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Research Article

Projected Changes in Extreme Weather Events as Simulated by Ensemble Model at Different RCP based Emission Scenarios for Punjab (India)

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ABSTRACT

Climate change induced climate variability is resulting in increased frequency of extreme weather events. Punjab state is primarily an agriculture based and such changes can hamper the crop production. So the present study was undertaken to analyze the projected temperature and rainfall simulated by Ensemble model available at *http://gismap.ciat.cgiar.org/MarkSimGCM*/ for changes in incidence of extreme weather events during mid-century (MC) (2020-49) and end-century (EC) (2066-95). Seven locations in Punjab viz., Ludhiana, Ballowal Saunkhri, Amritsar, Patiala, Bathinda, Faridkot, and Abohar were studied under four RCP (Representative Concentration Pathways) scenarios. The long-term projections indicate an increase in the maximum and minimum temperature, besides, reduction in rainfall at all locations under different RCP scenarios. The number of days with maximum temperature ranging 40-44°C is likely to increase in May at Bathinda and may go up to 630 and 650 days out of 30 years' time period during the MC (2020-49) and EC (2066-95), respectively. The number of cold wave days with minimum temperature ranging 0-5°C is likely to rise in January at Faridkot and Bathinda. The number of cold wave days with a minimum temperature ranging 0-5°C may go up to 898 and 570 days in the mid and EC, respectively. The frequency of extreme rainfall days having >30 mm rainfall is expected to increase in July during MC as compare to EC projections. The incidence of >30 mm rainfall during September will if coincide with grain development phase of rice in the state may be detrimental for the crop. The EC projections have also shown a greater rise in the prolonged drought spells. Hence, knowledge and data base of extreme weather events of a particular region can help in better crop planning. The probability analysis of occurrence of heat wave, cold wave, wet and dry spells is essentially required for successful crop planning, development of suitable agro-techniques, recommendation of suitable crop varieties, design of water-harvesting tanks, earthen dams and other soil conservation structures.

Key words: Extreme weather events, ensemble model, RCPs, rainfall, temperature

Introduction

The increase in frequency of extreme weather events due to global warming triggered climate changes have resulted in manifold increase in vulnerability and climatic risks in agriculture. Inter- and intra-seasonal weather variability and extreme weather events like droughts, floods, heat and cold waves, strong winds, hailstorms, cyclones etc. have increased over the recent decades (Singh and Kalra, 2016). The major processes which contribute towards climate change are burning of fossil fuels, industrial processes, deforestation and agriculture. Amongst the various greenhouse gases, carbon dioxide contributes

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by 76%, methane by 16%, nitrous oxides by 6% and chlorofluorocarbons by 2% towards changes in climate system (IPCC, 2014). Agriculture contributes 28% of the Indian greenhouse gas emissions primarily through methane emission from paddy fields, enteric fermentation in ruminant animals and nitrous oxides from application of manures and fertilizers to the soil (Aggarwal, 2008). Global circulation models (GCMs) have predicted rise in global average temperature by about 2°C by end of the century. The total precipitation is predicted to increase during *kharif* season, but its variability in time and space may vary at local level. There are evidences of increased heavy precipitation and decreased light precipitation in widespread parts of the globe due to global warming (Sai *et al.*, 2016). Due to highly erratic rainfall, there is an increased risk of drought as a result of increased prolonged dry spells, total dry days and decreased light precipitation days over India as a consequence of global warming (Mishra and Liu, 2014).

Changes in climate system are likely to have severe implications on agricultural production especially in the tropical and sub-tropical regions. Hatfield and Prueger (2015) reported that warmer and more extreme temperature events will significantly affect the plant growth. Extreme of low temperature, i.e. frost causes sterility and abortion of formed grains, while excessive high temperature causes reduction in grain number and duration of the grain filling period (Barlow *et al.*, 2015). Aggarwal (2008) has reported that under climate change scenarios crop production in India is likely to decrease by 10-40% despite the beneficial effects of higher CO_2 on crop growth. The uncertainty in rainfall leading to droughts and floods is likely to enhance year-to-year yield fluctuations. Though the reduced frequency of frost under warming scenarios may prove beneficial for frost sensitive crops like potato, peas etc. Kaur and Prabhjyot-Kaur (2015) have reported a gradual rise in minimum temperature of (0.07°C per year) over the past four decades at Ludhiana in Punjab. Though both maximum and minimum temperatures play an important role in crop production, but higher night temperatures result in increase in respiration thereby reducing the net gain in the form of grain yield.

De *et al.* (2005) observed that knowledge about changes in climate is helpful for preparedness in agriculture. In this context climate models provide this information to assess climate change impacts on different systems. The projected changes indicate an increase in the frequency of extreme events and in recent years the increased occurrence of such events has already drawn the attention of scientists for better understanding of their underlying causes (Kerr, 2013). Generally, extreme weather events do not occur due to a single cause but have various possible contributing factors which all have links to human influence (Field *et al.,* 2012; Stocker *et al.,* 2014). Also the rise in global annual temperatures is causing the continuing intensification of hot temperature extremes (Seneviratne *et al.*, 2014; Sillmann *et al.,* 2014). These rising temperature (Houghton *et al.*, 2001; Hirabayashi *et al.,* 2008; Nazarenko *et al.,* 2015) will lead to the increasing evaporation from the surface which will enhance the atmospheric humidity and precipitation (Held and Soden, 2002).

The economy of Punjab state is primarily dependant on agricultural sector and the climate change would be pivotal in influencing the crop production in the region. So this study attempts to analyze the changes in the incidence of climate extremes under RCPs based scenarios of climate change using the output from the Ensemble model in Punjab.

Material and Methods

Site description and model data used

Seven well distributed locations in Punjab state (Fig. 1) with available historical weather data base records were selected for the study. The daily data on maximum temperature (Tmax), minimum temperature (Tmin) and rainfall (RF) for the baseline period and projected data for MC (MC: 2020-49) and EC (EC: 2066-95) under different RCPs based emission scenarios were downloaded from the site *http://gismap.ciat.cgiar.org/MarkSimGCM/* for Ludhiana, (30°56′ N 75°48′ E 247 a.m.s.l.), Ballowal Saunkhri (30°07′ N 76°23′ E 355 a.m.s.l.), Amritsar (31°37′ N, 74°53′ E 231 a.m.s.l.), Patiala (30°20′ N, 76°28′ E 251 a.m.s.l.), Bathinda (30°12′ N, 74°57′ E 211 a.m.s.l.), Faridkot (30°40′ N, 74°45′ E 204

Fig. 1. Location map of selected seven stations

a.m.s.l.) and Abohar (30°58′ N, 74°36′ E 177 a.m.s.l). The downscaled data was then corrected by difference method after developing the suitable correction factors on monthly time scales using data for seven years (2010-2015) and then validated using data for two years (2016-2017) as given below:

$$X_{modelcorr} = X_{modeluncorr} – (X_{model} - X_{obs})$$

Where

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

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

X_{model} = Daily modeled value

X_{obs}= Daily observed value

The indices for extreme weather events evaluated in the study were:

a) *Heat wave* refers to a period of temperatures (4.0°C to 5.0°C) higher than the normal while temperature ≥ 5.0°C from normal is called severe heat wave. According to India Meteorological Department (IMD) heat wave is considered when the maximum temperature of a station reaches ≥ 40°C for plain regions (http://www.chandigarhmausam.in/uploads/Learn%20Meteorology.pdf).

b) *Cold wave* refers to a period when minimum temperatures is 4.0 to 5.0°C lower than the normal while temperature ≤ 5.0°C from normal is called severe cold wave. According to India Meteorological Department (IMD) cold wave is considered when the minimum temperature of a station is reaches < 10°C for plain regions.

c) *Heavy rainfall* is defined as the maximum annual 5-day consecutive rainfall. The rainfall ranging between > 4 mm/ hour and < 8 mm/hour is called heavy rainfall.

d) *Rainy day* as per IMD is a day having a rainfall ≥ 2.5 mm.

Results and Discussion

Changes in the occurrence of heat wave days

The occurrence of extremes of Tmax ranging 40-44°C and >44°C during the MC (2020-2049) and EC (2066-2095) periods at all seven locations under four RCP scenarios have been given in Table 1 and Table 2 respectively.

The number of days with Tmax ranging 40-44°C was projected to increase both under MC and EC periods. The highest number of heat wave days could be in May under RCP 8.5 scenario which were 645 (Bathinda), 513 (Ludhiana), 506 (Faridkot and Abohar), 465 (Ballowal Saunkhri), 463 (Amritsar) and 438 (Patiala) days during the MC. Similarly, during the EC period, the highest numbers of heat wave days are expected to occur in May which were 650 (Bathinda), 645 (Ludhiana), 629 (Abohar), 624 (Amritsar), 623 (Ballowal Saunkhri), 619 (Faridkot) and 563 (Patiala) days under RCP 8.5 scenarios (Table 1). Among all locations, the highest number of heat wave days was observed at Bathinda followed by Ludhiana and Abohar in the May month during EC. The total number of days with Tmax ranging 40-44°C was projected to be highest 1248 to 1564 (Bathinda) followed by 561 to 1014 (Faridkot) days under four RCP based emission scenarios during MC. Similarly, during the EC period, the highest total numbers of heat wave days are 1290 to 1690 (Bathinda) followed by 1053 to 1616 (Faridkot) days under four RCP based emission scenarios.

The model simulations indicate that there would also an increase in the number of days with Tmax

Table 1. Heat wave days as simulated by Ensemble model during MC (2020-49) and EC (2066-95)

Stations	Months	No. of heat wave days during MC (40-44°C)				No. of heat wave days during EC (40-44°C)			
		RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Ludhiana	April	24	36	16	40	30	140	125	294
	May	413	504	383	513	454	645	567	609
	June	240	331	221	336	315	577	519	566
	July	5	14	11	24	0	60	70	114
	Total	**682**	**885**	**631**	**913**	**799**	**1422**	**1281**	**1583**
Ballowal	April	30	44	29	28	30	158	147	276
Saunkhri	May	411	430	361	465	437	605	606	623
	June	176	262	168	285	207	534	499	621
	July	11	38	11	36	31	60	60	84
	Total	**628**	**774**	**569**	**814**	**705**	**1357**	**1312**	**1604**
Amritsar	April	30	53	30	56	30	171	164	294
	May	374	491	343	463	423	624	609	498
	June	179	276	188	240	210	526	491	611
	July	15	30	30	42	30	66	42	83
	Total	**598**	**850**	**591**	**801**	**693**	**1387**	**1306**	**1486**
Patiala	April	30	76	40	69	30	270	219	353
	May	353	432	425	438	432	541	537	558
	June	152	346	275	349	201	563	541	642
	July	31	44	60	38	34	36	52	219
	Total	**566**	**898**	**800**	**894**	**697**	**1410**	**1349**	**1772**
Bathinda	April	73	90	40	261	90	240	208	441
	May	614	602	630	645	600	518	571	650
	June	484	501	488	420	480	603	571	111
	July	94	113	90	238	120	152	155	488
	Total	**1265**	**1306**	**1248**	**1564**	**1290**	**1513**	**1505**	**1690**
Faridkot	April	20	23	3	31	270	114	101	276
	May	506	382	360	416	491	613	552	619
	June	362	187	180	192	565	441	331	575
	July	126	43	18	48	290	84	69	142
	Total	**1014**	**635**	**561**	**687**	**1616**	**1252**	**1053**	**1612**
Abohar	April	11	21	3	20	30	89	58	270
	May	395	484	406	506	469	629	619	491
	June	249	321	232	362	286	526	501	565
	July	90	106	90	126	90	187	173	290
	Total	**745**	**932**	**731**	**1014**	**875**	**1431**	**1351**	**1616**

Table 2. Heat wave days as simulated by ensemble model during MC (2020-49) and EC (2066-95)

Stations	Months	No. of heat wave days during MC (>44°C)				No. of heat wave days during EC (>44°C)			
		RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Ludhiana	April	-	-	-	-	-	-	-	16
	May	16	26	-	24	30	84	30	300
	June	28	29	21	29	30	60	37	198
	July	-	-	-	-	-	-	-	-
	Total	**44**	**55**	**21**	**53**	**60**	**144**	**67**	**514**
Ballowal	April	-	-	-	-	-	-	-	10
Saunkhri	May	16	25	-	20	30	70	29	258
	June	17	21	6	20	30	60	41	143
	July	-	-	-	-	-	-	-	-
	Total	**33**	**46**	**6**	**40**	**60**	**130**	**70**	**411**
Amritsar	April	-	-	-	-	-	-	-	13
	May	10	29	2	22	30	110	25	386
	June	5	22	3	12	30	60	39	116
	July	-	-	-	-	-	-	-	-
	Total	**15**	**51**	**5**	**34**	**60**	**170**	**64**	**515**
Patiala	April	-	-	-	-	-	30	14	56
	May	29	30	30	39	30	129	58	344
	June	6	30	30	30	30	60	51	164
	July	-	-	-	-	-	-	-	11
	Total	**35**	**60**	**60**	**69**	**60**	**219**	**123**	**575**
Bathinda	April	-	-	-	1	-	-	-	200
	May	66	98	30	580	90	352	249	880
	June	79	109	61	391	90	180	175	769
	July	-	-	-	10	-	-	-	74
	Total	**145**	**207**	**91**	**982**	**180**	**532**	**424**	**1923**
Faridkot	April	-	-	-	-	4	-	-	7
	May	30	13	-	15	402	30	30	251
	June	25	-	-	2	232	30	21	137
	July	-	-	-	-	56	-	-	-
	Total	**55**	**13**	**-**	**17**	**694**	**60**	**51**	**395**
Abohar	April	-	-	-	-	-	-	-	4
	May	29	30	5	30	30	82	30	402
	June	18	23	8	25	30	55	38	232
	July	-	-	-	-	-	-	-	56
	Total	**47**	**53**	**13**	**55**	**60**	**137**	**68**	**694**

>44°C during the EC as compared to the MC (Table 2). The highest number of heat wave days could be in May under RCP 4.5 and 8.5 scenarios which were 580 (Bathinda), 39 (Patiala), 30 (Abohar and Faridkot), 29 (Ludhiana and Amritsar) and 25 (Ballowal Saunkhri) days during the MC. Similarly, during the EC period, the highest numbers of heat wave days are expected to occur in May which were 880 (Bathinda), 402 days at Abohar, 386 (Amritsar),344 (Patiala), 300 (Ludhiana), 258 (Ballowal Saunkhri) and 251 (Faridkot) days under RCP 4.5 and 8.5 scenarios (Table 2). Among all locations, the highest number of heat wave days was observed at Bathinda followed by Patiala and Abohar in the May month during EC. The total number of days with Tmax ranging >44°C was projected to be highest 91 to 982 (Bathinda) followed by 35 to 69 (Patiala) days under four RCP based emission scenarios during MC. Similarly, during the EC period, the highest total numbers of heat wave days are 180 to 1923 (Bathinda) followed by 60 to 694 (Abohar) days under four RCP based emission scenarios. The numbers of days with Tmax of >44°C are likely to rise and may go up to 1189 and 2033 days under A1B scenario in near- and long-term scenarios respectively as compared to the baseline value of 1114 days (Prabhjyot-Kaur *et al*., 2016).

Changes in the occurrence of cold wave days

The occurrence of cold wave days of Tmin <0° and 0-5°C during MC (2020-2049) and EC (2066-2095) periods at all seven locations under four RCP scenarios have been given in Table 3 and Table 4 respectively.

Table 3. Cold wave days as simulated by ensemble model during MC (2020-49) and EC (2066-95)

Stations	Months	No. of cold wave days during MC (<0°C)				No. of cold wave days during EC (<0°C)			
		RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Ludhiana	January	142	141	146	124	90	83	72	12
	December	-	-	-	-	-	-	-	-
	Total	**142**	**141**	**146**	**124**	**90**	**83**	**72**	**12**
Ballowal	January	147	143	152	131	90	90	78	20
Saunkhri	December	-	-	-	-	-	-	-	-
	Total	**147**	**143**	**152**	**131**	**90**	**90**	**78**	**20**
Amritsar	January	214	170	188	164	134	90	90	49
	December	7	-	9	2	-	-	-	-
	Total	**221**	**170**	**197**	**166**	**134**	**90**	**90**	**49**
Patiala	January	141	121	128	97	90	60	45	55
	December	-	-	-	-	-	-	-	-
	Total	**141**	**121**	**128**	**97**	**90**	**60**	**45**	**55**
Bathinda	January	163	154	175	148	90	90	90	34
	December	-	-	-	-	-	-	-	-
	Total	**163**	**154**	**175**	**148**	**90**	**90**	**90**	**34**
Faridkot	January	172	158	179	152	90	90	90	37
	December	-	-	-	-	-	-	-	-
	Total	**172**	**158**	**179**	**152**	**90**	**90**	**90**	**37**
Abohar	January	207	171	194	161	130	90	90	35
	December	-	-	-	-	-	-	-	-
	Total	**207**	**171**	**194**	**161**	**130**	**90**	**90**	**35**

Table 4. Cold wave days as simulated by ensemble model during MC (2020-49) and EC (2066-95)

Stations	Months	No. of cold wave days during MC (0-5°C)				No. of cold wave days during EC (0-5°C)			
		RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Ludhiana	January	771	648	704	542	480	240	263	119
	February	259	250	291	181	164	105	87	1
	December	358	288	325	255	202	113	93	11
	Total	**1388**	**1186**	**1320**	**978**	**846**	**458**	**443**	**131**
Ballowal	January	813	702	755	578	510	282	278	131
Saunkhri	February	269	247	296	182	174	100	95	0
	December	352	284	319	247	208	120	93	12
	Total	**1434**	**1233**	**1370**	**1007**	**892**	**502**	**466**	**143**
Amritsar	January	861	819	836	709	526	454	404	160
	February	455	412	433	349	300	210	179	37
	December	471	428	467	365	330	192	175	45
	Total	**1787**	**1659**	**1736**	**1423**	**1156**	**856**	**758**	**242**
Patiala	January	415	383	455	307	261	180	172	90
	February	199	162	176	104	120	49	23	0
	December	211	153	209	134	120	60	50	3
	Total	**825**	**698**	**840**	**545**	**501**	**289**	**245**	**93**
Bathinda	January	876	809	833	671	570	375	347	156
	February	329	310	322	255	210	122	126	8
	December	319	274	345	232	180	120	100	16
	Total	**1524**	**1393**	**1500**	**1158**	**960**	**617**	**573**	**180**
Faridkot	January	898	828	847	679	596	409	369	156
	February	330	323	328	262	210	151	137	10
	December	301	250	320	209	180	90	93	13
	Total	**1529**	**1401**	**1495**	**1150**	**986**	**650**	**599**	**179**
Abohar	January	838	825	841	698	536	411	381	179
	February	329	314	321	254	210	151	134	10
	December	344	287	368	242	199	107	103	19
	Total	**1511**	**1426**	**1530**	**1194**	**945**	**669**	**618**	**208**

The number of days with Tmin of <0°C is projected to increase both under MC and EC periods. The highest numbers of cold wave days could be in January under RCP 2.6 and 8.5 scenarios, which were 214 (Amritsar), 207 (Abohar), 179 (Faridkot), 163 (Bathinda), 152 (Ballowal Saunkhri), 146 (Ludhiana) and 141 (Patiala) days during the MC. Similarly, during the EC period, the highest numbers of cold wave days are expected to occur in January which were 134 (Amritsar), 130 (Abohar) and 90 (Bathinda, Ballowal Saunkhri, Faridkot, Patiala and Ludhiana) days under RCP 2.6 scenario (Table 3). Among all locations, the highest number of cold wave days was observed at Amritsar followed by Abohar in the January month during EC. The total number of days with Tmin <0°C was projected to be highest 170 to 221 (Amritsar) followed by 161 to 207 (Abohar) days under four RCP based emission scenarios during MC.

Similarly, during the EC period, the highest total numbers of heat wave days are 49 to 134 (Amritsar) followed by 35 to 130 (Abohar) days under four RCP based emission scenarios.

The model simulations indicate that there would also an increase in the number of days with Tmin ranging 0-5°C during the MC as compared to the EC (Table 4). The highest number of cold wave days could be in January under RCP 2.6 scenario which were 898 (Faridkot), 876 (Bathinda), 861 (Amritsar), 838 (Abohar), 813 (Ballowal Saunkhri), 771 (Ludhiana) and 415 (Patiala) days during the MC. Similarly, during the EC period, the highest numbers of cold wave days are expected to occur in January which was 596 (Faridkot), 570 (Bathinda), 536 (Abohar), 526 (Amritsar), 510 (Ballowal Saunkhri), 480 (Ludhiana) and 261 (Patiala) days under RCP 2.6 scenario (Table 4). Among all locations, the highest number of cold wave days was observed at Faridkot followed by Abohar and Amritsar in the January month during EC. The total number of days with Tmin ranging 0-5°C was projected to be highest 1423 to 1787 (Amritsar) followed by 1150 to 1529 (Faridkot) days under four RCP based emission scenarios during MC. Similarly, during the EC period, the highest total numbers of cold wave days are 242 to 1156 (Bathinda) followed by 179 to 986 (Faridkot) days under four RCP based emission scenarios. The numbers of days with minimum temperature of less than 0°C are likely to be none as compared to baseline (692 days). However, the numbers of days with minimum temperature higher than 7°C are predicted to rise in long term A1B scenario reported by Prabhjyot-Kaur *et al.* (2016).

Changes in the occurrence of extreme rainfall days

The occurrence of extreme RF ranging 25-30 mm and >30 mm during the MC (2020-2049) and EC (2066-2095) periods at all seven locations under four RCP scenarios have been given in Table 5 and Table 6.

The number of days with extreme RF ranging 25-30 mm was projected to increase both under MC and EC periods. The highest number of extreme RF days could be in July under RCP 2.6 scenario which were 60 (Ludhiana), 30 days at Ballowal Saunkhri, 38 (Amritsar), 30 (Bathinda, Ballowal Saunkhri, Faridkot and Abohar) and 21 (Patiala) days during the MC. Similarly, during the EC period, the highest numbers of extreme RF days are expected to occur in July which was 69 (Ludhiana), 62 (Amritsar), 49 (Bathinda and Ballowal Saunkhri), 48 (Patiala), 36 (Faridkot) and 32 (Abohar) days under RCP 4.5, 6.0 and 8.5 scenarios (Table 5). Among all locations, the highest number of extreme RF days was observed at Ludhiana followed by Amritsar in the July month during EC. The total number of days with RF ranging 25-30 mm was projected to be highest 47 to 62 (Amritsar) followed by 31 to 60 (Ludhaiana) days under four RCP based emission scenarios during MC. Similarly, during the EC period, the highest total numbers of heat wave days are 21 to 98 (Amritsar) followed by 46 to 88 (Ballowal Saukhri) days under four RCP based emission scenarios.

The model simulations indicate that there would also an increase in the number of extreme RF days with RF ranging >30 mm during the MC as compared to the EC (Table 5). The highest number of extreme RF days could be in July under RCP 2.6 scenario and 8.5 scenarios which were 145 (Amritsar), 136 (Ludhiana), 90 (Patiala), 44 (Ballowal Saunkhri), 30 (Bathinda and Faridkot) and 9 (Abohar) days during MC. Similarly, during the EC period, the highest numbers of extreme RF days are expected to occur in July which was 181 (Amritsar), 150 (Ludhiana), 129 (Ballowal Saunkhri), 92 (Patiala), 51 (Bathinda), 41 (Faridkot) and 40 (Abohar), days under RCP 4.5 and 6.0 scenarios (Table 6). Among all locations, the highest number of extreme RF days was observed at Amritsar followed by Ludhiana and Ballowal Saukhri in the July month during EC. The total number of days with RF ranging >30 mm was projected to be highest 184 to 219 (Amritsar) followed by 170 to 218 (Ludhiana) days under four RCP based emission scenarios during MC. Similarly, during the EC period, the highest total numbers of RF ranging >30 mm are 172 to 244 (Ludhiana) days followed by 70 to 214 (Ballowal Saunkhri) days under four RCP based emission scenarios. The days with extreme rainfall of > 200 mm would increase to 7 days in long term over the baseline value of 0 day. The higher near-term and long-term annual, *kharif*, monsoon and winter rainfall are expected with exception of *rabi* which is projected to decline by the end of the 21st century under A2 and B2 scenarios

Table 5. Extreme rainfall days as simulated by ensemble model during MC (2020-49) and EC (2066-95)

Stations	Months	No. of extreme rainfall days during MC (25-30mm)				No. of extreme rainfall days during EC (25-30mm)			
		RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Ludhiana	June	-	1	-	2	-	9	-	-
	July	60	46	52	29	31	30	22	69
	August	-	9	-	-	1	-	27	30
	September	-	-	-	-	-	-	9	29
	Total	**60**	**56**	**52**	**31**	**32**	**39**	**58**	**119**
Ballowal	June	-	-	-	-	-	-	-	-
Saunkhri	July	30	30	30	30	30	30	49	30
	August	29	30	30	30	30	30	12	12
	September	-	-	-	-	-	28	-	4
	Total	**59**	**60**	**60**	**60**	**60**	**88**	**61**	**46**
Amritsar	June	8	8	-	7	3	4	-	11
	July	38	15	30	29	42	62	16	52
	August	16	24	30	19	-	32	5	29
	September	-	-	-	-	-	-	-	-
	Total	**62**	**47**	**60**	**55**	**45**	**98**	**21**	**92**
Patiala	June	-	-	-	-	-	-	2	-
	July	-	-	-	-	-	48	39	-
	August	21	-	1	10	16	-	-	34
	September	-	-	-	-	-	12	-	-
	Total	**21**		**1**	**10**	**16**	**60**	**41**	**34**
Bathinda	June	-	-	-	-	-	-	-	-
	July	30	30	30	30	30	30	49	30
	August	27	29	30	25	28	29	11	10
	September	-	-	-	-	-	28	-	4
	Total	**57**	**59**	**60**	**55**	**58**	**87**	**60**	**44**
Faridkot	June	-	-	-	-	-	-	-	-
	July	30	30	30	30	30	30	36	30
	August	5	30	28	30	30	30	19	4
	September	-	-	-	-	-	-	-	6
	Total	**35**	**60**	**58**	**60**	**60**	**60**	**55**	**40**
Abohar	June	-	-	-	-	-	-	-	-
	July	30	30	30	24	30	30	32	13
	August	-	-	20	6	-	16	13	11
	September	-	-	-	-	-	-	-	2
	Total	**30**	**30**	**50**	**30**	**30**	**46**	**45**	**26**

Table 6. Extreme rainfall days as simulated by ensemble model during MC (2020-49) EC (2066-95)

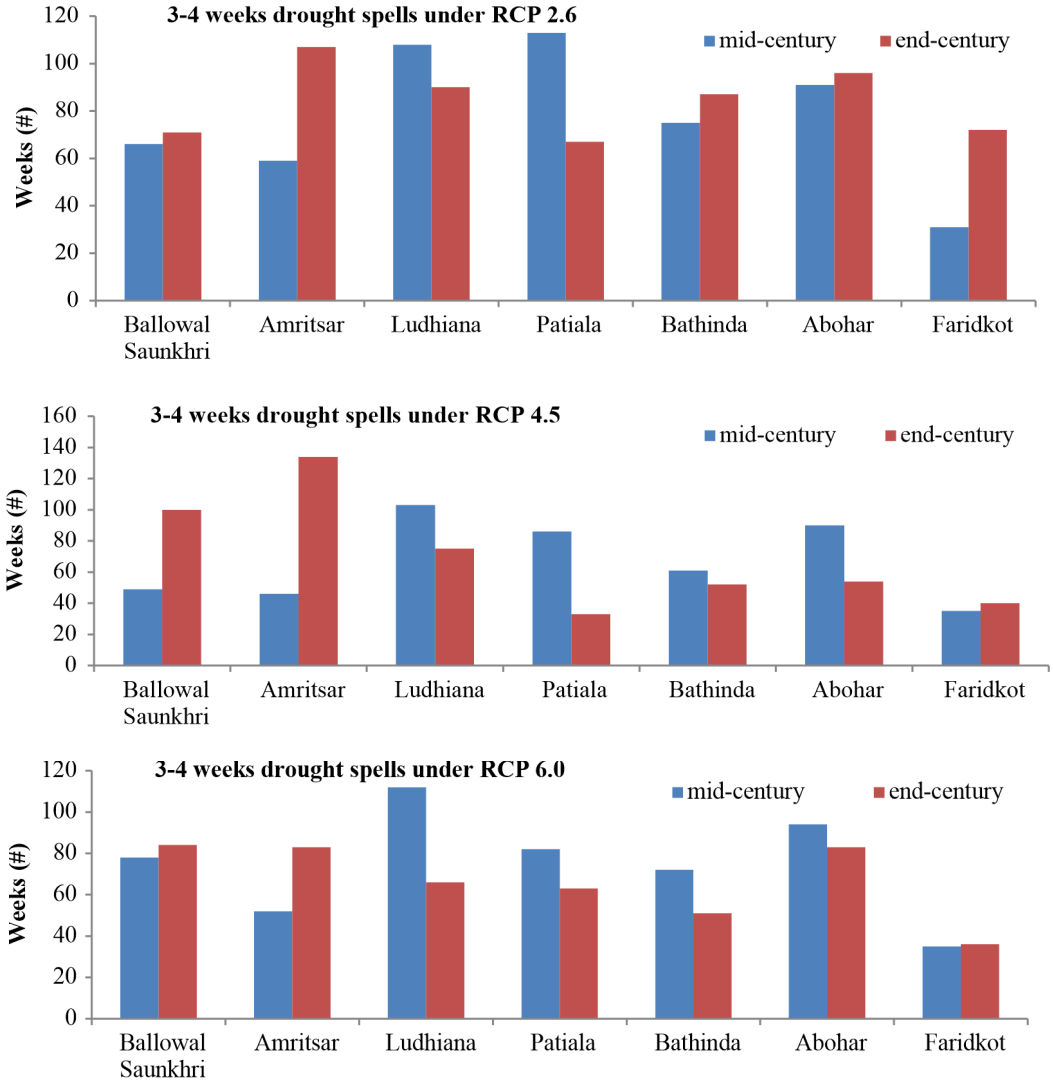
Stations	Months	No. of extreme rainfall days during MC (>30mm)				No. of extreme rainfall days during EC (>30mm)			
		RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Ludhiana	June	-	-	16	-	-	4	9	1
	July	106	115	109	136	118	150	115	88
	August	58	55	48	74	90	90	83	83
	September	13	-	-	8	-	-	-	-
	Total	**177**	**170**	**173**	**218**	**208**	**244**	**207**	**172**
Ballowal	June	-	-	-	-	-	-	-	-
Saunkhri	July	30	38	34	21	35	129	117	70
	August	-	4	2	44	10	85	58	36
	September	30	15	-	15	25	-	-	18
	Total	**60**	**57**	**36**	**80**	**70**	**214**	**175**	**124**
Amritsar	June	3	-	-	5	-	-	16	-
	July	119	141	120	145	166	181	180	101
	August	47	54	60	48	30	30	61	91
	September	15	24	30	18	-	-	30	-
	Total	**184**	**219**	**210**	**216**	**196**	**211**	**287**	**192**
Patiala	June	-	-	-	-	-	-	-	-
	July	90	90	90	90	90	90	92	90
	August	60	72	68	80	64	90	87	56
	September	-	-	-	-	-	-	-	30
	Total	**150**	**162**	**158**	**170**	**154**	**180**	**179**	**176**
Bathinda	June	-	-	-	-	-	-	-	-
	July	30	30	30	30	30	30	51	36
	August	-	-	-	-	-	-	42	24
	September	-	-	-	-	-	-	-	2
	Total	**30**	**30**	**30**	**30**	**30**	**30**	**93**	**62**
Faridkot	June	-	-	-	-	-	-	-	-
	July	30	30	30	30	30	30	41	34
	August	-	-	-	-	-	-	22	34
	September	-	-	-	-	-	-	-	9
	Total	**30**	**30**	**30**	**30**	**30**	**30**	**63**	**77**
Abohar	June	-	-	-	-	-	-	-	-
	July	-	-	-	9	-	14	8	8
	August	-	-	-	3	-	16	5	40
	September	-	-	-	-	-	-	-	6
	Total	**-**	**-**	**-**	**12**	**-**	**30**	**13**	**54**

reported by Prabhjyot-Kaur *et al* (2016). Wet and dry spell rainfall analysis was carried out for sub-mountainous region of Punjab to find out the initial and conditional probability of their occurrence using Markov chain approach. Weekly rainfall data from 1984 to 2010 was collected from meteorological observatory at Regional Research Station for *kandi* area, Ballowal Saunkhari. The probability of occurrence of wet spell was 73-100, 65-85, 46-81, 31-73 and 31-65% for wet limits of 10, 20, 30, 40 and 50 mm rainfall during Standard Meteorological Weeks (SMW) 26 to 35 whereas from SMW 39-52, it was 0-23, 0-15, 0-12, 0-8 and 0-8% and during SMW 1-22, it was 11-42, 4-23, 0-19, 0-12 and 0-12%, respectively for the corresponding wet limits.

The rainfall distribution for different crop seasons were also determined to adjust various crop phenophases and their planning based on moisture availability Agriculture is highly dependent on rainfall and many decisions are made based on the amounts of rainfall occurring during crop seasons (Kingra *et al*., 2013).

Changes in the occurrence of drought spells

The period of prolonged dry weather is called drought spell. The occurrence of drought spells 3-4 weeks and >4 weeks during the MC (2020-2049) and EC (2066-2095) periods at all seven locations under four RCP scenarios have been given in Fig. 2 and Fig. 3.



Contd...

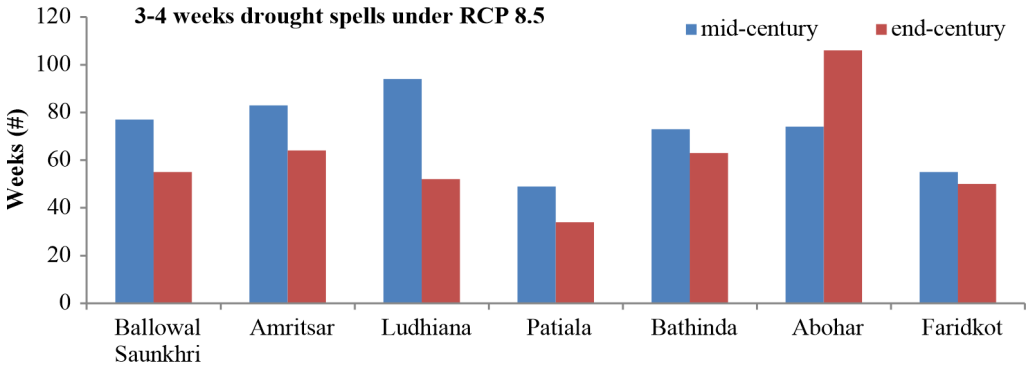
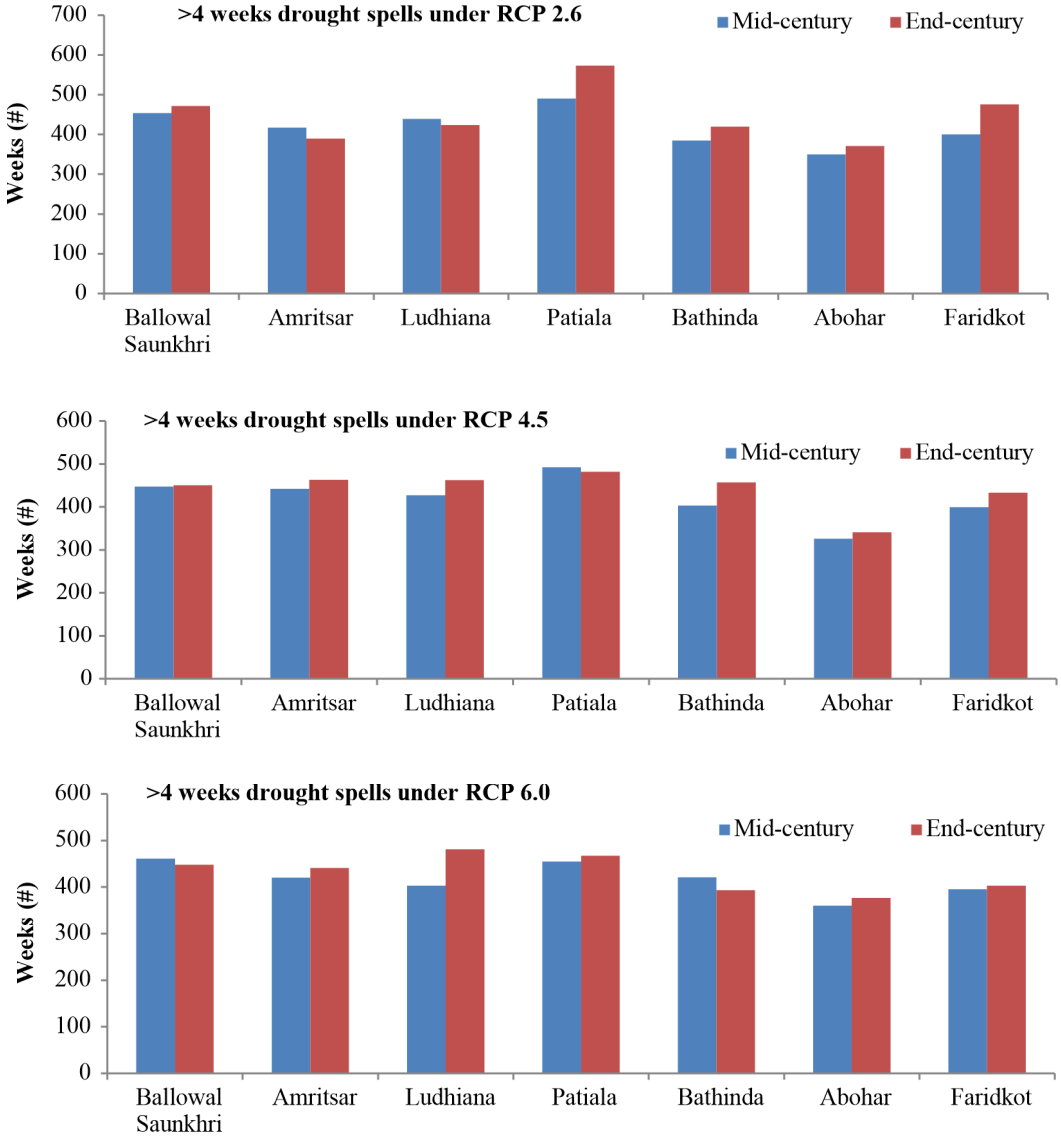


Fig. 2. Drought spells (3-4 weeks) simulated by ensemble model at different locations during MC (2020-49) and EC (2066-95) under four emission scenarios



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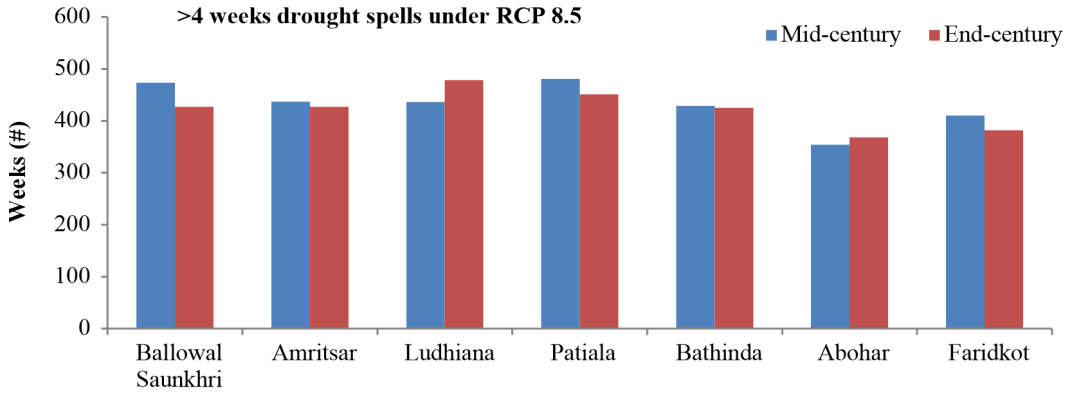

Fig. 3. Drought spells (>4 weeks) simulated by ensemble model at different locations during MC (2020-49) and EC (2066-95) under four emission scenarios

The number of days with drought spells 3-4 weeks (Fig. 2) was projected to increase both in MC and EC. The highest drought spells have been reported at Patiala followed by Ludhiana under RCP 2.6 scenario; at Amritsar followed by Ludhiana under RCP 4.5 scenario; at Ludhiana followed by Abohar under RCP 6.0 scenario; Abohar followed by Ludhiana under RCP 8.5 scenarios in both the mid and EC.

The number of days with drought spells >4 weeks (Fig. 3) was projected to increase both in MC and EC. The highest drought spells were projected at Patiala followed by Ballowal Saunkhri under RCP 2.6 scenario; at Patiala followed by Amritsar under RCP 4.5 scenario; at Ludhiana followed by Patiala under RCP 6.0 scenario; at Patiala followed by Ludhiana under RCP 8.5 scenario in both mid and EC. Relatively higher drought spells are projected to occur in the EC as compared to the MC. Kingra *et al*., (2016) reported the probability of occurrence of wet spell was 73-100, 65-85, 46-81, 31-73 and 31-65% for wet limits of 10, 20, 30, 40 and 50 mm rainfall during Standard Meteorological Weeks (SMW) 26 to 35 whereas from SMW 39-52, it was 0-23, 0-15, 0-12, 0-8 and 0-8% and during SMW 1-22, it was 11- 42, 4-23, 0-19, 0-12 and 0-12%, respectively for the corresponding wet limits in *kandi* region (Ballowal Saunkhri) of Punjab.

Conclusion

The analysis of the data simulated by Ensemble model indicated significant changes in the incidence of extreme weather events in Punjab state. The hotter and drier weather predicted by Ensemble model would affect major crops (rice, maize, wheat, cotton, sugarcane, etc) grown in the state. The incidence of heat wave days with temperature (40-44°C) and cold wave days with temperature (0-5°C) would adversely affect the crop growth and production as temperature both below and above the optimum range result in alteration in dry matter partitioning amongst plant parts, enhanced maintenance respiration losses and shortening of duration of crop growth period. Towards the EC in the state the number of days with temperature >44°C are projected increase 2-3 times but with <0°C are predicted to decline as compared to MC thereby indicating more hotter than more cold climates. The projected increase in rainfall >30mm during June to August maybe helpful for rice crop but during September month may prove detrimental for grain development phase. Punjab state economy is not only largely dependent on agriculture but it also contributes significantly to rice and wheat reserve pool of the country. So revised crop contingency planning would be needed to sustain the agricultural productivity of the state. Also new and focused research on this aspect would be helpful in tiding over the incidence of such extremes of weather in the state.

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gismap.ciat.cgiar.org/MarkSimGCM/ at daily interval under RCP scenarios for four agro-climatic zones of Punjab.

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