be more sensitive to temperature increase than vegetative stage (Reddy et al., 2005). Although projected rise in temperature may slightly enhance the cotton biomass but it significantly reduces fruit retention, causing low boll number and ultimately decrease yield (Bange & Milroy, 2004; Hatfield et al., 2011; Ayankojo et al. 2020). The projected increase in precipitation (31–52%) under both RCPs in current study has negatively impacted seed cotton yield under both irrigation treatments. The possible reason for decrease in seed yield under full irrigation could be the prolonged vegetative period and delay in maturity due to excessive rainfall. (Yang et al., 2014; Rahman et al., 2018). Moreover, rainfall (depending upon amount and frequency) during flowering could disturb the pollination process, while at the boll opening stage, it may deteriorate the fiber quality or even leads to fruit shedding that results in yield reduction. (Cetin & Basbag, 2010). On the other hand, under deficit irrigation, rainfall could compensate for the water deficiency to some extent and may ensure satisfactory

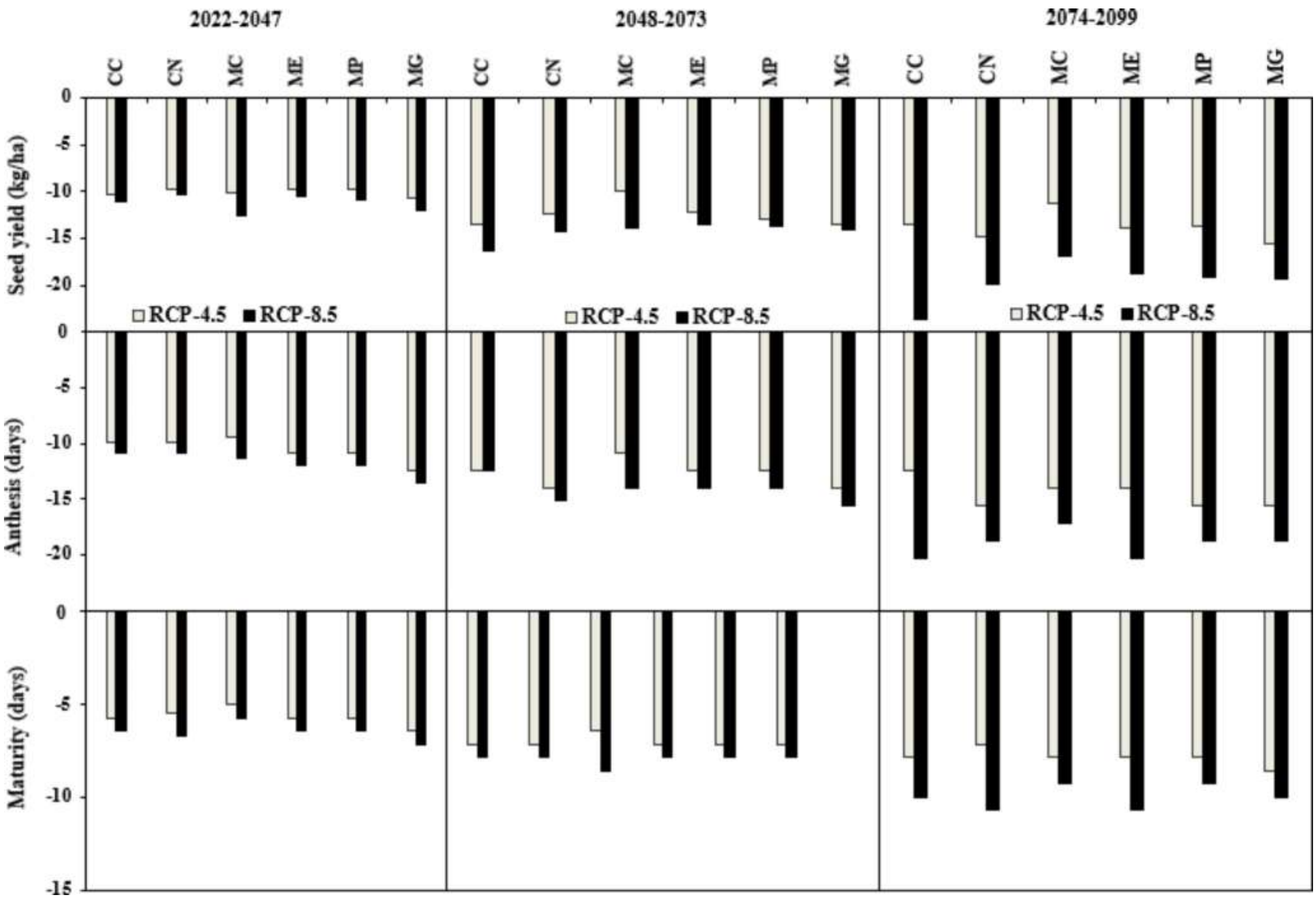

Fig. 7 Percent (%) change in model predicted values for anthesis, maturity, and seed cotton yield compared with full irrigation to baseline under 4.5 for 2022–2047, 2048–2073 and 2074–2099

yield (Shareef et al., 2018; Liu et al., 2022). Drastic yield reduction in cotton was noted with 1.8 °C rise in temperature and with 6% increase or decrease in rainfall compared to baseline (Iqbal, 2011).

The projected increase in temperature under climate change scenarios may leads to higher water demand due to enhanced evaporative water loss to the atmosphere. This elevated ET demand is compensated through shortening of the total crop duration in the field. However, irrigated cotton yield can get benefit from increased CO_2, if the projected increase in temperature remains below the threshold temperature. Because of high air temperatures during the growing season, CO_2 fertilization may have limited effects on cotton growth. Consequently, elevated CO_2 concentrations in the future may not benefit cotton growth, particularly under arid conditions having higher temperatures during the cropping season (Ayankojo et al., 2020). Findings of this study revealed that projected rise in temperature and rainfall in XUAR will seriously impact the irrigated cotton yield. However, in the absence of adequate water availability in future extreme weather conditions deficit irrigation could be employed to sustain cotton production with minimum yield loss. Because deficit irrigation aimed to stabilize rather than to maximize the yield in water scarce regions thus extending water availability for agriculture. This study could facilitate the cotton growers for better application of deficit irrigation under limited water conditions not only in the XUAR but also in other regions having similar conditions. Nonetheless, other adaptation measures (change in crop cultivars, sowing date, irrigation, crop rotation, and fertilizer management) based on crop models could help to offset the possible negative impacts of climate change on cotton production (Li et al., 2021). These adaptations are usually autonomous adaptations related to existing planting systems. Chen et al. (2019) suggested that seed cotton yield can be increased in future if current cultivars are replaced with cultivars having longer growth periods in arid regions. Replacing fast-maturing cultivars with slow maturing cultivars could increase cotton yield (Yang et al., 2014). However, these long duration cultivars will also require more seasonal irrigation water under future climate change due to increase in length of growing season, so application of irrigation at critical growth stages of crop could be a viable option to efficiently utilize available water in future (Chen et al., 2019). For irrigated cotton, Kothari et al. (2021) suggested high yielding ideotype with higher potential leaf size and increased partitioning to seed plus shell. Early planting, for instance sowing cotton one month earlier could be beneficial for good seed yield and mitigate the negative impacts of climate change in arid regions. Planting cotton five to six weeks earlier than current sowing date found effective to enhance seed cotton yield in Mississippi delta and Pakistan (Anapalli et al., 2016; Rahman et al., 2018). Furthermore, an increase (17%) in genetic potential of cultivars, split irrigation at critical growth stages, increasing nitrogen fertilization (30%), higher planting density (18% for spreading and 30% for erect type cultivars) would compensate the adverse impacts of climate change and improve cotton yield (Rahman et al., 2018). Selecting suitable cotton cultivar and sowing date in combination with water-saving irrigation approach may be a good choice for the local producers to ensure good crop yield under climate change.

Conclusion

The RZWQM-DSSAT model simulated the climate change impacts on cotton phenology and seed yield under deficit and full irrigation scenarios. The GCMs projected a substantial variation in temperature and rainfall under RCP 4.5 and 8.5 for 2022–2047, 2048–2073 and 2074–2099 in the study area. The number of days to anthesis and maturity have been predicted to decrease under both RCPs (4.5 and 8.5) for future periods with full and deficit irrigation treatments. However, decrease in number of days to anthesis and maturity was more pronounced under RCP 8.5 than RCP 4.5 for full and deficit irrigations especially in 2074–2099. Reduction in seed cotton yield is projected in all future periods under both RCP scenarios with full and deficit irrigation, but future yield loss with deficit irrigation was higher (19%) than full irrigation under RCP 8.5 near end of century. This decrease in yield is primarily corresponds to elevated temperature. Seed yield losses up to 10–19% was predicted with 25% deficit of irrigation compared to full irrigation for future periods. Findings of this study suggests that deficit irrigation could sustain cotton production without severely penalizing the yield, so it could be adopted as a valuable irrigation option under changing climate in XUAR and elsewhere with similar agro-climatic conditions.

Author Contribution Conceptualization (Zeeshan Ahmed and Dongwei Gui), original draft preparation (Zeeshan Ahmed and Sikandar Ali); review and editing (Xiaoping Chen and Zhiming Qi).

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Declarations

Conflict of Interest The authors declare no conflict of interest.

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