A critical analysis of the effect of projected temperature and rainfall for differential sowing of maize cultivars under RCP 4.5 and RCP 6.0 scenarios for Punjab

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Abstract
A simulation study was conducted for two maize cultivars (PMH1 and PMH2) under two Representative Concentration Pathways (RCPs) in four agroclimatic zones of Punjab state of India where climate change depicts a consistent rise in temperature and variability in rainfall. The temperature and rainfall varied from location to location so agroclimatic zone II (Ballowal Saunkhri), zone III (Ludhiana, Amritsar, and Patiala), zone IV (Bathinda), and zone V (Abohar and Faridkot) were selected for the study. The bias-corrected ensemble model data from seventeen global circulation models (GCMs) for RCP 4.5 and RCP 6.0 was used to simulate maize yield for a period of 70 years (2025–2095) using calibrated and validated CERES-Maize model. The simulated yield trend in Punjab under current dates of sowing indicated a strong negative correlation between the yield and the weather parameters under the two scenarios. Agroclimatic zones II, III, and V (Faridkot) observed an increase in temperature by 1 °C over the 70 years’ time period which led to lowering of the maize yield from high yield category (> 5000 kg/ha) to low (< 3000 kg/ha). The cv PMH1 was able to compensate these effects and performed better in agroclimatic zones II, III, and V (Faridkot). In agroclimatic zones IV (Bathinda) and V (Abohar), an increase in temperature by 2 °C is observed, which led to decline of yield categories from medium yield years to low yield years. Though the rainfall in the region was higher for low yield years, but the rainfall amount was insufficient to mitigate the impact of temperature. Under the future stabilization scenarios, amongst the current sowing dates, mid-June was found suitable in agroclimatic zones II and III and in agroclimatic zone V (Faridkot) both early and mid-June sowing dates performed well. Considering the suitable sowing dates under current farming practices, it would be easy to determine the future sowing window for maize cultivars in Punjab.

1 Introduction
Climate change is a phenomenon that has been occurring for a long term now, and it does pose the greatest threat to human beings in social, environmental as well as economic terms. The current rate of temperature increment indicates the global warming to reach 1.5 °C between 2030 and 2052 (Allen et al. 2018), while it could go up to 3–5 °C by the end-century in relation to pre-industrial times. Limiting the warming to 1.5 °C in the twenty-first century would not stop the heating impact, and the slow evolving changes in oceans would continue to persist even after 2100 leading to continuous rising of sea levels. IPCC during their fifth assessment report in 2014 adopted Representative Concentration Pathway (RCP) which has been driven in accordance with the estimated volume of greenhouse gases to get emitted in the future years, and they describe different climate scenarios that can be expected in the future. The four RCPs being used for the studies are RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 which are considered to cause radiative forcing of 2.6, 4.5, 6.0, and 8.5 W/m², respectively, by the year 2100. The report mentions the global mean surface temperature (GMST) to rise with increasing greenhouse gases over the twenty-first century. The predicted increase in GMST in relation to 1986–2005 would be 0.3 to 1.7 °C and 2.6 to 4.8 °C, while the precipitation would increase by more than 0.05 mm day⁻¹ and 0.15 mm day⁻¹ under RCP 2.6 and RCP 4.5, respectively (Collins et al. 2013). The Indian region estimates show an increase in temperature by 1.7 to 3.7 °C
and 2.3 to 4.7 °C during near future and by 2.2 to 4.3 °C and 3.7 to 6.1 °C during far future under the RCP 4.5 and RCP 8.5, respectively (Krishnan et al. 2020). Studies also show the direct impact of climatic variables on agriculture as all the physiological processes of the plants are linked to climate inputs. The alterations in temperature and precipitation pattern in different regions of the world have an influence on the crop water cycle as it changes the growth period, photosynthesis ability, and respiration pattern which ultimately leads to stress on crops and food security (Tao et al. 2003a, b). Studies represent a substantial reduction in yield of crops under a temperature change up to 2 °C during the dry seasons (Lobells et al. 2008; O’Neill 2007). Mall et al. (2004) depicted through a study on soybean productivity that under the future climate change, that agricultural production could be influenced by the changes in growth and transpiration pattern of crops. The physiological processes of crops such as respiration, photosynthesis, and photo-assimilate partitioning will suffer due to the increasing temperatures (Chartzoulakis and Psarras 2005; Yang and Zhang 2006). The rising temperatures are predicted to cause severe yield losses around the world (Awais et al. 2018, Lobell et al. 2011 and Rahimi-Moghaddam et al. 2018), and the global average yield is projected to decrease by 3.7% per 1 °C rise in temperature (Lobell et al. 2011 and Hatfield et al. 2011).

The climate change impact has been observed worldwide and at regional levels. For an agricultural country like India, it is very important to be familiar with these impacts and how the crops would react to the changing climate patterns in the future. These purposes are being served at various locations worldwide using scientific techniques like artificial chambers, but this being expensive is being replaced by crop simulation models which create similar environmental conditions like those on the field, thus fulfilling the purpose at lower costs. The models simulate yield under future conditions and help in determining the trend and optimization practices that would prove efficient in combating the climate change impact. Currently, the global circulation models (GCMs) provide scenarios which explain the future radiative forcings under increasing greenhouse gases, and these are used as crop model inputs for predicting yield. The crop simulation models project yield decrement for major cereal crops globally, but the magnitude of impact of these forcings on yield varies on regional as well as local basis.

A study in the Shaanxi province of China used CERES-Maize v4.6.7 to project future maize yield under RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5, and the results showed a negative correlation between temperature and maize yield. The yield was projected to decrease up to 9% in the region (Saddique et al. 2020). The predictions for Zambia under RCP 4.5 and RCP 8.5 from ensemble mean show an increase in temperature and a decrease in precipitation. These changes would influence the maize crop for which the anthesis and maturity would shorten in 2050 while the deviation in grain yield would range from 2.78 to 9.94%, − 3.81 to − 8.88%, and − 2.33 to 10.63% under different nitrogen application rates, i.e., 55.2 N kg/ha, 110.4 N kg/ha and 165.6 N kg/ha (Chisanga et al. 2020). An experiment in north western China studied the impact of climate change on maize yield in the region, and it showed a positive impact under temperatures less than 1 °C while a yield decrement by 10.8% per 1 °C warming (Han et al. 2021). The north-east region of Iran also depicted yield reduction at all locations during the future century from 2.6 to 82% from the baseline (Bannayan et al. 2016).

A calibrated and validated APSIM model was used to evaluate the climate change impact on maize yield in central India, and the results showed a decrease of − 44.4, − 20.0, − 19.7, − 17.9, and 22.5% under RCP 4.5 for N 0%, N 50%, N 100%, N 150%, and 100% organic, respectively, from the baseline (Sinha Nishant et al. 2021). The kharif season maize crop showed yield reduction with rise in temperature for all the locations considered under a study in Delhi, India, but the magnitude of impact at different locations varied (Singh et al. 2010). Byjesh et al. (2010) used HadCM3 model to simulate maize yields at high atmospheric temperature and observed a decline in yield which occurred due to reduced crop duration, i.e., days to 50% flowering and grain filling duration (GFD), and reduced leaf area index and leaf area duration. A considerable reduction in crop phenology was observed by them, to the extent of 16% (days to 50% flowering) and 14% (GFD) at 5 °C rise in temperature. Yield components like grain weight, test weight, and the number of grains were also impacted by high temperature. The results of the study depicted a decrease in the projected maize yield under reduction or no increase in rainfall at fixed temperature simulations. However, the HadCM3 model scenarios in comparison to “fixed temperature” scenarios project an increase in rainfall for various locations of India which results in less impact on maize yield. In a study by Kaur (2020), the projections for Punjab show that for RCPs 2.6, 4.5, 6.0, and 8.5, the maximum temperature would rise from 29.8–31.3 °C (baseline) to 30.5–31.6, 31.8–32.8, 31.6–32.6, and 33.6–34.7 °C, respectively, while the minimum temperature is projected to rise from 15.5–20.3 °C (baseline) to 17.8–19.1, 19.0–20.2, 19.2–20.5, and 21.1–22.4 °C, respectively, by the end of the twenty-first century. This projected increase in temperature will definitely impact this major agricultural state of India.

The results of a simulation study conducted by Srivastava et al. (2021) revealed that during the end-century (2051–2080) in eastern India, the irrigated maize crop may experience major yield loss, while the rainfed maize may experience an increase in grain yield. These projections clearly explain that in case of rainfed crop, the negative impact of temperature was nullified by rainfall. Thus, the
major factor influencing the growth and phenology of maize is temperature increment supported by deficit rainfall which causes an increase in the development rate and reduction in the growth period of crop leading to yield reduction.

The climate change event is global, but the impact is observed to be more pronounced on the developing countries like India where the economy is disturbed by the adverse effects. India is already known for its wide diversification may it be in culture, climate, crops, etc., and agriculture is considered as the backbone of India as most of the states of India depend on agriculture for its economy. Thus, climate change impact analysis is a must for the region, and these impacts need to be analyzed primarily for states contributing majorly to agriculture. Amongst these states comes Punjab which is known to be the major food provider in India and historical as well as current studies clearly show the shifting weather as well as crop patterns in Punjab leading to larger environmental issues and losses. Thus, keeping this scenario in mind, the study was conducted on kharif maize crop cultivars (PMH1 and PMH2) which are majorly grown in Punjab, and the relation between the yield and future projections for four agroclimatic zones of Punjab was analyzed in this study.

2 Material and methods

2.1 Location

Punjab extends from 29°33″N to 32°34″N latitude and 73°53″E to 76°56″E longitude occupying 1.54% of country’s total geographical area in the north-western region of India. The climate of the state is sub-tropical, semi-arid, and monsoon type. The annual average minimum and maximum temperatures for Punjab range between 29 to 32 °C and 15 to 20 °C, respectively. The temperature variation is observed during the kharif (monsoon) and rabi (winter) seasons when the mean maximum temperatures are 38 °C and 25 °C, respectively, and mean minimum temperatures are 23 °C and 8 °C, respectively. The rainfall variation within the state itself is very high in space as well as time with the mean annual rainfall ranging from 400 to 1300 mm. The monsoon season is the major contributor (75 to 80%) in rainfall, while minor contribution (20–25%) during the remaining 8 months is by western disturbances. The high variations in onset, duration, and withdrawal time of monsoon cause dry spells during the critical crop growth stages in the state. Punjab state is divided into six agroclimatic zones. Representative productive regions in four of these zones, viz, zone II (Ballowal Saunkhri), zone III (Ludhiana, Amritsar, and Patiala), zone IV (Bathinda), and zone V (Abohar and Faridkot), were considered for the study on maize productivity.

2.2 Model description

The most widely used crop growth models are the DSSAT models which have been designed to simulate the growth, development, and yield of the crops along with the changes in soil water, carbon, and nitrogen that takes place over the time under a particular cropping system (Jones et al. 2003). The first version of DSSAT was released in 1989, and it consisted of four crop models that are CERES-Maize (Jones and Kiniry, 1986), CERES-Wheat (Ritchie and Otter 1985), SOYGRO (Wilkerson et al. 1983), and PNUTGRO (Boote et al. 1987). Among all these models, CERES-Maize continues to dominate; it is in high demand globally and remains the mother-seed of other maize models like APSIM (Keating et al. 2003) and the CSM-IXIM (Lizaso et al. 2011). Jones and Kiniry (1986) described the CERES-Maize model as a simulation tool to explain the daily phenological growth and development under the influence of environmental factors (soil, weather, and crop management).

The present study used the calibrated and validated (Kothiyal et al. 2021) CERES-Maize (v 4.7.5) model to simulate the maize yield from 2025 to 2095 under the scenarios (RCP 4.5 and RCP 6.0) for sowing window (end May to June). Two major maize cultivars, long duration (PMH1) and short duration (PMH2), were used for determining the future yield trends of maize.

2.3 Yield assessment

The GCMs provide daily data for the weather parameters (maximum and minimum temperature, rainfall), and the ensemble of the seventeen GCMs was considered for the study. The corrected weather data (Kaur 2020) for two stabilization scenarios that are RCP 4.5 and RCP 6.0 were used as input in the CERES-Maize model for the region. The model used this data to simulate yield for 70 years (2025–2095) under the current sowing window of maize in Punjab keeping the management practices constant. The constant management practices helped in determining the impact of temperature and rainfall variations on the maize yield. The baseline from which the temperature and rainfall trend during the crop season studied was taken as recommended for the state (Prabhjyot-Kaur et al. 2020).

The statistical yield assessment was done using correlation coefficients calculated by Pearson’s correlation analysis (SAS, v 9.3), while the yield categories were prepared on the basis of simulated yield to observe the performance of maize crop under the considered scenarios and to indicate what further optimization can be done for the better performance of the crop. The study also helped in recognizing the zones that are not suitable for growing maize in Punjab.
3 Results

3.1 Temperature, rainfall, and yield relationship in Punjab

The correlation for the maize yield cultivars PMH1 (Fig. 1) and PMH2 (Fig. 2) clearly explains a strong negative relationship between temperature and maize yield, while the relationship for rainfall is also negative but comparatively weaker (Table 1). The rainfall variability is very high in all the agroclimatic zones especially in zones II and IV in Punjab. The maximum and minimum temperature showed a continuous increase from 34.5–36.0 and 27.5–29.5 °C, respectively (zones II and III), 36.0–38.0 and 27.5–29.5 °C, respectively (zone IV), and 35.0–37.0 and 27.5–30.0 °C, respectively (zone V) over the 70-year period with peak during the end-century. The rainfall during the maize growth period ranged between 200 and 600 mm under both the scenarios, but the variability and extremes were very high. The scatter plot matrix clearly showed a decline in yield with increase in temperature, in all the agroclimatic zones. However, the yield of maize was not clearly correlated with rainfall as large gaps were observed due to highly variable rainfall pattern under both the scenarios in Punjab state.

3.2 Yield assessment under RCP 4.5 and RCP 6.0

3.2.1 Agroclimatic zone II

Ballowal Saunkhri The cv. PMH1 gave higher yield (> 5000 kg/ha) during mid-June sowing, under both the scenarios (Figs. 3a and 4a) where the maximum and minimum temperature varied between 34–36 °C and 27–29 °C, respectively, with rainfall ranging between 300 and 470 mm. This high yield of maize was observed for all 70 years (2025–2095) under RCP 4.5 and for 62 years (2025–2087) under RCP 6.0 (Table 2). If the sowing of cv PMH1 was simulated from end of May or early June, then high yield of maize was observed during fewer years (11–13% and 30–64% under RCPs 4.5 and 6.0, respectively), while late June sowing of maize invariably gave medium yield (3000–5000 kg/ha) under both the scenarios. The critical evaluation of data in Table 2 revealed that medium yield of maize was simulated during the years when maximum and minimum temperature varied between 35–37 °C and 28–29 °C, respectively, with rainfall ranging between 300 and 530 mm. During the low yield years for cv PMH2 under RCP 6.0 scenario, the maximum, minimum temperature, and rainfall varied between 35–37 °C, 29–30 °C, and 400–490 mm, respectively.

Hence, a 1 °C increase in maximum (from 34–36 to 35–37 °C) and minimum (from 27–29 to 28–29 °C) led to lowering of yield of maize from high to medium yield category (> 5000 to 3000–5000 kg/ha). Further increase in minimum temperature from 28–29 to 29–30 °C lowered the maize yields from medium to low yield category (3000–5000 to < 3000 kg/ha). This effect was more visible in cv PMH2 compared to cv PMH1. Thus, in agroclimatic zone II, sowing of maize cv PMH1 during mid-June would be the most suitable option for the farmers of the region.

3.2.2 Agroclimatic zone III

Ludhiana The cv. PMH1 gave high yield (> 5000 kg/ha) during mid-June under both the scenarios (Figs. 3b and 4b) where the maximum, minimum temperature, and rainfall varied between 34–36 °C, 27–29 °C, and 350–750 mm, respectively. This high yield of maize was observed for all 70 years (2025–2095) under RCP 4.5 and RCP 6.0 scenarios (Table 3). If the sowing of cv PMH1 was simulated during end May or early June, then high yield of maize was observed during fewer years, while late June sowing of maize invariably gave medium yield (3000–5000 kg/ha) under both the scenarios. The temperature and rainfall data...
Fig. 1 Correlation matrix between projected yield of maize cv PMH1 and weather parameters (temperature and rainfall) during twenty-first century at different agroclimatic zones of Punjab
Fig. 2  Correlation matrix between projected yield of maize cv PMH2 and weather parameters (temperature and rainfall) during twenty-first century at different agroclimatic zones of Punjab
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in Table 3 depicted that medium yield of maize (sown during end May, early and late June) was simulated during the years when maximum, minimum temperature, and rainfall varied between 34–37 °C, 27–30 °C, and 370–780 mm, respectively. No low yield (< 3000 kg/ha) years were simulated for cv. PMH1 under both the scenarios in agroclimatic zone III (Ludhiana).

The cv. PMH2 in agroclimatic zone III (Ludhiana) simulated maize yields in all three categories of yield. It gave high yield (> 5000 kg/ha) during both mid- and end-June under both the scenarios (Figs. 5b and 6b) where the maximum and minimum temperature varied between 34–35 °C and 27–29 °C, respectively, with rainfall varying between 350 and 760 mm. This higher yield was observed for mid and end June sown maize for 22 years (2025–2047) and 70 years (2025–2095), respectively, under RCP 4.5 while for 42 years (2025–2067) and 46 years (2025–2071), respectively, under RCP 6.0 (Table 3). For end May, the simulated maize yield was medium (3000–5000 kg/ha) for all 70 years (2025–2095). The yield years for early, mid, and end June sown maize under both the scenarios varied among the three categories. The low yield years (< 3000 kg/ha) were observed for end May under RCP 6.0 when the maximum, minimum temperature, and rainfall varied between 36–37 °C, 29–30 °C, and 570–650 mm, respectively (Table 4). During the medium yield years under both the scenarios, the maximum and minimum temperature varied between 35–38 and 27–30 °C, respectively, with rainfall ranging between 360 and 690 mm.

The cv. PMH2 in agroclimatic zone III (Amritsar) simulated maize yields in all three categories. It gave high yield (> 5000 kg/ha) during both mid- and end-June under both the scenarios (Figs. 5c and 6c) where the maximum and minimum temperature varied between 34–35 °C and 27–29 °C, respectively, with rainfall ranging between 450 and 680 mm. This higher yield was observed for mid and end June sown maize for 12 years (2025–2037) and 45 years (2025–2070), respectively, under RCP 4.5 while for 28 years (2025–2053) and 50 years (2025–2075), respectively, under RCP 6.0 (Table 4). For end May, the simulated maize yield was medium (3000–5000 kg/ha) under RCP 4.5 for all 70 years (2025–2095). The yield years for early, mid, and end June sown maize under both the scenarios varied among the three categories. The low yield years (< 3000 kg/ha) were observed for end May under RCP 6.0 and for early

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### Table 1: Correlation matrix between predicted yield of maize cultivars (PMH1 and PMH2) and weather parameters during twenty-first century in Punjab

| Grain yield (kg/ha) | PMH1 | PMH2 |
|--------------------|------|------|
|                    | Tmax | Tmin | Rainfall | Tmax | Tmin | Rainfall |
| Zone II (Ballowal Saunkhri) | -0.871*** | -0.852*** | -0.513*** | -0.973*** | -0.964*** | -0.766*** |
| Zone III (Ludhiana, Amritsar, and Patiala) | -0.986*** | -0.986*** | -0.892*** | -0.991*** | -0.991*** | -0.912*** |
| Zone IV (Bathinda) | -0.978*** | -0.968*** | -0.851*** | -0.990*** | -0.992*** | -0.800*** |
| Zone V (Abohar and Faridkot) | -0.981*** | -0.971*** | -0.898*** | -0.992*** | -0.987*** | -0.888*** |

***Significant at P < 0.001

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option under the future scenarios for the farmers in agroclimatic zone III (Ludhiana).

Amritsar The cv. PMH1 gave high yield (> 5000 kg/ha) during mid-June under both the scenarios (Figs. 3c and 4c) with maximum, minimum temperature, and rainfall variations ranging between 34–36 °C, 27–29 °C, and 450–670 mm, respectively. This high yield of maize was observed for 50 years (2025–2078) under RCP 4.5 and for 65 years (2025–2090) under RCP 6.0 scenario (Table 4). If the sowing of cv PMH1 was simulated during end May, early, and end June, then high yield of maize was observed during fewer years, and the yield during these dates was variable, lying between medium and high yield category. Under RCP 4.5, end May sown maize observed medium yield for all 70 years. The low yield during 10 years (2080–2081; 2086–2095) was observed only for early June sowings under RCP 6.0 when the maximum, minimum temperature, and rainfall varied between 34–36 °C, 27–29 °C, and 370–780 mm, respectively (Table 4). During the medium yield years under both the scenarios, the maximum and minimum temperature varied between 35–38 and 27–30 °C, respectively, with rainfall ranging between 360 and 690 mm.

The cv. PMH2 in agroclimatic zone III (Amritsar) simulated maize yields in all three categories. It gave high yield (> 5000 kg/ha) during both mid- and end-June under both the scenarios (Figs. 5c and 6c) where the maximum and minimum temperature varied between 34–35 °C and 27–29 °C, respectively, with rainfall ranging between 450 and 680 mm. This higher yield was observed for mid and end June sown maize for 12 years (2025–2037) and 45 years (2025–2070), respectively, under RCP 4.5 while for 28 years (2025–2053) and 50 years (2025–2075), respectively, under RCP 6.0 (Table 4). For end May, the simulated maize yield was medium (3000–5000 kg/ha) under RCP 4.5 for all 70 years (2025–2095). The yield years for early, mid, and end June sown maize under both the scenarios varied among the three categories. The low yield years (< 3000 kg/ha) were observed for end May under RCP 6.0 and for early...
Fig. 3  Yield assessment for maize cv PMH1 sown from end May to June at different locations during 2025–2095 as simulated by CERES-Maize model using projected climate data of the ensemble model under RCP 4.5

**a** Ballowal Saunkhri

**b** Ludhiana

**c** Amritsar

**d** Patiala

**e** Bathinda

**f** Abohar

**g** Faridkot
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Fig. 4 Yield assessment for maize cv PMH1 sown from end May to June at different locations during 2025–2095 as simulated by CERES-Maize model using projected climate data of the ensemble model under RCP 6.0
Table 2  Yield distribution for maize cv PMH1 and PMH2 sown from end May to June at zone II (Ballowal Saunkhri) during 2025–2095 as simulated by CERES-Maize model using projected climate data of the ensemble model

| PMH1 (baseline: Tmax=34.4 °C; Tmin = 22.4 °C; rainfall = 888 mm) | Yield years (temperature and rainfall) | Yield category (<3000 kg/ha) | Low yield | Medium yield (3000–5000 kg/ha) | High yield (>5000 kg/ha) |
|---|---|---|---|---|---|
| | Yield category | 28-May | 6-June | 15-June | 24-June |
| PMH1 | Low yield | RCP 4.5 | RCP 6.0 | RCP 4.5 | RCP 6.0 | RCP 4.5 | RCP 6.0 | RCP 4.5 | RCP 6.0 |
| | Medium yield | 2027–2028; 2031–2034; 2039–2095 | 2037–2038; 2048–2095 | 2033–2034; 2036–2095 | 2071–2095 | All years | 2025–2026; 2029–2030; 2035–2038 | 2025–2032; 2035 | 2025–2070 | All years | 2025–2087 |
| | High yield | 2025–2026; 2029–2030; 2035–2038 | 2025–2036; 2039–2047 | 2025–2032; 2035 | 2025–2070 | All years | 2025–2087 | - | 2051–2060 |

PMH2 (baseline: Tmax=34.4 °C; Tmin = 22.4 °C; rainfall = 888 mm)
### Table 2 (continued)

| Yield years (temperature and rainfall) | Yield category | 28-May | 6-June | 15-June | 24-June |
|---------------------------------------|----------------|--------|--------|---------|---------|
| (temperature and rainfall)            | Low yield (< 3000 kg/ha) | RCP 4.5 | 2066–2095 | RCP 4.5 | 2066–2095 | RCP 4.5 | 2066–2095 | RCP 4.5 | 2066–2095 |
|                                       | Tmax = 36–37 °C | Tmin = 29–30 °C | RF = 420–490 mm | Tmax = 36–37 °C | Tmin = 29–30 °C | RF = 400–470 mm | Tmax = 36–37 °C | Tmin = 29–30 °C | RF = 400–470 mm | Tmax = 36–37 °C | Tmin = 29–30 °C | RF = 400–470 mm |
|                                       | Medium yield (3000–5000 kg/ha) | All years | 2025–2065 | All years | 2025–2065 | All years | 2025–2065 | All years | 2025–2065 |
|                                       | Tmax = 35–36 °C | Tmin = 28–29 °C | RF = 300–520 mm | Tmax = 35–36 °C | Tmin = 28–29 °C | RF = 360–490 mm | Tmax = 35–36 °C | Tmin = 28–29 °C | RF = 300–470 mm | Tmax = 35–36 °C | Tmin = 28–29 °C | RF = 300–470 mm |
|                                       | High yield (> 5000 kg/ha) | All years | 2025–2065 | All years | 2025–2065 | All years | 2025–2065 | All years | 2025–2065 |
|                                       | Tmax = 35–36 °C | Tmin = 28–29 °C | RF = 300–520 mm | Tmax = 35–36 °C | Tmin = 28–29 °C | RF = 360–490 mm | Tmax = 35–36 °C | Tmin = 28–29 °C | RF = 300–470 mm | Tmax = 35–36 °C | Tmin = 28–29 °C | RF = 350–530 mm |
|                                       | Tmax = 34–36 °C | Tmin = 28–29 °C | RF = 300–480 mm | Tmax = 34–35 °C | Tmin = 27–28 °C | RF = 300 mm | Tmax = 34–35 °C | Tmin = 27–28 °C | RF = 350–530 mm | Tmax = 34–35 °C | Tmin = 27–28 °C | RF = 360–450 mm |
Fig. 5 Yield assessment for maize cv PMH2 sown from end May to June at different locations during 2025–2095 as simulated by CERES-Maize model using projected climate data of the ensemble model under RCP 4.5
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Fig. 6  Yield assessment for maize cv PMH2 sown from end May to June at different locations during 2025–2095 as simulated by CERES-Maize model using projected climate data of the Ensemble model under RCP 6.0
Table 3  Yield distribution for maize cv PMH1 and PMH2 sown from end May to June at zone III (Ludhiana) during 2025–2095 as simulated by CERES-Maize model using projected climate data of the ensemble model

PMH1 (baseline: Tmax = 34.9 °C; Tmin = 23.3 °C; rainfall = 634 mm)

| Yield years (temperature and rainfall) | Yield category | 28-May | 6-June | 15-June | 24-June |
|---------------------------------------|----------------|--------|--------|---------|---------|
| Low yield (<3000 kg/ha)               | RCP 4.5        | -      | RCP 4.5| RCP 4.5 | RCP 4.5 | RCP 4.5 | RCP 6.0 |
| Medium yield (3000–5000 kg/ha)       | RCP 6.0        | -      | -      | -       | -       | -       | -       |
| Temperature and Rainfall              |                |        |        |         |         |         |         |
| Tmax = 35–37 °C                       | Tmin = 35–37 °C|        |        |         |         |         |         |
| Tmin = 28–30 °C                       | RF = 380–780 mm|        |        |         |         |         |         |
| High yield (>5000 kg/ha)              |                |        |        |         |         |         |         |
| Low yield (<3000 kg/ha)               | RCP 4.5        | -      | -      | -       | -       | -       | -       |
| Medium yield (3000–5000 kg/ha)       | RCP 6.0        | -      | -      | -       | -       | -       | -       |
| Temperature and Rainfall              |                |        |        |         |         |         |         |
| Tmax = 35–37 °C                       | Tmin = 35–37 °C|        |        |         |         |         |         |
| Tmin = 28–30 °C                       | RF = 350–760 mm|        |        |         |         |         |         |
| High yield (>5000 kg/ha)              |                |        |        |         |         |         |         |

PMH2 (baseline: Tmax = 34.9 °C; Tmin = 23.3 °C; rainfall = 634 mm)

| Yield years (temperature and rainfall) | Yield category | 28-May | 6-June | 15-June | 24-June |
|---------------------------------------|----------------|--------|--------|---------|---------|
| Low yield (<3000 kg/ha)               | RCP 4.5        | -      | RCP 4.5| RCP 4.5 | RCP 4.5 | RCP 4.5 | RCP 6.0 |
| Medium yield (3000–5000 kg/ha)       | RCP 6.0        | -      | -      | -       | -       | -       | -       |
| Temperature and Rainfall              |                |        |        |         |         |         |         |
| Tmax = 35–37 °C                       | Tmin = 35–37 °C|        |        |         |         |         |         |
| Tmin = 28–30 °C                       | RF = 370–570 mm|        |        |         |         |         |         |
| High yield (>5000 kg/ha)              |                |        |        |         |         |         |         |
Table 4 Yield distribution for maize cv PMH1 and PMH2 sown from end May to June at zone III (Amritsar) during 2025–2095 as simulated by CERES-Maize model using projected climate data of the ensemble model

| Yield years (temperature and rainfall) | Yield category | 28-May | 6-June | 15-June | 24-June |
|---------------------------------------|----------------|--------|--------|---------|---------|
| Low yield (< 3000 kg/ha)              |                | RCP 4.5 | RCP 6.0 | RCP 4.5 | RCP 6.0 |
| PMH1 (baseline: Tmax = 35.6 °C; Tmin = 22.5 °C; rainfall = 579 mm) |                |        |        |         |         |
| Medium yield (3000–5000 kg/ha)        |                |        |        |         |         |
| 2025–2095                             |                |        |        |         |         |
| Tmax = 35–37 °C                       |                |        |        |         |         |
| Tmin = 27–29 °C                       |                |        |        |         |         |
| RF = 400–610 mm                       |                |        |        |         |         |
| High yield (> 5000 kg/ha)             |                |        |        |         |         |
| 2025–2038                             |                |        |        |         |         |
| Tmax = 35–36 °C                       |                |        |        |         |         |
| Tmin = 27–28 °C                       |                |        |        |         |         |
| RF = 540–560 mm                       |                |        |        |         |         |

| PMH2 (baseline: Tmax = 35.6 °C; Tmin = 22.5 °C; rainfall = 579 mm) |                |        |        |         |         |
| Low yield (<3000 kg/ha)              |                | RCP 6.0 | RCP 4.5 | RCP 6.0 | RCP 6.0 |
| Medium yield (3000–5000 kg/ha)       |                |        |        |         |         |
| All years                             |                |        |        |         |         |
| 2025–2083                             |                |        |        |         |         |
| Tmax = 35–37 °C                       |                |        |        |         |         |
| Tmin = 27–29 °C                       |                |        |        |         |         |
| RF = 530–600 mm                       |                |        |        |         |         |
| High yield (> 5000 kg/ha)             |                |        |        |         |         |
| 2025–2037                             |                |        |        |         |         |
| Tmax = 34–35 °C                       |                |        |        |         |         |
| Tmin = 27–28 °C                       |                |        |        |         |         |
| RF = 540–550 mm                       |                |        |        |         |         |
Table 5  Yield distribution for maize cv PMH1 and PMH2 sown from end May to June at zone III (Patiala) during 2025–2095 as simulated by CERES-Maize model using projected climate data of the ensemble model

| PMH1 (baseline: $T_{max} = 35.0 \, ^\circ C$; $T_{min} = 23.9 \, ^\circ C$; rainfall = 649 mm) |
|---------------------------------------------|
| **Yield years** | **Yield category** | **28-May** | **6-June** | **15-June** | **24-June** |
| (temperature and rainfall) | | **RCP 4.5** | **RCP 6.0** | **RCP 4.5** | **RCP 6.0** | **RCP 4.5** | **RCP 6.0** | **RCP 4.5** | **RCP 6.0** |
| Low yield (< 3000 kg/ha) | | - | - | - | - | - | - | - | - |
| Medium yield (3000–5000 kg/ha) | | | | | | | | | |
| $T_{max} = 37 \, ^\circ C$ | $T_{min} = 29 \, ^\circ C$ | $R_F = 500$ mm | | | | | | | |
| | | $T_{max} = 36--37 \, ^\circ C$ | $T_{min} = 29--30 \, ^\circ C$ | $R_F = 460--550$ mm | $R_F = 360--550$ mm | $R_F = 370--550$ mm | | | |
| | | $T_{max} = 35--36 \, ^\circ C$ | $T_{min} = 28--29 \, ^\circ C$ | $R_F = 360--550$ mm | $R_F = 370--450$ mm | $R_F = 380--550$ mm | | | |
| | | $T_{max} = 34--35 \, ^\circ C$ | $T_{min} = 27--28 \, ^\circ C$ | $R_F = 350--550$ mm | $R_F = 360--450$ mm | $R_F = 370--550$ mm | | | |
| High yield (> 5000 kg/ha) | | | | | | | | | |
| | | | | | | | | | |
| PMH2 (baseline: $T_{max} = 35.0 \, ^\circ C$; $T_{min} = 23.9 \, ^\circ C$; rainfall = 649 mm) |
| **Yield years** | **Yield category** | **28-May** | **6-June** | **15-June** | **24-June** |
| (temperature and rainfall) | | **RCP 4.5** | **RCP 6.0** | **RCP 4.5** | **RCP 6.0** | **RCP 4.5** | **RCP 6.0** | **RCP 4.5** | **RCP 6.0** |
| Low yield (< 3000 kg/ha) | | - | - | - | - | - | - | - | - |
| Medium yield (3000–5000 kg/ha) | | | | | | | | | |
| $T_{max} = 36--37 \, ^\circ C$ | $T_{min} = 28--29 \, ^\circ C$ | $R_F = 370--550$ mm | | | | | | | |
| | | $T_{max} = 35--36 \, ^\circ C$ | $T_{min} = 28--29 \, ^\circ C$ | $R_F = 350--450$ mm | | | | | |
| | | $T_{max} = 34--35 \, ^\circ C$ | $T_{min} = 27--28 \, ^\circ C$ | $R_F = 350--450$ mm | | | | | |
| High yield (> 5000 kg/ha) | | | | | | | | | |
| | | | | | | | | | |
Table 6  Yield distribution for maize cv PMH1 and PMH2 sown from end May to June at zone IV (Bathinda) during 2025–2095 as simulated by CERES-Maize model using projected climate data of the ensemble model

| PMH1 (baseline: Tmax = 36.7 °C; Tmin = 23.9 °C; rainfall = 427 mm) | Yield years (temperature and rainfall) | Yield category | 28-May | 6-June | 15-June | 24-June |
|---|---|---|---|---|---|---|
| | RCP 4.5 | RCP 6.0 | | RCP 4.5 | RCP 6.0 | |
| Low yield (< 3000 kg/ha) | Tmax = 37–38 °C | Tmin = 28–29 °C | RF = 270–320 mm | All years | All years | All years |
| | 2025–2095 | 2032–2095 | | 2048–2067; 2082–2095 | 2062–95 | |
| | Tmax = 36–38 °C | Tmin = 28–30 °C | RF = 270–390 mm | All years | All years | All years |
| Medium yield (3000–5000 kg/ha) | Tmax = 37–38 °C | Tmin = 28–29 °C | RF = 270–300 mm | 2025–31 | - | - |
| High yield (> 5000 kg/ha) | - | - | - | - | - | - |

| PMH2 (baseline: Tmax = 36.7 °C; Tmin = 23.9 °C; rainfall = 427 mm) | Yield years (temperature and rainfall) | Yield category | 28-May | 6-June | 15-June | 24-June |
|---|---|---|---|---|---|---|
| | RCP 4.5 | RCP 6.0 | | RCP 4.5 | RCP 6.0 | |
| Low yield (< 3000 kg/ha) | Tmax = 37–38 °C | Tmin = 28–29 °C | RF = 270–320 mm | All years | All years | All years |
| | 2025–2095 | 2032–2095 | | 2048–2067; 2082–2095 | 2062–95 | |
| | Tmax = 36–38 °C | Tmin = 28–30 °C | RF = 270–390 mm | All years | All years | All years |
| Medium yield (3000–5000 kg/ha) | Tmax = 37–38 °C | Tmin = 28–29 °C | RF = 270–300 mm | 2025–31 | - | - |
| High yield (> 5000 kg/ha) | - | - | - | - | - | - |
Table 7  Yield distribution for maize cv PMH1 and PMH2 sown from end May to June at zone V (Abohar) during 2025–2095 as simulated by CERES-Maize model using projected climate data of the ensemble model

| PMH1 (baseline: Tmax = 35.7 °C; Tmin = 24.0 °C; rainfall = 262 mm) | Yield years (temperature and rainfall) | Yield category | 28-May | 6-June | 15-June | 24-June |
|---------------------------------------------------------------|--------------------------------------|----------------|--------|--------|---------|---------|
|                                                               |                                       | Low yield (<3000 kg/ha) | RCP 4.5 | RCP 6.0 | RCP 4.5 | RCP 6.0 |
|                                                               |                                       | Tmax = 36–38 °C; Tmin = 28–30 °C; RF = 220–300 mm | All years | All years | All years | All years |
|                                                               |                                       | Medium yield (3000–5000 kg/ha) | - | - | - | - |
|                                                               |                                       | High yield (> 5000 kg/ha) | - | - | - | - |
| PMH2 (baseline: Tmax = 35.7 °C; Tmin = 24.0 °C; rainfall = 262 mm) |                                       | Low yield (<3000 kg/ha) | RCP 4.5 | RCP 6.0 | RCP 4.5 | RCP 6.0 |
|                                                               |                                       | Tmax = 36–38 °C; Tmin = 28–30 °C; RF = 220–300 mm | All years | All years | All years | All years |
|                                                               |                                       | Medium yield (3000–5000 kg/ha) | - | - | - | - |
|                                                               |                                       | High yield (> 5000 kg/ha) | - | - | - | - |
June under RCP 4.5 and 6.0. During the low yield years, the maximum, minimum temperature, and rainfall varied between 36–37 °C, 28–29 °C, and 550–650 mm, respectively (Table 4). These variations during medium yield years for maximum, minimum temperature, and rainfall were 35–37 °C, 27–29 °C, and 350–690 mm, respectively.

Hence, for PMH1, a 1 °C increase in maximum (from 34–36 to 35–37 °C) and minimum (from 27–28 to 27–29 °C) led to lowering of yield of maize from high to medium yield category (> 5000 to 3000–5000 kg/ha), and an increase in minimum temperature from 27–29 to 28–29 °C lowered the maize yields from medium to low yield category (3000–5000 to < 3000 kg/ha). The cv PMH 2 simulated more number of low yield years than cv PMH1 due to a temperature rise of 1 °C in maximum (from 34–35 to 36–37 °C) and minimum temperature (from 27–28 to 27–29 °C). Hence, sowing of maize cv PMH1 during mid-June would be the most suitable in agroclimatic zone III (Amritsar).

**Patiala** The cv. PMH1 gave high yield during early and mid-June sowing (> 5000 kg/ha) under RCP 4.5 (Fig. 3d) and alone mid-June (Fig. 4d) under RCP 6.0 where the maximum and minimum temperature varied between 34–37 °C and 27–29 °C, respectively, with rainfall ranging between 360 and 560 mm. This higher yield of maize was observed for 70 years (2025–2095) under RCP 4.5 and for 63 years (2025–2081; 2083–2084; 2086–2092) under RCP 6.0 scenario (Table 5). If the sowing of cv PMH1 was simulated during end May, early June, and end June, then high yield of maize was observed during fewer years, and the yield during these dates varied between medium (3000–5000 kg/ha) and high. No low yield years were simulated for the cultivar. The temperature and rainfall variations during the simulated medium yield years were 35–37 °C, 28–29 °C, and 450–590 mm for maximum, minimum temperature, and rainfall, respectively, as depicted in Table 5.

The cv. PMH2 in agroclimatic zone III (Patiala) gave high yield (> 5000 kg/ha) during mid-June under RCP 4.5 and end-June under RCP 6.0 (Figs. 5d and 6d) where the maximum and minimum temperature varied between 34–36 °C and 27–29 °C, respectively, with rainfall ranging between 360 and 560 mm. This higher yield was observed for very few years, i.e., 1 year (2025) and 6 years (2025–2032) under RCP 6.0 scenario (Figs. 3e and 4e) where the maximum and minimum temperature varied between 36–37 °C and 27–29 °C, respectively, with rainfall ranging between 270 and 280 mm. This medium yield of maize was observed for 35 years (2025–2047, 2068–2081) under RCP 4.5 and for 36 years (2025–2061) under RCP 6.0 scenario (Table 5). If the sowing of cv PMH1 was simulated during end May, then very few medium yield years of maize were observed under RCP 6.0. The early and end June sown crop depicted poor crop performance under both the scenarios with low yield (< 3000 kg/ha) during all 70 years (2025–2095). The yield for all the dates of sowing varied between low and medium categories. During the low yield years, the maximum, minimum temperature, and rainfall varied between 35–39 °C, 27–30 °C, and 270–420 mm, respectively (Table 6). The maize cv PMH1 simulated few medium yield years under both the scenarios in agroclimatic zone IV.

**Bathinda** The cv. PMH1 gave medium yield during mid-June (3000–5000 kg/ha) under both the scenarios (Figs. 3e and 4e) where the maximum and minimum temperature varied between 36–37 °C and 27–28 °C, respectively, with rainfall ranging between 270 and 300 mm. This medium yield of maize was observed for 35 years (2025–2047, 2068–2081) under RCP 4.5 and for 36 years (2025–2061) under RCP 6.0 scenario (Table 6). If the sowing of cv PMH1 was simulated during end May, then very few medium yield years of maize were observed under RCP 6.0. The early and end June sown crop depicted poor crop performance under both the scenarios with low yield (< 3000 kg/ha) during all 70 years (2025–2095). The yield for all the dates of sowing varied between low and medium categories. During the low yield years, the maximum, minimum temperature, and rainfall varied between 35–39 °C, 27–30 °C, and 270–420 mm, respectively (Table 6). The maize cv PMH1 simulated few medium yield years under both the scenarios in agroclimatic zone IV.

The cv. PMH2 in agroclimatic zone IV gave medium yield (3000–4000 kg/ha) during mid-June under RCP 4.5 and RCP 6.0 (Figs. 5e and 6e) where the maximum and minimum temperature were 36 °C and 27–28 °C, respectively, with rainfall ranging between 270 and 280 mm. This medium yield was observed for very few years, i.e., 1 year (2025) and 14 years (2025–2039) under RCP 6.0 (Table 6). For end May, early June, and end June sowing, the simulated maize yield was low (< 3000 kg/ha) for all 70 years (2025–2095) under both the scenarios. The temperature and rainfall conditions as depicted in Table 6 showed that low maize yield was simulated when maximum and minimum temperature varied between 35–39 °C and 27–31 °C, respectively, with rainfall varying between 270 and 425 mm. For cv PMH2 medium yield (4000–5000 kg/ha) was simulated for very few years under both the scenarios in agroclimatic zone IV.

Hence, for cv PMH1, a 2 °C increase in maximum (from 36–37 to 38–39 °C) and 1 °C increase in minimum (from 27–29 to 2730 °C) led to lowering of yield of maize from
Table 8  Yield distribution for maize cv PMH1 and PMH2 sown from end May to June at zone V (Faridkot) during 2025–2095 as simulated by CERES-Maize model using projected climate data of the ensemble model

| PMH1 (baseline: Tmax = 35.1 °C; Tmin = 26.7 °C; rainfall = 382 mm) | Yield years (temperature and rainfall) | Yield category | 28-May | 6-June | 15-June | 24-June |
|---|---|---|---|---|---|---|
| | Low yield (<3000 kg/ha) | | RCP 4.5 | RCP 6.0 | RCP 4.5 | RCP 6.0 | RCP 4.5 | RCP 6.0 | RCP 4.5 | RCP 6.0 | RCP 4.5 | RCP 6.0 |
| Medium yield (3000–5000 kg/ha) | | | 2067–2095 | 2074–2095 | - | 2084–2095 | - | 2091–2095 | All years | All years |
| | Tmax = 36–37 °C | Tmax = 36–37 °C | Tmin = 29 °C | Tmin = 29–30 °C | RF = 270–370 mm | RF = 350–370 mm | RF = 274 mm | RF = 310–324 mm | RF = 306–406 mm |
| High yield (>5000 kg/ha) | | | 2025–2066 | 2025–2073 | All years | 2025–2083 | All years | 2025–2090 | - | - |
| | Tmax = 35–36 °C | Tmax = 35–36 °C | Tmin = 29–30 °C | Tmin = 28–29 °C | RF = 260–290 mm | RF = 260–290 mm | RF = 260–275 mm | RF = 258–356 mm | |

| PMH2 (baseline: Tmax = 35.1 °C; Tmin = 26.7 °C; rainfall = 382 mm) | Yield years (temperature and rainfall) | Yield category | 28-May | 6-June | 15-June | 24-June |
|---|---|---|---|---|---|---|
| | Low yield (<3000 kg/ha) | | RCP 4.5 | RCP 6.0 | RCP 4.5 | RCP 6.0 | RCP 4.5 | RCP 6.0 | RCP 4.5 | RCP 6.0 | RCP 4.5 | RCP 6.0 |
| Medium yield (3000–5000 kg/ha) | | | 2060–2095 | 2071–2095 | - | 2083–2095 | 2073–2095 | 2078–95 | 2025–2065; 2070–2074; 2091–2095 | 2025–2064; 2066–2067; 2069–2077; 2079; 2081; 2083; 2095 |
| | Tmax = 36–37 °C | Tmax = 36–37 °C | Tmin = 29 °C | Tmin = 29–30 °C | RF = 270–300 mm | RF = 270–370 mm | RF = 270–375 mm | RF = 274–360 mm | RF = 300–330 mm |
| High yield (>5000 kg/ha) | | | 2025–2059 | 2025–2070 | All years | 2025–2082 | 2025–2072 | 2025–2077 | 2066–2069; 2075–2090 | 2061; 2065; 2068; 2078; 2080; 2082; 2084–2094 |
| | Tmax = 35–36 °C | Tmax = 35–36 °C | Tmin = 28–29 °C | Tmin = 28–29 °C | RF = 260–290 mm | RF = 250–280 mm | RF = 250–280 mm | RF = 250–320 mm | RF = 310–325 mm | RF = 310–410 mm |
medium to low yield category (3000–5000 kg/ha). For cv PMH 2, an increase by 2 °C in maximum and minimum temperature was observed from 35–36 to 37–39 °C and from 27–28 to 28–31 °C, respectively. Though the rainfall for low yield years (270–420 mm and 270–425 mm) was higher than that for medium yield years (270–300 and 270–280 mm) for the cv PMH1 and PMH2, respectively, it was not sufficient to mitigate the negative impact of higher temperatures. Thus, in agroclimatic zone IV, both the cultivars failed under RCP 4.5 and RCP 6.0 scenarios for the considered sowing dates due to high temperatures and deficit rainfall. Hence, the high temperature and low and variable rainfall may render maize cultivation a non-profitable venture at Bathinda.

3.2.4 Agroclimatic zone V

Abohar The cv. PMH1 gave medium yield during mid-June (3000–5000 kg/ha) under both the scenarios (Figs. 3f and 4f) where the variation in maximum, minimum temperatures, and rainfall were observed between 35–36 °C, 28–29 °C, and 220–230 mm, respectively. This medium yield of maize was observed for very few years, i.e., 7 years (2025–2032) under RCP 4.5 and for 22 years (2025–2047) under RCP 6.0 scenario (Table 6). The end May, early June, and end June sown crop depicted poor crop performance under both the scenarios with low yield (< 3000 kg/ha) during all 70 years (2025–2095). During the simulated low yield years as depicted in Table 7, the maximum, minimum temperatures, and rainfall varied between 35–38 °C, 28–30 °C, and 220–340 mm, respectively. For cv PMH1, very few years gave medium yield, and all the sowing dates under both the scenarios yielded lesser than 3000 kg/ha in agroclimatic zone V (Abohar).

The cv. PMH2 in agroclimatic zone V gave medium yield (3000–4000 kg/ha) during end-June under RCP 4.5 and 6.0 scenarios (Figs. 5f and 6f) where the maximum and minimum temperatures were 35 °C and 28 °C, respectively, with rainfall ranging between 225 and 270 mm. This medium yield was observed for very few years, i.e., 5 years (2025–2030) under RCP 4.5 and 19 years (2030–2049) under RCP 6.0 (Table 7). For mid-June sowing under RCP 6.0, the simulated yield was medium for only 2 years (2025–2027). The end May, early June, and mid-June sown crop simulated low maize yield (< 3000 kg/ha) for all 70 years (2025–2095) under RCP 4.5 and RCP 6.0. The temperature and rainfall data in Table 7 revealed that low maize yield was simulated when maximum and minimum temperature varied between 35–38 and 28–30 °C, respectively, with rainfall ranging between 220 and 340 mm. For cv PMH2, medium yield (4000–5000 kg/ha) was simulated for very few years under both the scenarios in agroclimatic zone V (Abohar).

Hence, cv PMH1 observed a 2 °C in maximum temperature (from 35–36 to 37–38 °C) and 1 °C increase in minimum temperature (from 28–29 to 29–30 °C) which resulted in lowering of maize yield from medium to low yield category (3000–5000 to < 3000 kg/ha). The cv PMH2 observed this 2 °C increase from 35 °C to 36–38 °C and from 28 to 29–30 °C in maximum and minimum temperature, respectively. Though the rainfall variations in the region showed that the low maize yield years experienced higher rainfall (220–340 mm for both cultivars) than the medium yield years (220–230 and 225–270 mm for cv PMH1 and PMH2, respectively), the amount was not sufficient to mitigate the high temperature impact. Thus, the poor performance of maize cultivars in agroclimatic zone V (Abohar) under both the scenarios could be attributed to high temperatures and deficit rainfall and so would not be a suitable maize growing location in the state.

Faridkot The cv. PMH1 gave high yield during early and mid-June (> 5000 kg/ha) under RCP 4.5 and RCP 6.0 (Figs. 3g and 4g) where the maximum and minimum temperature varied between 34–36 °C and 27–29 °C, respectively, with rainfall ranging between 250 and 356 mm. This higher yield of maize was observed for 70 years (2025–2095) under RCP 4.5 for early and mid-June, while it was for 58 years (2025–2083) and 65 years (2025–2090), respectively, for early and mid-June under RCP 6.0 scenario (Table 8). If the sowing of cv PMH1 was simulated during end May, then high yield of maize was observed during fewer years, and the yield varied between medium (3000–5000 kg/ha) and high. Maize yield simulated for end-June was medium for all 70 years (2025–2095) with variations in maximum, minimum temperature, and rainfall between 34–36 °C, 27–29 °C, and 306–406 mm. The temperature and rainfall conditions in Table 8 depicted that medium yield of maize was simulated during the years when maximum and minimum temperature varied between 34–37 °C and 27–30 °C, respectively, with rainfall ranging between 270 and 406 mm. For cv PMH1, the simulated yield years varied between medium and high under both the scenarios in agroclimatic zone V (Faridkot).

The cv. PMH2 in agroclimatic zone V (Faridkot) gave high yield (> 5000 kg/ha) during early June under both the scenarios (Figs. 5g and 6g) where the maximum and minimum temperature varied between 35–36 °C and 28–29 °C, respectively, with rainfall ranging between 250 and 290 mm. This higher yield was observed for 70 years (2025–2095) and 57 years (2025–2082) under RCP 4.5 and RCP 6.0, respectively (Table 8). For early May, mid, and end June, the simulated maize yield was invariable between medium (3000–5000 kg/ha) and high (> 5000 kg/ha) under both the scenarios. The critical evaluation in Table 8 revealed that medium maize yield was simulated during the years
when maximum and minimum temperature varied between 34–37 °C and 27–30 °C, respectively, with rainfall ranging between 270 and 370 mm. For cv PMH2, the simulated yield years varied between medium and high under both the scenarios in agroclimatic zone V (Faridkot).

The cv PMH1 observed a 1 °C increase in maximum (from 34–36 to 34–37 °C) and minimum (from 27–29 to 27–30 °C) which resulted in lowering of maize yield from high to medium yield category (> 5000 to 3000–5000 kg/ha). The cv PMH2 observed this 1 °C increase in maximum and minimum temperature from 35–36 to 36–37 °C and from 27–29 to 28–30 °C. Thus, the performance of maize cultivars varied between medium and high yield years in agroclimatic zone V (Faridkot) under both the scenarios. The region was found suitable for sowing of PMH1 during early and mid-June, while early June sowing was more appropriate for PMH2 cultivar.

4 Discussions

4.1 Maize yield and projected climate conditions

The projected climate change scenarios raise concern to crop production all over the world. The IPCC projects an increase in the mean annual precipitation in the tropical and high northern latitudes and a decrease in the subtrigos, with an overall increase in temperature. Such fluctuations in rainfall and rise in temperature would adversely impact the evaporation and transpiration processes in plants which contribute to crop growth. The relationship between the yield and weather parameters simulated for different agroclimatic zones of Punjab showed an increase in temperature and high variability in rainfall during the maize crop season. The overall correlation of yield and weather parameters under both the scenarios (RCP 4.5 and 6.0) showed a steep decline in maize yield with temperature. In case of rainfall, large gaps were observed due to its high variability at different locations. The weather induced changes in growth and yield of crop can be better studied using crop simulation models. Kogo et al. (2019) reviewed various climate change impact studies and reported the CERES-Maize and APSIM models to be the dominant amongst the crop simulation models to project yield variations more accurately. These studies used projected data from multi-model ensembles for accurate predictions. Thus, the corrected ensemble model data under RCP 4.5 and RCP 6.0 was used as an input in CERES-Maize model to assess the maize yield in different agroclimatic zones of Punjab. In the present study, the rise in temperature and high rainfall variability within the different agroclimatic zones of Punjab may be the major reason for yield deviations under the two projected scenarios. The two stabilization scenarios (RCP 4.5 and RCP 6.0) observed a 1 °C increase in maximum and minimum temperature at agroclimatic zone II, agroclimatic zone III, and agroclimatic zone V (Faridkot) and an increase of 2 °C in agroclimatic zone IV and agroclimatic zone V (Abhor). The rainfall showed extremely large variation ranging between 200 and 800 mm during the maize crop season. Kogo et al. (2019) reported that the world maize yield would observe a decline by 8–38% under RCP 4.5 by the end of the twenty-first century. Future climate impact assessment on maize yield and food security in Malawi showed an increase in temperatures during the 2020s, 2050s, and 2080s by 0.7 to 0.8 °C, 1.6 to 2.3 °C, and 2.1 to 3.3 °C, respectively, and highly variable rainfall pattern which would lead to an increase or decrease of maize yield in the range 4.6 to 5.4%, –1.2 to 1.0%, and –3.0 to 0.2% for the respective time periods (Stevens and Madani 2016).

4.2 Additional factors influencing the yield

Kang et al. (2009) reported from a review of various studies that rising temperatures and fluctuating rainfall would reduce the water availability and crop production. In Punjab, maize cultivation is currently done under irrigated conditions, and so under future scenarios, an increase in the number of irrigations might help in reducing the high temperature effect. But under Punjab conditions, Sidhu et al. (2020) reported a continuous decline in the water table and found it to be higher in the central zone which is known as the “food bowl” of the country. So, the reducing water resources in the state may not render this additional irrigation a suitable adaptation measure. In a study conducted by Prabhjyot-Kaur et al. (2020) for the Sirhind canal tract of Punjab, which considered two conditions (a) first that the number of tube wells would remain the same till the end century as in 2018 and (b) second that they would increase till 2050. The results showed that the water table would fall under RCP 4.5 and RCP 6.0, respectively, by 5.7 m and 4.3 m for (a) and by 45 m and 57.5 m (b) till the end century. In an irrigated state like Punjab, two additional factors influence the yield, first being the rainfall amount and second being the soil. With the depleting water resources under future scenarios alone, alteration in irrigation application will not be a suitable adaptation strategy until combined with rainfall amount. Kijne et al. (2003) reported that an increase in amount of irrigation application would reduce the crop water productivity and increasing it remains a bigger challenge for the farmers. The soil properties vary from location to location, and under current soil conditions of Punjab, an increase/decrease in maize yield was observed under the future projections, but these properties may not remain the same in years to come. Popova and Kercheva (2005) reported that the soils with high water holding capacity would perform well under reduced availability of water because it will reduce the
drought frequencies and improve the crop yields. A poor soil water balance would lead to increased mean annual runoff so even with increased rainfall, an increase in irrigations would lead to additional runoff only (Holden and Brereton 2006). A climate change study in the Shandong province of Huanghualai under current soil conditions showed better yield of summer maize with increased fertilizer and irrigation application (Chen et al. 2012).

4.3 Role of rainfall in mitigating the impact of rising temperatures

Some studies reported the offset of temperature effect on crop growth with an increase in rainfall. In a study for Shijin irrigation district of China, maize yield decline by 10.8 kg/ha was observed with 1 °C rise in temperature and an increase by 3.3 kg/ha with 1 mm increase in rainfall under RCP 4.5 (Li et al. 2020). The study clearly indicates the compensatory effect of rainfall to avoid yield losses, but the projected variable rainfall in Punjab disturbs the physiological processes and phenological stages of the crop. Thus, it is difficult to analyze the mitigatory effect of rainfall in the different agroclimatic zones of Punjab. However, the low rainfall in Bathinda and Abohar would not be sufficient to mitigate the high temperature impact observed on the maize yield. The rainfall in the two regions was higher during the low yield years, but the temperature rise was an additional 2 °C which caused a yield decline from medium (3000–5000 kg/ha) to low (<3000 kg/ha) yield category. The temperature effects have been studied by different scientists across the world. A study by Pu et al. (2020) in northeast China indicated negative correlation of maize yields with relative humidity and temperatures but a positive correlation with precipitation, wind speed, and net solar radiation under RCP 4.5 and RCP 6.0. Under the predicted climate changes from 2015–2050, maize yield in northeast China showed an increase by 34.3% and 25.7% under RCP 4.5 and RCP 6.0, respectively. High temperatures during critical growth stages of maize crop result in yield losses such as an increase of 6 °C temperature during grain filling resulted in 10% yield losses in the US corn belt (Thomson 1966), while a 2 °C rise temperature along with 20% reduction in rainfall in sub Saharan Africa caused greater reductions in maize yields (Lobell and Burke 2010). Stone (2001) explained this to be caused due to significantly lower threshold of heat stress damage for reproductive organ than the other organs in crops. Schoper et al. (1987) studied the grain setting in maize and found it to be successful with viable pollen and its interception by receptive silks. This process is followed by the transmission of male gamete to the egg cell where the initiation and maintenance of embryo and endosperm development take place but the high temperature disturbs these processes leading to decreased number of grains, kernel weight, and number of fertilized ovules which ultimately causes yield loss (Naveenkumar et al. 2018). Various studies report that the temperature increase acts like a potential stimulator for the insect life cycles which increases by 5 times during the crop period (Petzoldt and Seaman 2005; Bale et al. 2002; Porter et al.1991) thus leading to poor yields. An annual and seasonal analysis of corrected GCM data for different districts of Punjab under SRES (Special Report on Emission Scenarios) by IPCC showed an increase in the temperature and rainfall during the kharif season. The projections indicated an increase in maximum and minimum temperature ranging 2.9–8.7 °C and 3.0–7.6 °C, respectively, at different locations, while the projected increase in rainfall was highest at Ballowal Saunkhri (1075 mm) and minimum at Bathinda (117 mm) (Kaur and Prabhjyot-Kaur 2019). However, in a later study for Punjab state by Kaur (2020) on RCP-based scenarios, though a similar increase in temperatures was reported, the rainfall was projected to decrease. Climate predictions by Dar et al. (2019) for Ludhiana district of Punjab showed an increment in the mean annual temperature by 1.56 °C during mid-century and by 3.11 °C during end-century, while the rainfall decrement was observed by 97.5 mm (12.8%) during mid-century and 89 mm (11.8%) during end-century. These temperature and rainfall impacts on maize yield trend were studied by (Kaur and Prabhjyot-Kaur 2019) under SRES scenarios, and the grain yield showed a negative linear trend for all the locations of Punjab. However, the SRES scenarios are not widely quantified as RCPs; thus, the yield predictions based on SRES can be taken as a general yield trend of maize in Punjab, while under RCPs, the quantification of yield is more accurate and specific to that particular RCP or radiative forcing.

The predicted variability in yield of major crops requires quantification on urgent basis for development of suitable varieties to combat the quantified losses. The current study under RCP 4.5 and RCP 6.0 depicted higher yield (>5000 kg/ha) years when the maize crop was sown during mid-June in agroclimatic zones II and III. However, at Faridkot lying in agroclimatic zone V, early June sown maize also performed well with higher yields (>5000 kg/ha). None of the sowing dates performed well under the two scenarios in agroclimatic zone IV and part of zone V (Abohar). Amongst the two cultivars, PMH1 performed well with comparatively larger number of high (>5000 kg/ha) yield years in agroclimatic zones II and III. In agroclimatic zone V (Faridkot), both the cultivars performed well with significant number of high yield years. Though Abohar and Faridkot lie in the same agroclimatic zone, but the difference lies in the soils of the two locations as well as the rainfall amount. Abohar lies more towards the Rajasthan state of India due to which it experiences arid type of climate and the projected rainfall is in the range of 220–340 mm which is towards lower side. However, in case of Faridkot, the projected
rainfall is in the range of 250–500 mm. So, maize yields were simulated in high yield category for all years in RCP 4.5 scenario, while for RCP 6.0 scenario, the two cultivars yielded high maize yield in 81–93% of the years. In case of zone IV, the increase in temperature is by nearly 2 °C. The suitable range of maximum/minimum temperature as seen from the analysis of simulated results is 34–36/27–29 °C, while in case of Bathinda, they are projected in the range of 36–39/27–31 °C. In the present times too, the average maximum/minimum temperature of Bathinda from June to September is 37/26 °C. Agroclimatic zone IV covers merely 19% of available geographical area of Punjab state. So, the temperature data of one location can suitably represent the whole of the zone. Such yield trends at different locations are mainly due to the temperature and rainfall variations which lead to changes in morphology, anatomy, physiology, and biochemical processes taking place in crops.

5 Limitations

Climate change studies hold many limitations as the crop growth models take ideal conditions which usually do not occur anywhere, including in India where the climate is highly variable. Also, the long-term climate effect on the soils of different regions is not considered under the future climatic projections which leads to some uncertainty in the results from the crop growth models.

6 Conclusions

The results of correlation between yield and projected weather conditions under differential sowing dates for the four agroclimatic zones of Punjab indicated a strong negative relationship. However, large gaps were observed in the rainfall pattern which is due to its high variability across the state. The temperature increase by 1 °C was observed in agroclimatic zones II (Ballowal saunkhri), III (Ludhiana, Amritsar, and Patiala), and V (Faridkot) which led to lowering of maize yield from high yield category to lower yield category. This effect was found to be more prominent in cv PMH2 where the low yield years were higher compared to cv PMH1. So cv PMH1 may be recommended for cultivation in agroclimatic zones II, III, and V (station Faridkot) of the state during the mid-June sowing period. At agroclimatic zone IV (Bathinda) and parts of V (Abohar), the yield of maize varied between medium and low category as a further increase in temperature by 2 °C was observed. Hence, due to the poor performance of maize cultivars for most of the years under RCP 4.5 and 6.0 scenarios in agroclimatic zone IV (Bathinda) and parts of V (Abohar)—which can be attributed to high temperatures and deficit rainfall—may render maize cultivation not to be a viable option for the farmers in these regions.

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Author contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Prabhjyot Kaur and Jatinder Kaur, Shivani Kothiyl, and Shivani Kothiyl. The first draft of the manuscript was written by Shivani Kothiyl, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability All data generated or analyzed during this study are included in this published article (and its supplementary information files).

Code availability The software (DSSAT) applied is available on the DSSAT site (DSSAT.net—Official Home of the DSSAT Cropping Systems Model), and after registration of the first author, the latest version (4.7.5) of the model was downloaded and employed.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing Interests The authors declare no competing interests.

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