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CLIMATE PROJECTIONS FOR PUNJAB: FUTURE TRENDS IN TEMPERATURE, SOLAR RADIATION, AND RAINFALL

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ABSTRACT

The study analyzed bias-corrected meteorological data based on the ensemble mean of four General Circulation Models (GCMs) under four Representative Concentration Pathways (RCPs): RCP2.6, RCP4.5, RCP6.0, and RCP8.5. Its objective was to assess average changes in key meteorological parameters for the mid-century (2020-2049) and end-century (2066-2095) periods on an annual basis, as well as during the kharif and rabi seasons, across four agroclimatic zones (AZ) of Punjab: AZ II (Ballowal Saunkhri), AZ III (Ludhiana, Amritsar, Patiala), AZ IV (Bathinda), and AZ V (Abohar, Faridkot). The analysis revealed increases in minimum and maximum temperatures ranging from 0.3°C to 7.5°C and 0.1°C to 4.6°C, respectively, with the most pronounced changes occurring toward the end of the century under the high-emission scenario (RCP8.5). The increase in minimum temperatures was greater than that of maximum temperatures, suggesting a reduction in the diurnal temperature range by approximately 2.5°C to 2.9°C during the mid and late 21st century. These projections indicate that Punjab's future climate may become hotter, drier, and cloudier. Such conditions are expected to increase crop water requirements and could adversely affect agricultural productivity.

Keywords: Climate change, Diurnal range, GCMs, Punjab, RCPs

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Since the evolution of earth, the climate change phenomenon has taken place at its own pace but recently the rising greenhouse gases (GHGs) in the atmosphere have added momentum to the process resulting in an effect on the temperature, precipitation, and hydrological cycles on the Earth. These changes are further projected to occur in future. The concentration of GHGs such as CO_2, CH_4, N_2O, etc. has increased in the atmosphere which has resulted in changes in the rainfall pattern, melting of glaciers, rise in sea level, and increase in the frequency of extreme events relative to crop development and length of crop growing season (Agnihotri *et al.*, 2017; Allen *et al.*, 2018). Various methods like statistical analytical tools, historical data analysis for environmental studies, and crop growth simulation models have been used to understand the holistic impact of climatic variability (Chandio *et al.*, 2023; Kaur *et al.*, 2023).

The historical and future trends of various weather parameters is currently possible with the use of data provided by the various General Circulation Models (GCMs)/Regional Circulation Models (RCMs) derived from 'Emission scenarios', developed by IPCC (IPCC, 2014). Moss *et al.* (2010) pointed out the requirement for new scenarios with more quantitative information and can explore the impact of different climate policies. Van Vuuren *et al.* (2011) discussed the process of development of a set of four new pathways which are the basis of near-term and long-term modelling experiments for the climate modelling community and are known as Representative Concentration Pathways (RCPs). The four RCPs span the radiative forcing values from 2.6 to 8.5 W/m^2 and a comprehensive data set is obtained from these pathways which have high spatial and sectoral resolutions for the period extending to 2100.

A study in the Narmada river basin area in Madhya Pradesh (Central India) used downscaled data from HadCM3 model (Hadley Center Coupled version 3) and predicted a rise in temperature, rainfall and potential evapotranspiration during the 2080s (Kundu *et al.*, 2016). Significant variations in rainfall patterns were observed at Jakarta, Indonesia for generated daily precipitation and temperature using the weather generator LARS-WG and a GCM (Daksiya *et al.*, 2017). Bal *et al.* (2016) assessed climate change in India using Providing Regional Climates for Impact Studies (PRECIS) and Regional Climate Model (RCM) and observed an increase within the range of 2.5-4.4°C in maximum temperature by the end-century, while the rainfall projections showed an

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increase ranging 15-24%. VijayaKumar *et al.* (2021) reported that the annual mean rainfall is expected to change by 0.1-2.2%, 0.3-0.7% and 1.5-3.2% (RCP 4.5), and 3.6-7.9%, 3.7-6.6% and 8.5-14% (RCP 8.5) during the near (2011-39), mid (2040-69) and late (2070-99) centuries, respectively. The annual mean minimum temperature is expected to increase by 0.60-0.73°C, 0.71-0.88°C, 1.20-1.42°C (RCP 4.5), and 1.77-2.14°C, 1.56-1.68°C, 3.06-3.73°C (RCP 8.5) during near, mid and late centuries respectively. Similarly, the annual mean maximum temperature is expected to increase by 0.61-0.66°C, 0.68-0.72°C and 1.35-1.55°C (RCP 4.5), and 1.79-1.97°C, 1.73-2.01°C and 3.08-3.44°C (RCP 8.5) during near, mid and late centuries, respectively.

Jalota *et al.* (2012) utilized the future climate data as provided by Tripathy *et al.* (2011) from the three GCMs, Hadley Center Coupled Model Version 3 (HadCM3), Australia's Commonwealth Scientific and Industrial Research Organization Mk2 (CSIRO-Mk2) and Second Version of Canadian Center for Climate Modeling and Analysis Coupled Global Climate Model (CCCMA-CGCM2) for Ludhiana, Punjab. The data were utilized for climate change prediction and its impact on the crop productivity of rice-wheat system for 2020, 2050 and 2080. Kaur and Kaur (2015) analyzed the temperature trend over four decades in different agroclimatic zones of Punjab. They observed an increasing trend in maximum temperature at Ballowal Saunkhari, Ludhiana, and Patiala and a decreasing trend at Amritsar and Bathinda while the minimum temperature indicated an increasing trend for all locations.

Punjab state is an agrarian economy and the changes in climatic variables will have a direct bearing on the growth and productivity of crops. The studies on historical climatic changes in the state have highlighted some of the changes in meteorological variables that hurt crop productivity. Also, global and national studies have predicted changes in temperature, rainfall, etc as per the predictions of GCMs. So, the present study was conducted to quantify the projected changes in climate so that plant breeders, policy planners, and administrators can take corrective and adaptive measures to sustain agricultural productivity in Punjab state.

MATERIALS AND METHODS

Study area

The study area was the Punjab state of India which occupies 1.5 per cent of the geographical area with a latitudinal extent of 29° 33' N to 32° 34' N and longitudinal extent of 73° 53' to 76° 56' E. The state has been divided into six agroclimatic zones based on the climate, soil and crops. These zones are zone I (Sub-Mountain Undulating Region), zone II (Undulating Plain Region), zone III (Central Irrigated Plain), zone IV (Western Plain Region), zone V (Western Region) and zone VI (Flood Plain Region (*Bet*)). The climate of the region is largely sub-tropical, semi-arid and monsoon type and the annual average maximum and minimum temperature ranges between 29 to 32°C and 15 to 20°C, respectively. The mean maximum and minimum temperature is 25°C and 8°C, respectively during *rabi* season, while 38°C and 23°C during *kharif* season, respectively. During the summer months of May and June the temperature reaches upto 44°C, while the winter months experience a temperature low upto 1°C during December and January. The mean annual rainfall within the state ranges from 400 to 1300 mm and more than 75 to 80 per cent of this rainfall is received during monsoon season (June through September). The rest 20 to 25 percent of rainfall is received during the remaining eight months under the influence of western disturbances (Kaur *et al.*, 2021).

Downscaling of the future meteorological data

Under the umbrella of *gisweb.ciat.cgiar.org/MarkSimGCM/* (Fig. 1), seventeen models are available. Out of these models, the ensemble mean of four GCMs (CSIRO-Mk 3.6.0, FIO-ESM, IPSL-CM5A-M, GISS-E2) was downscaled and used in the present study because an earlier study by Kaur *et al*. (2020) highlighted the more accurate predictive capabilities of these four models for Punjab (Table 1). The remaining thirteen models were not selected for the study under Punjab conditions due to their inherent limitation observed by Kaur *et al*. (2020). These models predict the meteorological data (maximum/minimum temperature, rainfall, and solar radiation) from 2010 to 2095 for four Representative Concentration Pathways (RCP) emission scenarios, i.e., RCP 2.6, RCP 4.5, RCP 6.0,and RCP 8.5.

Baseline for the analysis of the meteorological data

The actual historical meteorological data (as per availability of data) for seven locations in Punjab, i.e., Ballowal Saunkhri, Ludhiana, Amritsar, Patiala, Bathinda, Abohar and Faridkot for the past 8 years on temperature, solar radiation and rainfall recorded at the agro meteorological observatory was used for the calibration (2010-2015) and validation (2016-

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Table 1. Description of general circulation models

Sr. No.	Model name	Institutions	Resolution (degree)
1.	CSIRO-Mk 3.6.0	Commonwealth Scientific and Industrial Research Organization and the Queensland Climate Change Center of Excellence	1.875 x 1.875
2.	FIO-ESM	The First Institute of Oceanography, SOA, China	2.812 x 2.812
3.	GISS-E2-R	NASA Goddard Institute for Space Studies	2.0 x 2.5
4.	IPSL-CM5A-MR	Institute Pierre-Simon Laplace	1.2587 x 2.5

Table 2. Description of Representative Concentration Pathways (RCPs)

RCP	Description	Developed by
RCP 2.6	Its radiative forcing level first reaches a value around 3.1 W/m^2 during mid-century, returning to 2.6 W/m^2 by 2100. Under this scenario GHG emissions and emissions of air pollutants are diminished considerably over time.	IMAGE modelling team of the Netherlands Environmental Assessment Agency
RCP 4.5	It is a stabilization scenario where total radiative forcing is stabilized before 2100 by employing a range of technologies and strategies for reducing GHG emissions	Mini CAM modelling team at the Pacific Northwest NationalLaborator"s Joint Global Change Research Institute
RCP 6.0	It is a stabilization scenario where total radiative forcing is stabilized after 2100 without overshoot by employing a range of technologies and strategies for reducing GHG emissions	AIM modelling team at the National Institute for Environmental Studies, Japan
RCP 8.5	It is characterized by increasing GHG emissions over time representative of scenarios in the literature leading to high GHG concentrationlevels	MESSAGE modelling team and the IIASA Integrated Assessment Framework at the International Institute for Applied Systems Analysis (IIASA), Austria

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Table 3. Bias removal was done by Difference Method at following time scale

Parameters	Time-scale
Maximum temperature	Monthly scale
Rainfall	Monthly scale
Solar radiation	Daily scale
Minimum temperature	Not required

2017) of the baseline projected data by developing suitable correction factors (Kaur, 2020).

Bias removal of the simulated meteorological data

The bias removal of the simulated data (Table 3) was done using a Difference method (Eq 1) as suggested by Kaur (2020) and as given below:

$$X_{modelcorr} = X_{modeluncorr} - (X_{model} - X_{obs}) \quad \text{(Eq 1)}$$

where:

$X_{modeluncorr}$ = Daily modeled average of 6 years

$X_{modelcorr}$ = Daily corrected modelled average of 6 years

X_{model} = Daily modeled value

X_{obs} = Daily observed value

The bias removal of temperature and rainfall data was done on monthly and solar radiation on daily time scales. The analysis of the projected data (maximum and minimum temperature, rainfall, and solar radiation) in the mid (2020-2049) and end (2066-2095) of the 21st century under four RCPs (RCP 2.6, 4.5, 6.0, and 8.5) was compared with the baseline data of the seven locations of Punjab for ensemble mean.

Comparison of the projected data with historical data for the 21st century

The bias-corrected projected data (temperature, rainfall, and solar radiation) was compiled. The means of data were analyzed on an annual (1 January to 31 December), *kharif* (1 May to 30 October), and *rabi* (1 November to 30 April) season basis. These means of the projected data were then compared with corresponding means of historical

Table 4. Baseline data for different Agroclimatic zones of Punjab

Parameter/ Season	Locations						
	Agroclimatic zone II	Agroclimatic zone III			Agroclimatic zone IV	Agroclimatic zone V	
	Ballowal Saunkhri	Ludhiana	Amritsar	Patiala	Bathinda	Abohar	Faridkot
	(1984-2015)	(1970-2015)			(1977-2015)	(2000-2015)	
				Maximum temperature (°C)			
Annual	30.0	29.8	30.3	30.2	31.3	30.2	29.9
Kharif	34.4	34.9	35.6	35.0	36.7	35.7	35.1
Rabi	25.6	24.6	24.9	25.4	25.4	24.6	24.5
				Minimum temperature (°C)			
Annual	16.2	16.7	15.5	17.6	16.9	17.6	20.3
Kharif	22.4	23.3	22.5	23.9	23.9	24.0	26.7
Rabi	10.0	10.0	8.4	11.1	9.9	11.0	9.9
				Rainfall (mm)			
Annual	1049	759	722	774	517	323	468
Kharif	888	634	579	649	427	262	382
Rabi	159	126	144	125	90	68	87
				Solar radiation (Wm^{-2})			
Annual	16.2	16.2	16.2	16.2	16.2	16.2	16.2
Kharif	18.6	18.6	18.6	18.6	18.6	18.6	18.6
Rabi	13.9	13.9	13.9	13.9	13.9	13.9	13.9



Fig. 1. MarkSim DSSAT weather generator Snapshot

data for different locations in Punjab state. The actual data used (as per availability of data) for comparison for Ludhiana, Amritsar, and Patiala was from 1970-2015, for Ballowal Saunkhri was from 1984-2015, for Bathinda was from 1977-2015, for Faridkot was from 2000-2015 and for Abohar was from 2004-2015. The historical data for these locations is given in Table 4.

RESULTS AND DISCUSSION

Agroclimatic zone II (Ballowal Saunkhri)

At Ballowal Saunkhri, the maximum temperature (Fig. 2a and b) is projected to rise under the future scenarios from the baseline by 0.8-1.1, 0.8-1.1 and 0.6-1.0°C, respectively during mid century and by 0.9-3.3, 1.0-3.2 and 0.7-3.4°C, respectively during end century on annual, *kharif* and *rabi* season basis. However, the minimum temperature (Fig. 2c and d) would rise from baseline by 2.3-2.8, 3.8-4.4 and 0.5-1.1°C, respectively during mid-century and by 2.4-5.8, 4.0-7.1 and 0.6-4.4°C, respectively during end-century on annual, *kharif* and *rabi* season. The rainfall is projected to decrease by 545-578, 439-531 and 101-108 mm, respectively during mid-century and 505-561, 402-446 and 97-113 mm, respectively, during end-century (Fig. 2e and f) on annual, *kharif* and *rabi* season basis under the four scenarios. The solar radiation on annual, *kharif* and *rabi* season basis is projected to decrease by 0.8-0.9, 0.4-0.6 and 1.4-1.5 Wm^{-2}, respectively during mid-century and 0.7-0.8, 0.3-0.4 and 1.2-1.4 Wm^{-2}, respectively during end-century (Fig. 2g and h) under the four scenarios. The maximum and minimum temperature (Fig. 2b and d) under RCP8.5 observed a high increment during the end-century in *rabi* and *kharif* season, respectively, while the rainfall (Fig. 2f) showed minimum deviation in *rabi* season during mid and end-century under all the scenarios. The solar radiation (Fig. 2h) was observed to show a high decrease during all the seasons and both the centuries.

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Agroclimatic zone III (Ludhiana, Amritsar and Patiala)

Under zone III, the Ludhiana station indicated an increase in the maximum temperature (Fig. 3a and b) from the baseline by 0.5-0.9, 0.4-0.7 and 0.4-1.0°C during mid-century and by 0.6-3.7, 0.6-3.4 and 0.5- 4.0°C during end-century for annual, *kharif* and *rabi* season, respectively under the four RCP scenarios. The minimum temperature (Fig. 3c and d) also indicated an increase from baseline by 1.8-2.4, 3.0-3.5 and 0.5-1.1°C during mid-century and by 1.9-5.4, 3.1-6.2 and 0.7-4.5°C during end-century for annual, *kharif* and *rabi* season, respectively under the corresponding RCPs. The rainfall and the sunshine hours showed a decrease from baseline for both the centuries under all the scenarios and for the three seasons. This decrement for the rainfall (Fig. 3e and f) was by 163-201, 103-131 and 61-72 mm during mid-century and by 82-187, 39-131, 44-58 mm during end-century for the three seasons, respectively, under the four RCPs while for solar radiation (Fig. 3g and h) this decrease was found to be by 0.9-1.0, 0.5-0.6 and 1.4-1.5 Wm^{-2} during mid and by 0.8-1.0, 0.4-0.8 and 1.3-1.4 Wm^{-2} during end century for annual, *kharif* and *rabi* season, respectively under the four scenarios. At Ludhiana too the maximum and minimum temperature (Fig. 3b and d) observed similar results with high deviation in *rabi* and *kharif* season, respectively during the end-century under RCP8.5. The rainfall variability (Fig. 3f) was high with maximum variation observed under RCP6.0 during all the seasons and centuries and the solar radiation was observed to decrease in all the seasons and under all the RCPs during both the centuries with minimum decrease in *kharif* season during the end-century (Fig. 3h).

The maximum temperature (Fig. 4a and b) at Amritsar represented a similar increase from baseline by 0.3-0.8, 0.4-0.8 and 0.2-0.7°C during mid-century and by 0.4-3.7, 0.5-3.5 and 0.3-3.8°C during end-century from baseline, respectively on annual, *kharif* and *rabi* season basis under the RCPs. Under the four RCPs, the projected increase in minimum temperature (Fig. 4c and d) from baseline was by 2.1-2.7, 3.1-3.7 and 1.1-1.6°C during mid and by 2.3-5.7, 3.2-6.4 and 1.2-4.9°C during end-century for the above three seasons, respectively under RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 scenarios. The projections for the rainfall and solar radiation indicated a decrease from baseline, for both mid and end-century on annual, *kharif* and *rabi* season basis under all four scenarios except RCP6.0 where a slight increase (17mm) was seen during the end-century for *kharif* season. The decrease in rainfall (Fig. 4e and f) for mid-century was by 61-109, 8-46 and 53-75 mm and for end-century by 82-187, 39-131, 44-58 mm on annual, *kharif* and *rabi* season basis, respectively for the four scenarios. A similar decrease in solar radiation (Fig. 4g and h) was projected for mid-century by 1.3-1.4, 1.0-1.1 and 1.7-1.9 Wm^{-2} and end-century by 1.1-1.2, 0.9-1.0 and 1.7-1.8 Wm^{-2}, respectively for the three seasons and four RCPs. The maximum temperature (Fig. 4b) observed a high deviation in the annual and *rabi* seasons while minimum temperature (Fig. 4d) in the annual and *kharif* season under RCP8.5 during end-century. The rainfall (Fig. 4f) observed high deviation at the zone under RCP6.0 for all the seasons and both the centuries and under RCP8.5 in *kharif* season during end-century. The solar radiation (Fig. 4h) indicated a decrease in all the seasons and under all the four RCPs during both mid and end-century.

The projected change for the Patiala region from baseline indicated an increase in both maximum and minimum temperature while a decrease in rainfall and solar radiation for end and mid-century under the four RCPs on annual, *kharif* and *rabi* season basis. The rise in maximum temperature (Fig. 5a and b) from the baseline for the mid-century was by 0.8-1.2, 0.8-1.1 and 0.4-1.0°C and for the end-century by 0.9-4.0, 1.0-3.7 and 0.7-4.2°C, respectively on the three season basis while the rise in minimum temperature (Fig. 5c and d) from baseline ranged 1.4-1.9, 2.3-2.9 and 0.3-0.9°C and 1.5-4.9, 2.4-5.5 and 0.4-4.3°C for the respective centuries and seasons under the RCPs. The rainfall (Fig. 5e and f) decrement during mid-century from baseline ranged between 188-238, 134-170 and 55-68 mm and for end-century between 114-214, 71-158, 43-61 mm on annual, *kharif* and *rabi* season basis. The solar radiation (Fig. 5g and h) on the three-season basis showed a decrease from baseline by 1.0-1.2, 0.8-1.1 and 0.0-1.5 Wm^{-2}, respectively during mid-century and a decrease by 1.0-1.1, 0.8-1.0 and 1.2-1.4 Wm^{-2}, respectively during end-century under the four scenarios. The error bars in Fig. 3, 4 and 5 represent standard error for the four meteorological parameters. At Patiala, under RCP 8.5 significant deviations in annual and *rabi* season were observed for maximum temperature (Fig. 5b) during the end-century while minimum temperature (Fig. 5d) observed these significant deviations under the corresponding scenario during *kharif* season. The rainfall (Fig. 5f) observed significant deviations

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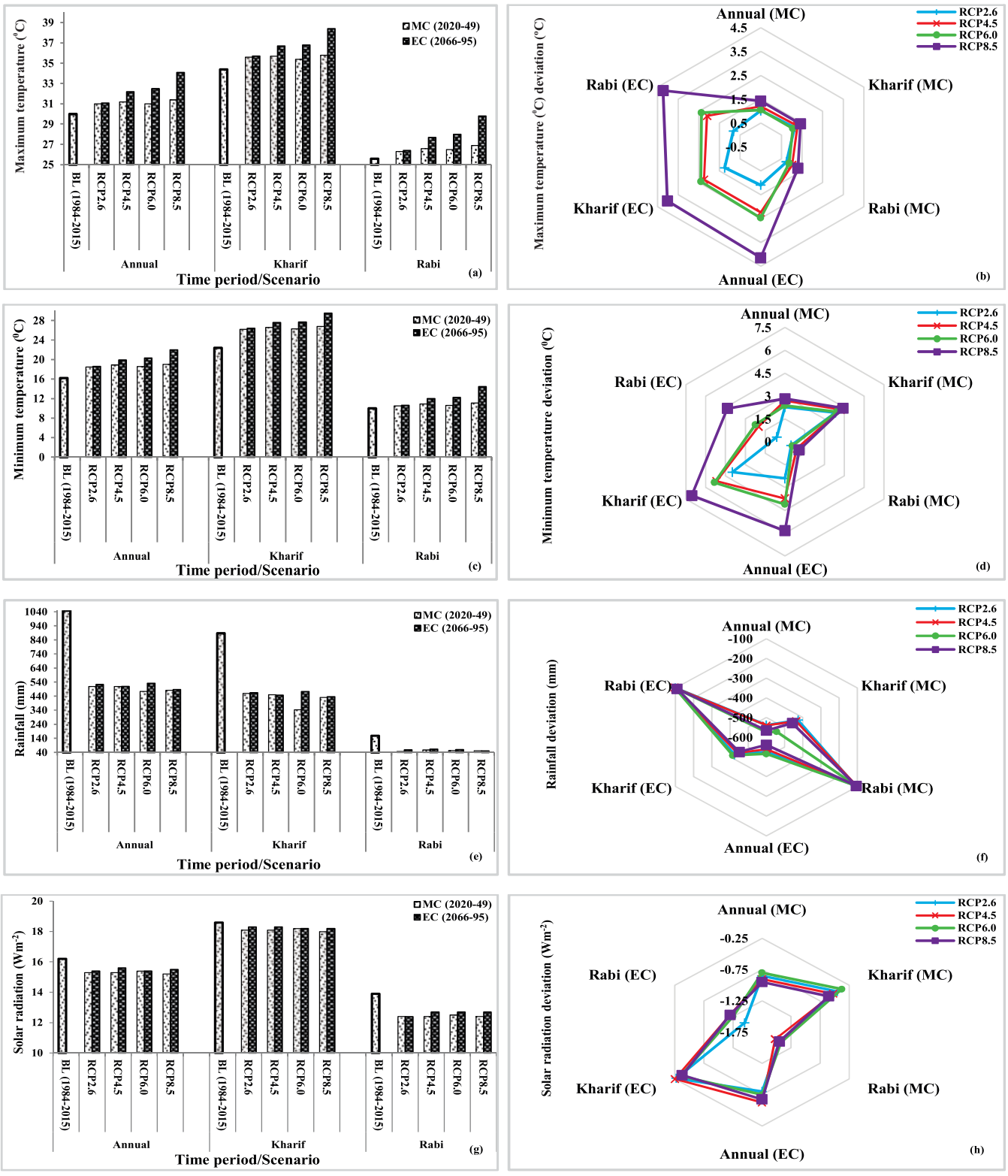


Fig. 2. Projected changes and deviation in (a and b) maximum temperature (°C), (c and d) minimum temperature (°C), (e and f) rainfall (mm) and (g and h) solar radiation (Wm^{-2}) under different scenarios simulated by ensemble mean of five General Circulation Models at Ballowal Saunkhri (Agroclimatic zone II). #(BL: Baseline, EC: End-century, MC: Mid-century, RCP: Representative Concentration Pathway)

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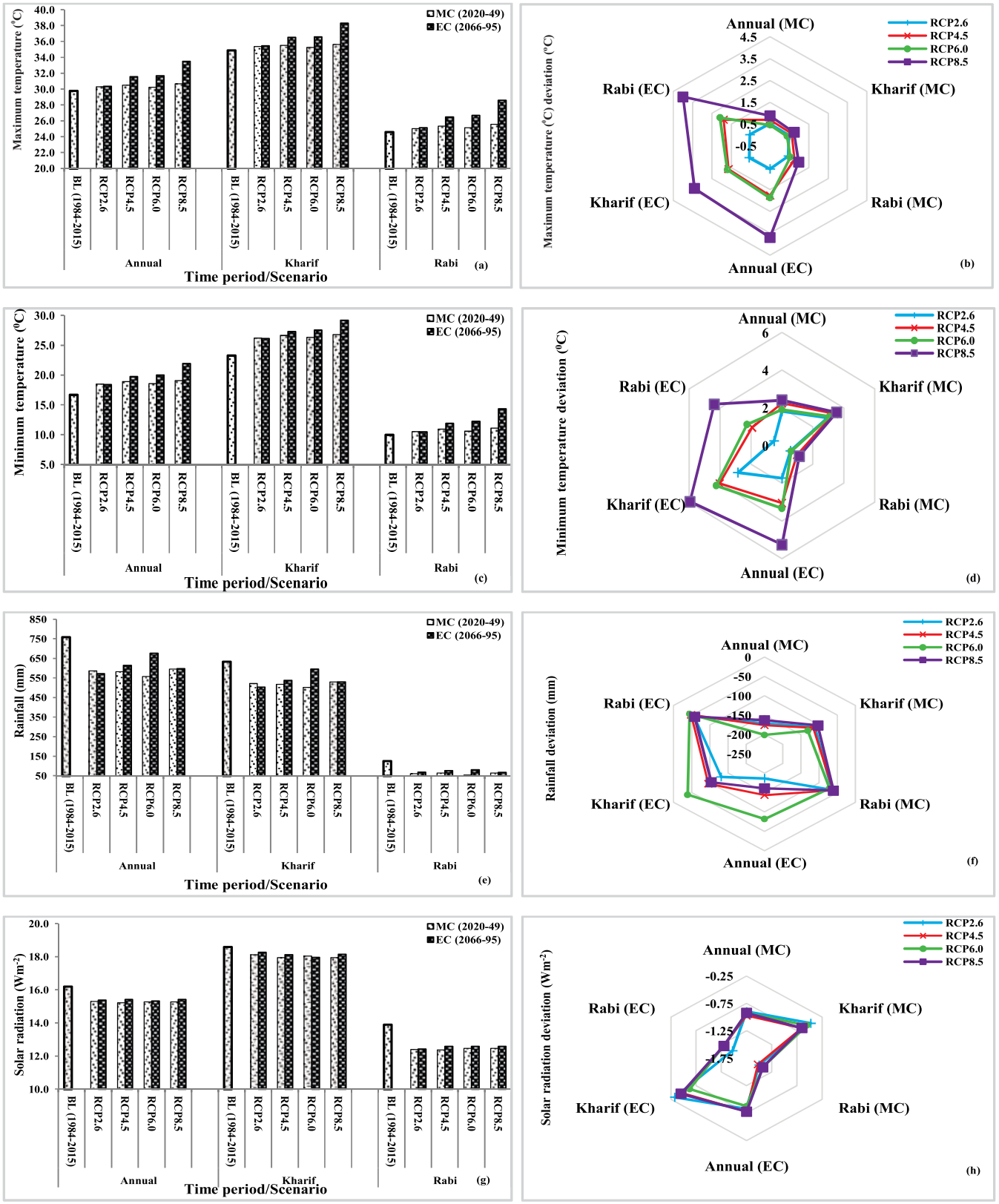


Fig. 3. Projected changes and deviation in (a and b) maximum temperature (°C), (c and d) minimum temperature (°C), (e and f) rainfall (mm) and (g and h) solar radiation (Wm^{-2}) under different scenarios simulated by ensemble mean of five General Circulation Models at Ludhiana (Agroclimatic zone III). #(BL: Baseline, EC: End-century, MC: Mid-century, RCP: Representative Concentration Pathway)

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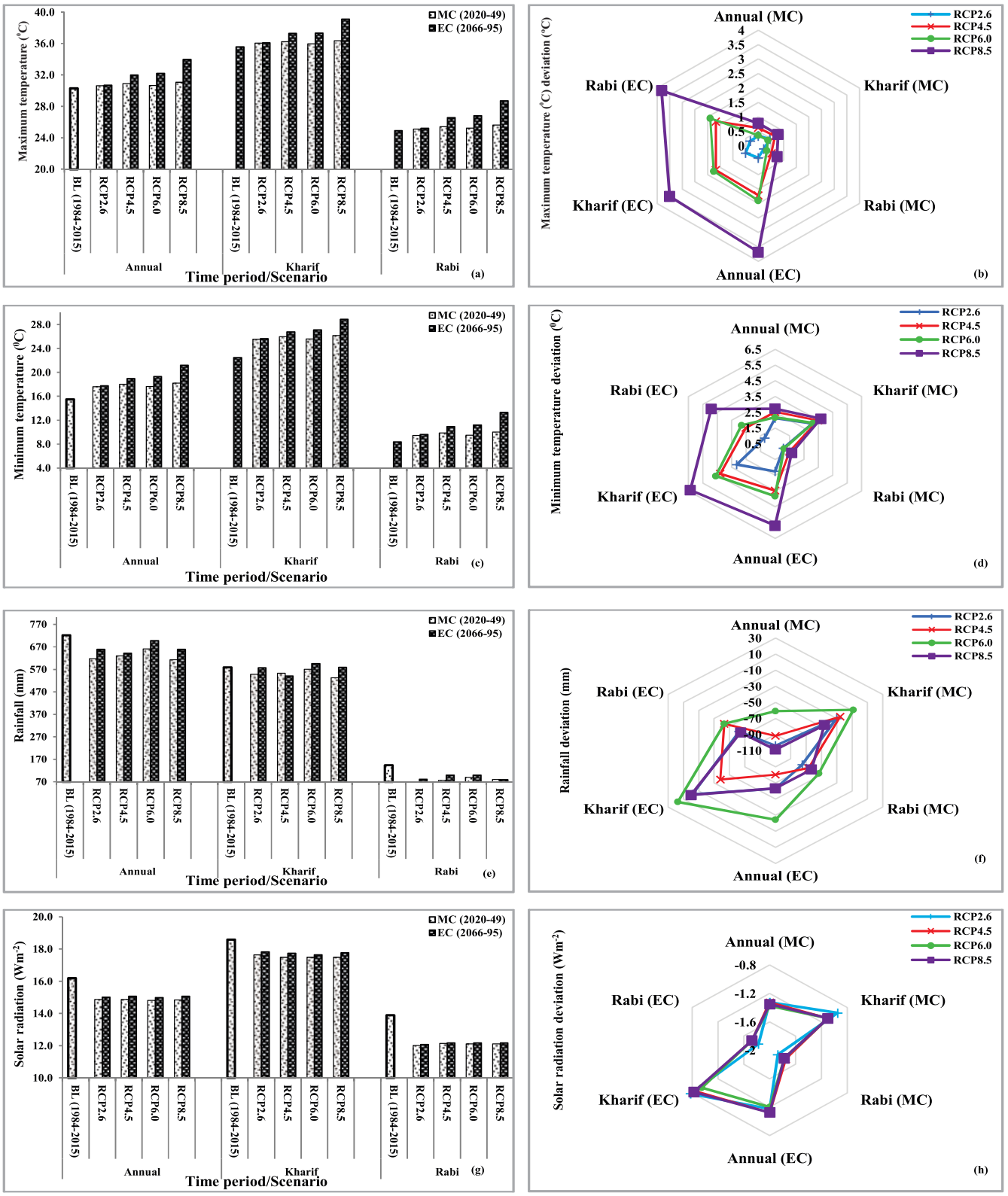


Fig. 4. Projected changes and deviation in (a and b) maximum temperature (°C), (c and d) minimum temperature (°C), (e and f) rainfall (mm) and (g and h) solar radiation (Wm^{-2}) under different scenarios simulated by ensemble mean of five General Circulation Models at Amritsar (Agroclimatic zone III). #(BL: Baseline, EC: End-century, MC: Mid-century, RCP: Representative Concentration Pathway)

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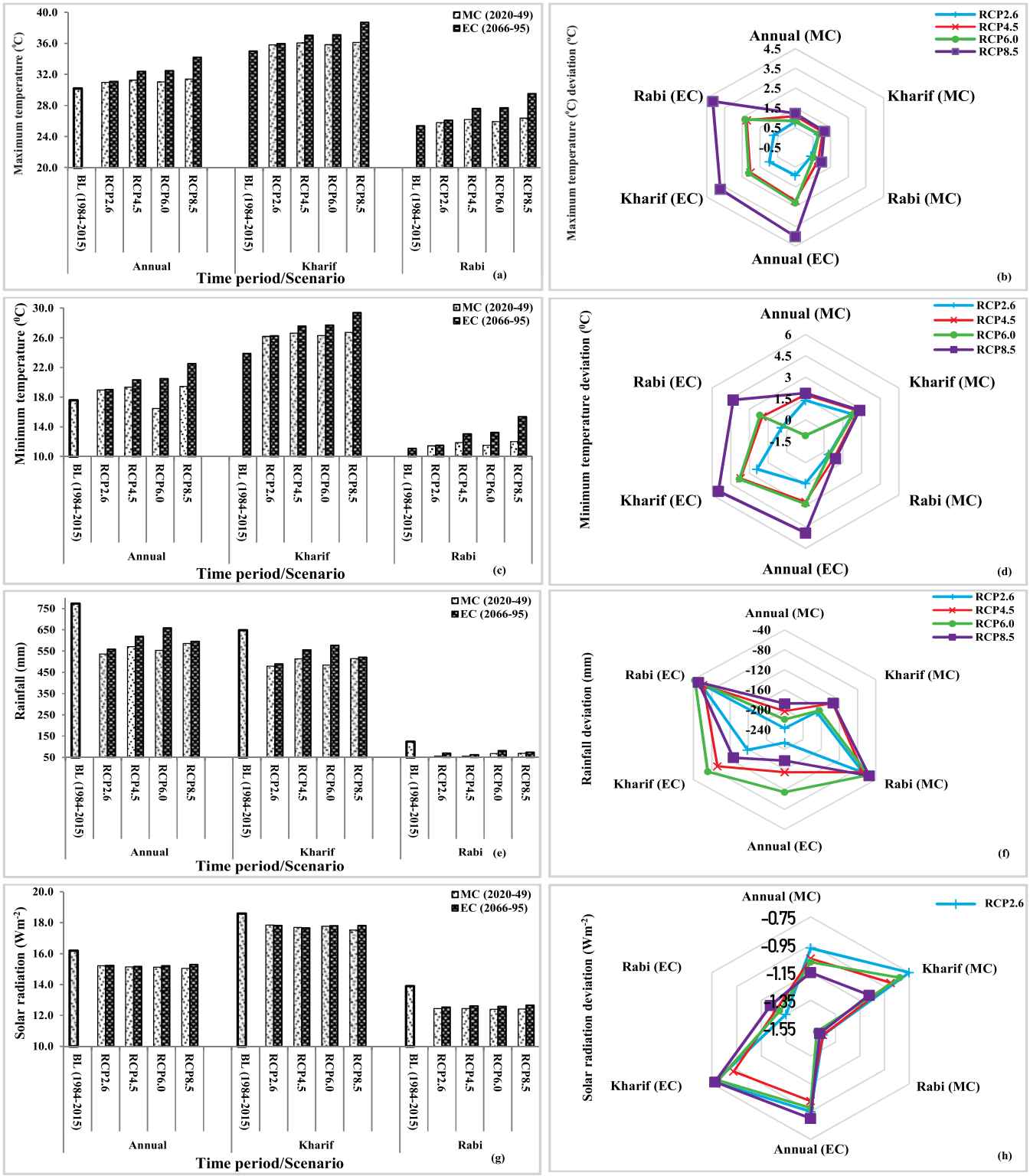


Fig. 5. Projected changes and deviation in (a and b) maximum temperature (°C), (c and d) minimum temperature (°C), (e and f) rainfall (mm) and (g and h) solar radiation (Wm^{-2}) under different scenarios simulated by ensemble mean of five General Circulation Modelsat Patiala (Agroclimatic zone III). #(BL: Baseline, EC: End-century, MC: Mid-century, RCP: Representative Concentration Pathway)

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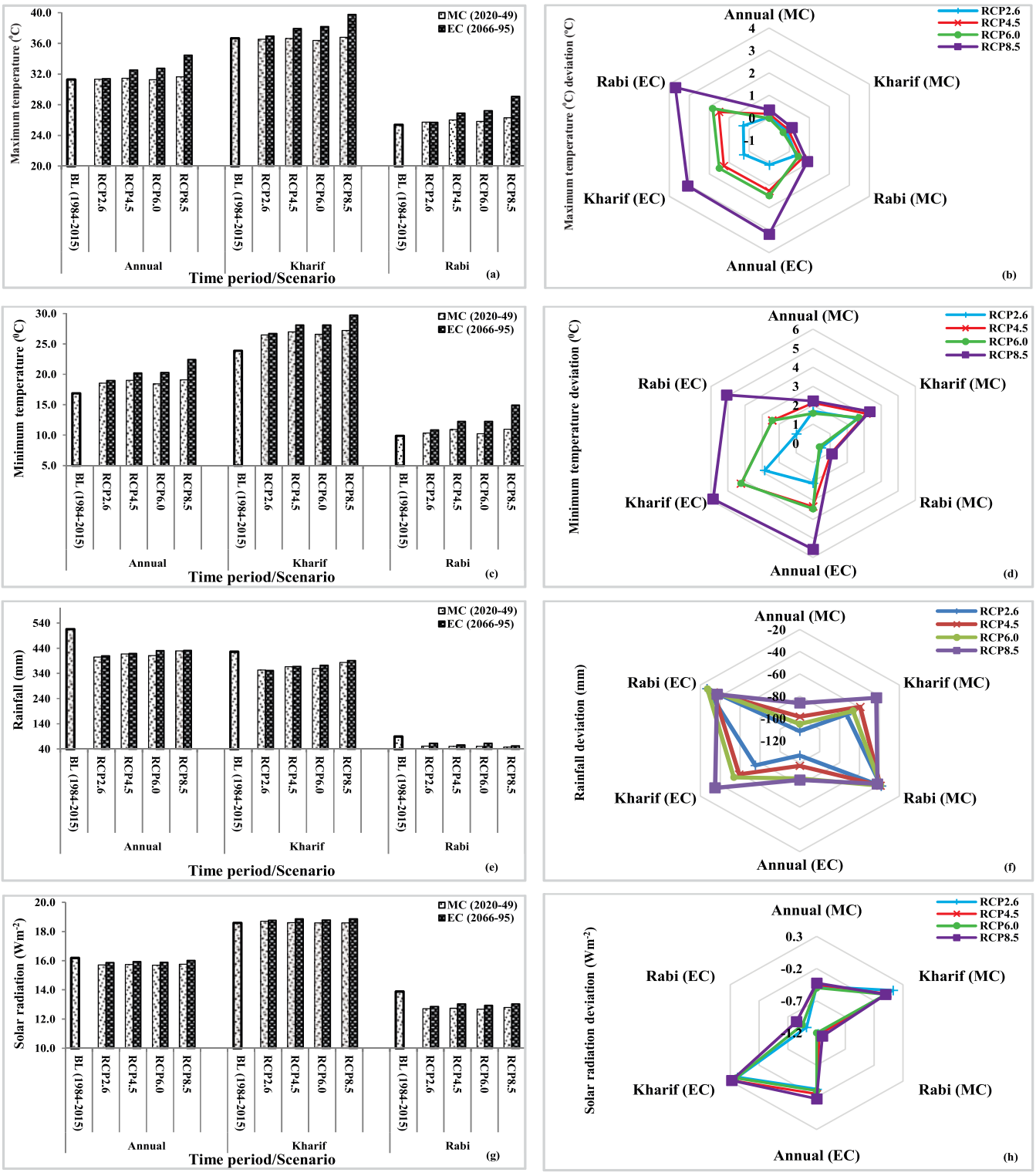


Fig. 6. Projected changes and deviation in (a and b) maximum temperature (°C), (c and d) minimum temperature (°C), (e and f) rainfall (mm) and (g and h) solar radiation (Wm^{-2}) under different scenarios simulated by ensemble mean of five General Circulation Models at Bathinda (Agroclimatic zone IV). #(BL: Baseline, EC: End-century, MC: Mid-century, RCP: Representative Concentration Pathway)

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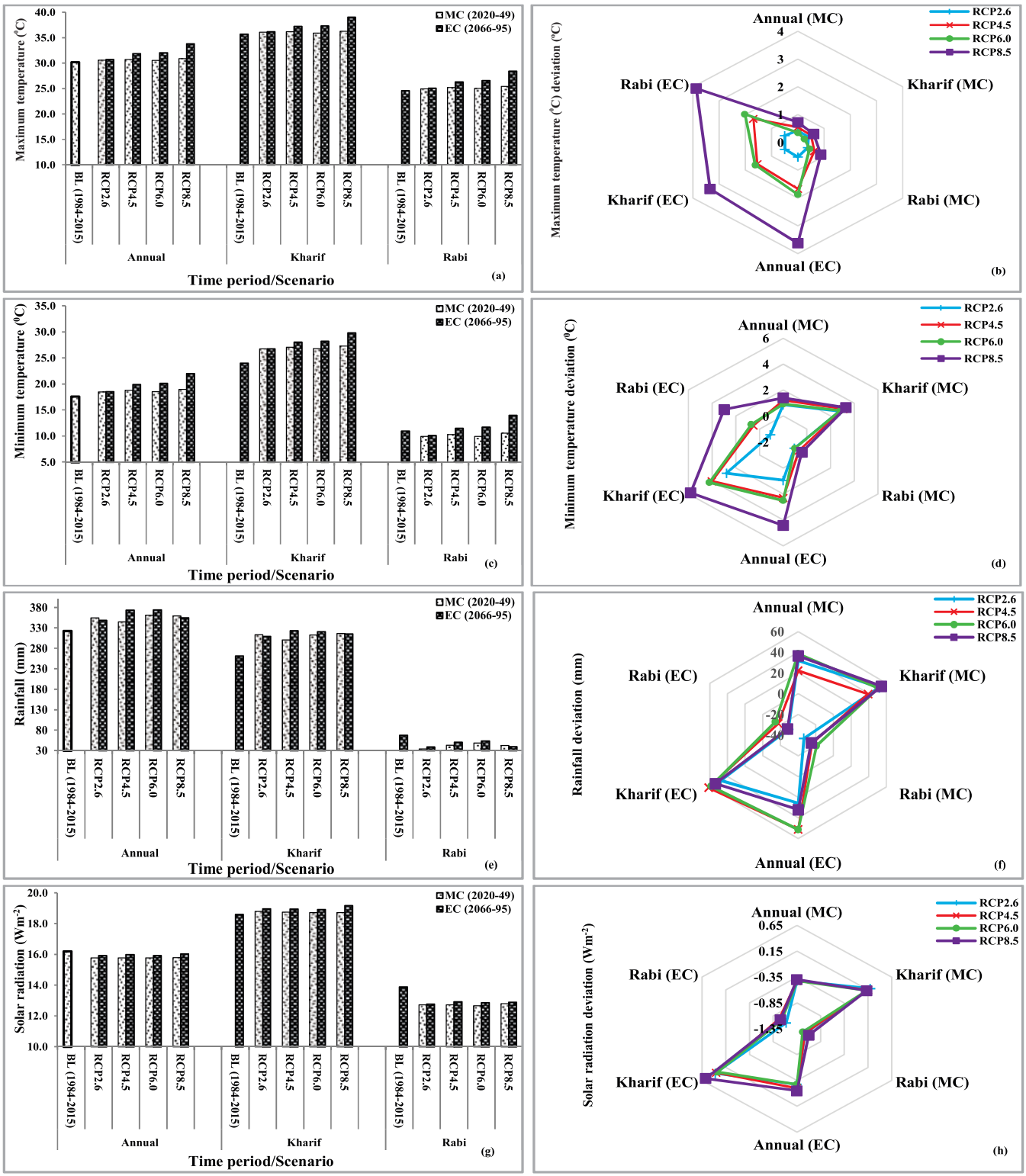


Fig. 7. Projected changes and deviation in (a and b) maximum temperature (oC), (c and d) minimum temperature (oC), (e and f) rainfall (mm) and (g and h) solar radiation (Wm-2) under different scenarios simulated by ensemble mean of five General Circulation Modelsat Abohar (Agroclimatic zone V). #(BL: Baseline, EC: End-century, MC: Mid-century, RCP: Representative Concentration Pathway)

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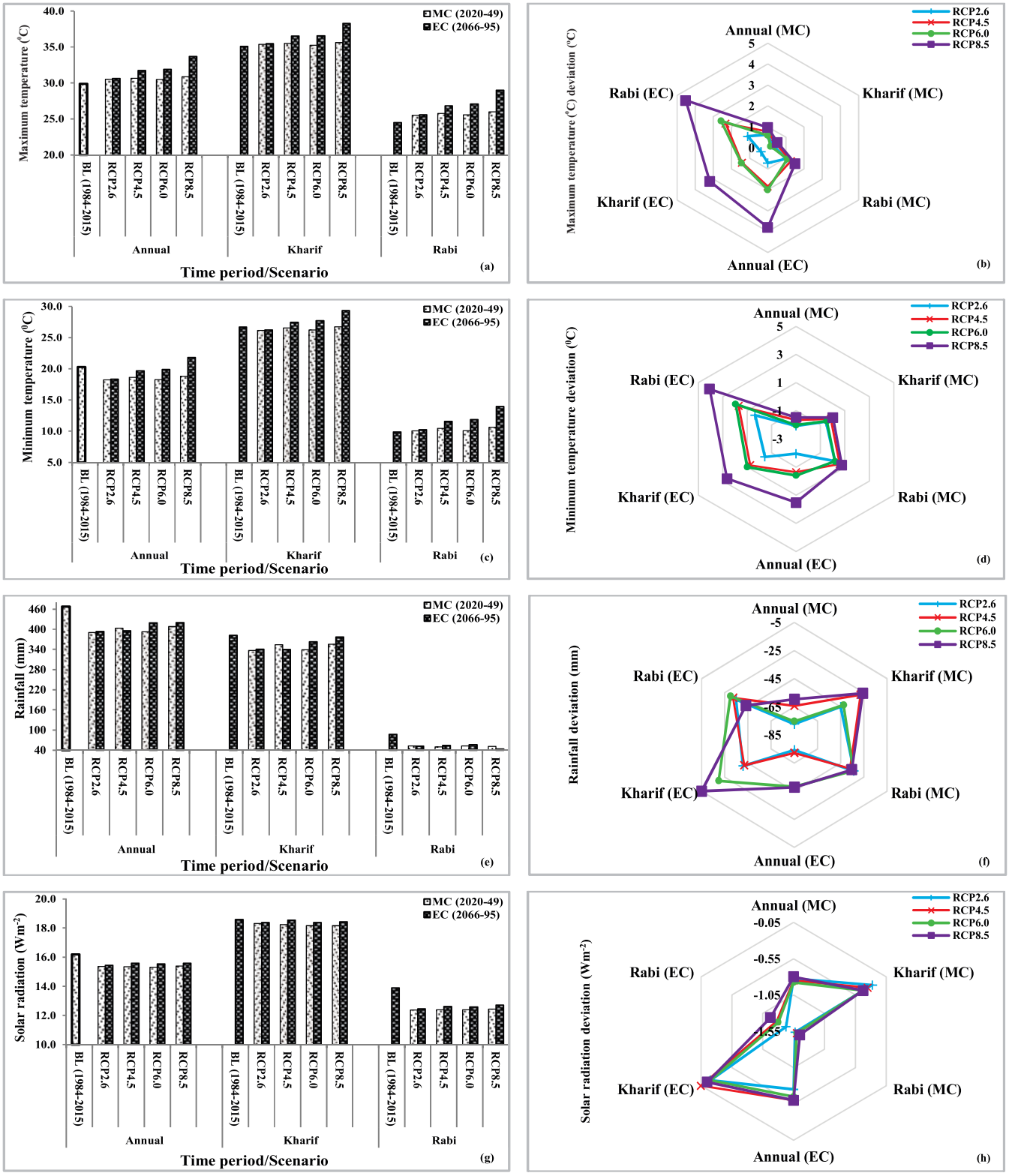


Fig. 8. Projected changes and deviation in (a and b) maximum temperature (oC), (c and d) minimum temperature (oC), (e and f) rainfall (mm) and (g and h) solar radiation (Wm-2) under different scenarios simulated by ensemble mean of five General Circulation Models at Faridkot (Agroclimatic zone V). #(BL: Baseline, EC: End-century, MC: Mid-century, RCP: Representative Concentration Pathway)

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Table 5. Overall projected changes in maximum temperature, minimum temperature, rainfall and solar radiation in Punjab

Season	Time-period	RCP2.6	RCP4.5	RCP6.0	RCP8.5
		Maximum temperature (°C)			
Annual (Baseline: 30.2°C)	Mid century (2020-49)	30.7	30.9	30.7	31.1
	End century (2066-95)	30.8	32.0	32.1	32.9
***Kharif* (Baseline: 35.3°C)**	Mid century (2020-49)	35.8	35.9	35.7	36.1
	End century (2066-95)	36.0	37.0	37.1	38.7
***Rabi* (Baseline: 25.0°C)**	Mid century (2020-49)	25.5	25.8	25.5	26.0
	End century (2066-95)	25.6	26.9	27.1	29.0
		Minimum temperature (°C)			
Annual (Baseline: 17.3°C)	Mid century (2020-49)	20.2	20.6	20.0	20.7
	End century (2066-95)	20.4	21.6	21.9	23.7
***Kharif* (Baseline: 23.8°C)**	Mid century (2020-49)	27.7	28.0	27.7	28.2
	End century (2066-95)	27.8	29.0	29.2	30.9
***Rabi* (Baseline: 10.0°C)**	Mid century (2020-49)	12.5	12.9	12.5	13.1
	End century (2066-95)	12.7	14.0	14.2	16.4
		Diurnal Range of temperature (°C)			
Annual (Baseline: 12.9°C)	Mid century (2020-49)	10.5	10.3	10.7	10.4
	End century (2066-95)	10.4	10.4	10.2	9.2
***Kharif* (Baseline: 11.5°C**	Mid century (2020-49)	8.1	7.9	8.0	7.9
	End century (2066-95)	8.2	8.0	7.9	7.8
***Rabi* (Baseline: 15.0°C)**	Mid century (2020-49)	13.0	12.9	13.0	12.9
	End century (2066-95)	12.9	12.9	12.9	12.6
		Rainfall (mm)			
Annual (Baseline: 659mm)	Mid century (2020-49)	485	493	487	497
	End century (2066-95)	485	505	536	499
***Kharif* (Baseline: 546mm)**	Mid century (2020-49)	429	435	418	438
	End century (2066-95)	426	441	468	446
***Rabi* (Baseline: 114mm)**	Mid century (2020-49)	54	58	60	59
	End century (2066-95)	60	64	68	55
		Solar radiation (Wm^{-2})			
Annual (Baseline: 16.2 Wm^{-2})	Mid century (2020-49)	15.4	15.3	15.3	15.3
	End century (2066-95)	15.5	15.6	15.5	15.6
***Kharif* (Baseline: 18.6 Wm^{-2})**	Mid century (2020-49)	18.2	18.1	18.1	18.1
	End century (2066-95)	18.2	18.2	18.1	18.2
***Rabi* (Baseline: 13.9 Wm^{-2})**	Mid century (2020-49)	12.4	12.4	12.4	12.5
	End century (2066-95)	12.7	12.8	12.8	12.9

under RCP 6.0 and under RCP 8.5 in *rabi* season during the end-century. The solar radiation (Fig. 5h) for the zone showed a significant deviation pattern in comparison to other locations and the solar radiation was observed to decrease for all the seasons under all four scenarios during the end-century but the mid-century observed these significant deviations in *kharif* season under RCP 2.6 and RCP 6.0.

Agroclimatic zone IV (Bathinda)

Bathinda, under zone IV indicated a little variant result in case of maximum temperature and

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solar radiation. The maximum temperature (Fig. 6a and b) of the region was predicted to increase from the baseline during the annual season by 0.1 and 0.2°C under RCP4.5 and RCP8.5, respectively while a decrease was observed by the same value for RCP2.6 and RCP6.0, respectively. During the *kharif* season, the decrement from baseline was by 0.1-0.4°C, except for RCP8.5 where no change in temperature was predicted and for the *rabi* season an increment by 0.2-0.8°C was observed under all four RCPs. The minimum temperature (Fig. 6c and d) of the region showed an increase from the baseline by 1.6-2.2, 2.6-3.2 and 0.4-1.1°C during mid-century and 2.0-5.4, 2.8-5.8 and 0.9-4.8°C during end-century for annual, *kharif* and *rabi* season under the four scenarios. The rainfall (Fig. 6e and f) was projected to decrease from baseline under all four scenarios by 94-114, 48-70 and 39-45 mm during mid and by 76-111, 34-75, 30-40 mm during end-century on annual, *kharif* and *rabi* season basis, respectively. During mid-century, the solar radiation (Fig. 6g and h) indicated a decrease from baseline by 0.4-0.5 and 1.1-1.2 Wm^{-2} for annual and *rabi* seasons, respectively under all RCPs while during the *kharif* season, an increment by 0.1 Wm^{-2} under RCP2.6 followed by no change in solar radiation was observed under the other RCPs. Similarly, the end century indicated a decrease from baseline by 0.2-0.4 and 0.8-1.0 Wm^{-2} on an annual and *rabi* season basis while the *kharif* seasons observed an increase by 0.1-0.2 Wm^{-2} under the four emission scenarios. The maximum temperature (Fig. 6b) observed significantly higher deviations under RCP 8.5 during end-century in comparison to other scenarios especially in *rabi* season while minimum temperature (Fig. 6d) observed similar trend during annual and *kharif* season. The rainfall (Fig. 6f) indicated high deviations during all the seasons and both the centuries under RCP 8.5 while the other scenarios followed similar trend with significant deviation observed in the *rabi* season during end-century. The four scenarios for solar radiation (Fig. 6h) observed similar deviation trends during all the seasons and both the centuries with higher deviation observed during the end-century in *kharif* season.

Agroclimatic zone V (Abohar, Faridkot)

The Abohar and Faridkot locations under zone V represent variations in projections for minimum temperature, rainfall and solar radiation in comparison to the other locations. The maximum temperature (Fig. 7a and b) for Abohar district during annual, *kharif* and *rabi* season was predicted to increase from baseline by 0.3-0.8, 0.3-0.6 and 0.4-0.9°C, respectively during mid and by 0.6-3.7, 0.5-3.4 and 0.6-3.9°C, respectively during end-century under the four RCPs. The minimum temperature (Fig. 7c and d) at Abohar observed an increase from baseline by 0.9-1.4 and 2.8-3.3°C during mid-century for annual and *Kharif* seasons, respectively while the *rabi* season observed a decrease by 0.5-1.1°C under the four scenarios. During the end-century minimum temperature was projected to increase from baseline by 1.0-4.4, 2.8-5.9 and 0.5-2.9°C on annual, *kharif* and *rabi* season basis for the four RCPs except RCP2.6 where a slight decrease by 0.9°C was found for the *rabi* season. The region observed increased rainfall (Fig. 7e and f) from baseline during mid and end-century by 20-33mm and 24-52mm, respectively on an annual basis and 37-51mm and 44-63mm, respectively on a *kharif* basis under the four scenarios. During the *rabi* season, a decrement in rainfall from baseline was observed at Abohar by 19-27mm and 16-31mm during mid and end-century, respectively under the four RCPs. The solar radiation (Fig. 7g and h) from the baseline was predicted to decrease by 0.4-0.5 and 1.1-1.3 Wm^{-2} during mid-century and by 0.2-0.3 and 1.0-1.2 Wm^{-2} during the end-century, respectively on an annual and *rabi* season basis. On *kharif* season basis, a rise by 0.1-0.2 Wm^{-2} during the mid-century and 0.3- 0.5 Wm^{-2} during end-century was observed under the RCPs. The *rabi* and annual season observed a significant deviation in maximum temperature (Fig. 7b) and minimum temperature (Fig. 7d) observed these deviations in *kharif* season during the end-century under RCP 8.5. The rainfall (Fig. 7f) observed significantly high deviations in *kharif* season during mid and end-century while the solar radiation (Fig. 7h) observed an increase during the mid and end-century in *kharif* season under all the four scenarios.

At Faridkot, the maximum temperature (Fig. 8a and b) on an annual, *kharif* and *rabi* season basis is predicted to increase from baseline period by 0.6-1.0, 0.1-0.5 and 1.0-1.5°C, respectively during mid-century and by 0.8-3.9, 0.4-3.2 and 1.2-4.6°C, respectively during end-century under RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 scenarios. During mid-century under the four RCP scenarios, the minimum temperature (Fig. 8c and d) showed a decrease from baseline by 1.5-1.7°C and 0.2-0.5°C under the corresponding seasons and scenarios except RCP8.5 where no change was observed during *kharif* season while the *rabi* season observed an increase by 0.2-0.7°C for the same century under the four RCPs. The

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end-century revealed an increase from baseline by 0.3-4.0°C for the *rabi* season and 0.8-2.7°C for *kharif* season under the four scenarios except RCP2.6 where the *kharif* season observed a slight decrement by 0.4°C. On annual season basis a decrease ranging between 0.4-1.9°C was obtained under all the four RCPs except RCP8.5 which obtained an increment by 1.5°C. The projected changes in rainfall (Fig. 8e and f) for Faridkot represented a decrease from baseline on annual, *kharif* and *rabi* season basis by 53-76, 25-42 and 30-35mm, respectively during mid-century and by 41-70, 15-38 and 33-44mm, respectively during end-century under the RCPs, except RCP8.5 where on annual basis a slight increase by 3mm was observed. Under the four RCP scenarios during mid and end century reduction in solar radiation (Fig. 8g and h) from baseline was in the range 0.4-0.5 and 0.2-0.4 Wm^{-2}, respectively on annual season basis while 1.1-1.2 and 0.8-1.0 Wm^{-2}, respectively on *rabi* season basis. The mid-century solar radiation on *kharif* season basis represented no change under the four scenarios except RCP2.6 where a slight increase by 0.1 Wm^{-2} was observed; the end-century too observed an increase in the range 0.1-0.2 under the RCP scenarios (Fig. 8d). At Faridkot, the maximum and minimum temperature (Fig. 8b and d) observed a significant increase during the end-century in *rabi* season under RCP 8.5. The rainfall (Fig. 8f) deviations in the zone were high in *kharif* season during the end-century and these were significant under RCP 8.5 for other seasons and centuries as well while solar radiation (Fig. 8h) was observed to decrease under all the scenarios in *Kharif* season during end-century.

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Overall projected changes in Punjab

The analysis of the data showed that in Punjab state (Table 5) there are projections of: (a) a slight increase in maximum temperature from 30.2, 35.3 and 25.0°C (baseline) to 30.7, 35.8 and 25.5°C (RCP 2.6); 30.9, 35.9 and 25.8°C (RCP 4.5); 30.7, 35.7 and 25.5°C (RCP 6.0); 31.1, 36.1 and 26.0°C (RCP 8.5) for annual, *kharif* and *rabi* season, respectively during mid-century. Similarly during the end-century the maximum temperature may vary from the baseline to 30.8, 36.0 and 25.6°C (RCP 2.6); 32.0, 37.0 and 26.9°C (RCP 4.5); 32.1, 37.1 and 27.1°C (RCP 6.0); 32.9, 38.7 and 29.0°C (RCP 8.5) on annual, *kharif* and *rabi* season, respectively. (b) the minimum temperature is projected to appreciably increase from 17.3, 23.8 and 10.0°C (baseline) during mid-century to 20.2, 27.7 and 12.5°C (RCP2.6); 20.6, 28.0 and 12.9°C (RCP4.5); 20.0, 27.7 and 12.5°C (RCP6.0); 20.7, 28.2 and 13.1°C (RCP8.5) for annual, *kharif* and *rabi* season, respectively. The increase in minimum temperature from baseline for respective seasons during the end century was 20.4, 27.8 and 12.7°C (RCP2.6); 21.6, 29.0 and 14.0°C (RCP4.5); 21.9, 29.2 and 14.2°C (RCP6.0); 23.7, 30.9 and 16.4°C (RCP8.5). (c) the rainfall was indicated to decrease from 659, 546 and 114mm (baseline) to 485, 429 and 54mm (RCP2.6); 493, 435 and 58mm (RCP4.5); 487, 418 and 60mm (RCP6.0); 497, 438 and 59mm (RCP8.5) on annual, *kharif* and *rabi* season basis, respectively during mid-century. Similar declining trend for end-century from baseline to 485, 426 and 60mm (RCP2.6); 505, 441 and 64mm (RCP4.5); 536, 468 and 68mm (RCP6.0); 499, 446 and 55mm (RCP8.5) was obtained during corresponding seasons. (d) the predicted solar radiation variations for mid-century from 16.2, 18.6 and 13.9 Wm^{-2} (baseline) were 15.4 Wm^{-2} (RCP2.6) and 15.3 Wm^{-2} (RCPs 4.5, 6.0 and 8.5) during annual season; 18.2 Wm^{-2} (RCP2.6) and 18.1 Wm^{-2} (RCPs 4.5, 6.0 and 8.5) during *kharif* season; 12.4 Wm^{-2} (RCPs 2.6, 4.5 and 6.0) and 12.5 Wm^{-2} (RCP8.5) during *rabi* season. Similarly, for the end-century from baseline the variations were 15.5 Wm^{-2} (RCP2.6), 15.6 Wm^{-2} (RCP4.5), 15.5 Wm^{-2} (RCP6.0) and 15.6 Wm^{-2} (RCP8.5) during the annual season; 18.2 Wm^{-2} (RCPs 2.6, 4.5 and 8.5) and 18.1 Wm^{-2} (RCP6.0) during *kharif* season; 12.7 Wm^{-2} (RCP2.6), 12.8 Wm^{-2} (RCPs 4.5 and 6.0) and 12.9 Wm^{-2} (RCP8.5) during *rabi* season.

Different zones of Punjab as discussed show variations in the meteorological parameters simulated by the four GCMs. The predicted and bias-corrected data indicate a trend of a slight increase in maximum but appreciable increase in minimum temperature followed by a decreasing trend in rainfall and solar radiation at different locations of Punjab. The highest increment in maximum and minimum temperature occurred during the end-century (2066-95) under RCP8.5 for all three seasons-annual, *kharif* and *rabi*. This increase under RCP8.5 may be due to its being a high-emission scenario where the greenhouse gases would continuously rise. Shafiq *et al.* (2019) analyzed the projections for the Kashmir Himalayas under different RCPs which revealed an increasing trend for both maximum and minimum temperature at all stations and the highest increase was observed under RCP8.5 of 0.7-2.3°C and 0.2-1.9°C for maximum and minimum temperature, respectively. The rainfall and solar radiation for all three seasons decreased by almost the same values for both mid

and end centuries for all the zones. The average change in rainfall for Abohar during the annual and *kharif* season indicated an increasing trend. Various studies at different locations indicated that such variations in meteorological parameters would harm the major cereal crops leading to low food availability for the future generation. A study published by ICAR under the Network Project on Climate Change (Venkateswarlu, 2017) reported that in India climate change impact could be such that it could reduce the food production by 4.5-9% in the medium term (2010-39) and by nearly 25% in the long term (2070-99). A study by Deb *et al.* (2015) at three major agricultural areas of Sikkim state (Geyzing, Gangtok, and Mangan) bias-corrected the GCM data and found the maximum temperature to increase up to 1.98 and 1.85 °C and minimum temperature to 2.31 and 1.96 °C during 2085 under A2 and B2 scenarios, respectively. The A2 and B2 scenarios showed maximum reduction in rainfall during 2085 of 22.6 and 19.5%, respectively for Geyzing and Gangtok while an increase of 11.4 and 12.4% was observed for Mangan under the corresponding scenarios and timeperiod.

The overall variations for different zones of Punjab described the maximum temperature, minimum temperature, rainfall and solar radiation trends in Punjab. The maximum and minimum temperature indicated an increase under all four scenarios and seasons during the mid and end centuries from the baseline. The rainfall and solar radiation variations in Punjab represented a decrease from the baseline during both centuries for the corresponding scenarios and seasons. These variations showed a major increase in temperature and a decrease in rainfall and solar radiation under the high emission scenario (RCP8.5) during the end-century (2066-95). This trend for the Punjab state ascertains that changes are required in the cropping pattern for efficient food production. Dar *et al.* (2019) observed similar results in a study for the Ludhiana district in central Punjab where the climate predictions revealed similar trends under the four RCPs and both centuries.

CONCLUSION

The study concluded that the minimum temperature for Punjab will increase more than the maximum temperature which would lead to a decline in the diurnal range of temperature. The rainfall and solar radiation are predicted to decrease under all four emission scenarios. The greater increment of both minimum and maximum temperature can be observed during the end-century (2066-95) which implies a major change in the climatic conditions of various agroclimatic zones of Punjab. Under the RCP8.5, a high emission scenario, a maximum increase in temperatures. The increasing temperatures were also supported by a decrease in the rainfall and solar radiation which will lead to erratic rainfall patterns for the region. The results indicate that the climate in Punjab is projected to become hotter and drier but more cloudy thereby implying that crops would experience thermal, moisture as well as radiative stresses. These stresses will lead to many harmful effects like a decline in agricultural productivity, an increase in insect-pest attacks, irrigation water demand, weather volatility, etc. Thus, in order to sustain agricultural productivity, there is a need to understand and implement adaptation strategies that can help in providing the food needs of the increasing population. The agricultural research should focus on climate-resilient technologies/ varieties. The policy planners should frame policies to reduce GHG emissions from all sectors.

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Authors' contribution

Conceptualization of research work and designing of experiments (PK, SK); Execution of simulation experiments for downscaling of data (JK); Analysis of data and interpretation (SSS, SK); Preparation of manuscript (PK, JK).

Conflicts of interest

Authors declare that there are no conflicts of interest.

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