Impact of projected climate change on rice (*Oryza sativa* L.) yield using CERES-rice model in different agroclimatic zones of India

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Climate change is projected to alter the growing conditions of rice crop in different regions of India. Crop growth simulation model (DSSATv4.6) was calibrated and evaluated with four rice cultivars: PR 118 in Amritsar, Ludhiana; HKR 126 in Hisar and Ambala; Pant 4 in Kanpur and Sugandha-1126 in Modipuram on different sowing dates. The average yield of the selected optimum dates was 6391, 6531, 7751, 7561, 4347 and 4131 kg/ha for Amritsar, Ludhiana, Hisar, Ambala, Modipuram and Kanpur respectively. Both temperature and CO_2 have increased. The combined effect of temperature and CO_2 indicates decreased yield rate in the future decades. The present study shows that rice yield will decrease in the future and this may be due to increase in temperature. According to projection results, for all the locations average yield is higher in the decade 2010, except Amritsar in the decade 2030 and Ludhiana in the decade 2050. The average yield at Hisar, Ambala, Modipuram and Kanpur in 2010 was 7744, 7654, 4347 and 4021 kg/ha respectively. Amritsar and Ludhiana showed maximum average yield of 6880 and 6877 kg/ha respectively, in the decade 2030. Such yield reductions in rice crops due to climate change are mediated through reduction in crop duration, grain number and grain filling duration. These projections nevertheless provide a direction of likely change in crop productivity in future climate change scenarios.

Keywords: Agroclimatic zones, climate change, crop simutation models, rice.

IN India, studies have shown an increasing trend in surface temperature during the last century[1]. Climate change is now evident mainly in terms of changes in temperature and rainfall rate and the world's climate has been greatly influenced by human activities[2]. The clear evidences of these changes are discussed in the literature[3–8]. For the next two decades, a warming of about 0.2°C per decade is projected for a range of emission scenarios (SRES; Special Report on Emissions Scenarios). Even if the concentration of all greenhouse gases (GHGs) and aerosols is kept constant at the year 2000 levels, a further warming of about 0.1°C per decade would be expected[2]. Changes in the global water cycle in response to warming over the 21st century will not be uniform. The contrast in precipitation between wet and dry season regions will increase, although there may be regional exceptions[2]. In the Indo-Gangetic Plains (IGP), wheat and rice are the two important crops for food security. They contribute more than 80% to the total production and play a vital role in employment and food security for hundreds of millions of rural families. The demand for wheat and rice is expected to increase between 2% and 2.5% per annum until 2020. The maximum and minimum temperatures are also important for rice crops; monthly temperature across the growing season ranges from 23.3°C to 27.7°C, with daily minimum temperatures of 15°C and maximum temperature of 39°C. Rice growth stage can be divided into two phases – vegetative and reproductive. The vegetative phase includes three stages – germination, early seedling growth and tillering. The reproductive phase is divided into several stages – stem elongation, panicle initiation, panicle development, flowering, milk grain, dough grain and mature grain stage.

Rice matures in 120–130 days when planted in a tropical beneficial environment. Weather parameters play an important role in rice growth. In this study we consider maximum temperature (°C), minimum temperature (°C) and precipitation (mm). Rice spends around 60 days in the first phase, i.e. vegetative phase, 30 days in the second phase, i.e. reproductive phase and around 30 days in the third stage, i.e. ripening phase[9].

IGP contribute ~15% of the world's wheat production and is a source of food to more than 200 million people[10]. According to the Inter-governmental Panel on Climate Change (IPCC), climate change is mainly attributed to human-induced activities and the sole driver of such change is CO_2 (refs 11–16). The yield variation depends on anthesis and maturity date which is directly affected by weather parameters, i.e. maximum and minimum temperature, precipitation and solar radiation. When

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temperature increases the crop will take a short period of time to mature and this will directly affect the yield with an increase in maximum temperature by 2°C and 4°C without any change in CO_2 concentration, wheat maturity is observed 17 and 30 days earlier. Increased temperature also affects the growth parameters of the crop like leaf area index and anthesis date. It was found to be maximum at about 100 days after sowing; then it declined up to the physiological maturity of crop. However, with the increase in temperature by 4°C, the vegetative phase of wheat crop was shortened and maximum leaf area index stage was observed around 50 days after sowing[17].

In the temperate region, temperature drops below freezing point for a couple of weeks. According to IPCC, CO_2 level will rise to 605–755 ppm by 2070 and there will be 1.5°C rise in temperature by 2015–2050 and 3°C by 2050–2100. Various studies have shown that with an increase in temperature by 2.5–4.9°C, the rice yield will decrease by 15–49% and wheat yield by 25–42% without CO_2 fertilization. IPCC has proposed the rate of increase in GHGs by an average of 1.6% per year, while particularly for CO_2 this rate is almost 1.9% per year[18]. All these can have a major impact on agricultural production and hence food security of any region. Global production of annual crops is expected to reduce significantly due to climate change by the end of the 21st century. Studies indicate considerable probability of loss in crop production in India with increase in temperature[4]. The yield of rice and wheat increased by 26.6% and 18.4% due to doubling of CO_2 levels and 17.1% and 8.6% due to increase in temperature respectively[19]. When the temperature decreased to 2°C and 4°C, the ripening of wheat crop was delayed by 20–38 and 10–17 days respectively, under temperate and subtropical conditions[20]. Current atmospheric CO_2 concentrations are higher than at any time in the last 15 million years[21]. Average annual surface temperature over the northern parts of India has been estimated to increase up to 3–5°C for high-emission scenario (A_2) and 2.5–4°C for low emission scenario (B_2) by the end of the 21st century[21]. Impact of climate change on wheat crop is well known[22–27]. The wheat crop has positive sign of increasing biomass potential under elevated CO_2 condition while increasing temperature has a negative impact on dry matter and quality components[28]. Planning and decision making in agriculture are challenging specially under changing climate. In this context, crop simulation model would be an easy tool. Performance of crop model under diverse climatic conditions has been tested[29,30]. The present study analyses impact of temperature and CO_2 together for rice-growing states under changing climate.

Materials and methods

The long term daily weather data (maximum temperature, minimum temperature, rainfall and solar radiation) at six locations (Ambala, Hisar, Ludhiana, Amritsar, Kanpur and Modipuram) were collected from NDC (National Data Centre, Pune); soil and data on crop/variety for these locations were collected from AMFUs (Agromet Field Units) under the FASAL (Forecasting Agricultural output using Space, Agro-meteorology and Land based observations) project and DSSATv4.6 (crop simulation model) was used for the study. The genetic coefficient of cultivars of rice crops is used for simulation[30]. The daily weather data at different agroclimatic zones of India were analysed to determine climatic variability.

Model description

DSSATv4.6 is process leaning cropping system model (CSM) that has the capability to simulate the growth, development, biomass production of crops over time as well as the soil water, carbon and nitrogen processes and management practices under dynamic environmental situation[31]. The model has the ability to simulate all these parameters based on different modules like carbon balance, water balance and nitrogen balance modules.

Weather data

The daily weather data (maximum and minimum temperature, rainfall and sunshine) of the study regions were collected from the India Meteorological Department (IMD) for different agroclimatic zones of the country for the period 1979–2010, except Modipuram station (1993–2010). The historical (1950–2013) and projected meteorological data (2014–2060) have been downloaded from the website of the Centre for Climate Change Research, Indian Institute of Tropical Meteorology (IITM), Pune, India[32]. Laboratories de Meteorology Dynamique (LMDzoR) has one of the very high-resolution simulations of the present climate and future projections based on ultra-high resolution global climate models. The ultra-high storm reproductions are continuously determined at the high performance computer (HPC) Office at IITM, as a joint effort between CCCR and LMD. The atmosphere model is focused around an adaptation of an air GCM from LMDZ, France. The model has zooming proficiencies in a 35 km × 35 km determination over Indian rainstorm locale and 1° × 1° lat. and long. determination. Sunshine hours are converted into solar radiation and direct radiation converted to temperature[27].

Soil parameters

The location-wise soil parameters used in the DSSATv4.6 model are thickness of five layers, layer-wise sand, clay, bulk density, soil organic carbon and soil hydraulic characters. Soil pH, EC and slope also are required as inputs for different locations. The terms 'lower limit' and

Table 1. Genetic coefficients of the selected rice cultivar

Rice cultivar	P1	P2R	P5	P2O	G1	G2	G3	G4
Pant-4	480	50	470	11.4	50	0.290	1.00	0.80
HKR 126	630	160	390	12	55	0.250	0.75	1.00
PR118	650	190	510	11.5	60	0.260	1.00	1.00
Sugandha-1126	650	65	500	12.0	44	0.240	0.80	1.00

Source: Singh *et al.*[34].

'drained upper limit' correspond to the permanent wilting point and field capacity respectively[33]. Total extractable soil water is a function of soil physical characteristics as well as rooting depth of rice crop.

Genetic coefficients

Calibrated and validated genetic coefficients of rice varieties grown in north India (Pant 4, HKR 126, PR 118 and Sugandha-1126) were collected from ref. 34 (Table 1).

DSSATv4.6 model

Detailed methodologies for simulating impacts of changing climate on crop production have been described earlier[35]. Main driver program interlinks all databases and different crop simulation models within the DSSATv4.6 program. Different varieties, temperature and CO_2 scenarios were used as treatments to run the simulation model. A total of 180 time simulations have been made in the study by running DSSATv4.6 software. CERES-rice model accurately predicted flowering and physiological maturity of all varieties. These results indicate that plant growth, development and yield can be simulated efficiently for the conditions at the experimental site.

Results and discussion

In the present study, we selected six locations (Hisar, Ambala, Amritsar, Ludhiana, Kanpur and Modipuram) which represent three states of India, viz. Punjab, Haryana and Uttar Pradesh. Dominating cultivars of rice crop were selected, viz. HKR 126 (Hisar and Ambala), PR-118 (Amritsar and Ludhiana), Pant-4 (Kanpur) and Sugandha-1126 (Modipuram) with sowing dates 24 June, 1 July, 8 July, 15 July, 22 July and 29 July of rice crop. The CERES rice model accurately predicted flowering and physiological maturity of all varieties. These results indicate that plant growth, development and yield can be simulated efficiently for the conditions at the experimental site.

The sowing dates were considered at an interval of a week with 24 June being the first date of sowing. The dominating cultivar HRR 126 of Ambala and Hisar was used. In Ambala, the yield was observed to be 7482, 7283, 7763, 8120, 7381 and 6831 kg/ha respectively, for the sowing dates 24 June, 1 July, 8 July, 15 July, 22 July and 29 July (Figure 1). The observed data from 1979 to 2010 for Ambala station showed the declining trend for both maximum and minimum temperature and increasing trend for precipitation from 2008 to 2010 (Figure 2). The yields for the respective sowing dates observed in the case of Hisar were 7218, 7182, 7641, 8291, 7280 and 6641 kg/ha for the same sowing date as Ambala. Also, it was found to be the maximum yield on 15 July which was the same as in the case of Ambala. The weather data showed the declining trend for both maximum and minimum temperature from 1979 to 2005 and increasing trend for rainfall from 2003 to 2005 (Figure 2).

In Ludhiana, the yield was observed to be 7764, 7523, 7210, 6788, 6453 and 5954 kg/ha (Figure 1). The climatic variation in observed data for Ludhiana shows slight decrease in maximum temperature and increase in minimum temperature, and increasing trend for rainfall with a large increase from 1991 to 1998 (Figure 2). At Amritsar the yield was 7282, 7083, 6763, 6660, 6468 and 6435 kg/ha for the respective sowing dates[16]. Maximum yield in case of these two stations was obtained when 24 June was considered as the sowing date. The maximum temperature at Amritsar showed a small decrease in 2011 and rainfall showed an increasing trend and also showed a large increasing trend in 2002, 2003, 2010 and 2011 (Figure 2).

In the case of Kanpur, the yields[16] were found to be 4001, 4066, 3849, 4164, 4137 and 3760 kg/ha (Figure 1). Also, from 1979 to 1981 the maximum temperature showed increasing trend, and minimum temperature decreases and a decreasing trend in rainfall, after this small increase in rainfall and again it shows decreasing trend (Figure 2). In Modipuram, the yield[16] was 4118, 4127, 4278, 4385, 4377 and 4264 kg/ha (Figure 1)[16]. For Modipuram station observed data from 2000 to 2011 were analysed and results showed a decreasing trend for both maximum and minimum temperature, while rainfall showed an increasing trend; a large increase from 2000 to 2002, then a decline from 2003 to 2004 and again it showed an increasing trend in 2009 and 2010 (Figure 2). It was interesting to note that the sowing date with maximum yield was found to be same for the stations of the same state. In case of stations in Uttar Pradesh and Haryana, the sowing date with maximum yield was found on the same date (15 July). The average yield of the selected optimum dates/week was 6391, 6531, 7751, 7561, 4347 and 4131 for Amritsar, Ludhiana, Hisar, Ambala, Modipuram and Kanpur respectively[16] (Figure 1).

Impact of climate change on rice yield

The impact of the projected changes in climatic parameters such as atmospheric CO_2, temperature and rainfall on rice crop production was assessed using crop simulation model (DSSATv4.6 model) for six locations in India. In the decade, 15 July 2010 showed maximum yield followed by 8 July and 22 July. Results showed at 15 July yield decreased in later decades and yield at 1 July showed an increasing trend. Also, 24 June showed increasing trend with maximum yield on 1 July for the decade 2070. Thus, in future, 24 June and 1 July will be the part of sowing window in Haryana for selected cultivars (Figure 3). Figure 4 shows the variation of maximum and minimum temperature and precipitation of model-projected data from 1950 to 2059 for Ambala. There is an increase in maximum temperature particularly from 1990 to 1994 and slight decrease in minimum temperature and

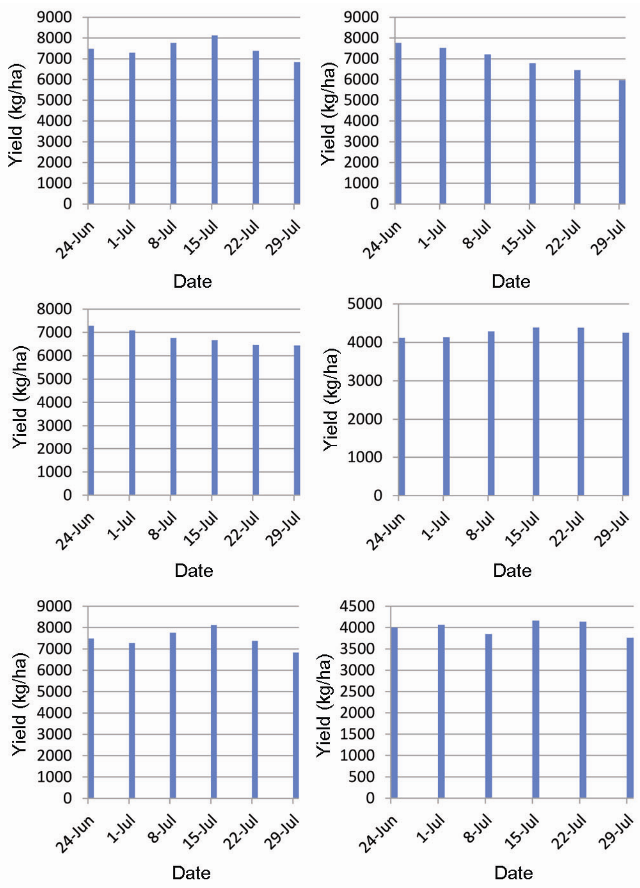

Figure 1. Rice yield (kg/ha) variation at Ambala, Amritsar, Ludhiana, Modipuram, Hisar and Kanpur.

precipitation in the future. The downloaded model data also showed huge variation in precipitation. Figure 4 also shows the variation of maximum and minimum temperature and precipitation of model-projected data from 1950 to 2059. There is an increase in maximum temperature particularly from 1994 and 2018 and slight increase in minimum temperature in the future. Precipitation has showed variation and large decrease from 2044 to 2048. Figure 3 shows results for Amritsar and Ludhiana; PR 118 is the dominating cultivar. Maximum yield showed on 24 June and then the trend decreases for all the sowing weeks. In the decade 2030, 15 and 22 July have showed the same yield, then after decade 2030, 15, 22 and 29 July have showed almost the same result. In Figure 4, for Amritsar station, the model data downloaded from 1950 to 2055 include both historical and future projected data. Figure 3 shows annual increasing trend for maximum and minimum temperature, but huge variation in precipitation with declining trend. For Ludhiana, 24 June is also maximum yield sowing week and in the decade 2030, 8, 15 and 22 July show almost the same yield, but 29 July shows increasing trend of yield and has maximum yield in the decade 2090 (Figure 3). The yield variation depended on anthesis and maturity date which are directly affected by weather parameters, i.e. maximum and minimum temperature, rainfall and solar radiation. Figure 4 shows climatic variation of simulated data. The results showed a slight increase in maximum and minimum temperature. Precipitation showed decreasing trend for the same station. It shows large increasing trend in 1958–1961 and 2002–2007. Pant 4 was considered for Kanpur station and according to the results, 29 July showed maximum yield which is followed by 5 August and 1 July. Yield shows a decreasing trend in future decades and sowing window for this variety is 15 July, 29 July and 5 August; 22 July also shows good results in future and it may be considered as one of the optimum dates (Figure 3). In Figure 4, simulated or model data downloaded from 1950 to 2050 are available for Kanpur station. Results showed increasing trend for both maximum and minimum temperature and large decrease in temperature trend from 2022 to 2026. Sugandha-1126 was the dominating variety of Modipuram location. Also, 15 and 22 July showed maximum yield compared to other selected sowing dates. Up to the decade 2030, 22 July showed increasing trend and after the decade 2030, 22 and 29 July showed almost the same result (Figure 3). In Figure 3 for Modipuram station, model data downloaded from 1950 to 2052 include both historical and future projected data. Figure 4 shows annual increasing trend for maximum and minimum temperature, but huge variation in precipitation with declining trend. Table 2 shows decadal comparison of average yield of three optimum sowing dates for a particular location in each decade. Here, three sowing weeks giving maximum yield have been considered to compute the average yield of the station.

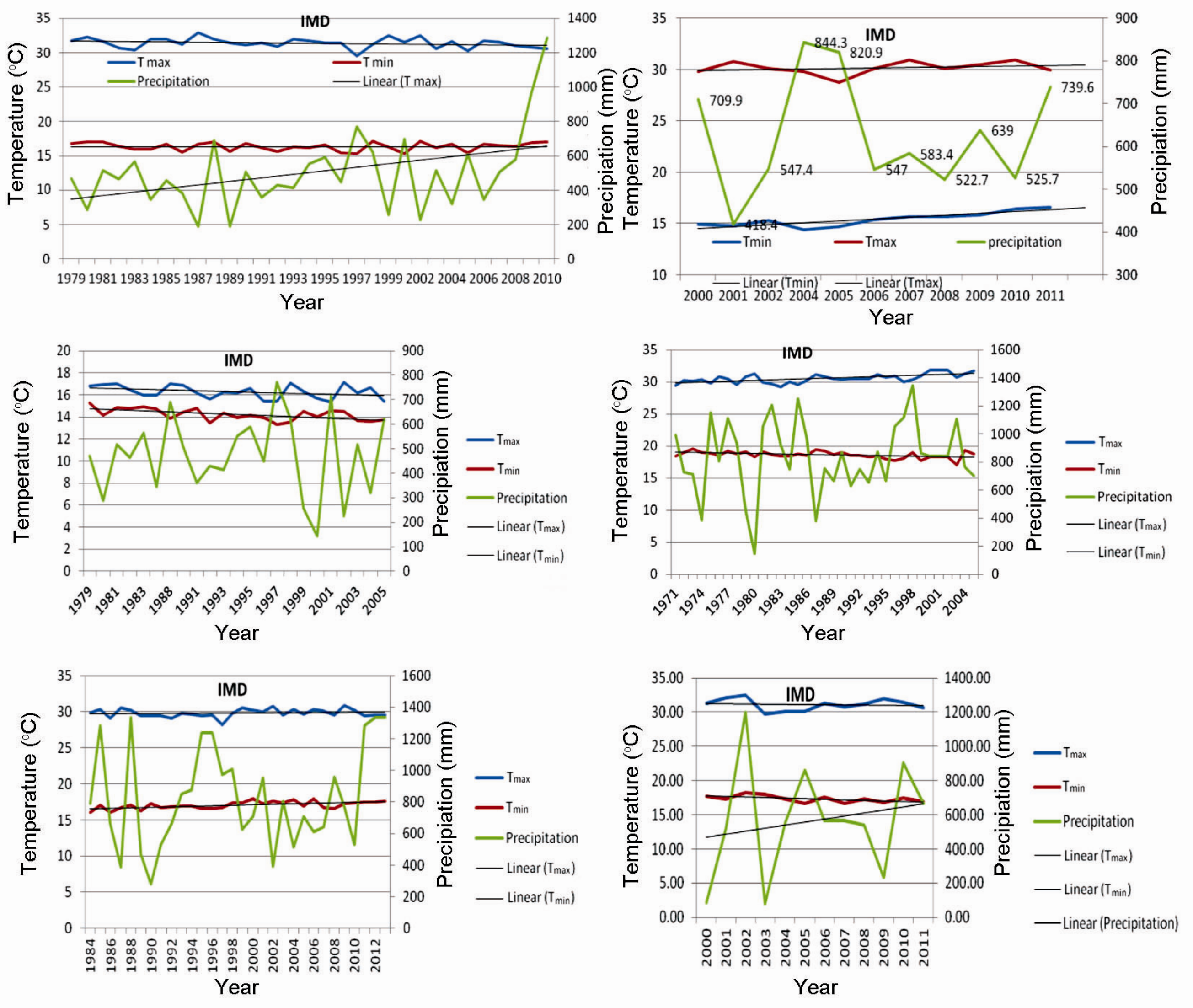

Figure 2. Variation in weather parameters of observed data at Ambala, Hisar, Amritsar, Ludhiana, Kanpur and Modipuram stations.

Simple arithmetic mean of yields is calculated. For all the locations average yield is higher in the decade 2010, except for Amritsar in the decade 2030 and Ludhiana in the decade 2050. The average yield at Hisar, Ambala, Modipuram and Kanpur in 2010 was 7744, 7654, 4347 and 4021 kg/ha respectively. Amritsar and Ludhiana showed maximum average yield of 6880 kg/ha and 6877 kg/ha respectively, in the decade 2030 (Table 2). According to the results, rice yield will decrease in future, and this may be due to increase in temperature. According to IPCC, that elevated CO_2 will also increase up to 460 ppm in 2100; so this increased CO_2 levels also have a positive impact on yield rate and yield will increase, there was a decrease in yield rate due to temperature effect but also increase CO_2 abundance, due to this yield rate increases. So there is no large variation in the result; a slight decrease in yield was observed[29]. In rice, very high temperature during reproductive stage induces spikelet sterility, thereby affecting the seed setting and hence reducing yield[36]. The main cause of floret sterility induced by high temperatures at flowering is anther indehiscence. For setting grain number cooler temperature is needed, but any increase in minimum temperature causes decrease in fertilized spikelet number in rice[37,38]. High temperatures during the grain formation stage affected the grain number and grain weight thus reducing the yield.

Conclusion

Among all the atmospheric factors, increased temperature and CO_2 are the key factors of climate change, which are supposed to have a major influence on rice yield. In climate change, higher temperature plays an important role than CO_2 in the tropics. A significant increase in yield may be expected because of increase in CO_2 as rice is a

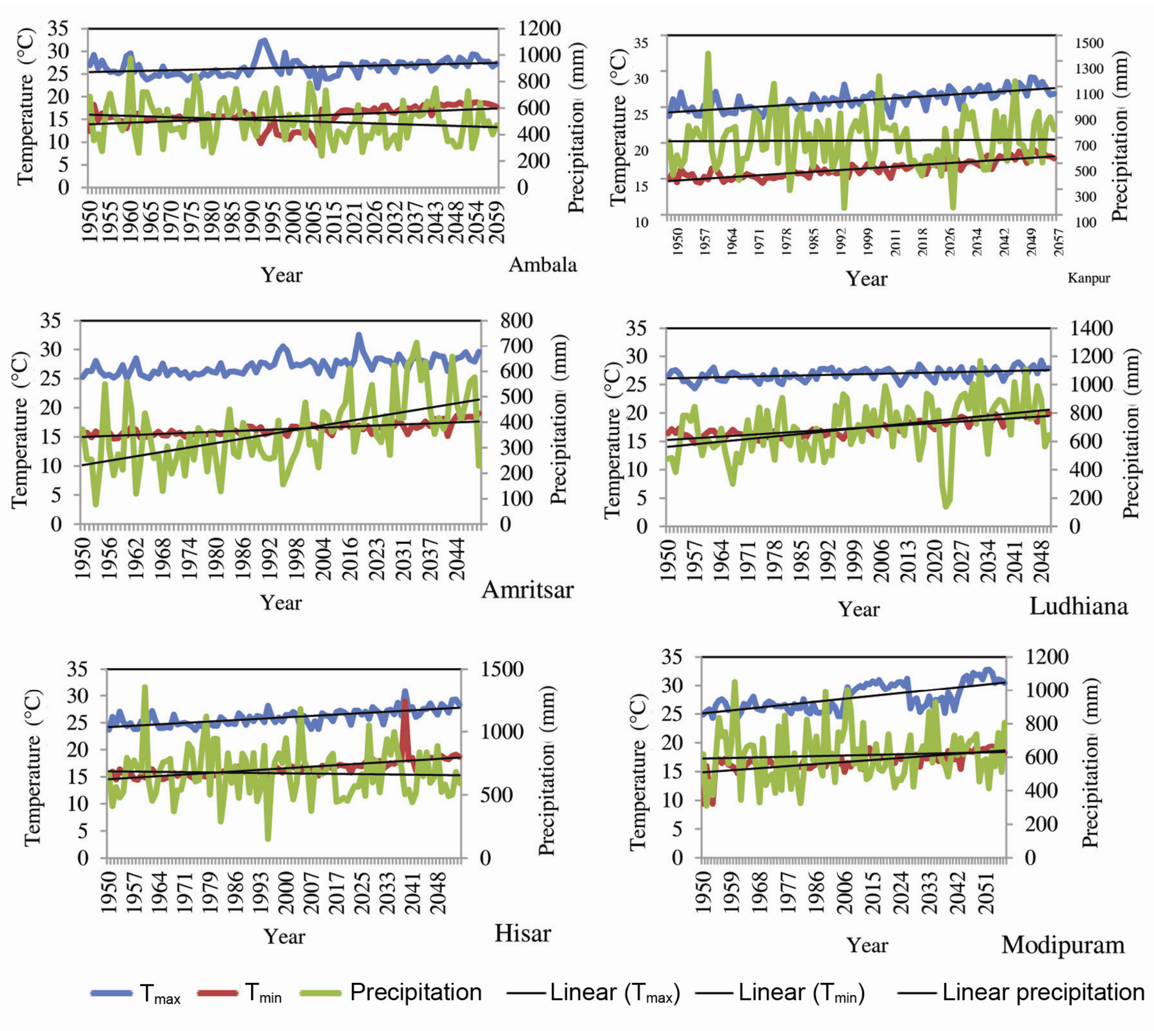

Figure 3. Variation in weather parameters of LMDZoR (Ambala, Amritsar, Hisar, Kanpur, Ludhiana and Modipuram).

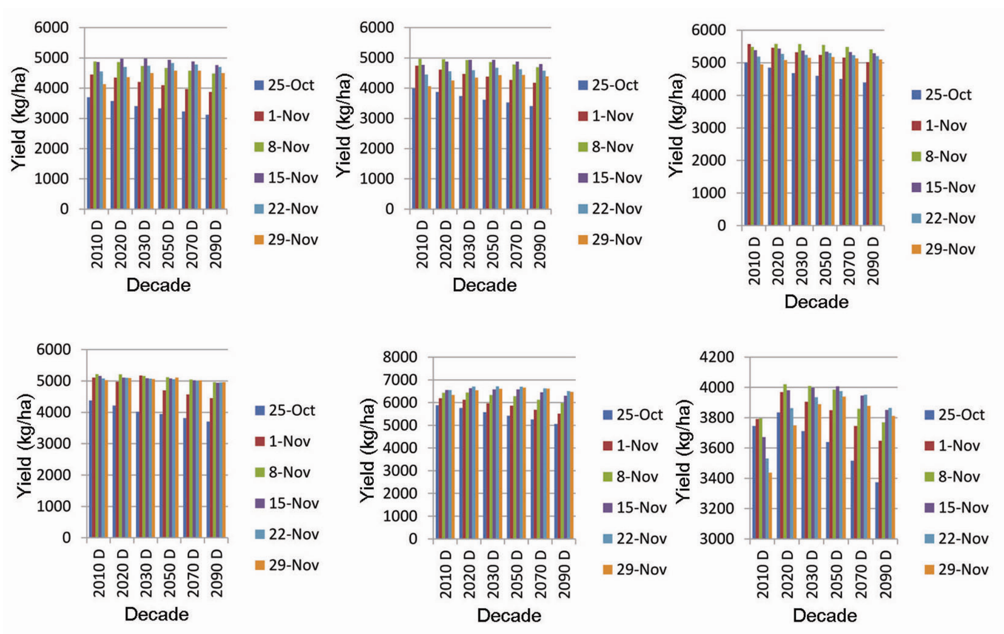

Figure 4. Decadal rice yield variation at Hisar, Ambala, Amritsar, Ludhiana, Kanpur and Modipuram stations.

Table 2. Decadal average yield (kg/ha) of different agoclimatic zones in India

Location/decade	2010	2020	2030	2050	2070	2090
Amritsar	6399	6846	6880	6873	6358	6216
Ludhiana	6521	6655	6877	6702	6647	6594
Hisar	7744	7528	7108	6772	6322	6243
Ambala	7654	7428	7266	6803	6822	6354
Modipuram	4347	4301	4167	4055	3935	3816
Kanpur	4021	3956	3896	3853	3773	3725

C_3 plant. However, this study projects an overall reduction in productivity of rice crop in all main rice-producing states in India. In this study climatic trend analysis of six stations has been done for about 100 years. This is important in considering the long-term pattern. In projection data, maximum and minimum temperature showed increasing trend for all the selected locations, except Amritsar and Ambala; both these stations showed increasing trend for maximum temperature but decreasing trend for minimum temperature. Precipitation decreases for all the locations, except Amritsar, which showed increasing trend.

We found rice crop is more temperature-sensitive; in future decades yield will decrease due to increase in temperature because it directly affects the anthesis and maturity days of the crop. Due to increase in temperature crop will mature early and yield will decrease in future decades. In this study climatic trend analysis of the stations was done for around 100 years. This is important in considering long-term pattern. We used model downloaded data (LMDzoR), and correlated temperature of observed data and downloaded data for the same years. For rice, dominating variety of each location was selected, i.e. HKR 126 (Ambala and Hisar), Pant 4 (Kanpur), Sugandha (Modipuram) and PR 118 (Amritsar and Ludhiana). According to projection results, Pant 4, Sugandha-1126 and PR 118 have the same sowing window, i.e. 15 July, 29 July and 5 August. Sowing window for Hisar and Ambala (HKR 126) is 8, 15 and 22 July. Average yield of three optimum sowing dates for a particular location, i.e. Ambala, Hisar, Amritsar, Ludhiana, Kanpur, Modipuram was 4729, 4768, 5344, 5150, 6518 and 3644 kg/ha respectively. According to projection results, for all the locations average yield was higher in the decade 2010, except Amritsar in the decade 2030 and Ludhiana in the decade 2050. The average yield at Hisar, Ambala, Modipuram and Kanpur in 2010 was 7744, 7654, 4347 and 4021 kg/ha respectively. Amritsar and Ludhiana showed maximum average yield of 6880 and 6877 kg/ha respectively, in the decade 2030 due to rise in temperature. However, adaptation options provide an opportunity to minimize the yield loss.

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