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Past and General Circulation Model-driven future trends of climate change in Central Indian Punjab: ensuing yield of rice–wheat cropping system

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Climate data recorded for the last 40 years (1971–2010) at meteorological station of Punjab Agricultural University, Ludhiana (Central Indian Punjab) and future changes in climate data derived from three General Circulation Models (GCMs), viz. HadCM3, CSIRO-Mk2 and CCCMA-CGCM2, were analysed. Past data showed increase in temperature, decrease in open pan evaporation and irregular trends in rainfall. Amongst GCMs, the HadCM3 model showed rela-

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tively more increase in minimum than maximum temperature. Averaged across GCMs and scenarios, CropSyst model-simulated crop yields of rice–wheat system showed 7%, 15% and 25% decrease in rice and 10%, 20% and 34% in wheat for the years 2020, 2050 and 2080 respectively.

Keywords: Climate change trends, crop yields, General Circulation Models, rice–wheat system.

RICE–wheat is a dominant cropping system of Central Punjab. Under the existing climatic conditions, productivity of rice and wheat is 5.5 and 4.2 tonne ha^{-1} at the state level and 7.5 and 5.6 tonne ha^{-1} in research experiments respectively. Recently, from 20 years (1989–2008) simulations, Jalota *et al.*[1] reported that yields ranged from 5.0 to 6.3 tonne ha^{-1} of rice and from 4.8 to 5.6 tonne ha^{-1} of wheat depending upon climatic variability. There are projections that global CO_2 and temperature levels are going to increase under various scenarios of climate change[2]. In the past century temperature across the globe has increased by 0.74°C. In Central Indian Punjab, past climate data of 30 years (1971–2000) showed a gradual increase ranging from 0.4 to 1.4°C $year^{-1}$ in minimum temperature[3]. In climate-change studies, a number of General Circulation Models (GCMs), viz. Hadley Center Coupled Model Version 3 (HadCM3), Australia's Commonwealth Scientific and Industrial Research Organization-Mk2 (CSIRO-Mk2) and Second Version of Canadian Center for Climate Modeling and Analysis-Coupled Global Climate Model (CCCMA-CGCM2) have been used to predict changing levels of CO_2 and temperature under different scenarios. Various studies such as computer simulations and controlled experiments have been conducted to evaluate the direct (physiological processes of plants like photosynthesis, respiration, evapotranspiration and phenology) and indirect (weather-induced incidence of diseases and thermal and water stress) impact of increased CO_2 and temperature[4,5]. Increased air temperature had negative impact on rice and wheat crop productivity[6–9]. Unlike temperature, increased CO_2 was found to enhance crop productivity[10–13]. In most of the simulation studies[3,14–17], effects of CO_2 and temperature were evaluated by changing either temperature or CO_2. Creation of such variability in one climatic parameter does not represent the integrated variability caused by all climatic parameters representing actual climate change. Therefore, the present study was undertaken with the objectives to (i) analyse changes in long-term historical observed weather data, (ii) create future climate data using output from GCMs on maximum temperature (T_{max}), minimum temperature (T_{min}) and rainfall (RF) to have integrated climate variability and (iii) simulate ensuing rice–wheat productivity in the projected climatic environment.

For analysis of past climate, last 40 years' (from 1971 to 2010) daily data on T_{max}, T_{min} and RF, recorded at meteorological station of Punjab Agricultural University, Ludhiana (30°56′N, 75°52′E and 247 m amsl) were used.

Projected climate data on T_{max}, T_{min} and RF were derived from three GCMs, i.e. HadCM3, CCCMA-CGCM2 and CSIRO-MK2 for three years, i.e. 2020, 2050 and 2080. Rationale for using these three GCMs over others was to obtain change in T_{max} and T_{min} instead of average temperature, which was required as input in weather data to the cropping system simulation model (CropSyst) used in this study. Climate data for the years of 2020, 2050 and 2080 represent the averaged data of 30 years, i.e. from 2010 to 2039, from 2040 to 2069 and from 2070 to 2099 respectively. Source of the GCM data was the IPCC report[2]. In this study, the scenarios defined in Special Report on Emissions Scenarios[18], with regionalization impact (one for economic development (A2) and the other for environmental development (B2)) were taken into consideration to understand the two extreme situations in the Indian region. The projected changes generated by different climate models were on a global scale with different spatial resolution. Taking the origin and spatial resolution of each climate model, line (latitude) and sample (longitude) for India (latitude 8–38°N and longitude 67–108°E) were computed and data for the same line and sample were retrieved from the original data. The line and sample for India were different in each model due to different resolution. Data visualization and all the processing were done using the ENvironment for Visualizing Images (ENVI) software. Geo-referencing of the data was done using the origin latitude and longitude for India and then re-sampled to common resolution (1° × 1°). Monthly change data for Ludhiana station were retrieved from the re-sampled (1° × 1°) image against a baseline data, that is the average of 30 years (from 1961 to 1990) of the three GCMs. For more details refer to Tripathy *et al.*[19]. The projected change was then applied to the actual observed weather data of location for a period of 21 years (1989–2009), which may be more accurate than the global climate baseline[20], to simulate the impact of climate change.

Yield and duration of rice (variety PR 111) and wheat (variety PBW 343) crops in rice–wheat system were simulated using the CropSyst model[21]. This model had already been intensively parameterized with the experimental data observed at the Research Farm, Punjab Agricultural University, Ludhiana in Central Punjab, India during the years 2003–2004, 2007–2008 and 2008–2010. Details of experimental treatments, initial soil profile data (layer-wise soil moisture, NO_3–N, NH_4–N, organic carbon (OC), sand, silt, clay and soil water content at 0.33 and 15 bar) and crop file are given elsewhere[9,22,23]. Using past (1989–2009) and GCM-derived future (2020, 2050 and 2080) weather data, crop growth duration (planting to flowering, flowering to grain filling, grain filling to maturity and maturity to harvest) and yield were simulated for rice–wheat system without and with elevated

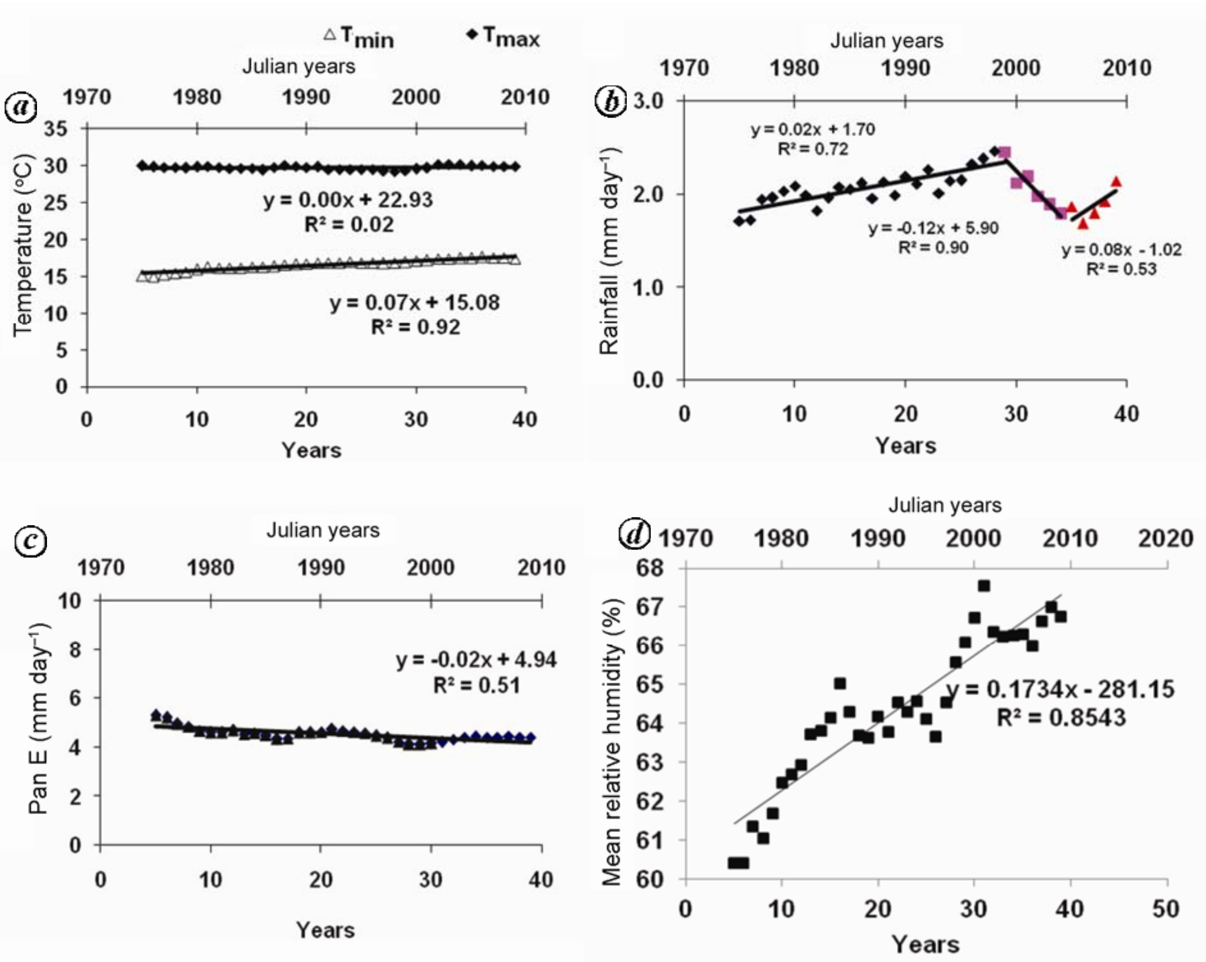

Figure 1. Five-years' moving average of past climate data (1971–2010): temperature (***a***), rainfall (***b***), pan evaporation (***c***) and mean relative humidity (***d***) at Ludhiana, Central Indian Punjab.

CO_2 (420 ppm in 2020, 480 ppm in 2050 and 540 ppm in 2080) levels. This was done intentionally to assess the magnitude of unfavourable effect of temperature encountered by the favourable effect of increased CO_2 in both the crops. In the crop model, effect of CO_2 was captured by biomass transpiration coefficient and daily crop radiation use efficiency-Gratio coefficient[24].

Trends of the past climate data from 1971 to 2010 presented as five-years' moving average showed 0.07°C annual increase in T_{min}, almost no change in T_{max} (Figure 1 *a*) and irregular trends in RF (Figure 1 *b*). Rainfall increased from 1971 to 1999; decreased from 1999 to 2006 and again increased from 2006 to 2010. Such variations on the decadal scale are forced by changes in the monsoon circulation pattern, surface boundary conditions, North Atlantic deep water production and solar activity[25]. Open pan evaporation decreased at the rate of 0.02 mm day^{-1} per annum (Figure 1 *c*) because of increased relative humidity (Figure 1 *d*). Decrease in pan evaporation has also been reported in other studies elsewhere. There was an annual reduction in pan evaporation of 2–4 mm year^{-1} in both the northern and southern hemisphere[26,27]. In general, climate change trends showed warming of the atmosphere.

The projected averaged annual T_{max} was found to increase by 1.1 ± 0.5°C, 2.5 ± 0.7°C and 3.5 ± 0.8°C in 2020, 2050 and 2080 respectively. Similarly, projected increase in average annual T_{min} was 1.7 ± 0.5°C, 3.0 ± 0.4°C and 4.1 ± 0.6°C in 2020, 2050 and 2080 respectively. The magnitude of increase/decrease for different months is discussed elsewhere[28]. Comparison of generated future trends of temperature (averaged over scenarios) by different models (Figure 2 *a*) showed that predictions made by the HadCM3 model were of similar trend as those of the past, i.e. less increase in T_{max} than T_{min} (shown in Figure 1). Increase in temperature averaged over models was more in A2 scenario than B2 (Figure 2 *b*). There is uncertainty associated with the projected temperature and precipitation, which is related to gas emission scenario in a given location depending upon the driving forces (population, economy, technology, energy, land use and agriculture)[18] and accuracy of the climate model.

The simulated yields of rice and wheat by already calibrated and tested CropSyst model[9,23] were 7.0 ± 0.87 and

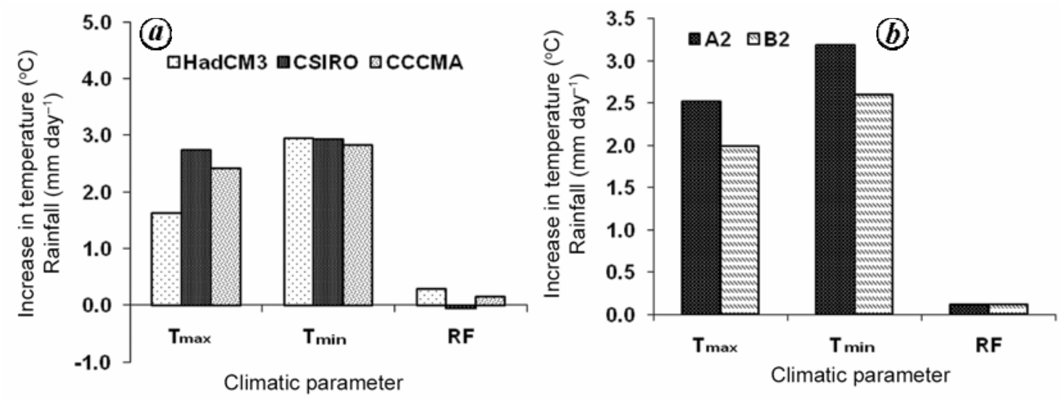

Figure 2. Comparison of increase in temperature and rainfall in different models (***a***) and scenarios (***b***).

Table 1. Projected percentage decrease in rice and wheat yields with changed future climate (without and with CO_2) under different General Circulation Models and scenarios

	2020				2050				2080			
	Had-CM3	CSIRO-Mk2	CCCMA-CGCM2	Mean	Had-CM3	CSIRO-Mk2	CCCMA-CGCM2	Mean	Had-CM3	CSIRO-Mk2	CCCMA-CGCM2	Mean
Without CO_2												
Rice												
A2	1.4	5.4	7.1	4.7	11.0	18.4	19.0	16.1	22.4	30.9	34.3	29.2
B2	1.1	14.3	12.1	9.2	6.1	16.6	16.9	13.2	15.9	24.4	19.3	19.9
Mean	1.3	9.9	9.6	6.9	8.6	17.5	17.9	14.7	19.1	27.6	26.8	25
Wheat												
A2	9.1	7.7	9.7	8.8	18.9	24.1	24.4	22.5	39.5	42.1	41.4	41.0
B2	9.1	12.7	10.0	10.6	17.9	19.7	15.5	17.7	25.6	30.5	25.5	27.2
Mean	9.1	10.2	9.8	9.7	18.4	21.9	19.9	20.1	32.6	36.3	33.4	34.1
With CO_2												
Rice												
A2	3.3*	1.1	2.7	0.1	1.3	9.4	10.1	6.9	9.7	19.4	23.4	17.5
B2	3.6*	10.1	8.0	4.8	4.0*	7.3	7.9	3.7	2.1	12.0	6.0	6.7
Mean	3.4*	5.6	5.4	2.5	1.4*	8.4	9.0	5.3	5.9	15.7	14.7	12.1
Wheat												
A2	4.4	2.9	4.8	4.0	9.1	14.8	15.2	13.0	27.9	30.8	30.0	29.5
B2	4.2	8.2	5.3	5.9	8.0	10.0	5.3	7.8	12.0	17.4	11.7	13.7
Mean	4.3	5.5	5.1	5.0	8.6	12.4	10.2	10.4	19.9	24.1	20.8	21.6

Values with *indicate increase in yield.

6.6 ± 0.92 tonne ha^{-1} with crop duration (planting to harvest) of 101 and 161 days respectively, for the existing climate data (1989–2009). These values were close to those observed under field experiments by other researchers in this region[23,29–31]. Simulations for the future years, i.e. for 2020, 2050 and 2080 involving projected T_{max}, T_{min} and RF by different GCMs and scenarios showed decrease in yield of rice and wheat crops (Table 1) under the current management practice of soil, water and crop, i.e. transplanting of rice on 20 June and sowing of wheat on 5 November; irrigation to rice as flooding for first 15 days after transplanting and keeping soil surface moist thereafter and to wheat at irrigation water depth/cumulative open pan evaporation ratio of 0.9; fertilizer nitrogen at 120 kg ha^{-1} to each crop. The magnitude of decrease in yield with changed climate in 2020, 2050 and 2080 (averaged over GCMs and scenarios) was 6.9%, 14.7% and 25% respectively, in rice. The corresponding values for wheat were 9.7%, 20.1% and 34.1% respectively. These results are in line with those of other researchers. For instance, Peng *et al.*[7] observed that the yield of rice decreased by 10% for every 1°C rise in growing season T_{min}. Similarly, Jalota *et al.*[9] projected 12% decrease in rice yield with 3°C increased mean temperature of the present (29.6° ± 0.4°C). A decline of 0.45 tonne ha^{-1} in wheat yield, with increase in temperature from 0.5°C to 1.5°C has been reported by Kalra *et al.*[8]. Decline in production of rice and wheat crops in many parts of Asia in the past few decades due to increasing temperature has been reported[6]. Yield decline in both the crops was comparatively higher in A2 scenario than in B2 because of higher projected temperature in the former (Figure 2).

The impact of climate change was more on wheat than rice. This may be ascribed to the increased projected T_{min} and T_{max} and decreased rainfall in the months of January to March synchronizing reproductive and grain development stages of wheat[28]. All these conditions reduce both duration to anthesis and to maturity, leading to poor grain fill in wheat[32,33]. Moreover, at high temperature energy is lost through the process of transpiration by the plant and reduced energy results in poor grain formation and yield. Such effects are less in rice because of relatively lower temperature at maturity and these may not aggravate in future as the projected temperature rise is also less[28]. In the present study, a strong correspondence between reduction in yield and shortening of crop duration under higher temperature was observed in all GCMs and scenarios. Averaged over GCMs and scenarios, crop duration in 2020, 2050 and 2080 was reduced by 6, 11 and 16 days in rice and 12, 21 and 28 days in wheat respectively[28]. Compared to the results discussed above, involving the effect of temperature only, inclusion of CO_2 along with these parameters resulted in less decrease in crop yield. The decrease in rice yield was reduced to 2.5%, 5.3% and 12.1% in 2020, 2050 and 2080 respectively (Table 1). Corresponding reduction in wheat was 5.0%, 10.4% and 21.6% respectively. This lesser decrease in yield was attributed to the yield-enhancing effect of CO_2 encountering the yield-decreasing effect of temperature. Though relative improvement in yield was more in rice with inclusion of CO_2, the yield levels were still lower than at existing baseline temperature and CO_2. Quantitatively, CO_2 enhanced yield by 4.4%, 9.4% and 12.9% in rice and 4.7%, 9.7% and 12.5% in wheat in the years 2020, 2050 and 2080 respectively. Yields were comparatively lower in A2 scenario than that in B2.

The results of the present study suggest that amongst the three GCMs (HadCM3, CSIRO-Mk2 and CCCMA-CGCM2) and two scenarios (A2 and B2), HadCM3 model and A2 scenario predict more increase in minimum than maximum temperature in future climate change in the Central Indian Punjab region, which is in line to that of the past trends. In future climate, decrease in productivity of rice–wheat system is expected because of the overpowering yield-decreasing effect of increased temperature over yield-enhancing effect of increased CO_2. To bring impact of climate change on crop productivity closer to the real situation, it is meaningful to make future studies with regional climate models with higher resolution for multi locations in the region by taking simultaneous changes in T_{max}, T_{min}, RF, CO_2, etc. rather than an individual parameter. It is worth mentioning here that there would have been large amount of uncertainty (uncertainties in the magnitude of climate change, its spatial and temporal distribution and in the crop models simulating crop behaviour) associated with the yield changes computed in this study. Notwithstanding these uncertainties, climate change will drive reductions in crop yield[34].

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Germination of *Hippophae rhamnoides* L. seed after 10 years of storage at ambient condition in cold arid trans-Himalayan Ladakh region

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The actinorhizal plant seabuckthorn (*Hippophae rhamnoides* L., Elaeagnaceae) is a wind-pollinated dioecious crop. In the present work we study two important aspects of germination of seabuckthorn seeds: (i) germination-related studies of aged seed stored up to 10 years under ambient condition in cold arid condition and (ii) the effect of seed pre-soaked treatment on germination-related parameters of aged seeds. Seed stored up to 6 years does not show any significant difference in germination percentage. However, seeds aged 9 and 10 years showed significant reduction in germination percentage, being 65.3 and 65.67 respectively, compared to 100 and 99 in one- and two-year-old seeds respectively. KNO_3 pre-soaking treatment showed negative effect on seed germination. Correlation studies showed that with advancement of age of seabuckthorn seed, the moisture content, germination percentage and seed vigour index decrease. It takes more time for seeds to germinate with ageing. Similarly, decrease in moisture content results in decrease in germination percentage and seed vigour index. Results showed that short- and medium-term storage of seeds could be achieved at ambient condition in cold arid region at lower cost without the limitation of space.

Keywords: Pre-soaking treatment, seabuckthorn, seed age, seed germination.

STUDY of behaviour of seed germination and the factors controlling the process in an environment is an important aspect not only for physiologists and ecologists, but also for seed technologists. Seed moisture content and storage temperature are the most important factors affecting seed longevity and vigour during storage[1]. Preferable conditions for long-term seed storage are 3–7% moisture content and –18°C temperature[2]. However, its use in developing countries has been greatly limited because of the high cost of building and operation[3]. Storage of seeds in cold

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