Effect of inter- and intra-seasonal variations in meteorological parameters on wheat yields in Punjab

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ABSTRACT

A study was conducted to evaluate the effect of variations in meteorological parameters on wheat (*Triticum aestivum L.* emend. Flori & Paol) yields during 1970-2005 and also as simulated with CERES-wheat model. The technology trend model of historical wheat yields in Punjab indicated that over the past 2 to 3 decades, at Ballowal Saunkhri, Amritsar, Ludhiana, Patiala and Bathinda the wheat yields have increased @ 64.2, 76.3, 62.8, 87.3 and 71.1 kg/ha/year respectively. An analysis of historical meteorological data and past wheat yields revealed that for January, February and March the most favourable maximum temperatures for wheat yields were in the range of 16.1-18.0 $^\circ$C, $\leq$21.0 $^\circ$C and 28.1-30.0 $^\circ$C respectively while minimum temperatures were in the range of 3.1-5.0 $^\circ$C, 5.1-7.0 $^\circ$C and 11.1-13.0 $^\circ$C respectively. The simulation study using CERES-wheat model revealed that the temperature increase mostly affected the early (October) sown crop during fourth week of January up to first fortnight of March; the timely (November) sown crop during February and March; the late (fourth week of November) sown crop during March; and very late (December) sown crop during March and first week of April. An analysis of historical wheat yields and weekly meteorological parameters at Ludhiana revealed that during the high yield (>5 000 kg/ha) crop years, the maximum and minimum temperatures remained near normal ($\pm$ 2°C); the rainfall was also normal or slightly above/below normal under assured irrigated conditions. From mid-February to March, dry and clear weather proves beneficial for grain filling in wheat. On the other hand, during low yield (<4 600 kg/ha) crop years, although the temperatures were favourable but very heavy rainfall showers were received during the anthesis and grain-filling period of wheat crop. The weather also remained cloudy and sunshine hours were invariably below or near normal while the relative humidity remained above (3-10 %) or near normal during most part of the crop season. Hence, these conditions were ascertained to be the most pertinent reason for relatively low-wheat yields.

Key words: Temperature, rainfall, relative humidity, sunshine, wheat yield, technology trend model

Wheat (*Triticum aestivum L.* emend. Flori & Paol) is the most important winter season cereal crop in Punjab occupying nearly 3.3 million ha. A study on shifts in area, production and productivity of wheat in Punjab during the past 3 decades revealed a significant increase in area, productivity and also its production in most of the districts of Punjab (Prabhjyot-Kaur *et al.* 2006). The state represents the subtropical irrigated winter wheat environments where the normal sowing period extends from last week of October to third week of November and late sowing of the crop is continued even upto December (PAU, 2006).

Wheat being a cool season crop requires low temperature conditions. Higher temperature during the early growth stages is unfavourable for tillering while during later growth stages it reduces the duration of grain formation and hinders proper grain filling. Chaurasia *et al.* (1991) reported that maximum temperature during March contributed negatively while the minimum temperature contributed positively to wheat yield in Punjab. Simulations of wheat yields using CERES-wheat model indicate that within-season temperature deviations from normal play a prominent role in determining the final yield of normal sown wheat crop (Prabhjyot-Kaur and Hundal 2007). Hundal and Prabhjyot-

Kaur (2007) reported that with an increase in temperature upto 1.0 $^\circ$C from normal, the wheat maturity was advanced by 6 days and the yield decreased by 10 % from normal. Wheat in Punjab is grown under assured irrigated conditions (97%), thereby decreasing the influence of below normal rainfall on growth and yield of the crop.

Regression techniques on historical station yields have been employed to evaluate the yield trends for crops (Stewart and Dwyer 1990). However, yield trends may be visualized better through crop simulation models which allow prediction of potential yields over several years as affected by variation in weather alone. A comparison of observed yields with the weather driven predicted potential yields could be a better indicator of the magnitude of the contribution of other factors to yield trends (Bell and Fischer 1994).

The present study was, therefore, designed to analyze the effect of variations in inter- and intra-seasonal meteorological parameters on wheat yields in Punjab and also to use CERES-Wheat model as a tool to simulate the effect of variations in intra-season temperatures on wheat sown under early, normal and late conditions.

MATERIALS AND METHODS

Input data description

The historical wheat yields for 5 different locations in the state (Ballowal Saunkhri, 1985-86 to 2004-05; Bathinda, 1980-81 to 2004-05; Amritsar, Ludhiana and Patiala, 1970-71 to 2004-05) were collected from the Statistical Abstracts of Punjab. Corresponding daily weather data on maximum and minimum temperature and rainfall for these locations were also obtained for use in the study.

The historical observed wheat yields for the 5 different locations in the state were regressed against time to develop a linear predictive model to assess the rate at which wheat yields have increased over time due to advancement in technology. Wheat yields during the past decade were analyzed corresponding to selected range of temperatures during January, February and March for the 5 locations to assess the favourable / unfavourable range of temperatures for optimum wheat yields.

A detailed analysis for the past 7 crop years was conducted for location of Ludhiana (30^0 54′ N, 75^0 48′ E, 247 m above mean sea level) where daily weather data for maximum and minimum temperature, rainfall, sunshine hours, maximum and minimum relative humidity were available for the study. The normals of weather data for Ludhiana station were computed from daily weather data for the past 36 years (1970-2005). Weekly deviations from normal meteorological parameters during each wheat crop season were tabulated to identify the influence of meteorological parameters on wheat yield.

CERES-wheat (Crop Environment Resource Synthesis) model incorporates the effect of daily maximum and minimum temperature, solar radiation and rainfall. Any changes in weather parameters affect the simulated growth and yield of wheat crop. The CERES-wheat which was adopted in the International Benchmark Site Network for Agrotechnology Transfer (IBSNAT, 1990) has been calibrated and validated at Ludhiana (Hundal and Prabhjyot-Kaur, 1997) and was used in the present simulation study. The weather data for the study were collected from the meteorological observatory of the Punjab Agricultural University, Ludhiana. The fertilizer, irrigation, and management practices as recommended in the packages of practices of the Punjab Agricultural University were assumed while using the model.

The simulation study was conducted to assess the effect of rise in temperature above normal during different periods of wheat crop growth. Wheat yield was simulated for early (October), timely (November), and late (fourth week of November and December) sown wheat crop. The study was carried out with the following assumptions:

(1)   Weather remained normal in rest of the crop growth period, other than the period in which increase in temperature was imposed

(2)   The crop remained free of other stresses such as water, nutrient and insect-pests.

RESULTS AND DISCUSSION

Trend analysis of historical wheat yield in Punjab

The past actual yields for 5 different locations in the state were regressed against time to develop a linear predictive model to assess the rate at which wheat yields have increased over time due to advancement in technology (Fig.1). Wheat yields at Ballowal Saunkhri, Amritsar, Ludhiana, Patiala and Bathinda, have increased over the past 3 decades @ 64.2, 76.3, 62.8, 87.3 and 71.1 kg ha^{-1} year^{-1}, respectively. The actual inter-seasonal variation in yield would presumably be due to a combination of variations in weather conditions and fluctuations in the degree to which the farmer's practices are optimized during each crop season. Although wheat crop varieties have also changed over the period but abrupt changes in year-to-year yield are more due to intra-seasonal weather variations. The technology model predicted yield was in accordance with the advancement in technology, i.e. improvement in farmer's practices, introduction of improved varieties etc. The negative deviation in actual yield compared to technology model predicted yield indicates that the intra-seasonal weather was probably unfavourable in some part of the crop season and vice-versa.

On perusal of the recent years (from 1990 onwards), the model prediction indicates that positive deviation in actual yield over the technology model predicted yield was maximum at Ballowal Saunkhri during 1996-97, Amritsar during 1999-2000, Ludhiana during 2000-01, Patiala during 1992-93 and Bathinda during 1999-2000 (Table 1). On the other hand, the deviation in actual yield over the technology model predicted yield during the same period was most negative (unfavourable) at Ballowal Saunkhri during 2004-05, Amritsar during 1997-98, Ludhiana during 1997-98, Patiala during 2003-04, and Bathinda during 1997-98. A further perusal of historical wheat yields for Amritsar and Bathinda revealed the highest yield of 4 855 and 4 614 kg ha^{-1}, respectively during the crop year 1999-2000.

Relationship between yield and monthly meteorological parameters

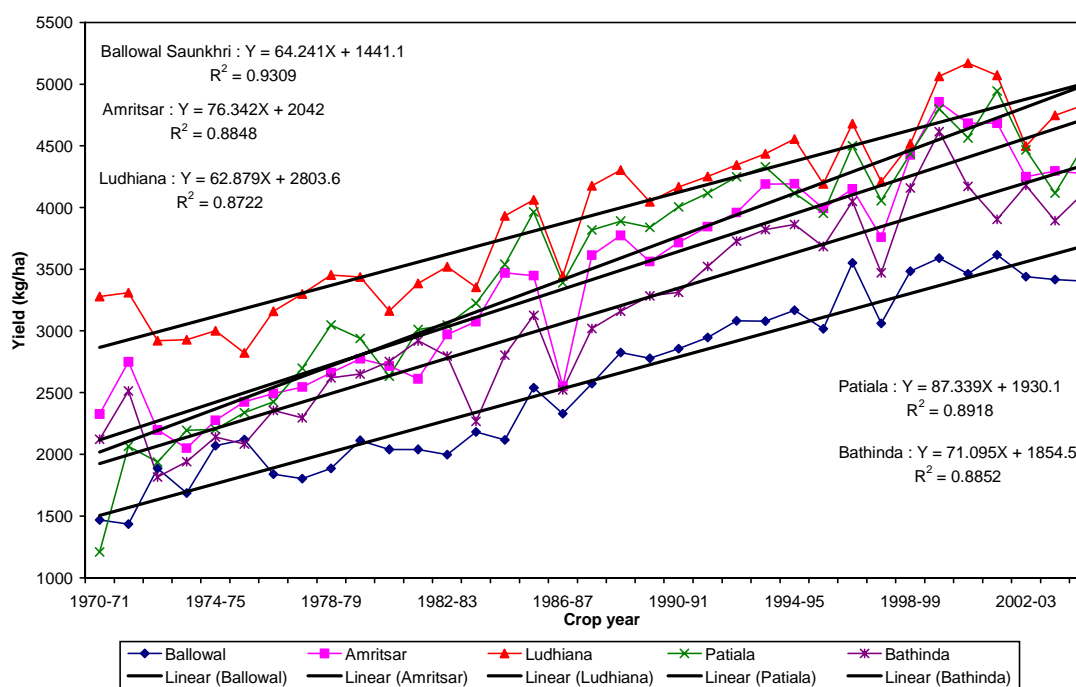In Punjab the normal sowing period of wheat extends

Fig. 1: Variation in wheat yield at different locations in Punjab over the past 3 decades

from fourth week of October to third week of November. Hence the meteorological parameters during January, February and March (vegetative and reproductive crop phases) play a prominent role in determining the final wheat yield. The normal monthly meteorological parameters at different locations in the state are given in Table 2. In Punjab the normal maximum temperature at various locations is in the range of 20.6–22.3, 18.3–19.6, 21.1–22.6 and 26.7–27.9°C for December, January, February and March, respectively. Similarly, the normal minimum temperature is in the range of 4.3–7.5, 3.7–6.6, 6.1–8.8 and 10.8–13.3°C for December, January, February and March, respectively.

Though wheat crop is grown under assured irrigation conditions in Punjab, but the rainfall received during tillering, flowering and grain formation stages of wheat not only proves beneficial for the crop but also helps in saving supplemental irrigation. The normal rainfall at various locations is in the range of 8.6–29.8, 17.3–36.5, 16.7–40.6 and 15.6–38.3 mm for December, January, February and March, respectively (Table 2).

Analysis of the temperatures during January, February and March was done and average wheat yield corresponding to particular range of maximum and minimum temperatures for these 3 months, for various locations are presented in Table 3. The perusal of data revealed that maximum temperature in the range of 16.1–18.0°C for January, $\leq$21.0 $^{\circ}$C for February and 28.1-30.0°C for March were most

favourable for optimum wheat yield (Table 3). Similarly, the minimum temperature in the range of 3.1–5.0°C for January, 5.1-7.0°C for February and 11.1-13.0°C for March were most favourable for wheat yield in the region.

Simulation of effect of intra-seasonal temperature rise on yield

The simulation study was conducted using CERES-Wheat model to assess the effect of intra-seasonal increase of temperature from normal on yield of wheat sown on different dates. The study was carried out with the assumption that weather remained normal in rest of the crop growth period and the crop remained free of water and nutrient stress and pest infestation. The simulation results revealed that in general, an increase in temperature from mid-February to mid- March severely affected the yield of early, normal and late sown wheat. A further scrutiny revealed that the temperature increase mostly affected the early (October) sown crop during fourth week of January, February and up to first fortnight of March; the timely (November) sown crop during February and March; the late (fourth week of November) sown crop during March; and very late (December) sown crop during March and first week of April.

The analysis revealed an increase of temperature from normal decreased grain yield at the following rates :

- Temperature increase in fourth week of January

Table 1 : Actual wheat yield (kg ha⁻¹) and its deviations (%) from technology trend yield at different locations in Punjab

Crop year	Ballowal Saunkhri		Amritsar		Ludhiana		Patiala		Bathinda	
	Actual yield (kg ha⁻¹)	Deviation (%)	Actual yield (kg ha⁻¹)	Deviation (%)	Actual yield (kg ha⁻¹)	Deviation (%)	Actual yield (kg ha⁻¹)	Deviation (%)	Actual yield (kg ha⁻¹)	Deviation (%)
1970-71	1 468	-2.5	2 326	+9.8	3 279	+14.4	1 209	-40.1	2 121	+10.1
1971-72	1 435	-8.6	2 749	+25.3	3 310	+13.0	2 067	-1.8	2 513	+25.8
1972-73	1 885	+15.4	2 198	-3.2	2 922	-2.3	1 939	-11.5	1 817	-12.1
1973-74	1 687	-0.6	2 051	-12.6	2 929	-4.1	2 195	-3.7	1 940	-9.3
1974-75	2 070	+17.4	2 276	-6.1	3 001	-3.7	2 204	-6.9	2 141	-3.1
1975-76	2 120	+16.1	2 424	-3.0	2 823	-11.2	2 338	-4.7	2 085	-8.6
1976-77	1 840	-2.7	2 493	-3.2	3 160	-2.6	2 424	-4.6	2 356	+0.2
1977-78	1 803	-7.8	2 546	-4.0	3 301	-0.2	2 699	+2.7	2 298	-5.2
1978-79	1 888	-6.5	2 662	-2.5	3 454	+2.5	3 048	+12.2	2 620	+5.0
1979-80	2 114	+1.5	2 773	-1.2	3 436	+0.1	2 939	+4.8	2 653	+3.4
1980-81	2 041	-4.9	2 715	-5.8	3 163	-9.5	2 633	-8.9	2 753	+4.4
1981-82	2 041	-7.7	2 612	-11.7	3 384	-4.9	3 012	+1.1	2 920	+7.8
1982-83	1 998	-12.2	2 971	-2.1	3 521	-2.8	3 048	-0.6	2 798	+0.7
1983-84	2 181	-6.8	3 076	-1.1	3 354	-13.4	3 225	+2.3	2 267	-20.4
1984-85	2 117	-11.9	3 471	+8.9	3 932	-0.1	3 539	+9.2	2 804	-4.0
1985-86	2 539	+2.8	3 448	+5.6	4 063	+1.6	3 964	+19.1	3 127	+4.5
1986-87	2 329	-8.1	2 552	-23.6	3 446	-15.1	3 391	-0.7	2 523	-17.6
1987-88	2 574	-0.9	3 614	+5.8	4 176	+1.3	3 818	+9.0	3 020	-3.6
1988-89	2 825	+6.1	3 774	+8.1	4 303	+2.8	3 890	+8.4	3 160	-1.4
1989-90	2 780	+2.0	3 562	-0.2	4 046	-4.8	3 839	+4.4	3 284	+0.2
1990-91	2 855	+2.3	3 717	+2.0	4 168	-3.4	4 005	+6.4	3 313	-1.0
1991-92	2 947	+3.2	3 844	+3.3	4 252	-2.8	4 115	+6.8	3 523	+3.0
1992-93	3 082	+5.6	3 959	+4.2	4 321	-2.1	4 249	+7.9	3 728	+6.8
1993-94	3 080	+3.3	4 190	+8.1	4 435	-1.5	4 329	+7.5	3 822	+7.3
1994-95	3 168	+4.0	4 193	+6.1	4 556	-0.2	4 118	+0.1	3 862	+6.3
1995-96	3 017	-3.0	3 993	-0.8	4 192	-9.4	3 952	-5.9	3 685	-0.5
1996-97	3 552	+11.8	4 149	+1.1	4 680	-0.2	4 501	+5.0	4 049	+7.3
1997-98	3 062	-5.5	3 759	-10.1	4 211	-11.4	4 056	-7.3	3 470	-9.7
1998-99	3 484	+5.5	4 427	+4.0	4 518	-6.2	4 436	-0.6	4 160	+6.2
1999-00	3 591	+6.6	4 855	+12.1	5 064	+3.8	4 800	+5.5	4 614	+15.7
2000-01	3 463	+0.9	4 682	+6.2	5 169	+4.6	4 564	-1.6	4 172	+2.8
2001-02	3 616	+3.4	4 683	+4.4	5 073	+1.4	4 944	+4.6	3 905	-5.4
2002-03	3 439	-3.4	4 250	-6.8	4 498	-11.2	4 467	-7.2	4 180	-0.5
2003-04	3 417	-5.7	4 296	-7.4	4 747	-7.5	4 118	-15.9	3 895	-8.8
2004-05	3 402	-7.8	4 276	-9.3	4 828	-7.0	4 501	-9.7	4 120	-5.1

decreased the grain yield by 0.99, 0.66 and 0.70 % per °C for wheat sown in fourth week of October, first week of November, and second week of November, respectively.

- Temperature increase in first fortnight of February decreased the grain yield by 2.88 and 1.87 % per °C for wheat sown in fourth week of October, and first week of November, respectively.

- Temperature increase in second fortnight of February decreased the grain yield by 2.40, 3.30, 2.15, 1.26 and 0.69 % per °C for wheat sown in fourth week of October, first week, second week, fourth week of November, and first week of December, respectively.

- Temperature increase in first fortnight of March decreased the grain yield by 2.40, 2.10, 2.98, 3.51 and 3.15 % per °C for wheat sown in fourth week of October, first week, second week, fourth week of November, and first week of December, respectively.

- Temperature increase in second fortnight of March decreased the grain yield by 1.24, 2.15 and 3.40 % per °C for wheat sown in second week, fourth week of November, and first week of December, respectively.

Comparison of meteorological parameters during high, medium and low yield crop seasons

The recent past 7 crop seasons at Ludhiana were

Table 2 : Normal monthly meteorological parameters at different locations in Punjab

Month	Ballowal Saunkhri	Amritsar	Ludhiana	Patiala	Bathinda
Maximum temperature (^{o}C)					
December	21.6	21.4	20.6	21.6	22.3
January	19.2	18.9	18.3	18.9	19.6
February	22.6	21.7	21.1	21.7	22.3
March	27.8	26.7	26.4	27.2	27.9
Minimum temperature (^{o}C)					
December	6.4	4.3	6.4	7.5	6.0
January	5.2	3.7	5.6	6.6	4.8
February	7.7	6.1	7.4	8.8	7.5
March	12.1	10.8	11.5	13.3	12.0
Rainfall (mm)					
December	29.8	13.1	16.7	18.8	8.6
January	36.5	26.9	28.0	29.5	17.3
February	40.6	34.1	33.6	29.5	16.7
March	25.4	38.3	21.6	22.2	15.6

classified on the basis of the observed yield (with the assumption that technology advancement would not contribute to variation in yield) as follows:

(1) **High yield crop seasons** (>5 000 kg ha^{-1}): crop seasons 1999-2000, 2000-01 and 2001-02

(2) **Medium yield crop seasons** (4 600 – 5 000 kg ha^{-1}) : crop seasons 2003-04, 2004-05 and 2005-06

(3) **Low yield crop seasons** (<4 600 kg ha^{-1}) : crop season 2002-03

High yield crop season

During the crop year 1999-2000, 2000-01 and 2001-02, yields of 5 064, 5 169 and 5 073 kg ha^{-1}, respectively were recorded at Ludhiana (Table 1). The maximum temperature during December was above normal by up to 1.8 ^{o}C during crop year 1999-2000 and up to 3.9 ^{o}C during 2000-01; but was near normal ($\pm$2^{o}C) during the crop year 2001-02. During January, the maximum temperature remained below normal up to 4^{o}C during crop year 1999-2000 and 2000-01 and was near or slightly above normal (1.8^{o}C) during crop year 2001-02. During February, the maximum temperature remained below normal (>2^{o}C) during crop year 1999-2000, above normal (2-3 ^{o}C) during crop year 2000-01 and near normal ($\pm$1.8^{o}C) during crop year 2001-02. During March, the maximum temperature remained near normal ($\pm$2.1^{o}C) during crop year 1999-2000, above normal by up to 2.7^{o}C during crop year 2001-02 and was invariably above normal (2-4°C) during crop year 2000-01.

The minimum temperature during December was near normal ($\pm$1.5^{o}C) during crop year 1999-2000 and 2000-01; and was above normal during the crop year 2001-02. During

January the minimum temperature remained mostly above normal during crop year 1999-2000 but below normal during 2000-01 and was near normal during the crop year 2001-02. During February the minimum temperature remained between the range of $\pm$2 and 3°C during the 3 crop years. During March it remained below normal during crop year 1999-2000 but above normal during crop year 2000-01 and 2001-02. These data on temperatures during the crop season do not explain any conclusive favourable effect on high crop yields.

During the 3 high yield crop years a below normal rainfall was recorded (Table 4). However, as wheat is grown under assured irrigation conditions, the crop did not experience any water stress. The maximum and minimum relative humidity generally remained above normal. However, the minimum relative humidity was normal or below normal during February and March during the 3 crop years. The sunshine hours remained slightly above or below normal (+2.5 to -4 hr) during the 3 crop years (Table 5).

Medium yield crop season

During the crop year 2003-04, 2004-05 and 2005-06 yields of 4 747, 4 828 and 4 780 kg/ha, respectively were reported at Ludhiana (Table 1). The maximum temperature during December and January was near or below normal during the 3 crop years. During February the maximum temperature remained below normal (>2°C) during crop year 2004-05, near or above normal (2-3°C) during crop year 2003-04 and above normal (>4°C) during crop year 2005-06. During March, the maximum temperature remained near normal ($\pm$1.5^{o}C) during crop year 2004-05 and 2005-06; and was invariably above normal (>4°C) during crop year 2003-04.

The minimum temperature during December was above

Table 3 : Range of temperatures during January, February and March and corresponding average wheat yields during the past decade at different locations in Punjab

Temperature	Yield (kg ha^{-1}) and number of years in past decade				
	Ballowal Saunkhri	Amritsar	Ludhiana	Patiala	Bathinda
Maximum temperature (^oC)		*January*			
≤16.0	3 439 (1)*	4 250 (1)	4 498 (1)	4 467 (1)	-
16.1-18.0	3 484 (1)	4 507 (5)	4 865 (5)	4 480 (4)	4 190 (6)
18.1-20.0	3 415 (6)	4 146 (4)	4 539 (4)	4 391 (5)	3 777 (4)
>20.0	3 317 (2)	-	-	-	-
		February			
≤21.0	3 402 (1)	4 460 (3)	4 695 (3)	4 651 (2)	4 367 (2)
21.1-22.0	3 591 (1)	3 876 (2)	4 596 (5)	4 210 (2)	4 180 (1)
22.1-23.0	3 210 (3)	4 389 (4)	4 747 (1)	4 500 (3)	3 854 (5)
>23.0	3 484 (5)	4 682 (1)	5 169 (1)	4 373 (3)	4 034 (2)
		March			
≤ 26.0	3 062 (1)	4 095 (3)	4 446 (2)	4 056 (1)	4 042 (2)
26.1-28.0	3 464 (3)	4 332 (3)	4 646 (4)	4 284 (5)	3 867 (2)
28.1-30.0	3 434 (5)	4 597 (3)	4 917 (3)	4 648 (3)	4 107 (5)
>30.0	3 417 (1)	4 296 (1)	4 747 (1)	4 118 (1)	3 895 (1)
Minimum temperature (^oC)		*January*			
≤3.0	3 462 (1)*	4 044 (4)	-	-	-
3.1-5.0	3 337 (5)	4 553 (5)	4 920 (2)	4 501 (1)	3 463 (1)
5.1-7.0	3 474 (4)	4 427 (1)	4 560 (5)	4 543 (6)	3 337 (5)
>7.0	-	-	4 443 (3)	4 169 (3)	3 474 (1)
		February			
≤5.0	-	4 502 (2)	-	-	-
5.1-7.0	3 535 (3)	4 372 (7)	5 064 (1)	4 800 (1)	4 332 (2)
7.1-9.0	3 395 (7)	3 759 (1)	4 657 (9)	4 512 (5)	3 875 (6)
>9.0	-	-	-	4 244 (4)	4 170 (2)
		March			
≤ 9.0	-	-	-	-	-
9.1-11.0	3 402 (3)	4 288 (5)	5 064 (1)	-	4 614 (1)
11.1-13.0	3 351 (4)	4 386 (5)	4 615 (5)	4 464 (4)	3 905 (5)
>13.0	3 478 (3)	-	4 708 (4)	4 414 (6)	3 970 (4)

* Figures in parenthes indicate the number of years

normal during crop year 2003-04 and 2004-05; and was below normal during the crop year 2005-06. During January the minimum temperature remained near or above normal during crop year 2004-05 and 2005-06; and was above normal during the crop year 2003-04. During February and March the minimum temperature remained above normal during the three crop years and was especially above normal by >4^oC during the crop year 2005-06.

During the 3 medium yield crop years a below normal rainfall was recorded during December (Table 4). Then during January, above normal rainfall of +42 and +37 mm was received during crop year 2003-04 and 2004-05; and near normal rainfall was recorded during crop year 2005-06. During February, rainfall was 14 mm below normal during 2003-04 and 14 mm above normal during crop year 2004-05 while practically no rainfall was recorded during crop year 2005-06. March remained dry during crop year 2003-04 and above normal rainfall of +26 and +25 mm rainfall

was recorded during crop year 2004-05 and 2005-06, respectively. However as wheat is grown under assured irrigation conditions so less rainfall did not lead to any water stress.

The maximum relative humidity invariably remained above normal (>3 %) during the crop year 2003-04 and 2004-05; and was near or below normal during crop year 2005-06. The minimum relative humidity was invariably above normal (>10 %) during the crop year 2004-05, above normal (>10%) during December to mid February during the crop year 2003-04 and near or below normal during crop year 2005-06. The sunshine hours remained near or below normal during the 3 crop years. However it was above normal from mid-February to mid-March (>2 hr) during the crop year 2003-04 (Table 5).

Low yield crop season

During crop year 2002-03 an average yield of 4 498 kg ha^{-1} was reported for Ludhiana (Table 1). The maximum

Table 4: Comparison of weekly rainfall deviation (mm) from normal during high, medium and low yield years at Ludhiana for past seven crop years of 1999-00 to 2005-06

Month	Week No.	Normal rainfall (mm)	High wheat yield year (>5 000 kg ha^{-1})			Medium wheat yield year (4 600 – 5 000 kg ha^{-1})			Low wheat yield year (<4 600 kg ha^{-1})
			1999-00	2000-01	2001-02	2003-04	2004-05	2005-06	2002-03
December	49	3.3	-3.3	-3.3	-3.3	-3.3	-3.3	-3.3	-3.3
	50	2.2	-2.2	-2.2	2.6	6.2	-2.2	-2.2	-2.2
	51	5.8	-5.8	-5.8	-3.4	-5.8	-5.8	-5.8	-4.9
	52	4.8	-4.8	-4.8	-4.8	-4.8	0.9	-4.8	1.2
January	1	4.8	-4.8	-0.4	-4.8	-4.8	-4.8	1.4	-4.8
	2	4.7	30.8	-4.7	-4.7	-4.7	-4.7	-4.7	-4.7
	3	5.2	-4.4	-5.2	0.8	42.6	-4.3	5.4	-5.2
	4	9.5	3.9	-9.5	-9.5	-9.5	37.9	-9.5	12.9
February	5	5.9	9.3	-5.9	-5.9	14.1	-5.5	-5.9	9.8
	6	7.3	17.2	-7.3	6.7	-7.3	21.9	-7.3	-7.3
	7	12.8	-12.8	-12.8	-12.8	-12.8	5.0	-12.8	88.0
	8	8.4	-8.4	-8.4	-8.4	-8.4	-8.4	-8.4	5.1
	9	7.5	-7.5	-7.5	-5.3	-7.5	-6.5	-6.7	25.4
March	10	5.2	3.6	-5.2	-0.8	-5.2	8.6	-0.1	-5.2
	11	4.7	-4.7	-4.7	-4.7	-4.7	-1.0	15.7	-4.7
	12	5.9	5.9	-5.9	-3.3	-5.9	17.8	1.1	-5.9
	13	2.9	-2.9	0.5	-2.9	-2.9	-2.9	-2.9	12.1

Table 5: Comparison of weekly sun-shine hours deviation from normal during high, medium and low yield years at Ludhiana for past seven crop years of 1999-00 to 2005-06

Month	Week No.	Normal sunshine hours (Hrs)	High wheat yield year (>5 000 kg ha^{-1})			Medium wheat yield year (4 600 – 5 000 kg ha^{-1})			Low wheat yield year (<4 600 kg ha^{-1})
			1999-00	2000-01	2001-02	2003-04	2004-05	2005-06	2002-03
December	49	8.08	-1.98	1.32	0.62	-1.4	0.4	0.3	-0.7
	50	7.17	1.03	0.63	-1.47	-2.0	0.3	0.8	-1.2
	51	6.52	0.58	0.58	1.68	-4.1	-2.4	-3.0	-0.2
	52	6.04	-0.44	1.06	-2.84	-2.5	-3.3	-1.5	-1.5
January	1	6.38	-4.18	-4.28	-1.08	-3.7	-1.4	-0.7	-4.4
	2	6.47	-3.87	-1.27	-0.67	1.4	0.3	1.0	-3.9
	3	6.65	2.35	-0.25	-2.65	-5.1	0.3	-2.4	-3.2
	4	7.1	-0.2	1.3	1.3	-1.4	-1.5	2.1	-0.9
February	5	7.46	-1.66	2.84	1.94	-1.2	1.0	0.0	-2.6
	6	8.1	-3.1	2	-1.8	-0.1	-5.7	-0.9	0.6
	7	7.72	1.28	-0.42	0.78	0.9	-2.7	-1.8	-2.0
	8	8.32	1.28	-1.02	-0.92	2.1	-0.4	-0.1	-0.6
	9	8.25	2.15	2.35	-2.35	2.3	-4.0	1.8	-1.1
March	10	8.55	1.35	1.85	-0.25	2.4	-0.9	-1.9	0.9
	11	7.98	2.42	1.32	3.02	2.3	-0.9	-0.6	1.1
	12	8.56	-0.56	-0.46	0.84	-0.3	-1.0	0.7	0.2
	13	9.18	1.62	-1.18	1.12	1.7	2.3	1.4	-1.4

temperature remained generally near or below normal during most of crop season except first to third week December and third to fourth week of March. The minimum temperature were near or above normal by up to 2°C except second to third week of January and second week of March when these were slightly below normal. During the crop year 2002-03 the weather remained cloudy and sunshine hours were invariably below normal by up to 3.9 hr (Table 5). Also the maximum relative humidity was near or above normal (>3 %) throughout the crop season except second week December

and first to second week of March. The minimum relative humidity was near or above normal (>10%) throughout the crop season.

The growing season up to third week of January, generally experienced below normal rainfall (Table 4). Thereafter mostly above normal rainfall was received except mid-March. Heavy rainfall was received in February and early March. This period coincides with the booting to grain-filling stages in wheat crop sown under early, normal and late sowing conditions. A very heavy rainfall during this stage

proves harmful for growth and development of grains in wheat crop. Also this very heavy rainfall of +88 mm above normal may have caused waterlogging of the root system and this may be the reason for low yields inspite of the fact that temperature scenarios were quite favourable for the wheat crop.

CONCLUSION

During the high wheat yield crop years it was observed that both the maximum and minimum temperature remained normal $\pm$ 2°C throughout the crop season. Coupled with favourable temperature regimes, slightly above normal, normal or below normal rainfall helps in leading to high wheat productivity under a situation where crop is grown under assured irrigation conditions and additional irrigations nullify the effect of water stress. Moreover, dry (relative humidity near or below normal) and clear (sunshine hours near or above normal) weather from mid-February to March proves beneficial for grain-filling stage in wheat.

During the medium wheat yield crop years it was observed that both the maximum and minimum temperature remained within $\pm$4°C from normal throughout the crop season. Coupled with less favourable temperature regimes above normal rainfall (+20mm) during mid-January (crop year 2003-04) and February (crop year 2004-05) which coincides with the booting and anthesis stage of wheat sown under early, normal and late dates of sowing led to decrease in final yields. During crop year 2005-06 though no heavy rainfall was received but as the temperature remained >4°C above normal during February which coincides with anthesis and grain-filling stage of wheat sown under early, normal and late dates of sowing of wheat crop, so final yield of wheat was decreased. Moreover, slightly humid (relative humidity near or above normal) and slightly cloudy (sunshine hours near or below normal) weather from mid-February to March is not favourable for grain-filling stage in wheat crop and results in decrease in wheat production.

Low wheat yield were recorded during the crop year 2002-03 at Ludhiana.. Though the temperature scenarios were favourable during this crop year for wheat crop development, but the weather remained cloudy and sunshine hours were invariably near or below normal (>1 hr). Also the maximum and minimum relative humidity was near or above normal (>3-10%) during most part of the crop season. Very heavy rainfall showers were received during the anthesis

and grain-filling period of wheat crop (second fortnight of February) sown under early, normal and late dates of sowing which may have caused waterlogging of the root system. It may be concluded that this might be the reason of low wheat yields in spite of the fact that temperature scenarios were quite favourable for the wheat crop.

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