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A CRITICAL APPRAISAL OF VARIABILITY IN WHEAT YIELD AS AFFECTED BY METEOROLOGICAL PARAMETERS IN IRRIGATED PLAINS OF CENTRAL PUNJAB

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ABSTRACT

A study was conducted to evaluate the effect of variability in meteorological parameters, i.e. maximum (T_{max}) and minimum (T_{min}) temperature, sunshine hours (SShr) and rainfall (RF) during three stages of wheat, i.e. Vegetative (VG), Flowering (FL) and grain filling (GF) stage. The analysis was done for three years each with highest and lowest wheat yield amongst recent 13 years for Ludhiana station. The highest yield (5375 kg/ha) during 2011-12 was achieved with warmer temperatures (T_{max} and T_{min}+0.6°C above normal) due to cloudy (SShr -98hr below normal) weather during VG stage, cooler temperatures (T_{max} and T_{min} 0.5-1.5°C below normal) due to humid (RF+13mm above normal) and cloudy (SShr-19hr below normal) weather during FL stage and cooler temperature (T_{max}-0.2°C below normal) with cloudy (SShr-68hr below normal) weather during GF stage. The lowest yield (4392 kg/ha) of wheat during 2008-09 was due to cumulative effect of heat stress during VG (T_{max} +0.9°C and T_{min}+1.2°C above normal), FL (T_{max} +2.1°C and T_{min}+2.8°C above normal) and GF (T_{max} +1.5°C and T_{min}+0.8°C above normal) stages coupled with cloudy weather during VG and FL stage due to SShr 96 and 11 hr lesser than normal, respectively. The study revealed that during the VG, FL and GF stage respectively of three high yield years, the favourable range of T_{max} are 22.1-23.4, 17.5–20.0 and 26.0–29.5°C, T_{min} are 8.3–8.9, 5.8–8.7 and 12.3– 14.9°C, SShr are 362-446, 108-191 and 543-580 hr.

Keywords: Rainfall, Sunshine hour, Temperature, Wheat, Yield

Wheat is one of the staple food grains in India with a monthly consumption of 4.25 kg per person in rural areas and 4.00 kg per person in urban areas. It is cultivated on the largest land area, i.e., more than 240 million ha and also ranks the highest in terms of production. It is often stated that wheat cultivation in India is a "gamble of temperature" (Howard, 1924). Being a cool-season crop, it grows ideally with cool weather during vegetative period and warm weather during its maturity period (Sandhu *et al*., 2019). Porter and Gawith (1999) reported that the optimum temperature for wheat is ~22°C for vegetative development and 21°C for reproductive development, while ~35.4°C is the maximum limit for grain filling. Later Rao *et al* (2015) conducted an analysis on the sensitivity of wheat yields to temperature in India and reported that the wheat yields appear to be becoming more sensitive to minimum temperature (T_{min}), especially during post-anthesis period. Mean wheat yields for the period 1980–2011 declined by 7% (204 kg ha^{-1}) for a 1° C rise in T_{min}. Exposure to continual T_n exceeding 12°C for 6 days and maximum temperature (T_{max}) exceeding 34°C for 7 days during post-anthesis period are the other thermal constraints in achieving high productivity.

The warming of the earth-atmosphere system is gaining certainty and the estimates given by NASA's Goddard Institute for Space Studies (GISS) reveal that the earth's average temperature has increased by a little more than 1°C since 1880 and the two-thirds of this warming has occurred since 1975 which is estimated @0.15 to 0.20°C per decade (Anonymous, 2020). High temperature affects wheat crop development, i.e. there is an acceleration in time to maturity, spikelet fertility, i.e. reproductive stages being sensitive to high temperatures (Shah *et al*., 2003; Porter *et al*., 1999), leaf senescence, i.e. it gets accelerated with maximum temperatures above 34°C (Rao *et al*., 2015; Pramod *et al*., 2017) and a lethal temperature effect on the whole plant (Tao *et al*., 2015), i.e. the immediate crop maturity or death if maximum temperature exceeds a certain threshold for a given number of days. In India, major wheat growing areas lie in the north wherein there are predictions of an increase in the number of days with maximum temperatures exceeding physiologically critical thresholds (>40 ◦C) during most part of the year (Fischer et al., 1980). So further research on adaptive strategies such as shifts of sowing dates, cultivars and agronomic management practices (Tao *et al*., 2015; Pramod *et al*., 2017) to combat the adverse effect of temperature on wheat are gaining importance.

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The threat of global warming is a major concern for scientists since India's surface temperature is projected to increase by 1-4°C by the end of the 21st century (DEFRA, 2005). So, the problem of feeding 1.39 billion mouths (Anonymous 2022) in the country needs to redressed. Punjab is the major wheat producing state in India with wheat cultivation done on 35.20 lakh hectare and a productivity of 50.04 q/ha (Anonymous, 2021). So, the incidences of aberrant weather conditions are a major cause of concern for Punjab state in particular and the country in general. Keeping this objective in view the present study was undertaken to critically assess the climatic conditions reasons for low and high wheat yields obtained in the past in Punjab state.

MATERIALS AND METHODS

In this impact assessment study the data on area and yield for wheat crop during recent crop years (2007-08 to 2019-20) for Ludhiana was taken from statistical abstracts (Anononymous, 2020). The daily meteorological data's (temperature, rainfall and sunshine hours) for the corresponding years were taken from the records of Agrometeorological observatory, Department of Climate Change & Agricultural Meteorology, Punjab Agricultural University Ludhiana. These data were analysed on daily, weekly (Standard Meteorological Week –SMW) and crop stage-wise basis after segregating it based on low yield and high yield years over the recent crop years. The basic assumption made was that during recent decade the contribution of agro-technological advancement would be similar and any abrupt deviation (positive or negative) in yield of wheat would primarily be due to meteorological parameters.

The wheat crop stage-wise (Vegetative: 44 to 2 SMW, flowering: 3 to 6 SMW and grain filling stage: 7 to 16 SMW) comparisons and their deviations from long term normals for meteorological parameters computed from 1970 to 2015 (Prabhjyot-Kaur et al., 2016) were made on daily (29 October - 22 April) and weekly (44 to 16 SMW) basis for both high and low yield years. Linear regression estimates and their coefficients involving one or more independent variables, which best predicted the value of the dependent variable were also computed.

RESULTS AND DISCUSSION

Changes in area and yield of wheat

Over the recent decade the area under wheat crop decreased from 2,58,000 ha (2007-08) to 2,50,000 ha (2019-20) while the yield varied from a low of 4392 kg/ha (2008-09) to a high yield of 5375 kg/ha (2011-12) (Fig. 1). The area under wheat crop increased during years 2007-08, 2008-09 and 2009-10 and decreased during rest of the years. The average yield of wheat from crop year 2007-08 to 2019-20 is 4910.8 kg/ha. Assuming the influence of technological advancement to be nearly nil over the recent decade, then the yield of wheat was above average (4910.8 kg/ha) during six years and with peak highest during 2011-12 when it was +8.6% more than average. During remaining seven years the yield

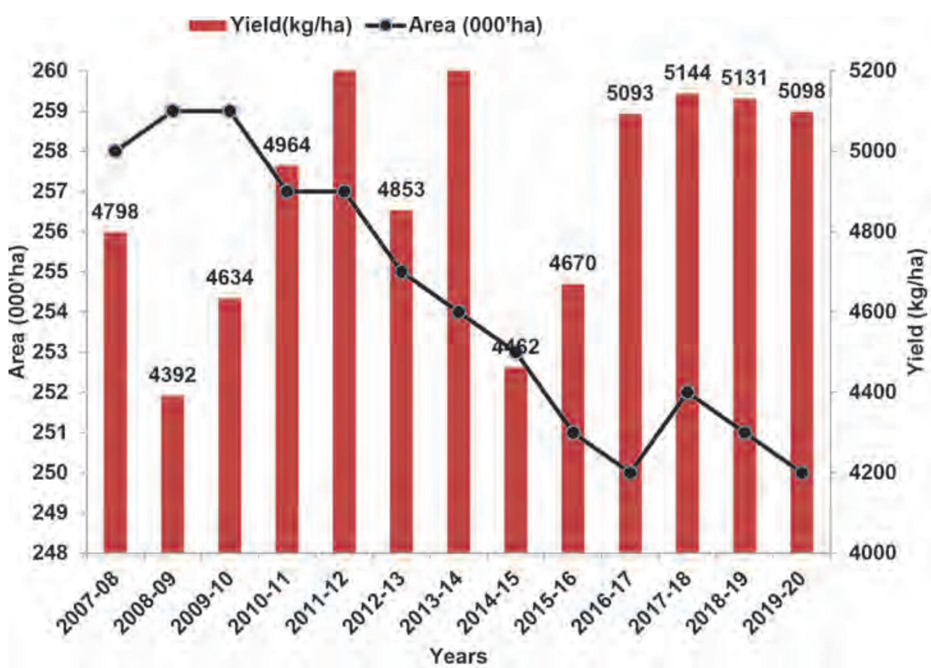

Fig. 1. Changes in the area and yield of wheat over the past decade at Ludhiana (2008-09 to 2019-20)

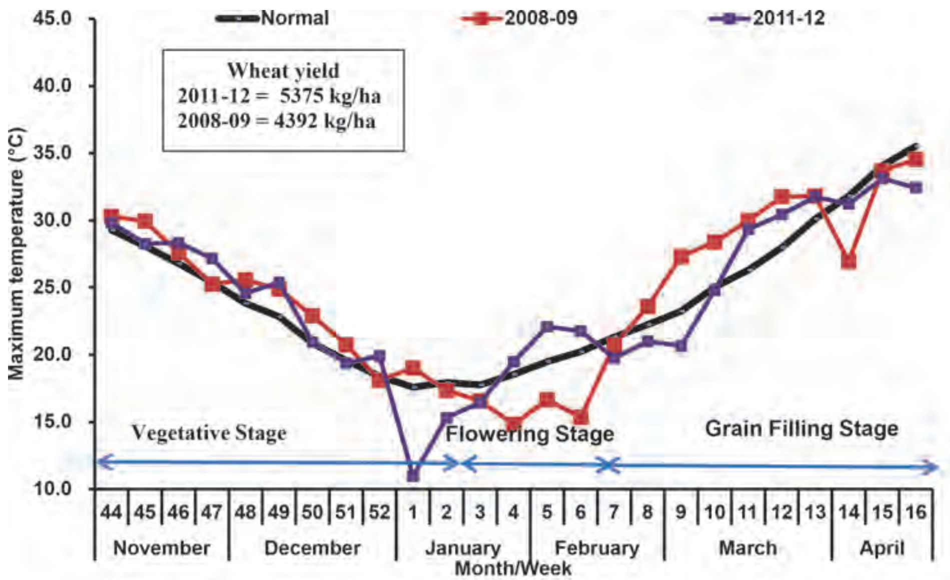

Fig. 2. Comparison of stage wise weekly maximum temperature with normal for low and high yield years of wheat at Ludhiana

was below average and the lowest yield was observed during 2008-09 i.e., -12.0% less than average yield.

Crop stage-wise comparison of wheat yield with weather parameters

Temperature

The wheat crop stage-wise i.e. vegetative (VG), flowering (FL) and grain filling (GF) stage comparison of weekly maximum (T_{max}) and minimum (T_{min}) temperature with normal values was made for three low yield and three high yield years. Amongst the low yield years (2008-09, 2009-10 and 2014-15), the weekly T_{max} remained below normal during VG and FL stage (1.0 to 1.5 °C) but was above normal during the GF stage (1.5 to 3.8 °C). However, during the high yield years (2011-12, 2013-14 and 2017-18), the weekly T_{max} during VG, FL and GF stage was above normal (0.5-1.7 °C) (Fig. 2). Among the low yield year, the weekly T_{min} among all the stages remained above normal (0.1 to 3.0 °C). However, during the high yield years, the weekly T_{min} remained above normal during FL and GF stage (2.0 to 2.5 °C) but remained close to normal during the VG stage (Fig. 3). During 2011-12 when peak highest yield of wheat was achieved then both the T_{max} and T_{min} were above normal by ~0.5 – 0.7°C during VG stage, below normal ~0.4 – 1.2°C during FL stage and below normal by ~0.2°C during GF stage. On the other hand, during 2008-09 when peak lowest yield of wheat was achieved then both the Tmax and Tmin were above normal by ~0.9 – 1.2°C during VG stage, above normal ~2.1 – 2.8°C during FL stage and above normal by ~0.8 – 1.5°C during GF stage. Kumar *et al* (2013) in an earlier study have also reported that excessive heat stress during reproductive stages including FL and GF stages hamper the final yield. In an earlier study conducted by Singh et al (2008) in Punjab reported that maximum and minimum temperature of 25.6 and 10.8 °C during the grain filling stage lead to high productivity of wheat in the south western regions of the state.

Sunshine hour

The bright sunshine hour (SShr) is extremely important for the photosynthetic activity and biomass accumulation of the crop. The normal total hours of sunshine during wheat season are 1332 with 488, 234 and 610 hrs during the VG, FL and GF stages. During the high yield years 2011-12, 2013-14 and 2017-18 the cumulative sunshine received were 380, 406 and 303 hour, respectively during VG stage, 230, 140 and 244 hour, respectively during FL stage and 543, 580 and 581 hour, respectively during GF stage (Fig. 4). While during the low yield years 2008-09, 2009-10 and 2014-15 the cumulative SShr received were 391, 340 and 373 hours, respectively during VG stage, 227, 137 and 157 hour, respectively during FL stage and 647, 639 and 502 hour, respectively during GF stage. Since clear sky conditions not only lead to increased duration of sunshine but also increase the air temperature. During the two low yield years 2009-10 and 2014-15 cloudy weather during FL stage and increase in temperature due to clear sky during 2008-09 and 2009-10 led to decline in yield of wheat crop. These results are in conformity with the earlier reporting by Pathak *et al*. (2003) that the negative trends in solar radiation and an increase in minimum temperature are resulting in declining trends of potential yields of wheat in the Indo-Gangetic plains of India.

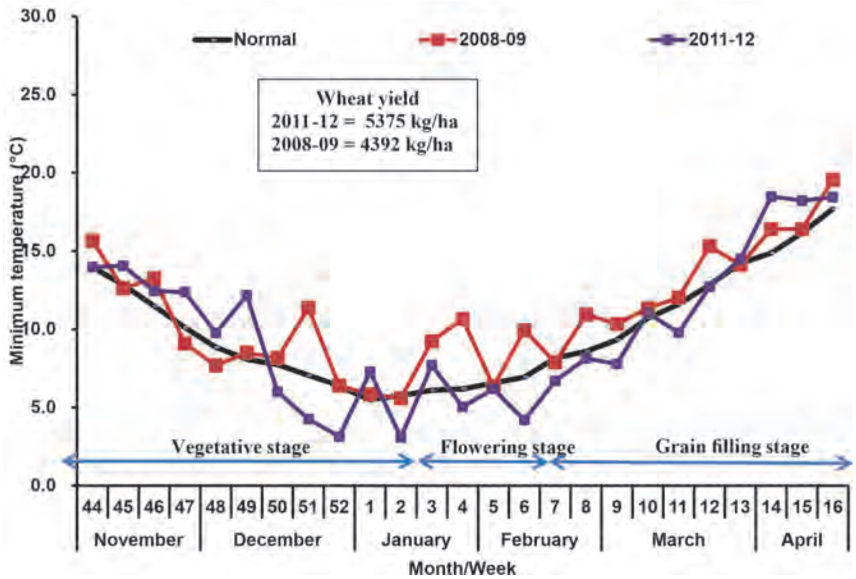

Fig. 3. Comparison of stage wise weekly minimum temperature with normal for low and high yield years of wheat at Ludhiana

Rainfall

Rainfall (RF) furnishes the water which contributes to the transportation of the nutrients for plant development. The normal total RF during wheat season are 122.8 mm with 27.0, 34.3 and 61.5 mm received during the VG, FL and GF stages. During the high yield years 2011-12, 2013-14 and 2017-18 the cumulative RF received were 24.0, 29.8 and 31.0 mm, respectively during VG stage, 43.4, 58.3 and 20.8 mm, respectively during FL stage and 24.7, 99.9 and 34.6 mm, respectively during GL stage (Fig. 5) thereby indicating fair distribution of RF, i.e. 16-36%, 24-47% and 27-53% of the total RF during the VG, FL and GF stages, respectively. While during the low yield years 2008-09, 2009-10 and 2014-15 the cumulative RF received were 4.0, 23.5 and 42.6 mm, respectively during VG stage, 31.0, 25.0 and 35.4 mm, respectively during FL stage and 46.2, 5.4 and 141.4 mm, respectively during GL stage there by indicating skewed distribution of RF, i.e. 5-44%, 16-46% and 10-64% of the total RF during the VG, FL and GF stages, respectively.

Porter (1980) reported that the amount and timing of rainfall have a very important impact. Hence excessive / deficit rainfall at FL or at late GF stage of wheat leads to decline in yield due to pollen sterility / desiccation and at FL stage and lodging / water stress at late GF stage.

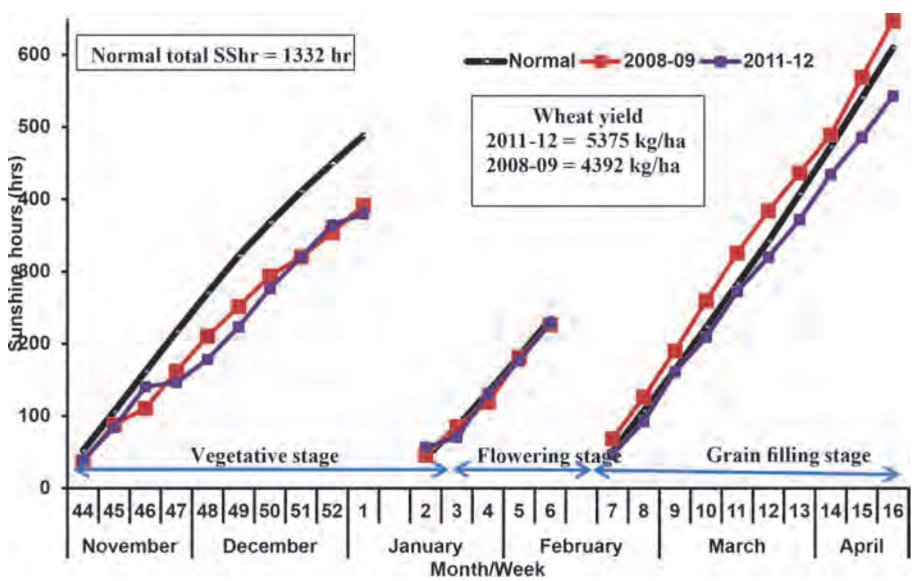

Fig. 4. Comparison of crop stage wise weekly cumulative sunshine hours with normal for low and high yield years of wheat at Ludhiana

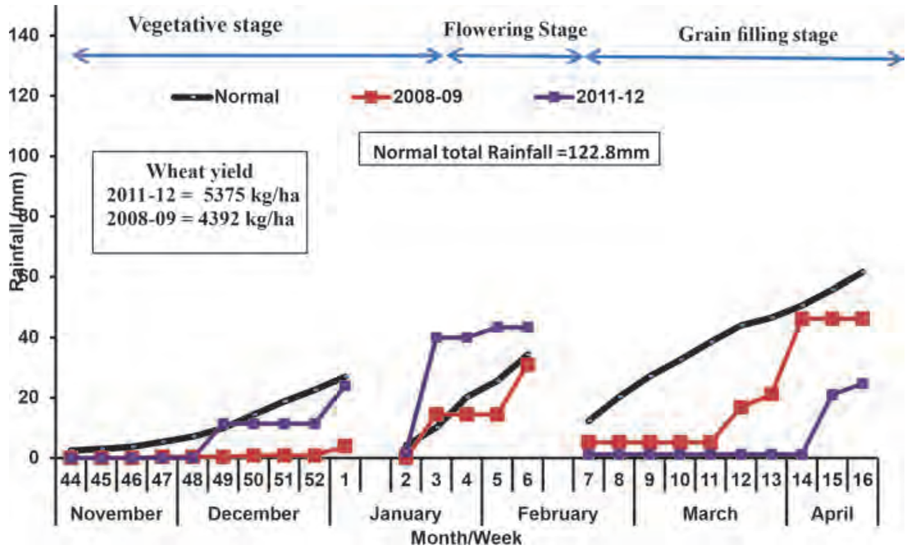

Fig. 5. Comparison of stage wise weekly cumulative rainfall with normal for low and high yield years of wheat at Ludhiana

Shah and Paulsen (2003) have also revealed that productivity of wheat gets negatively impacted more by the combined stresses of heat and water than by either stress alone as the direct effect is on the photosynthetic processes of the plant.

Deviation of weather parameters from normal during high and low yield years

During VG stage of the highest yield (5375 kg/ha) year 2011-12, the weekly T_{max} and T_{min} were 0.6°C above normal and due to cloudy but dry weather sunshine was 98 hr and RF was 4 mm lesser than normal (Figs. 6 to 9). Later during the FL stage weekly T_{max} was 1.5°C and T_{min} was 0.5°C below normal and SShr were 19 hr lesser than normal but RF was 13.3 mm above normal. Then during GF stage the T_{max} was slightly below normal by 0.2°C and T_{min} was near normal and due to cloudy but dry weather SShr were 68 hr and RF was 36 mm lesser than normal. During the VG stage of 2013-14 (5226 kg/ha) the weekly T_{max} was 0.6°C below normal and T_{min} was 0.1°C above normal and due to cloudy but dry weather SShr were 96 hr and RF was 0.3 mm lesser than normal (Figs. 6 to 9). Later during the FL stage due to cloudy and wet weather with SShr 84 hr lesser than normal and RF 30 mm above normal though the weekly T_{max} was 1.2°C below normal but the T_{min} was 2.5°C above normal. Then the cool temperatures during GF stage with the below normal weekly T_{max} (by 2.0°C) and T_{min} (by 0.3°C) with cloudy and wet weather with SShr 31 hr lesser than normal but RF 38 mm more than normal proved conducive for grain development stage of wheat. During the VG stage of the year 2017-18, the

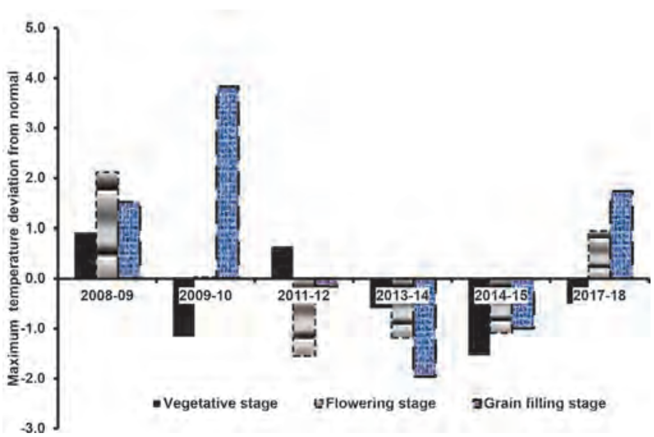

Fig. 6. Deviation of maximum temperature (°C) from normal at different growth stages of wheat crop during high (2011-12, 2013-14, 2017-18) and low (2008-09, 2009,10, 2014-15) yield years at Ludhiana

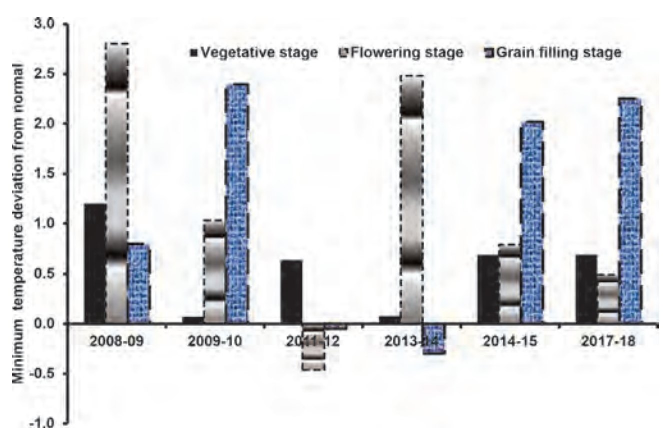

Fig. 7. Deviation of minimum temperature (°C) from normal at different growth stages of wheat crop for high (2011-12, 2013-14, 2017-18) and low (2008-09, 2009,10, 2014-15) yield years at Ludhiana

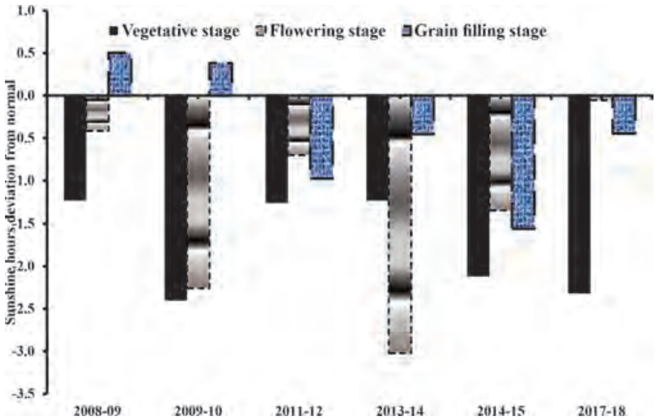

Fig. 8. Deviation of sunshine hours (hour) from normal at different growth stages of wheat crop for high (2011-12, 2013-14, 2017-18) and low (2008-09, 2009,10, 2014-15) yield years at Ludhiana

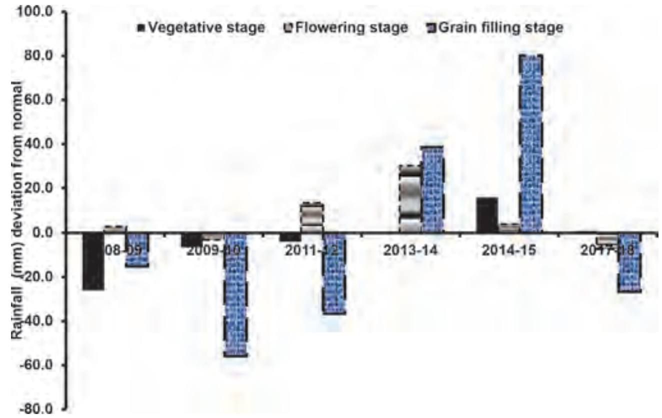

Fig. 9. Deviation of rainfall (mm) from normal at different growth stages of wheat crop for high (2011-12, 2013-14, 2017-18) and low (2008-09, 2009,10, 2014-15) yield years at Ludhiana

weekly T_{max} was 0.5°C below normal and T_{min} was 0.7°C above normal and due to cloudy and humid weather the SShr were 181 hr below normal and RF was 1.0 mm more than normal (Figs. 6 to 9). Later during the FL stage the weather was clear with SShr slightly below normal by 1 hr and lesser than normal RF (by 7.3 mm) resulted in above normal weekly T_{max} (by 1.0°C) and T_{min} (by 0.5°C). Accordingly, the T_{max} / T_{min} in the range of 22.1 – 23.4 / 8.3 – 8.9°C during the VG stage, 17.5 – 20.0 / 5.8 – 8.7°C during FL stage and 26.0 – 29.5 / 12.3 – 14.9°C during GF stage are conducive for high yield of wheat. Porter and Gawith (1999) conducted an exhaustive review of temperature requirements for wheat and have summarized that the optimum mean temperature during vegetative and grain filling stages are 19-21 and 22-25^{o}C, respectively.

During the VG stage of the lowest yield (4392 kg/ha) year 2008-09, the above normal weekly T_{max} by 0.9°C and T_{min} by 1.2°C above normal and due to cloudy but dry weather SShr were 96 hr and RF was 26 mm lesser than normal (Fig 6 to 9). Later during the FL stage, the hot weather continued with above normal weekly T_{max} by 2.1°C and T_{min} by 2.8°C with SShr 11 hr lesser than normal but RF 2.9 mm above normal. Finally, during GF stage, above normal T_{max} (+1.5°C) and T_{min} (+0.8°C) induced hot and clear (SShr 35 hr above normal) but dry (RF 15 mm lesser than normal) weather induced the cumulative effect of heat and water stress resulted in record lowering of wheat yield over the past one decade at Ludhiana. The weather was persistently cloudy (SShr 165, 38 and 109 hr below normal during VG, FL and GF stage, respectively), wet (RF 16, 4 and 80 mm above normal during VG, FL and GF stage, respectively) with cool days (T_{max} -1.5, -1.1 and -1.0 °C below normal during VG, FL and GF stage, respectively) and hot nights (T_{min} 0.7, 0.8 and 2.0°C above normal during VG, FL and GF stage, respectively) during the year 2014-15. So a combination of wet and cloudy weather induced cool days and hot and humid nights cause low/high thermal and radiative stress which ultimately reduces the wheat yield (Figs. 6 to 9). These results are in concurrence with the observations made by Rao *et al.* (2015) that wheat yield are highly sensitive to high temperature stress, especially the minimum temperature stress during the post anthesis period. Though during the year 2009-10, the weather conditions were favourable during VG and FL stages with weekly T_{max} -1.2 and -0.1°C below normal, respectively, T_{min} 0.1 and 1.0°C above normal, respectively and due to partly cloudy weather the SShr were 187 and 63 hr below normal, respectively and RF was 6.6 and 3.1 mm lesser than normal, respectively (Figs. 6 to 9). However, during the GF stage the weather was clear (SShr 27 hr above normal), dry (RF 56 mm lesser than normal) and hot (T_{max} and T_{min} above normal by 3.8 and 2.4°C, respectively). So then dry and warmer temperatures due to clear sky during GF stage resulted in lowering of grain yield of wheat during 2009-10 and it was very similar to lowest yield year 2008-09. The T_{max} / T_{min} /SShr in the range of 21.2 – 23.7°C / 8.3 – 9.4°C/355-446 hr during the VG stage, 17.9 – 21.1°C / 7.0 – 9.0°C/129-181 hr during FL stage and 26.8°C – 31.6 / 13.4 – 15.0°C/503-647 hr during GF stage are not favourable for wheat.

Correlation of wheat yield with meteorological parameters

The correlation analysis between grain yield of wheat and meteorological parameters over the past decade (2007-08 to 2019-20) revealed that the yields were negatively correlated with T_{max} (r = -0.06), T_{min} (r = -0.11) and RF (r = -0.04) observed during the VG stage, while the SShr was positively correlated (r = +0.04)

Table 1. Stage wise correlation (r values) of wheat yield (2008-09 to 2019-20) with meteorological parameters

Crop growth phase	Temperature (°C)		Rainfall (mm)	Sunshine hours (hrs)
	Maximum	Minimum		
Vegetative stage (44 SMW- 2 SMW)	-0.06	-0.11	-0.04	0.04
Flowering Stage (3 SMW - 6 SMW)	0.74*	-0.37	0.30	0.03
Grain filling Stage (7 SMW - 16 SMW)	-0.08	-0.54**	-0.23	-0.26

*indicates value significant at p=0.05
** indicates value significant at p=0.10

Table 2. Stage wise linear regression analysis of wheat yield (2008-09 to 2019-20) with weather parameters

Meteorological parameters	Statistics	Crop growth stages		
		Vegetative	Flowering	Grain filling
Maximum temperature	Intercept (kg/ha)	5413.49	1678.52	5379.2
	Slope (°C)	-21.85	172.33	-16.10
	Multiple R	0.057	0.7361	0.081
	R^2	0.003	0.542	0.0064
	Adjusted R^2	-0.09	0.496	-0.092
	Standard error	330.53	224.11	330.02
	F value	0.86	0.0063	0.803
Minimum temperature	Intercept (kg/ha)	5410.52	5730.14	7463.21
	Slope (°C)	-54.63	-112.88	-183.36
	Multiple R	0.11	0.369	0.54
	R^2	0.011	0.1363	0.289
	Adjusted R^2	-0.087	0.050	0.218
	Standard error	329.14	307.68	279.11
	F value	0.74	0.237	0.071
Rainfall (RF)	Intercept (kg/ha)	4940.23	4820.25	5026.8
	Slope (mm)	-0.981	2.780	-1.800
	Multiple R	0.03825	0.302	0.2328
	R^2	0.0014	0.0915	0.054
	Adjusted R^2	-0.0983	0.00074	-0.04
	Standard error	330.85	315.56	321.99
	F value	0.906	0.339	0.466
Sunshine hours (SSH)	Intercept (kg/ha)	4815.77	4878.26	5892.22
	Slope (hrs)	0.268	0.271	-1.68
	Multiple R	0.0434	0.0255	0.2554
	R^2	0.0018	0.0006	0.065
	Adjusted R^2	-0.0979	-0.0992	-0.028
	Standard error	330.78	330.98	320.11
	F value	0.893	0.937	0.4230

Table 3. A summation of crop stage wise meteorological parameters determining the yield of wheat in Central Punjab

Meteorological parameter	Vegetative Stage (44-02 SMW)			Flowering Stage (03-06 SMW)			Grain filling Stage (07-16 SMW)		
	Normal	Highest yield year 2011-12 (5375 kg/ha)	Lowest yield year 2008-09 (4392 kg/ha)	Normal	Highest yield year 2011-12 (5375 kg/ha)	Lowest yield year 2008-09 (4392 kg/ha)	Normal	Highest yield year 2011-12 (5375 kg/ha)	Lowest yield year 2008-09 (4392 kg/ha)
Maximum temperature (°C)	22.7	23.4	23.7	19.0	17.5	21.1	27.8	27.6	29.3
Minimum temperature (°C)	8.2	8.9	9.4	6.2	5.8	9.0	12.6	12.6	13.4
Sunshine hour (hr)	542.7	444.1	446.4	192.5	172.9	180.9	611.5	543.4	646.7
Rainfall (mm)	30.1	26.0	4.0	28.1	41.4	31.0	61.3	24.7	46.2

(Table 1). During FL stage of wheat crop the T_{max}, RF and SShr showed positive correlation i.e r = +0.74, r = +0.30 and r = +0.03, respectively, while the T_{min} showed negative correlation i.e = -0.37 respectively. Since the T_{max} during flowering stage is significantly (r = +0.74*) correlated, so clear sky conditions with higher daytime are beneficial for the FL stage of wheat crop. The wheat yields revealed negative relationship of T_{max} (r = -0.08) and T_{min} (r = - 0.54**), RF (r = -0.23) and SShr (r = -0.26) recorded during GF stage. So the negative correlation of T_{min} during GF stage indicate that cooler nighttime temperatures are conducive for wheat yields. These results are in concurrence with the findings of Rao *et al*. (2015).

Regression analysis of wheat yield with meteorological parameters

Linear regression models were developed for predicting wheat yield with meteorological parameters at different phenological stages (Table 2) using the observed data for recent decade (2008-19). In linear regression, T_{max} at VG and GF stages seems to be influencing yields negatively and positively at FL stage whereas T_{min} negatively at VG, FL and GF stages. The effect of SShr on grain yield was found to be positive at VG and FL stage and negative at GF stage. Bahrami *et al.* (2020) conducted a statistical analysis to determine the influence of weather parameters on wheat and observed that sunshine duration had a highly significant relationship and hence clear sky and bright sunshine during GF stage are favourable for high yield of wheat.

The analysis of the meteorological parameters with grain yield of wheat in during the three high yield years (2011-12, 2013-14 and 2017-18) indicates that during VG stage of wheat the weekly T_{max} in the range of 22.1 – 23.4°C, T_{min} in the range of 8.3 – 8.9°C, SShr in the range 362-446 hr and RF in the range of 26-31 mm followed by weekly T_{max} in the range of 17.5 – 20.0°C, T_{min} in the range of 5.8 – 8.7°C, SShr in the range 108-191 hr and RF in the range of 21-58 mm during FL stage are conducive for optimum growth and development of wheat (Table 3). Later during the GF stage of wheat extending from mid-February to 3rd week of April, T_{max} in the range of 26.0 – 29.5°C, T_{min} in the range of 12.3 – 14.9°C, SShr in the range 543-580 hr and RF in the range of 25-100 mm help in achieving the high yield of wheat crop. The results of such studies are helpful for formulating the weather based insurance schemes in the region.

Authors' contribution

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

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