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ORIGINAL ARTICLE

Productivity of rainfed wheat as affected by climate change scenario in northeastern Punjab, India

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Abstract Wheat (*Triticum aestivum* L.) is grown as a rainfed crop in the sub-mountainous region of the Punjab state of India, with low crop and water productivity. The present study aims to assess the effect of climate change scenario (A1B) derived from PRECIS—a regional climate model—on wheat yield and water productivity. After minimizing bias in the model climate data for mid-century (2021–2050), evapotranspiration (ET) and yield of wheat crop were simulated using Decision Support System for Agrotechnology Transfer, version 4.5, model. In the changed climate, increased temperature would cause reduction in wheat yield to the extent of 4, 32 and 61 % in the mid-century periods between 2021–2030, 2031–2040 and 2041–2050, respectively, by increasing water stress and decreasing utilization efficiency of photosynthetically active radiation. The decreases in crop water productivity would be 40, 56 and 76 %, respectively, which are caused by decreased yield and increased ET. Planting of wheat up to November 25 till the years 2030–2031 seems to be helpful to mitigate the climate change effect, but not beyond that.

Keywords Climate change scenario · Bias correction · DSSAT model · Rainfed wheat yield · Water productivity · Water stress

Introduction

Worldwide, 82 % of the cropland cultivated is under rainfed conditions (Laux et al. 2010). As per IPCC reports, temperature is likely to rise in future. In northeastern Punjab state, constituting 9.9 % area (major parts of the Shiwalik hills sandwiched between Indo-Gangetic alluvial plains and rocky Himalayas of India), wheat is grown as a rainfed crop. The yield here is very low (1,500–4,100 kg ha^{-1}) compared to the potential of 5,000 and 5,500 kg ha^{-1} (Ghuman and Sur 2001). Rains in this region occur as monsoons and typically cease mostly during the second week of September, leaving low residual moisture in the soil profile, which affects the yield of post rainy season wheat crop (Ghuman and Sur 2001; Sharma et al. 2005). It is documented that crop yields are affected by three major specific factors, that is, atmospheric carbon dioxide concentration, precipitation and temperature (Alexandrov and Hogenboom 2000; Bannayan et al. 2005, 2010, 2011; Holden et al. 2003; Morison and Morecroft 2006). Under water-deficit conditions, higher temperatures coupled with a reduced water supply are likely to reduce crop production (Syre et al. 1997; Turner 2001; Kimball et al.

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1995). IPCC reports prominently mention that the global warming process is occurring rapidly. By 2030, global temperatures are expected to rise roughly 1 °C relative to late-twentieth-century values, regardless of any changes in greenhouse gas production. Under such conditions of elevated temperature, crop yields are likely to decrease because of higher rates of night respiration (Peng et al. 2004), decreased nutrient absorption (Matasubayashi 1965), less number of grains per spike or high spikelet sterility (Haris et al. 2011; Yoshida 1961), and less sink capacity at grain filling (Lal et al. 1998; Kobata and Uemuki 2004). Although increases in CO_2 enhance yield, an increase in temperature beyond 38 °C would cancel out the beneficial impacts and wheat yield may decrease by 20 % in India (Attri and Rathore 2003). For rainfed crops, sowing date is very important to ensure enough soil moisture during both planting and the growing period to avoid water stress and reduction in yields (Nendel et al. 2012; Phillips 1991). In spite of large number of uncertainties (Kumar et al. 2011a, b), simulation studies are one of the main methods for investigating potential impacts of climate change on agro-ecosystems (Haris et al. 2011; Aggarwal 2008). The CERES-Wheat model is one of the most popular wheat models (Pecetti and Hollington 1997). Furthermore, it has been tested in many sites across the world, and the results indicate its capability to simulate grain yields under dry conditions (Rinaldi 2004). The impact of the climate change scenario derived from general circulation models (GCMs) on crop duration and yield of wheat in the arid and semi-arid areas of the world is documented in the literature (Downing et al. 1997; Luo et al. 2003; Nassiri et al. 2006; Turner 2001; Menzel and Fabian 1999; Whetton 2001; Jalota et al. 2012). GCM projections provide the necessary weather data for future-oriented crop simulations (Reddy and Pachepsky 2000; Mall et al. 2004). Rosenzweigh and Parry (1994) predicted that the plant growth period in Iran would decrease significantly and cereal production would decrease by 5–40 % under rainfed agriculture by 2080. The present study was undertaken with the objectives to (1) gather climate data on temperatures and rainfall for baseline and future from *Providing Regional Climates for Impacts Studies* (PRECIS) regional climate model, minimizing bias in the modeled data, (2) calibrate and validate DSSAT model with the collected field data, and (3) assess the impact of climate change scenario on crop period, yield and water productivity of rainfed wheat with different dates of planting.

Materials and methods

Site and climate

A field study was carried out at the Research Farm of Punjab Agricultural University's Regional Research Station, Ballowal Saunkhri, Nawanshahar (30°41′–32°30′N, 75°30′–75°48′E and 355 m above m.s.l.), in the Punjab state (73° 53′–76°55′ E longitude and 29°33′–32°31′N latitude) of India from the 2003–2004 to 2009–2010 growing seasons. The experiment involving rainfed wheat cultivar PBW 175 was conducted in a randomized block design with three replications. The soil is fine loamy fluventic ustochrept. The sand, silt and clay contents were determined with pipette method (Gee and Bauder 1986), bulk density with core method (Blake and Hartage 1986) and hydraulic conductivity with constant head method (Jalota et al. 1998). EC was measured with solu bridge method, pH with potentiometric method (Jackson 1973) and OC by wet digestion method (Walkley and Black 1934). Ammonical and nitrate nitrogen were determined by Kjeldahal method (Keeney 1982). The slope of the area ranges between 1 and 4 %. The climate of the area is semi-arid. Daily weather data of maximum and minimum temperature and rainfall for the period from 1984 to 2010 were collected from Ballowal Saunkri weather station of Punjab Agricultural University, Ludhiana.

Crop growth model

DSSAT (Decision Support System for Agrotechnology Transfer) is a research tool for crop production analyses (Jones et al. 2003). It requires a minimal amount of data that can be easily collected by experimentalists. Simulations were made by first selecting a location and soil, then building crop rotations with management schedules. The location parameters included longitude, latitude, daily weather data files and ET models. The soil parameters included specification of soil layers, thickness, texture, bulk density, cation-exchange capacity, pH and volumetric water content at water potentials at field capacity (−30 kPa) and wilting point (−1,500 kPa). The management options in the model included cultivar selection, planting, irrigation, fertilization, tillage operations, harvest and chemical application. The methods selected in the simulation were Priestley–Taylor/Ritchie—evapotranspiration; Soil Conservation Service—infiltration; Canopy curve (daily)—photosynthesis; Ritchie Water Balance—hydrology; Ceres (Godwin)—organic matter; and Ritchie–Ceres—soil evaporation.

The DSSAT model was calibrated using the observed experimental data of grain yield and biomass of the wheat crop for 3 years (2003–2004 to 2005–2006). The other parameters for the crop file were left as the defaults given in the model (Jones et al. 2003). The crop genetic input parameters used for wheat cultivar are given in Table 1.

At the start of the experiment, physical and chemical properties of soil were determined up to a 150-cm depth with 15-cm intervals following standard procedure (Table 2).

These values were used in the model for calibration, validation and applications of the DSSAT model. Weather data used in the model were daily rainfall, maximum temperature and minimum temperature, which were recorded at the station. The solar radiation was generated from the temperature data using the Weatherman model (Jones et al. 2003). The model also incorporated the information on management operations performed the wheat crop experiment. The calibrated model validated on the independent data set of 4 years (2006–2007 to 2009–2010).

Prediction capability of the model was tested by the following indicators

1. Nash–Sutcliffe modeling efficiency (*ME*) (Nash and Sutcliffe 1970)

$$ME = 1 - \frac{\left[\sum_{i=1}^{n} (o_i - p)^2\right]}{\left[\sum_{i=1}^{n} (o_i - \bar{o})^2\right]},$$

where o_i is the observed value corresponding to p_i (predicted value), and $\bar{o}$ is the observed mean.

Table 1 Genetic coefficients for wheat chosen during calibration of the DSSAT model

Variety	PIV	PID	P5	G1	G2	G3	PHINT
PBW 175	25	55	700	20	38	1.3	80

P1 V, days at optimum vernalizing temperature required to complete vernalization; P1D, percentage reduction in development rate in a photoperiod 10 h shorter than the threshold relative to that at the threshold; P5, grain filling (excluding lag) phase duration (°C d), G1, Kernel number *per* unit canopy weight at anthesis; G2, standard kernel size under optimum conditions (mg); G3, standard, non-stressed dry weight (total, including grain) of a single tiller at maturity (g); PHINT, interval between successive leaf tip appearances (°C d)

2. Root mean square error:

$$RMSE = \left\{\sum_{i=1}^{N} \frac{1}{n}(p_i - o_i)^2\right\}^{0.5},$$

where n is the number of cases, p_i is the predicted value, and o_i is the corresponding observed value. The *RMSE* is an index of actual error produced by the model.

3. Index of agreement (d) (Willmott 1981):

$$d = 1 - \frac{\sum_{i=1}^{n} (p_i - o_i)^2}{\sum_{i=1}^{n} (|p_{i'}| + |o_{i'}|)^2},$$

where $p_i' = p_i - \bar{p}$ and $o_i' = o_i - \bar{o}$. $\bar{p}$ and $\bar{o}$ are the predicted and observed means, respectively.

Nash–Sutcliffe modeling efficiencies can range from $-\infty$ to 1. The simulation results are considered to be good if $ME \geq 0.75$ and satisfactory if $0.36 \leq ME \leq 0.75$ (Popov 1979). An efficiency of 1 ($ME = 1$) corresponds to a perfect match between modeled values and observed data. An efficiency of 0 ($ME = 0$) indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero ($-\infty < ME < 0$) occurs when the observed mean is a better predictor than the model. The index of agreement (d) is a measure of the degree to which the predicted variation precisely estimates the observed variation where $d = 1$ corresponds to perfect agreement. Model outputs taken were grain yield, growth length periods and evapotranspiration. Crop water productivity was estimated as marketable yield/evapotranspiration.

Climate change scenario data

The A1B scenario is characterized by a future world of rapid economic growth, global population that peaks in the

Table 2 Physical and chemical properties of the experimental soil

Soil depth (cm)	Sand (kg kg^{-1})	Clay (kg kg^{-1})	Bulk density (Mg m^{-3})	Hydraulic conductivity (mm h^{-1})	pH	OC (%)	NH_4–N (kg ha^{-1})	NO_3–N (kg ha^{-1})
0–15	0.62	0.29	1.4	31.0	7.5	0.25	15.6	13.5
15–30	0.63	0.39	1.5	34.1	7.4	0.23	10.8	9.6
30–45	0.66	0.30	1.5	42.3	7.6	0.22	11.5	8.6
45–60	0.65	0.28	1.6	42.1	7.5	0.21	12.8	7.5
60–75	0.66	0.28	1.6	57.8	7.5	0.20	11.7	4.4
75–90	0.66	0.27	1.6	60.3	7.5	0.14	13.7	5.4
90–105	0.66	0.28	1.7	54.8	7.6	0.19	8.0	4.1
105–120	0.68	0.26	1.7	43.2	7.6	0.17	3.9	7.5
120–135	0.68	0.26	1.6	48.9	7.6	0.15	3.9	8.5
135–150	0.71	0.25	1.7	68.5	7.7	0.11	5.9	3.2

mid-century and declines thereafter, and rapid introduction of new and more efficient technologies. This scenario also represents balanced mix of technologies and sustainable socioeconomic and technological development. Climate data on daily maximum temperature (Tmax), minimum temperature (Tmin) and rainfall (RF) of Ballowal Saunkhri under A1B scenario for baseline (1984–1990) and mid-century (2020–2050) were derived from regional climate model PRECIS. This model is based on the atmospheric component of the HadCM3 climate model (Gordon et al. 2000) and is described in depth by Jones et al. (2004). PRECIS output was obtained in binary format from the Indian Institute of Tropical Meteorology (IITM), Pune, India. At IITM, three QUMP (Quantifying Uncertainty in Model Predictions), that is, Q0, Q1 and Q14, runs were carried out for the period 1961–2098 and were utilized to generate an ensemble of future climate change scenarios for the Indian region (Kumar et al. 2011a, b). Seasonal trends were evaluated for biases in Tmax, Tmin and RF using statistical parameters including mean (μ), standard deviation (σ) and variance (σ^2). The biases were minimized by applying a correction factor (Δx), which was equal to the averaged daily difference of observed and modeled values taken for each Julian day (365 days) averaged from 5 years data (1984–1988). Δx was applied to the uncorrected modeled data ($x\,\mathrm{model}_{\mathrm{uncor}}$) according to Eq. 1 to give a corrected value ($x\,\mathrm{model}_{\mathrm{cor}}$) closer to the observed one.

$$x\,\mathrm{model}_{\mathrm{cor}} = x\,\mathrm{model}_{\mathrm{uncor}} + (\Delta x). \tag{1}$$

Similar to the correction factors for the daily values, factors at other time scales, that is, monthly and annual, were also developed. This procedure was also used to correct Tmax, Tmin and RF data. Validation of these correction factors was tested on an independent data set covering 2 years (1989 and 1990). Recently Jalota et al. (2013) also used such approach to minimize bias in modeled climate data.

Simulations

Long-term simulations (2001–2050) were made using four time slices, viz. present, MC1 (2001–2010), MC2 (2021–2030), MC3 (2031–2040) and MC4 (2041–2050). These time slices were used to study the effect of climate change on duration, grain yield and ET of wheat crop with seven dates of sowing, that is, October 15 (D_1), October 25 (D_2), November 05 (D_3), November 15 (D_4), November 25 (D_5), December 05 (D_6) and December 15 (D_7).

Results and discussion

Bias correction of modeled climate data

Seven years (1984–1990) of monthly averages of observed and PRECIS modeled Tmax, Tmin and RF for the study area showed that the annual cycle of the modeled temperature reasonably represented the observed (Fig. 1). However, the modeled values of Tmax (Tmax mod) were more than those of the observed (Tmax Obs) from February to May and less from June to December. Tmin modeled (Tmin mod) also followed a similar trend to that of Tmax mod from January to June, and lower than the observed values in the months of November and December. Tmax mod peaked one month earlier (in May) than that of the observed (in June), whereas the Tmin mod and observed peaked in the month of June. Tmin mod matched with Tmin observed (Tmin Obs)

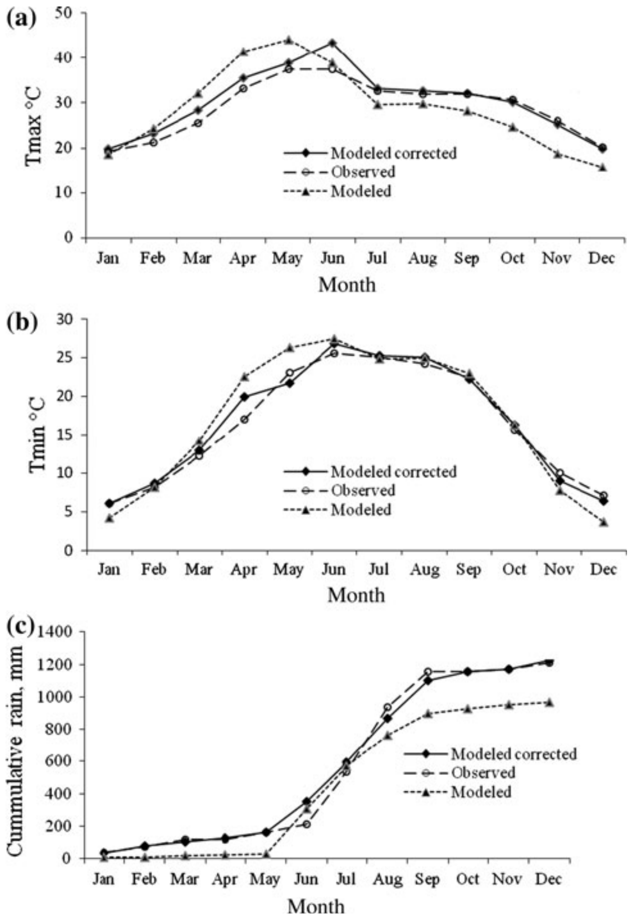

Fig. 1 Monthly observed, modeled and modeled corrected Tmax, Tmin and precipitation of 1989 and 1990 (average)

from February to March and again from July to November, but became less from November to January. The corrected data of Tmax (Fig. 1a) and Tmin (Fig. 1b) were found to be closer to the observed values with respect to time trends and magnitude during wheat growth season. The modeled RF remained higher during the crop growth season of wheat (December–April) except the month of November. Annual total modeled RF was 246 mm less than that of the observed (1,212 mm). Time trends of rainfall showed that the modeled cumulative rainfall (CRF) was less than the observed, except in June and July (Fig. 1c). With correction, it is not only that time trends became similar to that of the observed but also the difference in model (corrected) and observed CRF was reduced to 14 mm only. *RMSE* of model-corrected Tmax and Tmin was 7 % each, which falls in the excellent to good category (Jamieson et al. 1991). However, even after correction, *RMSE* of model RF remained high (62 %).

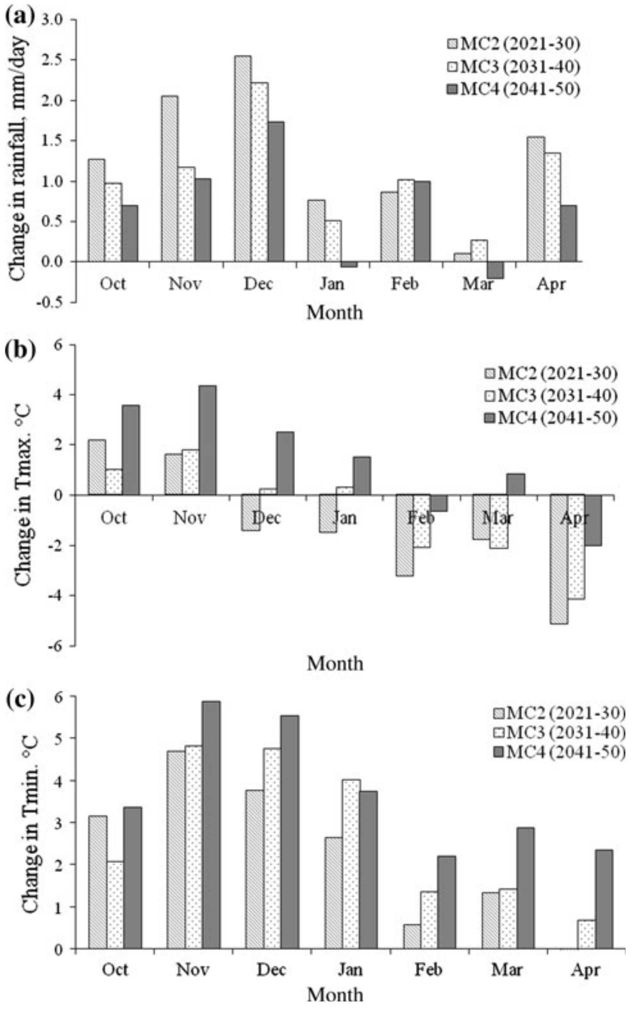

Fig. 2 Monthly change in rainfall, maximum and minimum temperatures under AIB scenarios in different time slices of mid-century (2021–2050) by PRECIS-RCM model with reference to observed baseline (2001–2010)

Climate change scenarios

Averaged over the ten years in each time slice of the future, monthly trends showed that compared to the present (2000–2010), the change in RF was positive in all months except January and March for the period of 2041–2050 (Fig. 2). A negative change in Tmax was observed in all months of crop growth from 2021 to 2030, except October and November. A positive change was also observed in December, January and March during the time slice of 2041–2050. The maximum increase occurred in November in all of the time slices, which coincides with the germination of the wheat crop with the current sowing date. Tmin increased for all of the months, with the largest increase occurring in November.

Model calibration and validation

During the calibration phase, attempts were made to minimize deviation between observed and modeled values. The *RMSE*, *ME* and *d* values during calibration were 0.12, 0.97 and 0.99 for biomass, and 0.10, 0.87 and 0.95 for yield, respectively (Table 3). The corresponding values during validation were 0.17, 0.91 and 0.98 for biomass and 0.09, 0.57 and 0.87 for yield, respectively. The coefficients of determination were high (0.84–0.99).

Table 3 Model performance statistics for grain yield and biomass during calibration (2003–2004 to 2005–2006) and validation years (2006–2007 to 2009–2010)

Statistics	Calibration		Validation	
	Yield	Biomass	Yield	Biomass
Root mean square error (*RMSE*)	0.10	0.12	0.09	0.17
Nash–Sutcliffe modeling efficiency (*ME*)	0.87	0.97	0.57	0.91
Index of agreement (*d*)	0.95	0.99	0.87	0.98
Coefficient of determination (R^2)	0.99	0.99	0.84	0.95

Table 4 Simulated wheat yield in relation to sowing dates of rainfed wheat

Date of sowing	D_1	D_2	D_3	D_4	D_5	D_6	D_7	Mean
Time slice	Grain Yield of wheat (kg ha^{-1})							
MC1	2,343	2,318	2,254	2,215	2,235	2,212	2,119	2,242
MC2	1,574	2,357	2,814	2,982	2,426	1,690	1,301	2,163
MC3	1,063	1,335	1,842	1,832	1,522	1,495	1,516	1,515
MC4	1,003	1,360	978	844	650	656	673	881
Mean	1,496	1,843	1,972	1,968	1,708	1,513	1,402	

D_1—October 15, D_2—October 25, D_3—November 05, D_4—November 15, D_5—November 25, D_6—December 05, D_7—December 15; MC1 (2001–2010), MC2 (2021–2030), MC3 (2031–2040) and MC4 (2041–2050)

Wheat yield

During MC1, simulated yields of wheat with recommended N fertilizer (80 kg ha^{-1}) were 2,242 ± 521 kg ha^{-1} with crop durations (planting to harvest) of 150 days. Higher yields (2,318–2,343 kg ha^{-1}) were obtained by planting wheat through October 25 (Table 4), after which wheat yield decreased continuously. The yield decreased by almost 10 % when wheat was sown in the middle of December. With late planting, crops experience water stress at the reproductive stage and the duration of anthesis to maturity decreases with rise in temperature. In the same region, wheat yield reduction of 20 and 30 % were observed when the sowing date was shifted from November 1 to 16 and 30, respectively, as reported by Jalota et al. (2010) from a simulation study with CropSyst model. Kumar and Sharma (2006) also reported higher simulated grain yields for crops sown in the first fortnight of November using DSSAT CERES-Wheat model.

Simulations for future time slices with current management practices (sowing of wheat in mid-October to December; fertilizer nitrogen at 80 kg ha^{-1}) showed that mean wheat yield (across dates of sowing) decreased by 3.5, 32.4 and 60.7 % in MC2, MC3 and MC4 time slices, respectively (Table 4). Yield decline in changed climate scenarios was found to be directly related to increased Tmax and Tmin (Fig. 3) in the crop growth season, synchronizing reproductive and grain development stages of wheat. The minimum temperature increased by 1.9, 2.8 and 3.4 °C in MC2, MC3 and MC4, respectively, whereas the maximum temperature increased by 1.3 °C in MC4 (Table 5). Besides increased temperature, crop simulation showed that an increased water stress and decreased utilization efficiency of photosynthetically active radiation (PAR) also contributed to yield reduction. The water stress (0–1 scale) was increased from 0.215 (MC1) to 0.231 (MC2), 0.296 (MC3) and 0.365 (MC4), and utilization efficiency of the PAR was decreased from 1.70 (MC1) to 1.65, 1.54 and 1.35 g MJ^{-1} in MC2, MC3 and MC4, respectively. Wheat growth period (sowing to physiological maturity) was shortened by 8 days in MC4 time slice in comparison with the MC1 (Fig. 4). With increase in rainfall and temperatures, ET was increased by 94, 75 and 16 mm in MC2, MC3 and MC4 time slices compared to MC1 (Table 6). The corresponding increase in soil water evaporation (E) was 98, 119 and 103 mm, and decrease in transpiration (T) component was 5, 44 and 87 mm, respectively. Crop water productivity was decreased by 40, 56 and 73 % in MC2, MC3 and MC4 time slices, respectively, compared to MC1 (Table 7). This decrease in water productivity is due to decreased yield and increased ET in future time slices.

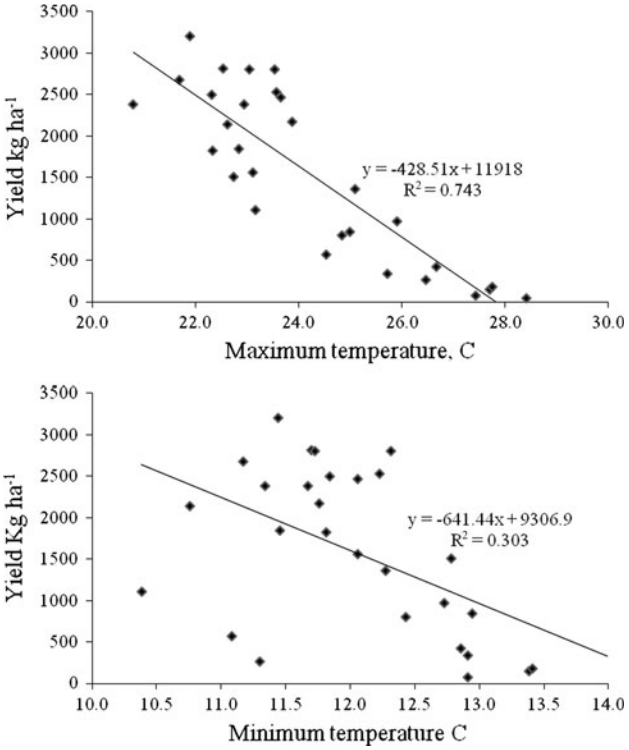

Fig. 3 Yield of wheat as influenced by maximum and minimum temperature

Table 5 Predicted average rainfall, minimum and maximum temperature during the growth season of the wheat in different time slices of mid-century

Years	D_1	D_2	D_3	D_4	D_5	D_6	D_7	Mean
Rainfall								
MC1	119	123	125	127	127	129	194	135
MC2	342	334	335	324	307	281	263	312
MC3	286	280	279	291	286	265	252	277
MC4	238	224	210	207	215	203	190	212
Mean	246	240	237	237	234	219	224	
Maximum temperature								
MC1	24.5	24.5	24.3	24.4	24.6	25.0	25.5	24.7
MC2	23.2	22.9	22.7	22.5	22.5	22.8	23.3	22.8
MC3	24.1	23.9	23.8	23.7	23.8	24.1	24.7	24.0
MC4	26.1	25.9	25.7	25.8	25.8	26.1	26.5	26.0
Mean	24.5	24.3	24.1	24.1	24.2	24.5	25.0	
Minimum temperature								
MC1	9.2	9.1	9.1	9.1	9.4	9.7	10.2	9.4
MC2	11.5	11.3	11.2	11.1	11.2	11.4	11.8	11.3
MC3	12.1	12.1	12.0	12.0	12.2	12.4	12.8	12.2
MC4	12.6	12.5	12.6	12.6	12.8	13.2	13.5	12.8
Mean	11.3	11.2	11.2	11.2	11.4	11.7	12.1	

D_1—October 15, D_2—October 25, D_3—November 05, D_4—November 15, D_5—November 25, D_6—December 05, D_7—December 15; MC1 (2001–2010), MC2 (2021–2030), MC3 (2031–2040) and MC4 (2041–2050)

Table 6 Simulated evaporation and transpiration in relation to sowing dates of rainfed wheat in different time slices of mid-century

Years	D_1	D_2	D_3	D_4	D_5	D_6	D_7	Mean
Evaporation (mm)								
MC1	61	59	59	58	55	55	58	58
MC2	183	156	147	139	150	159	161	156
MC3	190	182	170	184	187	171	158	177
MC4	163	150	159	163	174	164	152	161
Mean	149	137	134	136	142	137	132	
Transpiration (mm)								
MC1	141	143	139	139	141	138	132	139
MC2	110	144	166	177	147	111	85	134
MC3	80	91	116	109	89	87	91	95
MC4	65	79	58	53	38	36	36	52
Mean	99	114	120	120	104	93	86	

D_1—October 15, D_2—October 25, D_3—November 05, D_4—November 15, D_5—November 25, D_6—December 05, D_7—December 15; MC1 (2001–2010), MC2 (2021–2030), MC3 (2031–2040) and MC4 (2041–2050)

Table 7 Crop water productivity of rainfed wheat in relation to sowing dates in different time slices of mid-century

	D_1	D_2	D_3	D_4	D_5	D_6	D_7	Mean
Crop water Productivity (Kg grain m^{-3})								
MC1	1.19	1.17	1.15	1.14	1.15	1.15	1.13	1.15
MC2	0.52	0.75	0.86	0.90	0.77	0.55	0.43	0.68
MC3	0.36	0.46	0.59	0.57	0.52	0.51	0.51	0.50
MC4	0.34	0.46	0.34	0.30	0.24	0.24	0.25	0.31
Mean	0.60	0.71	0.73	0.73	0.67	0.61	0.58	0.60

D_1—October 15, D_2—October 25, D_3—November 05, D_4—November 15, D_5—November 25, D_6—December 05, D_7—December 15; MC1 (2001–2010), MC2 (2021–2030), MC3 (2031–2040) and MC4 (2041–2050)

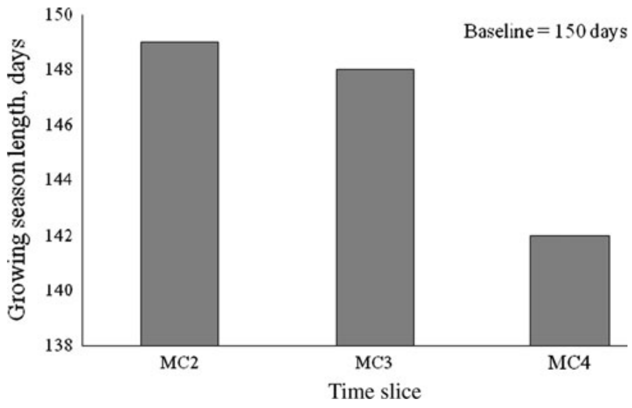

Fig. 4 Growth period length of wheat under climate change process with PRECIS under AIB scenario in different time slices of mid-century

General discussion and conclusion

Under rainfed conditions, wheat production largely depends on soil moisture. The results of simulations suggest that in future, though rainfall will increase, increased temperature will shorten the growing season duration, reduce transpiration and decline yield to very low levels. These results of decreased yield with increased temperature are in agreement with those of other studies (Jalota et al. 2012; Rai et al. 2004; Rezaie and Bannayan 2011; Tao et al. 2004; Tewolde et al. 2006). In certain situations where temperature is lower than the optimum, the elevated temperature may in fact enhance the growth rate of crops (Turner 2001; Attri and Rathore 2003). However, any further increases in temperature may reduce yield (Lal 2011). Such high temperature conditions (Fig. 5a) increased water stress from 0.231 to 0.365 (0–1 scale) (Fig. 5b) and decreased utilization efficiency of photosynthetically active radiation (PAR) from 1.70 to 1.35 (g MJ^{-1}) (Fig. 5c) during the crop growth season. These yield limiting factors result in shriveled grains and consequent reduction in grain weight and yield (Wiegand and Cuellar 1981; Saini and Dadhwal 1986; Kobata et al. 1992). Increased temperature between anthesis and physiological maturity is more critical than at other growth

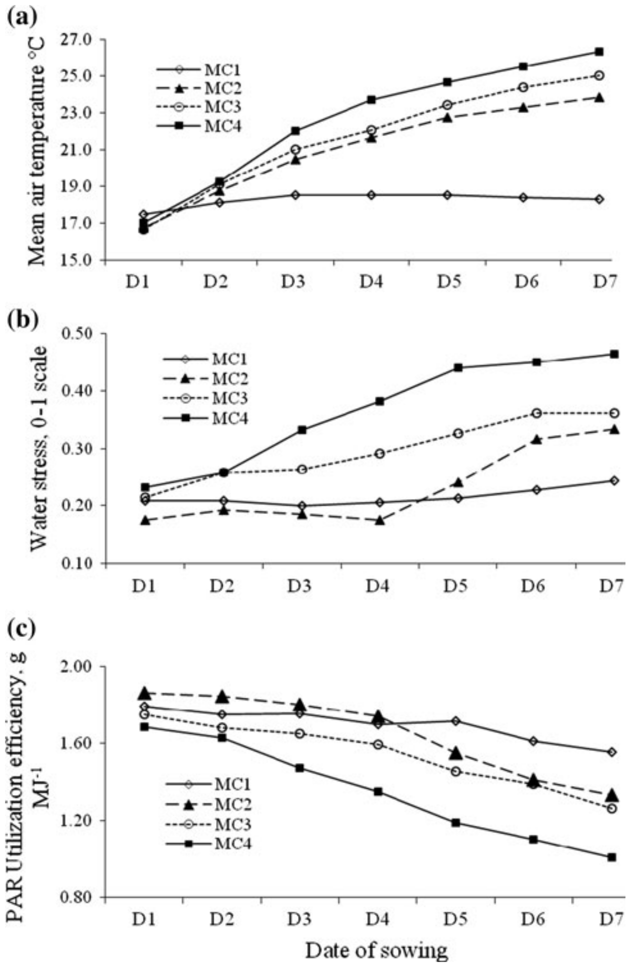

Fig. 5 Wheat yield limiting factors under climate change scenario in different time slices of mid-century. D_1—October 15, D_2—October 25, D_3—November 05, D_4—November 15, D_5—November 25, D_6—December 05, D_7—December 15; MC1 (2001–2010), MC2 (2021–2030), MC3 (2031–2040) and MC4 (2041–2050)

stages as it causes injury or irreversible damage, which is generally called 'heat stress' (Wahid et al. 2007), reduces the duration, which is associated with a reduction in grain weight (Farooq et al. 2011; Warrington et al. 1977; Shpiler and Blum 1986), increases floret abortion (Wardlaw and Wrigley 1994) and results in reduced grain yield. In the present study, the mean air temperature between anthesis and physiological maturity was increased by 2.8, 3.4 and 4.4 °C in MC2, MC3 and MC4 from 18.3 °C in MC1.

This study concludes that in northeastern Punjab of India, rainfed wheat yield would decline by 32 and 61 % in the time slices of 2031–2040 and 2041–2050, respectively, under A1B climate change scenario of regional climate model PRICIS because of increased mean air temperature, increased water stress and decreased utilization efficiency of photosynthetically active radiation during the mid-century. Besides a yield reduction, water productivity would also decrease. This adverse effect of climate change can be lessened by shifting planting dates of wheat before November 15 for the years 2021–2030; thereafter, yield will inevitably decrease due to the lower temperatures during early periods of crop growth, which would lengthen the vegetative phase and expose the sensitive wheat growth stage to extreme environmental conditions of heat and water stresses. Under such conditions, duration of both anthesis and maturity are shortened and lead to poor grain fill (Arora and Gajri 1998). Sharp decreases (10–50 %) in rainfed wheat yield over the next few decades in north-eastern Iran have also been predicted by Rezaie and Bannayan (2011). It is worth to mention here that there are large uncertainties in the magnitude of climate change, its spatial and temporal distribution and in the crop models simulating crop behavior associated with the yield changes computed in this study. Despite these uncertainties, climate change will clearly cause reductions in crop yields. The results of this study further demonstrate the need to focus future research on breeding new temperature-tolerant cultivars to overcome decreases in yield and also there is also a need for research on other cropping systems that tolerate heat better.

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