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SPATIAL AND TEMPORAL EVALUATION OF RAIN-ASSOCIATED AGROMETEOROLOGICAL METRICS

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ABSTRACT

This study evaluates the spatial and temporal variability of rain-associated agrometeorological metrics across seven locations in Punjab, India (Amritsar, Ballowal Saunkhri, Bathinda, Faridkot, Ludhiana, Patiala and Abohar) under present (2016-2025), mid-century (2026-2060) and end-century (2066-2095) climate scenarios. At the annual scale, total rainfall during the present period ranges from 296 to 732 mm with 28-42 rainy days. Projected mid-century values vary between 274 and 719 mm with 28-42 rainy days, while end-century projections indicate a wider variability, ranging from 261 to 770 mm and 32-45 rainy days. Seasonal analysis reveals distinct trends between the *kharif* (May-October) and *rabi* (November-April) seasons. During the *kharif* season, total rainfall ranges from 268 to 672 mm (22-42 rainy days) in the present period, 232 to 653 mm (25-42 rainy days) in mid-century and 214 to 699 mm (21-44 rainy days) by end-century. In contrast, *rabi* season rainfall remains substantially lower, ranging from 24 to 92 mm (3-9 rainy days) in the present period and 31 to 111 mm (2-10 rainy days) in mid-century. End-century projections suggest continued variability in *rabi* rainfall and rainy days across locations. Overall, the results indicate considerable spatial heterogeneity and temporal shifts in rainfall distribution with implications for seasonal crop planning and water resource management in the region.

Keywords: Climate change projections, Crop planning, Seasonal rainfall variability, Water resource management

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Climate change is widely recognized as one of the greatest threats to life and livelihoods on Earth. Substantial evidence indicates that the climate system is undergoing changes at local, regional and global scales (Choudhary *et al.*, 2019; Fitzpatrick *et al.*, 2008). These changes have altered global precipitation and temperature patterns to varying degrees across different regions of the world (Root *et al.*, 2005; Williams *et al.*, 2007). Among all sectors, agriculture is particularly vulnerable to climatic variability and long-term climate change (Sanchez-Cohen *et al.*, 2013). In India, rainfall is the most critical determinant of crop productivity as nearly 60% of the cultivated area is rain-fed. Climate projections are primarily derived from simulations generated by global climate models (Qian *et al.*, 2016). These projections indicate potential changes in total precipitation, number of rainy days, frequency and intensity of extreme rainfall events and shifts in the onset and withdrawal of the monsoon (Gautam *et al.*, 2013). Variations in rainfall patterns can adversely affect crop productivity in multiple ways (Apata, 2010). Water stress due to deficient rainfall can reduce germination and vegetative growth, while excessive rainfall may cause lodging, pollen washout and other forms of crop damage. Therefore, assessing rain-associated agrometeorological metrics for both present and future periods across different locations is essential for sustaining crop yields under changing climatic conditions (Feizi *et al.*, 2015).

Studies conducted so far have suggested that the rainfall trends show a very diverse pattern at regional and national scales due to disproportion in natural resources (Sahu and Khare, 2015). There are increasing and decreasing trends in monthly rainfall (Becker *et al.,* 2006). The temporal and spatial distribution of rainfall from 1961 to 2008 in northeast China has been observed by Liang *et al.* (2011). In India, decreasing trends of annual and monsoon rainfall over the Eastern Ganga canal command area and in north-east, central north-east India and west-central India have also been observed (Kumar *et al.,* 2010, Krishan *et al.,* 2018).

Multiple climate change-related studies at the global and national scale have been performed, but the literature for the regional scale is limited. Punjab, being an agricultural state, is highly vulnerable to changes in meteorological factors and climate change especially temperature and rain. Though the trends of extreme weather conditions in different climatic zones have been studied by Kaur *et al.,* (2021), information on the rain-associated agro-meteorological metrics at

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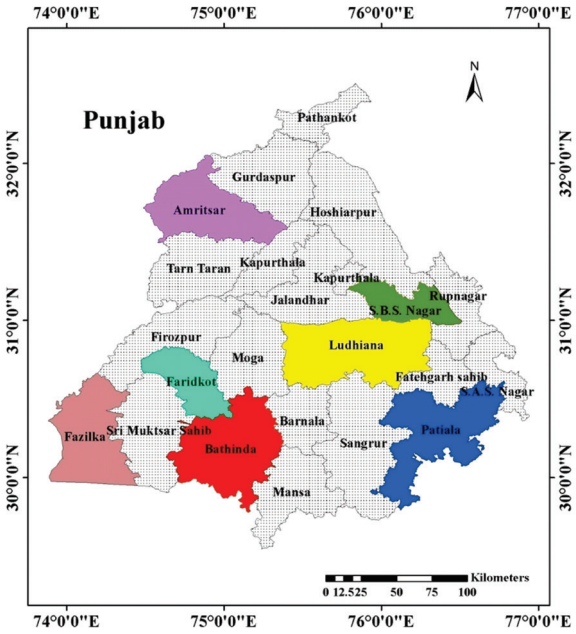


Fig. 1. Map of the study region (Punjab, India)

spatial and temporal scales is lacking. Therefore, the present study was undertaken to assess and analyze the projected changes in annual and seasonal rainfall, along with the number of rainy days, across different locations in Punjab, India under various climate change models and future time slices.

MATERIALS AND METHODS

The study was conducted at seven locations in Punjab, India: Ludhiana (30°56′ N, 75°48′ E; 247 m amsl), Ballowal Saunkhri (30°07′ N, 76°23′ E; 355 m amsl), Amritsar (31°37′ N, 74°53′ E; 231 m amsl), Patiala (30°20′ N, 76°28′ E; 251 m amsl), Bathinda (30°12′ N, 74°57′ E; 211 m amsl), Faridkot (30°40′ N, 74°45′ E; 204 m amsl) and Abohar (30°58′ N, 74°36′ E; 177 m amsl) (Fig. 1). Daily rainfall data for the period 2010-2095 were generated using the MarkSim weather generator (*http://gismap.ciat.cgiar.org/MarkSimGCM/*) based on four global climate models, CSIRO-Mk3-6-0, FIO-ESM, IPSL-CM5A-MR and an ensemble mean, under four Representative Concentration Pathway (RCP) scenarios (RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5). Observed daily rainfall data for the baseline period (2010-2017) were obtained from agro-meteorological observatories of Punjab Agricultural University to evaluate and compare model projections. The bias in the modelled data was removed by correcting the daily modeled data using the difference method (Eq. 1) as described below:

$$Xmodel_{corr} = Xmodel_{uncorr} - (X_{model} - X_{obs}) \quad \text{Eq.1}$$

where,

$Xmodel_{uncorr}$: Daily modelled data

$Xmodel_{corr}$: Daily corrected modelled data

X_{model} : Daily modelled value

X_{obs} : Daily observed value

The bias in the projected modelled data was minimized by applying the difference method (Kaur *et al.,* 2021). For that, at first, the daily correction factor, *i.e.* daily difference between model data (X_{model}) and observed data (X_{obs}) of rainfall for each Julian day (365 days) was calculated. Thereafter, the correction factors were subtracted from the modelled uncorrected ($Xmodel_{uncorr}$) values so that the model corrected ($Xmodel_{corr}$) values come closer to the actual observed values. The model's performance was tested by evaluating its Root Mean Square Error (RMSE). From the daily model corrected data, the number of rainy days (cumulative daily rainfall ≥ 2.5 mm) (https://www.hindawi.com/journals/tswj/2012/894313/) was estimated. Total rainfall/year as well as number of rainy days/year were calculated annually and seasonally (*kharif*: May-October; *rabi*: November-April) during present (2016-2025), mid-century (2026-2060) and end century (2061-2095) time slices. The increasing or decreasing trends of rainy days/year across different models and scenarios were determined by fitting regression educations to the data of the rainfall parameters over time from 2016 to 2095 years.

RESULTS AND DISCUSSION

Variability in cumulative rainfall/year

The cumulative total rainfall/year changed in different time slices across locations under four climate change models and scenarios (Table 1). The average annual rainfall as predicted by the four models and climatic scenarios in the state varied from 430 (IPSLCM5A-MR: RCPs 8.5) to 510 mm (CSIRO-Mk 3-6-0: RCP 2.6) during the present time (2016-25), 442 (FIO-ESM: RCP 6.0) to 537 mm (Ensemble: RCP 8.5) during mid-century (2026-60) and 433 (FIO-ESM: RCP 6.0) to 553 mm (IPSLCM5A-MR: RCPs 6.0) during end-century (2061-95) (Table 1).

During the present time slice (2016-2025) total rainfall/year at Ludhiana ranged from 515 mm (IPSLCM5A-MR: RCP 6.0) to 593 mm (FIO-ESM: RCP 2.6); at Ballowal Saunkhri from 407 to 574 mm (IPSLCM5A-MR: RCPs 8.5 and 4.5, respectively); at Amritsar from 525 mm (IPSLCM5A-MR: RCP 8.5) to 732 mm (Ensemble: RCP 6.0); at Patiala from 470 mm (IPSLCM5A-MR: RCP 8.5) to 630 mm (CSIRO-Mk 3-6-0: RCP 2.6); at Bathinda from 371 mm (FIO-ESM: RCP 4.5) to 441 mm (CSIRO-Mk 3-6-0: RCP 4.5); at Faridkot from 356 mm (FIO-ESM: RCP 4.5) to 422 mm (Ensemble: RCP 8.5); and at Abohar from 296 mm (FIO-ESM: RCP 2.6) to 392 mm (CSIRO-Mk 3-6-0:

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Table 1. Predicted average annual total rainfall by four climate models under four RCP scenarios in the present time, mid- and end-century in Punjab

Station	CSIRO-Mk 3-6-0 model				FIO-ESM model				IPSLCM5A-MR model				Ensemble model			
	RCPs				RCPs				RCPs				RCPs			
	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5
Present Time (2016-25)																
Ludhiana	581	585	589	577	593	583	563	590	522	592	515	539	534	530	527	559
Ballowal Saunkhri	503	446	460	479	512	504	494	412	479	574	426	407	473	450	460	441
Amritsar	634	621	608	635	608	601	615	600	541	594	553	525	659	715	732	718
Patiala	630	559	533	576	492	501	480	505	486	588	524	470	518	550	521	536
Bathinda	435	441	437	427	381	371	390	436	389	391	424	390	387	373	417	392
Faridkot	411	415	420	404	383	356	391	376	379	392	370	372	397	420	419	422
Abohar	378	346	392	351	296	327	319	357	380	374	384	305	331	327	328	342
Average	**510**	**488**	**491**	**493**	**466**	**463**	**465**	**468**	**454**	**501**	**457**	**430**	**471**	**481**	**486**	**487**
Mid-Century (2026-60)																
Ludhiana	631	621	615	630	573	561	552	592	602	612	562	654	573	625	589	627
Ballowal Saunkhri	561	532	524	519	423	486	410	448	519	527	503	545	470	549	496	550
Amritsar	673	687	596	623	615	593	586	607	587	566	612	576	634	684	695	719
Patiala	625	616	620	611	488	500	480	576	510	596	618	624	580	636	568	664
Bathinda	425	443	447	425	361	363	390	432	392	418	407	432	391	388	421	411
Faridkot	399	421	423	403	359	355	356	386	393	410	398	433	422	424	589	439
Abohar	354	349	357	354	289	274	321	365	380	354	364	346	357	339	349	350
Average	**524**	**524**	**512**	**509**	**444**	**447**	**442**	**487**	**483**	**498**	**495**	**516**	**490**	**521**	**530**	**537**
End-Century (2061-95)																
Ludhiana	614	625	631	571	564	536	548	493	559	670	701	705	588	651	770	650
Ballowal Saunkhri	565	501	500	448	468	429	398	375	472	532	590	593	486	619	496	504
Amritsar	683	679	627	605	563	564	553	536	586	595	634	680	643	689	695	733
Patiala	664	598	613	577	465	500	502	585	513	661	719	640	569	690	568	622
Bathinda	411	405	405	443	348	379	377	397	385	405	428	399	385	413	421	441
Faridkot	385	384	397	442	364	362	352	357	380	388	436	383	427	404	384	449
Abohar	334	373	371	345	261	291	299	303	335	338	366	316	339	369	349	361
Average	**522**	**509**	**506**	**490**	**433**	**437**	**433**	**435**	**461**	**513**	**553**	**531**	**491**	**548**	**526**	**537**

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RCP 6.0).

During the mid-century (2026-2060) total rainfall/year at Ludhiana is projected to range from 552 mm (FIO-ESM: RCP 6.0) to 631 mm (CSIRO-Mk 3-6-0: RCP 2.6); at Ballowal Saunkhri from 410 mm (FIO-ESM: RCP 6.0) to 561 mm (CSIRO-Mk 3-6-0: RCP 2.6); at Amritsar from 576 mm (IPSLCM5A-MR: RCP 8.5) to 719 mm (Ensemble: RCP 8.5); at Patiala from 488 mm (FIO-ESM: RCP 2.6) to 664 mm (Ensemble: RCP 8.5); at Bathinda from 361 mm (FIO-ESM: RCP 2.6) to 447 mm (CSIRO-Mk 3-6-0: RCP 6.0); at Faridkot from 355 mm (FIO-ESM: RCP 4.5) to 589 mm (Ensemble: RCP 6.0); and at Abohar from 274 mm (FIO-ESM: RCP 4.5) to 380 mm (IPSLCM5A-MR: RCP 2.6).

The variability in rainfall/year during the end-century (2066-2095) at Ludhiana is projected to range from 493 mm (FIO-ESM: RCP 8.5) to 770 mm (Ensemble: RCP 6.0); at Ballowal Saunkhri from 375 mm (FIO-ESM: RCP 8.5) to 619 mm (Ensemble: RCP 4.5); at Amritsar from 536 mm (FIO-ESM: RCP 8.5) to 733 mm (Ensemble: RCP 8.5); at Patiala from 465 mm (FIO-ESM: RCP 2.6) to 719 mm (IPSLCM5A-MR: RCP 6.0); at Bathinda from 348 mm (FIO-ESM: RCP 2.6) to 443 mm (CSIRO-Mk 3-6-0: RCP 8.5); at Faridkot from 352 mm (FIO-ESM: RCP 6.0) to 449 mm (Ensemble: RCP 8.5); and at Abohar from 261 mm (FIO-ESM: RCP 2.6) to 373 mm (CSIRO-Mk 3-6-0: RCP 8.5).

Variability in the *kharif* season (May-October) rainfall

During the *kharif* season, the total rainfall/year changed in different time slices across locations under four climate change models and scenarios (Table 2). The average *kharif* season rainfall as predicted by the four models and climatic scenarios in the state varied from 380 (IPSLCM5A-MR: RCPs 8.5) to 448 mm (CSIRO-Mk 3-6-0: RCP 2.6) during the present time (2016-25), 386 (FIO-ESM: RCP 4.5) to 477 mm (Ensemble: RCP 8.5) during mid-century (2026-60) and 370 (FIO-ESM: RCP 6.0) to 504 mm (Ensemble: RCPs 6.0) during end-century (2061-95) (Table 2).

During the present time slice *kharif* season rainfall at Ludhiana ranged from 448 mm (IPSLCM5A-MR: RCP 6.0) to 590 mm (FIO-ESM: RCP 8.5); at Ballowal Saunkhri from 362 to 516 mm (IPSLCM5A-MR: RCPs 8.5 and 4.5, respectively); at Amritsar from 459 to 672 mm (IPSLCM5A-MR: RCPs 8.5 and 6.0, respectively); at Patiala from 420 mm (FIO-ESM: RCP 4.5) to 559 mm (CSIRO-Mk 3-6-0: RCP 2.6); at Bathinda from 326 mm (FIO-ESM: RCP 4.5) to 387 mm (IPSLCM5A-MR: RCP 6.0); at Faridkot from 307 mm (FIO-ESM: RCP 4.5) to 374 mm (CSIRO-Mk 3-6-0: RCP 6.0) and at Abohar from 268 mm (IPSLCM5A-MR: RCP 8.5) to 345 mm (CSIRO-Mk 3-6-0: RCP 6.0).

The variability in *kharif* season rainfall/year during the mid-century at Ludhiana is projected to range from

Table 2. Predicted average annual total rainfall during the *kharif* (May-October) season by four climate models under four RCP scenarios in the present time, mid- and end-century in Punjab

Station	CSIRO-Mk 3-6-0				FIO-ESM				IPSLCM5A-MR				Ensemble			
	RCPs				RCPs				RCPs				RCPs			
	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5
Present Time (2016-25)																
Ludhiana	520	523	526	522	526	512	513	590	451	538	448	461	471	467	491	497
Ballowal Saunkhri	448	406	400	424	453	440	457	382	424	516	376	362	419	394	413	391
Amritsar	547	533	520	546	531	533	550	539	472	545	672	459	593	639	476	651
Patiala	559	489	456	506	440	420	440	441	435	550	431	424	460	500	463	472
Bathinda	376	369	352	368	336	326	335	374	350	352	387	352	358	346	356	355
Faridkot	349	364	374	349	323	307	322	325	337	339	322	331	335	355	368	349
Abohar	338	304	345	307	270	292	284	329	327	331	341	268	287	289	292	300
Average	**448**	**427**	**425**	**432**	**411**	**404**	**414**	**426**	**399**	**453**	**425**	**380**	**418**	**427**	**408**	**431**
Mid-Century (2026-60)																
Ludhiana	581	567	554	562	518	493	508	589	542	530	491	567	505	555	518	557
Ballowal Saunkhri	511	481	471	461	383	424	365	386	479	463	434	471	406	469	435	499
Amritsar	596	618	508	514	562	516	529	530	522	480	620	487	581	631	496	653
Patiala	555	561	555	550	451	424	426	515	469	544	520	547	509	571	505	592
Bathinda	370	395	392	377	319	308	358	382	360	377	351	396	373	351	372	364
Faridkot	341	381	379	361	310	304	314	338	352	371	331	379	354	354	338	366
Abohar	295	304	307	313	271	232	286	317	341	303	299	301	289	292	290	308
Average	**464**	**472**	**452**	**448**	**402**	**386**	**398**	**437**	**438**	**438**	**435**	**450**	**431**	**460**	**422**	**477**
End-Century (2061-95)																
Ludhiana	552	534	558	489	482	463	468	476	491	584	615	632	520	591	699	596
Ballowal Saunkhri	510	428	429	385	409	364	330	307	419	459	532	535	434	557	543	466
Amritsar	611	569	527	521	474	480	474	447	500	485	691	590	585	637	531	678
Patiala	602	527	535	494	405	422	439	527	451	619	636	569	496	622	624	557
Bathinda	356	360	358	406	301	328	319	324	346	351	359	364	353	372	417	404
Faridkot	341	338	337	400	307	310	302	306	335	331	379	351	356	355	380	413
Abohar	289	323	326	300	214	247	258	249	291	385	310	280	290	323	335	338
Average	**466**	**440**	**439**	**428**	**370**	**373**	**370**	**377**	**405**	**459**	**503**	**474**	**433**	**494**	**504**	**493**

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491 mm (IPSLCM5A-MR: RCP 6.0) to 589 mm (FIO-ESM: RCP 8.5); at Ballowal Saunkhri from 365 mm (FIO-ESM: RCP 6.0) to 511 mm (CSIRO-Mk 3-6-0: RCP 4.5); at Amritsar from 480 mm (IPSLCM5A-MR: RCP 4.5) to 653 mm (Ensemble: RCP 8.5); at Patiala from 424 mm (FIO-ESM: RCP 4.5) to 592 mm (Ensemble: RCP 8.5); at Bathinda from 308 mm (FIO-ESM: RCP 4.5) to 396 mm (IPSLCM5A-MR: RCP 8.5); at Faridkot from 304 mm (FIO-ESM: RCP 4.5) to 381 mm (CSIRO-Mk 3-6-0: RCP 4.5); and at Abohar from 232 mm (FIO-ESM: RCP 4.5) to 341 mm (IPSLCM5A-MR: RCP 2.6).

During end-century *kharif* (May-October) season rainfall at Ludhiana is projected to range from 463 mm (FIO-ESM: RCP 4.5) to 699 mm (Ensemble: RCP 6.0); at Ballowal Saunkhri from 307 mm (FIO-ESM: RCP 8.5) to 535 mm (IPSLCM5A-MR: RCP 8.5); at Amritsar from 447 mm (FIO-ESM: RCP 8.5) to 691 mm (IPSLCM5A-MR: RCP 6.0); at Patiala from 405 mm (FIO-ESM: RCP 2.6) to 636 mm (IPSLCM5A-MR: RCP 6.0); at Bathinda from 301 mm (FIO-ESM: RCP 2.6) to 417 mm (Ensemble: RCP 6.0); at Faridkot from 302 mm (FIO-ESM: RCP 6.0) to 413 mm (Ensemble: RCP 8.5); and at Abohar from 214 mm (FIO-ESM: RCP 2.6) to 385 mm (IPSLCM5A-MR: RCP 4.5).

Variability in the *rabi* season (November-April) rainfall

During the *rabi season,* the total rainfall/year

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Table 3. Predicted average annual total rainfall during *rabi* (November-April) season by four climate models under four RCP scenarios in the present time, mid- and end-century in Punjab

Station	CSIRO-Mk 3-6-0				FIO-ESM				IPSLCM5A-MR				Ensemble			
	RCPs				RCPs				RCPs				RCPs			
	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5
Present Time (2016-25)																
Ludhiana	62	64	63	56	68	71	51	53	67	54	67	77	64	66	57	62
Ballowal Saunkhri	58	40	60	53	58	63	38	30	58	60	50	46	54	57	48	51
Amritsar	88	87	89	88	81	68	65	60	68	48	81	66	65	72	59	67
Patiala	73	68	74	68	53	82	47	64	47	39	92	45	55	51	58	64
Bathinda	61	73	87	61	44	45	27	62	39	38	36	38	26	24	60	38
Faridkot	62	47	45	55	60	46	70	51	44	54	46	41	64	64	51	76
Abohar	32	42	47	43	36	35	35	38	53	43	42	35	43	38	35	36
Average	**62**	**60**	**66**	**61**	**57**	**59**	**48**	**51**	**54**	**48**	**59**	**50**	**53**	**53**	**53**	**56**
Mid-Century (2026-60)																
Ludhiana	51	53	56	73	53	76	41	57	61	68	65	72	67	64	59	63
Ballowal Saunkhri	50	53	50	65	40	67	46	52	41	58	61	62	58	63	46	53
Amritsar	77	67	96	103	52	80	59	83	64	90	112	82	54	52	76	66
Patiala	65	55	61	66	37	73	55	57	42	46	93	72	63	60	61	70
Bathinda	57	53	60	52	42	52	35	55	33	47	58	39	21	36	49	34
Faridkot	61	46	49	46	47	53	43	52	41	43	63	63	63	74	45	73
Abohar	32	37	45	46	40	41	36	55	43	53	70	56	52	46	56	49
Average	**56**	**52**	**60**	**64**	**44**	**63**	**45**	**59**	**46**	**58**	**75**	**64**	**54**	**56**	**56**	**58**
End-Century (2061-95)																
Ludhiana	63	92	78	76	82	77	76	65	66	95	98	71	73	55	75	60
Ballowal Saunkhri	54	70	61	59	67	56	69	50	50	68	65	69	57	55	45	31
Amritsar	72	106	111	74	82	78	77	84	83	120	107	94	60	52	56	55
Patiala	59	67	73	83	56	74	67	52	63	51	95	66	65	64	60	52
Bathinda	56	46	40	41	47	54	53	71	44	57	70	35	33	45	52	40
Faridkot	42	45	51	52	55	54	51	48	43	55	64	59	68	50	50	39
Abohar	43	48	50	45	44	50	37	45	40	55	68	43	47	48	43	33
Average	**56**	**68**	**66**	**61**	**62**	**63**	**61**	**59**	**56**	**72**	**81**	**62**	**58**	**53**	**54**	**44**

changed significantly in different time slices across locations under four climate change models and scenarios (Table 3). The average *rabi* season rainfall as predicted by the four models and climatic scenarios in the state varied from 48 (FIO-ESM: RCPs 6.0; IPSLCM5A-MR: RCPs 4.5) to 66 mm (CSIRO-Mk 3-6-0: RCP 6.0) during the present time (2016-25), 44 (FIO-ESM: RCP 2.6) to 75 mm (IPSLCM5A-MR: RCP 6.0) during mid-century (2026-60), and 44 (Ensemble: RCP 8.5) to 72 mm (IPSLCM5A-MR: RCPs 4.5) during end-century (2061-95) (Table 3).

During the present time slice, *rabi* season rainfall at Ludhiana ranged from 51 mm (FIO-ESM: RCP 6.0) to 77 mm (IPSLCM5A-MR: RCP 6.0); at Ballowal Saunkhri from 30 to 63 mm (FIO-ESM: RCPs 8.5 and 4.5, respectively); at Amritsar from 48 mm (IPSLCM5A-MR: RCP 4.5) to 89 mm (CSIRO-Mk 3-6-0: RCP 6.0); at Patiala from 39 to 92 mm (IPSLCM5A-MR: RCPs 2.6 and 6.0, respectively); at Bathinda 24 mm (Ensemble: RCP 4.5) to 87 mm (CSIRO-Mk 3-6-0: RCP 6.0); at Faridkot from 41 mm (IPSLCM5A-MR: RCP 8.5) to 76 mm (Ensemble: RCP 8.5); at Abohar from 32 mm (CSIRO-Mk 3-6-0: RCP 2.6) to 53 mm (IPSLCM5A-MR: RCP 2.6).

The variability in *rabi* season rainfall/year during mid-century at Ludhiana is projected to range from 41 to 76 mm (FIO-ESM: RCPs 6.0 and 4.5, respectively); at Ballowal Saunkhri from 40 to 67 mm (FIO-ESM: RCPs 2.6 and 4.5, respectively); at Amritsar from 52 mm (FIO-ESM: RCP 2.6) to 112 mm (IPSLCM5A-MR: RCP 6.0); at Patiala from 37 mm (FIO-ESM: RCP 2.6) to 93 mm (IPSLCM5A-MR: RCP 6.0); at Bathinda from 21 mm (Ensemble: RCP 2.6) to 60 mm (CSIRO-Mk 3-6-0: RCP 6.0); at Faridkot from 41 mm (IPSLCM5A-MR: RCP 2.6) to 74 mm (Ensemble: RCP 4.5); at Abohar from 32 mm (CSIRO-Mk 3-6-0: RCP 2.6) to 70 mm (IPSLCM5A-MR: RCP 6.0).

Similarly, during the end-century the variability in *rabi* season rainfall/year at Ludhiana ranged from 55 mm (Ensemble: RCP 4.5) to 98 mm (IPSLCM5A-MR: RCP 6.0); at Ballowal Saunkhri from 31 mm (Ensemble: RCP 8.5) to 70 mm (CSIRO-Mk 3-6-0: RCP 4.5); at Amritsar from 52 mm (Ensemble: RCP 4.5) to 111 mm (IPSLCM5A-MR: RCP 6.0); at Patiala from 51 to 95 mm (IPSLCM5A-MR: RCPs 4.5 and 6.0, respectively); at Bathinda from 33 mm (Ensemble: RCP 2.6) to 71 mm (FIO-ESM: RCP 8.5); at Faridkot from 39 to 68 mm (Ensemble: RCPs 8.5 and 2.6, respectively); and at Abohar from 33 mm (Ensemble: RCP 8.5) to 68 mm (IPSLCM5A-MR: RCP 6.0).

Trend analysis of rainfall/year

The time trend analysis of rainfall per year during 80 years (2016-2095) in Punjab state exhibited significant

Table 4. Rate of change in rainfall/year and its coefficient of determination (R^2) as influenced by climate change models and scenarios at different locations in Punjab

Station	CSIRO-Mk 3-6-0				FIO-ESM				IPSLCM5A-MR				Ensemble			
	RCPs				RCPs				RCPs				RCPs			
	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5
Ludhiana	0.078 (0.006)	0.051 (0.002)	0.610 (0.213)	-0.678 (0.165)	0.042 (0.001)	-0.848 (0.202)	0.328 (0.180)	-0.523 (0.141)	0.157 (0.006)	1.181 (0.369)	2.785 (0.780)*	2.899 (0.722)*	0.731 (0.272)	2.258 (0.775)*	4.532 (0.638)*	1.388 (0.396)
Ballowal Saunkhri	0.674 (0.306)	0.140 (0.007)	1.218 (0.371)	-1.211 (0.306)	-0.366 (0.025)	-1.211 (0.478)*	-0.679 (0.116)	-0.367 (0.027)	-0.120 (0.010)	-0.080 (0.002)	1.251 (0.385)	2.599 (0.694)*	0.442 (0.102)	2.899 (0.828)*	2.266 (0.846)*	0.732 (0.100)
Amritsar	0.575 (0.344)	-0.145 (0.007)	-0.649 (0.161)	0.372 (0.029)	-0.493 (0.181)	-0.590 (0.231)	0.893 (0.654)*	-0.873 (0.498)*	0.367 (0.118)	-0.250 (0.048)	0.143 (0.01)	2.085 (0.776)*	-0.866 (0.270)	-0.609 (0.213)	-0.059 (0.001)	0.585 (0.209)
Patiala	0.847 (0.340)	0.685 (0.183)	1.152 (0.385)	-0.738 (0.179)	-0.114 (0.012)	0.377 (0.164)	0.153 (0.08)	1.380 (0.548)	0.208 (0.074)	0.851 (0.289)	2.119 (0.632)*	2.324 (0.613)*	0.958 (0.218)	1.957 (0.594)*	2.328 (0.786)*	1.351 (0.285)
Bathinda	-0.500 (0.628)*	-1.047 (0.322)	-0.192 (0.013)	-0.821 (0.372)	-0.269 (0.207)	0.237 (0.115)	-0.104 (0.017)	-0.492 (0.415)	-0.458 (0.285)	-0.446 (0.144)	0.019 (0.000)	-0.336 (0.071)	-0.179 (0.133)	0.631 (0.454)	0.348 (0.198)	0.945 (0.349)
Faridkot	-0.309 (0.27)	-0.449 (0.129)	-0.102 (0.007)	-0.163 (0.017)	0.076 (0.010)	0.040 (0.003)	-0.554 (0.616)*	-0.573 (0.446)	-0.242 (0.098)	-0.498 (0.218)	1.130 (0.614)*	-0.049 (0.001)	0.480 (0.282)	-0.419 (0.231)	-0.053 (0.005)	0.0496 (0.222)
Abohar	-0.647 (0.540)*	1.058 (0.591)*	0.235 (0.031)	-0.15 (0.015)	-0.226 (0.112)	-0.361 (0.101)	-0.165 (0.031)	-0.960 (0.485)*	-0.867 (0.525)*	-0.782 (0.501)*	-0.777 (0.496)*	0.345 (0.056)	-0.121 (0.045)	0.802 (0.640)*	0.558 (0.302)	0.261 (0.108)

*Significant R^2 values

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variability across locations, models and RCP scenarios (Table 4). The CSIRO-Mk 3-6-0 model predicted a significant decrease in rainfall at Abohar (R^2=0.02 to 0.59), Ludhiana (R^2=0.17), Bathinda (R^2=0.01 to 0.63), Faridkot (R^2=0.01 to 0.27), Abohar (R^2=0.54 to 0.59) (Table 4).

The IPSLCM5A-MR model predicted a significant increase in rainfall at Ludhiana (R^2=0.72 to 0.78), Ballowal Saunkhri (R^2=0.69), Amritsar (R^2=0.78), Patiala (R^2=0.61 to 0.63), Faridkot (R^2=0.61) and Abohar (R^2=0.49 to 0.53), but a significant decrease at Bathinda (R^2=0.07 to 0.29).

The Ensemble model predicted a significant increase in rainfall at Ludhiana (R^2=0.64 to 0.78), Ballowal Saunkhri (R^2=0.83 to 0.85), Patiala (R^2=0.59 to 0.78) and Abohar (R^2=0.64) but a significant decrease at Amritsar (R^2=0.001 to 0.27), Bathinda (R^2=0.13), Faridkot (R^2=0.005 to 0.231) and Abohar (R^2=0.05).

Amongst the four models, the FIO-ESM model invariably predicted a decreasing trend across the locations in Punjab. The model predicted a significant increase in rainfall at Amritsar (R^2=0.65), but a significant decrease at Ludhiana (R^2=0.14 to 0.20), Ballowal Saunkhri (R^2=0.03 to 0.48), Amritsar (R^2=0.18 to 0.50), Patiala (R^2=0.01), Bathinda (R^2=0.01 to 0.45), Faridkot (R^2=0.45 to 0.62) and Abohar (R^2=0.03 to 0.49).

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Table 5. Predicted variability in the number of rainy days/year by four climate models under four RCP scenarios in the present time, mid- and end-century in Punjab

Station	CSIRO-Mk 3-6-0				FIO-ESM				IPSLCM5A-MR				Ensemble			
	RCPs				RCPs				RCPs				RCPs			
	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5
Present Time (2016-25)																
Ludhiana	35	35	35	37	38	36	38	35	36	34	33	37	34	33	34	33
Ballowal Saunkhri	38	37	36	39	36	35	34	30	32	32	35	33	33	32	32	30
Amritsar	46	44	45	46	41	40	38	38	40	42	38	38	47	47	47	44
Patiala	40	38	40	40	38	37	39	38	35	38	39	37	38	39	40	40
Bathinda	42	41	38	40	39	40	38	36	38	36	36	28	40	38	39	39
Faridkot	37	40	40	37	39	38	35	37	38	39	42	37	41	41	38	36
Abohar	34	37	35	36	31	32	30	34	36	36	37	29	36	36	37	38
Average	**39**	**39**	**38**	**39**	**37**	**37**	**36**	**35**	**36**	**37**	**37**	**34**	**38**	**38**	**38**	**37**
Mid-Century (2026-60)																
Ludhiana	36	36	37	40	37	37	35	35	37	39	37	40	34	35	34	35
Ballowal Saunkhri	40	40	40	41	34	33	32	35	33	35	33	37	31	34	33	34
Amritsar	41	40	44	40	41	39	36	39	45	42	36	40	40	42	43	43
Patiala	40	40	41	41	38	39	38	42	38	36	38	38	41	41	37	42
Bathinda	40	34	38	36	38	37	35	38	39	33	38	35	38	37	41	39
Faridkot	38	35	38	37	36	37	36	39	39	42	37	37	40	37	40	40
Abohar	37	36	37	35	28	31	31	35	37	35	35	31	37	39	38	36
Average	**39**	**37**	**39**	**39**	**36**	**36**	**35**	**38**	**38**	**37**	**36**	**37**	**37**	**38**	**38**	**38**
End-Century (2061-95)																
Ludhiana	35	40	44	40	38	35	36	33	37	41	42	41	35	38	44	40
Ballowal Saunkhri	41	40	39	38	34	30	31	28	35	39	35	39	34	35	36	38
Amritsar	38	41	40	40	37	36	37	37	42	44	37	44	41	35	42	45
Patiala	39	39	42	43	37	39	39	40	42	39	42	42	41	43	42	43
Bathinda	40	36	34	36	34	38	37	32	40	38	40	37	39	36	38	40
Faridkot	40	39	35	36	35	36	39	36	37	39	37	36	38	39	41	35
Abohar	35	34	37	39	27	32	29	28	32	35	40	33	36	38	33	37
Average	**38**	**38**	**39**	**39**	**35**	**35**	**35**	**33**	**38**	**39**	**39**	**39**	**38**	**38**	**39**	**40**

Variability in the number of rainy days/year

The number of rainy days varied in different time slices across locations under four climate change models and scenarios (Table 5). The average number of rainy days as predicted by the four models and climatic scenarios in the state varied from 34 (IPSLCM5A-MR: RCPs 8.5) to 39 (CSIRO-Mk 3-6-0: RCP 2.6,4.5 and 8.5) during the present time (2016-25), 35 (FIO-ESM: RCP 6.0) to 39 (CSIRO-Mk 3-6-0: RCP 2.6, 6.0 and 8.5) during mid-century (2026-60), and 33 (FIO-ESM: RCP 8.5) to 40 (Ensemble: RCPs 8.5) during end-century (2061-95) (Table 5).

During present time slice the number of rainy days/year at Ludhiana ranged from 33 (Ensemble: RCPs 4.5 and 8.5) to 38 (FIO-ESM: RCPs 2.6 and 6.0); at Ballowal Saunkhri from 30 (FIO-ESM and Ensemble: RCP 8.5) to 39 (CSIRO-Mk 3-6-0: RCP 8.5); at Amritsar from 38 (FIO-ESM and IPSLCM5A-MR: RCPs 6.0 and 8.5) to 47 (Ensemble: RCPs 2.6, 4.5 and 6.0); at Patiala from 35 (IPSLCM5A-MR: RCP 2.6) to 40 (CSIRO-Mk 3-6-0 and Ensemble); at Bathinda from 28 (IPSLCM5A-MR: RCP 8.5) to 42 (CSIRO-Mk 3-6-0: RCP 2.6); at Faridkot from 35 (FIO-ESM: RCP 6.0) to 42 (IPSLCM5A-MR: RCP 6.0); and at Abohar from 29 (IPSLCM5A-MR: RCP 8.5) to 38 (Ensemble: RCP 8.5).

During the mid-century the number of rainy days/year at Ludhiana is projected to range from 34 (Ensemble: RCPs 2.6 and 6.0) to 40 (CSIRO-Mk 3-6-0

Table 6. Predicted variability in the number of rainy days/year during *kharif* season (May-October) by four climate models under four RCP scenarios in the present time, mid- and end-century in Punjab

Station	CSIRO-Mk 3-6-0				FIO-ESM				IPSLCM5A-MR				Ensemble			
	RCPs				RCPs				RCPs				RCPs			
	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5
Present Time (2016-25)																
Ludhiana	27	28	28	29	29	29	29	30	29	30	26	31	26	25	28	27
Ballowal Saunkhri	30	30	28	30	28	26	28	26	26	27	28	29	25	24	25	22
Amritsar	38	36	37	38	32	32	31	30	33	36	33	31	38	36	38	35
Patiala	31	29	31	31	31	28	31	38	29	32	30	30	30	34	32	33
Bathinda	35	33	30	31	33	33	34	29	33	30	31	25	34	33	31	33
Faridkot	30	32	34	30	32	29	32	30	31	32	27	31	32	32	34	28
Abohar	30	33	31	30	28	27	25	30	31	31	31	23	31	32	31	32
Average	**32**	**32**	**31**	**31**	**30**	**29**	**30**	**30**	**30**	**31**	**29**	**29**	**31**	**31**	**31**	**30**
Mid-Century (2026-60)																
Ludhiana	29	29	28	32	31	29	27	28	31	32	28	33	26	28	28	28
Ballowal Saunkhri	32	33	32	33	29	27	26	27	29	28	26	30	25	27	26	28
Amritsar	32	32	35	30	35	30	29	29	36	33	32	32	33	33	34	33
Patiala	33	33	32	33	33	30	32	42	32	31	29	30	31	34	30	35
Bathinda	33	27	30	29	32	30	29	30	32	27	31	29	34	32	34	33
Faridkot	30	27	30	30	29	30	31	32	33	30	30	30	32	33	30	32
Abohar	31	30	29	31	26	25	26	29	32	29	27	26	30	31	32	31
Average	**31**	**30**	**31**	**31**	**31**	**29**	**29**	**31**	**32**	**30**	**29**	**30**	**30**	**31**	**31**	**31**
End-Century (2061-95)																
Ludhiana	27	32	35	34	29	26	28	26	30	32	33	33	27	28	37	33
Ballowal Saunkhri	33	32	32	30	27	23	24	21	29	32	29	33	26	27	30	34
Amritsar	29	32	30	31	27	27	28	27	33	32	36	33	33	27	33	38
Patiala	32	31	33	35	31	30	31	44	34	34	33	35	32	35	35	36
Bathinda	33	29	28	30	28	31	30	25	32	31	30	33	33	34	32	35
Faridkot	31	32	30	29	29	28	29	30	31	30	30	31	33	32	30	29
Abohar	30	28	30	31	23	25	24	24	26	29	31	28	31	30	28	31
Average	**31**	**31**	**31**	**31**	**28**	**27**	**28**	**28**	**31**	**31**	**32**	**32**	**31**	**30**	**32**	**34**

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and IPSLCM5A-MR: RCP 8.5); at Ballowal Saunkhri from 32 (FIO-ESM: RCP 6.0) to 41 (CSIRO-Mk 3-6-0: RCP 8.5); at Amritsar from 36 to 42 (IPSLCM5A-MR: RCPs 6.0 and 4.5, respectively); at Patiala from 36 (IPSLCM5A-MR: RCP 4.5) to 42 (FIO-ESM: RCP 8.5); at Bathinda from 33 (IPSLCM5A-MR: RCP 4.5) to 41 (Ensemble: RCP 6.0); at Faridkot from 35 (CSIRO-Mk 3-6-0: RCP 4.5) to 42 (IPSLCM5A-MR: RCP 4.5); and at Abohar from 28 (FIO-ESM: RCP 2.6) to 39 (Ensemble: RCP 4.5).

The variability in the number of rainy days/year during end-century at Ludhiana ranged from 35 to 44 (CSIRO-Mk 3-6-0: RCPs 2.6 and 6.0, respectively); at Ballowal Saunkhri from 35 (IPSLCM5A-MR: RCP 2.6) to 41 (CSIRO-Mk 3-6-0: RCP 2.6); at Amritsar from 35 to 45 (Ensemble: RCPs 4.5 and 8.5, respectively); at Patiala from 37 (FIO-ESM: RCP 2.6) to 43 (CSIRO-Mk 3-6-0: RCP 8.5); at Bathinda from 32 (FIO-ESM; RCP 8.5) to 40 (CSIRO-Mk 3-6-0, IPSLCM5A-MR and Ensemble); at Faridkot from 35 (CSIRO-Mk 3-6-0 and FIO-ESM) to 41 (Ensemble: RCP 6.0); and at Abohar from 35 (CSIRO-Mk 3-6-0: RCP 2.6) to 40 (IPSLCM5A-MR: RCP 6.0).

Number of rainy days during the *kharif* season (May-October)

The number of rainy days during the *kharif* season varied in different time slices across locations under four climate change models and scenarios (Table 6). The average number of rainy days during the *kharif* season rainfall as predicted by the four models and climatic scenarios in the state varied from 29 (FIO-ESM: RCPs 4.5; IPSLCM5A-MR: RCPs 6.0, 8.5) to 32 (CSIRO-Mk 3-6-0: RCP 2.6 and 4.5) during the present time (2016-25), 29 (FIO-ESM: RCP 4.5 and 6.0; IPSLCM5A-MR: RCPs 6.0) to 32 (IPSLCM5A-MR: RCP 2.6) during mid-century (2026-60) and 27 (FIO-ESM: RCP 4.5) to 34 (Ensemble: RCPs 8.5) during end-century (2061-95) (Table 6).

During the present time slice the number of rainy days during *kharif* season at Ludhiana ranged from 25 (Ensemble: RCP 4.5) to 31 (IPSLCM5A-MR: RCP 8.5); at Ballowal Saunkhri from 22 (Ensemble: RCP 8.5) to 30 (CSIRO-Mk 3-6-0: RCPs 2.6, 4.5 and 8.5); at Amritsar from 30 (FIO-ESM: RCP 8.5) to 38 (CSIRO-Mk 3-6-0 and Ensemble); at Patiala from 29 (CSIRO-Mk 3-6-0 and IPSLCM5A-MR) to 34 (Ensemble: RCP 4.5); at Bathinda from 25 (IPSLCM5A-MR: RCP 8.5) to 35 (CSIRO-Mk 3-6-0: RCP 2.6); at Faridkot from 27 (IPSLCM5A-MR: RCP 6.0) to 34 (CSIRO-Mk 3-6-0: RCP 6.0); at Abohar from 25 (FIO-ESM: RCP 6.0) to 33 (CSIRO-Mk 3-6-0: RCP 4.5).

The variability in the *kharif* season rainy days/year during mid-century at Ludhiana ranged from 28 (FIO-ESM: RCP 6.0) to 33 (IPSLCM5A-MR: RCP 8.5); at Ballowal Saunkhri from 25 (Ensemble: RCP 2.6) to 33 (CSIRO-Mk 3-6-0: RCPs 4.5 and 8.5); at Amritsar from 29 (FIO-ESM: RCPs 6.0 and 8.5) to 36 (IPSLCM5A-MR: RCP 2.6); at Patiala from 29 (IPSLCM5A-MR: RCP 6.0) to 42 (FIO-ESM: RCP 8.5); at Bathinda from 27 (CSIRO-Mk 3-6-0: RCP 4.5) to 34 (Ensemble: RCPs 2.6 and 6.0); at Faridkot from 27 (CSIRO-Mk 3-6-0: RCP 4.5) to 33 (IPSLCM5A-MR and Ensemble); at Abohar from 25 (FIO-ESM: RCP4.5) to 32 (IPSLCM5A-MR and Ensemble).

During the end-century the *kharif* season rainy days at Ludhiana ranged from 26 (FIO-ESM: RCP 8.5) to 37 (Ensemble: RCP 6.0); at Ballowal Saunkhri from 21 (FIO-ESM: RCP 8.5) to 34 (Ensemble: RCP 8.5); at Amritsar from 27 (FIO-ESM: RCPs 2.6 and 4.5) to 38 (Ensemble: RCP 8.5); at Patiala from 30 to 44 (FIO-ESM: RCPs 4.5 and 8.5, respectively); at Bathinda from 28 (CSIRO-Mk 3-6-0 and FIO-ESM) to 34 (Ensemble: RCP 4.5); at Faridkot from 28 (FIO-ESM: RCP 4.5) to 33 (Ensemble: RCP 2.6); and at Abohar from 23 (FIO-ESM: RCP 2.6) to 31 (Ensemble: RCP 2.6).

Number of rainy days during *rabi* season (November-April)

The rainy days during *rabi* season varied across different time slices and locations under four climate change models and scenarios (Table 7). The average *rabi* season rainy days as predicted by the four models and climatic scenarios in the state varied from 4 (IPSLCM5A-MR: RCP 8.5) to 7 (CSIRO-Mk 3-6-0: RCP 2.6, 4.5, 6.0 and 8.5; IPSLCM5A-MR: RCP 6.0; Ensemble: RCPs 6.0) during the present time (2016-25), 5 (FIO-ESM: RCP 2.6 and 6.0) to 7 (CSIRO-Mk 3-6-0: RCP 2.6, 6.0 and 8.5; FIO-ESM: RCP 4.5 and 8.5; IPSLCM5A-MR: RCP 6.0) during mid-century (2026-60), and 5 (IPSLCM5A-MR: RCPs 8.5) to 8 (IPSLCM5A-MR: RCPs 6.0) during end-century (2061-95) (Table 7).

During present time slice the number of rainy days at Ludhiana ranged from 4 (IPSLCM5A-MR: RCPs 4.5 and 8.5) to 8 (FIO-ESM: RCP 2.6); at Ballowal Saunkhri from 3 (IPSLCM5A-MR: RCP 8.5) to 8 (CSIRO-Mk 3-6-0: RCP 6.0); at Amritsar from 5 (IPSLCM5A-MR: RCP 8.5) to 8 (all four models); at Patiala from 4 (IPSLCM5A-MR: RCP 2.6) to 9 (CSIRO-Mk 3-6-0: RCP 8.5); at Bathinda from 3 (FIO-ESM: RCP 6.0) to 8 (CSIRO-Mk 3-6-0 and FIO-ESM); at Faridkot from 5 (IPSLCM5A-MR and CSIRO-Mk 3-6-0) to 8 (Ensemble: RCP 2.6); and at Abohar from 4 (FIO-ESM: RCPs 2.6, 6.0 and 8.5) to 7 (IPSLCM5A-MR: RCP 2.6).

The variability in the *rabi* season rainy days/year during mid-century at Ludhiana ranged from 4 (FIO-ESM: RCP 6.0) to 8 (CSIRO-Mk 3-6-0: RCP 8.5); at

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Table 7. Predicted variability in number of rainy days/season during *rabi* season (November-April) by four climate models under four RCP scenarios in the present time, mid- and end-century in Punjab

Station	CSIRO-Mk 3-6-0				FIO-ESM				IPSLCM5A-MR				Ensemble			
	RCPs				RCPs				RCPs				RCPs			
	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5
Present Time (2016-25)																
Ludhiana	7	5	5	6	8	5	6	5	7	4	6	4	6	6	6	6
Ballowal Saunkhri	7	7	8	7	7	7	5	4	5	6	7	3	6	7	6	6
Amritsar	7	8	7	7	8	7	7	7	6	6	8	5	6	8	8	8
Patiala	8	7	7	9	5	8	6	6	4	6	8	5	6	5	7	7
Bathinda	7	8	6	8	6	6	3	8	6	7	6	4	4	5	7	5
Faridkot	5	6	6	7	6	6	7	7	6	7	6	5	8	7	7	6
Abohar	5	6	7	6	4	5	4	4	7	6	6	5	6	5	6	6
Average	**7**	**7**	**7**	**7**	**6**	**6**	**5**	**6**	**6**	**6**	**7**	**4**	**6**	**6**	**7**	**6**
Mid-Century (2026-60)																
Ludhiana	7	5	6	8	6	6	4	7	6	5	6	6	7	6	5	6
Ballowal Saunkhri	6	6	7	7	5	6	5	7	4	7	6	6	6	6	5	5
Amritsar	9	8	8	9	6	8	6	8	7	8	10	6	7	6	8	8
Patiala	7	7	6	7	5	7	6	6	3	5	7	7	5	6	7	7
Bathinda	7	6	7	6	5	7	5	7	7	6	6	5	4	5	6	4
Faridkot	6	7	6	7	6	6	6	7	6	6	7	6	7	7	6	7
Abohar	6	5	6	6	2	6	4	6	6	6	7	6	5	7	7	7
Average	**7**	**6**	**7**	**7**	**5**	**7**	**5**	**7**	**6**	**6**	**7**	**6**	**6**	**6**	**6**	**6**
End-Century (2061-95)																
Ludhiana	8	6	7	6	9	6	5	5	7	5	7	6	6	6	6	5
Ballowal Saunkhri	6	7	7	6	6	6	6	6	5	6	6	5	7	7	5	6
Amritsar	9	9	8	8	8	8	8	8	7	10	10	7	8	7	8	6
Patiala	7	7	6	6	5	7	7	5	6	3	7	5	6	8	7	6
Bathinda	6	6	6	5	5	7	6	6	5	6	8	4	5	7	6	4
Faridkot	6	7	7	6	5	6	5	5	5	6	7	4	7	6	7	5
Abohar	7	6	7	6	6	5	5	4	6	7	8	4	6	8	5	4
Average	**7**	**7**	**7**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**8**	**5**	**6**	**7**	**6**	**5**

Ballowal Saunkhri from 4 (IPSLCM5A-MR: RCP 2.6) to 7 (CSIRO-Mk 3-6-0, FIO-ESM and IPSLCM5A-MR); at Amritsar from 6 (FIO-ESM and IPSLCM5A-MR) to 10 (IPSLCM5A-MR: RCP 6.0); at Patiala from 3 (IPSLCM5A-MR: RCP 2.6) to 7 (all four models); at Bathinda from 4 (Ensemble: RCPs 2.6 and 8.5) to 7 (CSIRO-Mk 3-6-0, FIO-ESM and IPSLCM5A-MR); at Faridkot from 6 to 7 (all four models); and at Abohar from 2 (FIO-ESM: RCP 2.6) to 7 (IPSLCM5A -MR and Ensemble).

The *rabi* season rainy days/year during end-century at Ludhiana is projected to range from 5 (FIO-ESM and IPSLCM5A-MR) to 9 (FIO-ESM: RCP 2.6); at Ballowal Saunkhri from 5 (IPSLCM5A-MR and Ensemble) to 7 (CSIRO-Mk 3-6-0 and Ensemble); at Amritsar from 6 (Ensemble: RCP 8.5) to 10 (IPSLCM5A-MR: RCPs 4.5 and 6.0); at Patiala from 5 (FIO-ESM and IPSLCM5A-MR) to 7 (all four models); at Bathinda from 4 (IPSLCM5A-MR and Ensemble) to 8 (IPSLCM5A-MR: RCP 6.0); at Faridkot from 4 (IPSLCM5A-MR: RCP 8.5) to 7 (CSIRO-Mk 3-6-0, IPSLCM5A-MR and Ensemble); and at Abohar from 4 (FIO-ESM, IPSLCM5A-MR and Ensemble) to 8 (Ensemble: RCP 4.5).

Trend analysis of rainy days

The time trend analysis of rainy days during 80 years (2016 to 2095) in Punjab state exhibited significant variability across locations, models and RCP scenarios (Table 8). The CSIRO-Mk 3-6-0 model predicted a significant increase in rainy days at Ludhiana (R^2=0.71

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to 0.78) and Abohar (R^2=0.72), but a significant decrease at Amritsar (R^2=0.24 to 0.75) (Table 8).

The IPSLCM5A-MR model predicted a significant increase in rainy days at Ludhiana (R^2=0.40 to 0.83), Ballowal Saunkhri (R^2=0.60 to 0.65), Patiala (R^2=0.51 to 0.66), Bathinda (R^2=0.53 to 0.58) and Abohar (R^2=0.53), but a significant decrease at Abohar (R^2=0.0.36).

The Ensemble model predicted a significant increase in rainy days at Ludhiana (R^2=0.59 to 0.76), Ballowal Saunkhri (R^2=0.51 to 0.61), Patiala (R^2=0.63), but a significant decrease at Amritsar (R^2=0.51) and Faridkot (R^2=0.29).

Amongst the four models, the FIO-ESM model invariably predicted a decreasing trend across the locations in Punjab. The model predicted a significant decrease in rainy days at Ludhiana (R^2=0.21 to 0.24), Ballowal Saunkhri (R^2=0.26 to 0.51), Amritsar (R^2=0.53), Bathinda (R^2=0.51 to 0.58), Faridkot (R^2=0.21 to 0.49), and Abohar (R^2=0.49).

In the present study, critical analysis of total rainfall on annual and seasonal scales as projected by four climate models across climatic scenarios points out that the magnitude of total rainfall, the number of rainy days and their trends may change spatially and temporally during the 21st century in Punjab. The variations within the projected datasets may result in erratic projections of rainfall-associated agro-meteorological metrics.

Mishra and Liu (2014) observed that the projected warming of the atmosphere in a region and consequent decrease in rainfall enhances the risk of drought and prolonged dry spells. Earlier studies by Dash *et al.* (2009, 2011) have reported significantly decreased frequencies of light precipitation days and an increasing trend of prolonged dry spells during the later half of the 20th century in India. This increase in prolonged dry spells, decrease in light precipitation and rainy days suggests the weakening of the Indian summer monsoon circulation over India. This hypothesis of a weakening of monsoon circulation in a warming environment is supported by the reductions in low-level wind fields and easterly jet (Sreekala *et al.,* 2013; Bansod *et al.*, 2012). In the study region, a recent study by Sandhu and Kaur (2023) waning in monsoon rainfall in Punjab was observed. The monsoon rainfall since the year 2000 was deficient for 18 years (90% of 20 years), as compared to the earlier 30 years (1970 to 1999), when it was below normal for 10 years (33% of 30 years). A recent study by Kaur *et al.* (2025) has attributed this decline in monsoon rainfall to resource and water-intensive cultivation of rice on >3 Mha area in a small state having a geographical area of only 5.03 Mha. They concluded that continuous flooding in rice fields during June to September months, which coincide with the monsoon rainfall season, is hindering the buildup of

Table 8. Rate of change in number of rainy days/year and its coefficient of determination (R^2) as influenced by climate change models and scenarios at different locations

Station	CSIRO-Mk 3-6-0				FIO-ESM				IPSLCM5A-MR				Ensemble			
	RCPs				RCPs				RCPs				RCPs			
	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5
Ludhiana	-0.004 (0.004)	0.105 (0.712)*	0.178 (0.779)*	0.023 (0.083)	0.001 (0.000)	-0.058 (0.212)	-0.005 (0.002)	-0.057 (0.246)	0.009 (0.006)	0.057 (0.221)	0.182 (0.829)*	0.083 (0.404)	0.009 (0.018)	0.082 (0.269)	0.197 (0.761)*	0.117 (0.591)*
Ballowal Saunkhri	0.042 (0.256)	0.026 (0.082)	-0.006 (0.004)	-0.039 (0.181)	-0.043 (0.120)	-0.094 (0.406)	-0.059 (0.263)	-0.121 (0.511)*	0.043 (0.167)	0.129 (0.604)*	0.051 (0.140)	0.102 (0.649)*	0.036 (0.073)	0.037 (0.123)	0.126 (0.509)*	0.102 (0.611)*
Amritsar	-0.104 (0.424)	0.001 (0.000)	-0.047 (0.240)	-0.096 (0.745)*	-0.093 (0.526)*	-0.084 (0.531)*	0.032 (0.104)	-0.029 (0.171)	-0.018 (0.022)	0.049 (0.135)	0.109 (0.375)	0.095 (0.383)	-0.034 (0.065)	-0.164 (0.511)*	-0.037 (0.105)	0.043 (0.143)
Patiala	-0.024 (0.093)	0.005 (0.009)	-0.005 (0.006)	0.075 (0.326)	-0.026 (0.043)	-0.006 (0.004)	0.007 (0.007)	-0.009 (0.009)	0.103 (0.506)*	0.081 (0.373)	0.078 (0.397)	0.124 (0.656)*	0.031 (0.145)	0.077 (0.627)*	0.100 (0.626)*	0.036 (0.277)
Bathinda	-0.022 (0.100)	-0.014 (0.016)	-0.024 (0.041)	-0.042 (0.078)	-0.101 (0.585)*	-0.016 (0.021)	0.008 (0.008)	-0.121 (0.515)*	-0.012 (0.014)	0.095 (0.391)	0.093 (0.530)*	0.109 (0.582)*	-0.000 (0.000)	-0.004 (0.001)	0.029 (0.128)	0.008 (0.009)
Faridkot	0.022 (0.068)	0.016 (0.048)	-0.001 (0.000)	-0.024 (0.031)	-0.050 (0.207)	-0.029 (0.103)	-0.075 (0.489)	-0.050 (0.207)	-0.031 (0.078)	0.005 (0.003)	0.086 (0.418)	-0.028 (0.075)	-0.018 (0.061)	-0.041 (0.129)	-0.045 (0.141)	-0.059 (0.288)
Abohar	0.0081 (0.011)	-0.060 (0.468)*	0.155 (0.720)*	0.003 (0.001)	-0.025 (0.114)	-0.005 (0.005)	-0.014 (0.024)	-0.115 (0.499)*	-0.089 (0.355)	-0.028 (0.051)	0.096 (0.534)*	0.063 (0.228)	0.014 (0.142)	0.028 (0.121)	-0.068 (0.116)	-0.055 (0.215)

*Significant R^2 values

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pressure gradient required for the onward movement of monsoon currents in northern plains of India.

In the present study, total annual rainfall as predicted by four climate models under four climatic scenarios during the present time (2016-25) varied from 430 to 510mm, which increased to 444-537mm during mid-century (2026-60) and to 433-548 mm during end-century (2061-95). Though the average rainy days in the state varied from 34 to 39 days across the locations, there is a projected decrease in the southwestern region and an increase in the central regions of the state. Among the four climate models, the FIO-ESM model invariably predicted a decreasing trend in rainy days across the locations during the 21st century in Punjab.

The analysis of the rainfall datasets across the state revealed that the total annual rainfall/year was maximum at Patiala followed by Amritsar, Ballowal Saunkhri, Ludhiana, Bhatinda, Faridkot and Abohar in decreasing order. But, the number of rainy days/year was predicted to be maximum at Amritsar followed by Ludhiana, Patiala, Ballowal Saunkhri, Bhatinda, Faridkot and Abohar in decreasing order. These results corroborate the findings of Kaur *et al.* (2021), which reveal similar trends in the Shivalik foothills. A noticeable trend of decreasing rainfall and increasing temperature was observed from north-east to south-west Punjab, persisting across both *kharif* and *rabi* seasons. The state of Punjab, situated in the IGP, has a semi-arid and subtropical climate, with annual rainfall varying across different regions, from 250-350 mm in the southwest to 900-1000 mm in the northeast's sub-mountainous zones (Kaur *et al.,* 2020, 2021, 2022).

However, among the four models, peak rainfall amounts were predicted by the Ensemble model, followed by the CSIRO-Mk 3-6-0, IPSLCM5A-MR and FIO-ESM models in decreasing order. The maximum number of rainy days/year was predicted by CSIRO-Mk 3-6-0 model, followed by the Ensemble, IPSLCM5A-MR, and least by the FIO-ESM model. The prediction of rainfall was maximum under the RCP 4.5 scenario, followed by RCP 6.0, RCP 8.5 and least under the RCP 2.6 scenario. The rainy days/year were predicted to be maximum under the RCP 2.6 scenario, followed by RCP 4.5 and RCP 6.0, and least under the RCP 8.5 scenario. The rainfall, as well as the rainy days in Punjab state, are projected to increase during mid-century and later decrease by the end of the century.

The analysis of rainfall datasets in the present study showed that annual and seasonal differences in total rainfall and number of rainy days, along with time trends, exist and vary with time slices of climate change, the model used, climate change scenario, and locations in Punjab state. Within the state, the total rainfall received is maximum at Patiala (in south-east) and the number of rainy days at Amritsar (north-west), respectively, but both are minimum at Abohar (south-west). The time trend analysis of rainfall and rainy days showed an increase by the model IPSLCM5A-MR under RCP 6.0 and a decrease by the FIO-ESM model under RCP 4.5 and 8.5. The spatial distribution of total rainfall within the state showed peak rainfall at Patiala followed by Amritsar, Ballowal Saunkhri, Ludhiana, Faridkot, Bhatinda and Abohar in decreasing order. However, the total number of rainy days was maximum at Amritsar, followed by Ludhiana, Patiala, Ballowal Saunkari, Bhatinda, Faridkot and Abohar in decreasing order. Averaged over locations, the temporal total rainfall during mid-century and end-century is predicted to increase by 4.2% from the present time (476 mm) annually; 4.2 and 4.5%, respectively from the present time (421 mm) during *kharif* season and 2.4 and 9.8%, respectively from the present time (56 mm) during *rabi* season. This increase in rainfall is, however, predicted to occur in nearly the same number (increase <1%) of rainy days.

CONCLUSION

The results of the present study are important for Punjab state in which resource and water-intensive agriculture forms the basic backbone for the food security of India. So, the location specific rain asociated agrometeorological metrics are of practical implications to assess water availability for crop production and adoption of suitable water management/irrigation practices to minimize the adverse impacts of climate changes on agriculture productivity, also to increase/improve drainage facilities/structures and remove/store excess water to be utilized during the critical pheno-phases of the crop.

Authors' contribution

Conceptualization of research work and designing of experiments (JK, PK); Execution of field/lab experiments and data collection (JK, PK); Analysis of data and interpretation (JK, PK, SK); Preparation of manuscript (JK, PK, SK).

Conflict of interests

Authors declare that there is no conflict of interests.

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