18

Global Climate Change vis-à-vis Crop Productivity

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1. INTRODUCTION

It is now well known that climate is changing worldwide. The past two decades have witnessed globally a rapid increase in the awareness of climatic change and triggered widespread apprehension amongst scientists and governments about its global implications (Gadgil, 1996; Malone and Brenkert, 2008; Baer and Risbey, 2009). These climatic changes are the result of changes in atmospheric gaseous constituents, vegetation/crop cover and biodiversity (Fig. 1).

The Inter-Governmental Panel on Climate Change (IPCC) in its recently released report has reconfirmed that the global atmospheric concentrations of greenhouse gases (GHGs) have increased markedly as a result of human activities (IPCC, 2007). Between 1000 and 1750 AD, the CO_2, methane

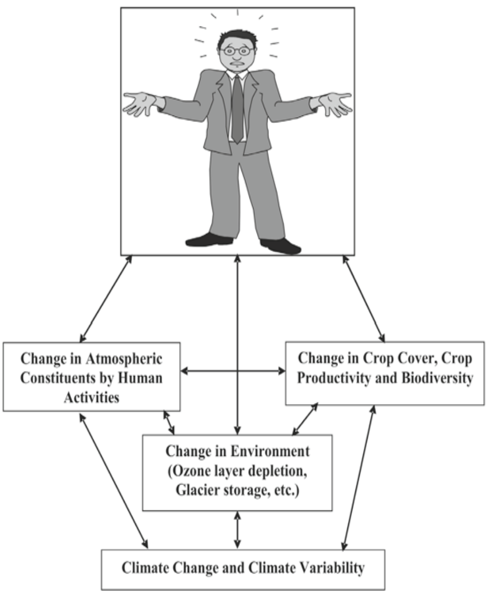

Fig. 1 Climate change as induced by anthropogenic activities and its effect on humans.

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and nitrous oxide concentrations were 280 ppm, 700 ppb and 270 ppb, respectively. In 2005, these values have increased to 379 ppm, 1774 ppb and 319 ppb, respectively (IPCC, 2007). The global increases in CO_2 concentrations are primarily due to fossil fuel use and land use change, while those of methane and nitrous oxide are primarily due to agriculture. These increases in GHGs have resulted in the warming of climate system by 0.74 ^oC between 1906 and 2005 (Sathaye et al., 2006; Ghude et al., 2009). Eleven of the last twelve years (1995-2006) rank amongst the 12 warmest years in the instrumental record of global surface temperature since 1850 (IPCC, 2007). The rate of warming has been much higher in the recent decades and the night time minimum temperatures have been increasing at twice the rate of daytime maximum temperatures. The quantity of rainfall and its distribution has also become more uncertain. In some places, climatic extremes such as droughts, floods, timing of rainfall and snowmelt have also increased. The sea level has risen by 10-20 cm with regional variations (Gosain et al., 2006; Unnikrishnan et al., 2006). Similarly, snow cover is also believed to be gradually decreasing (De la Mare, 2009).

CO_2 is vital for photosynthesis and hence for plant growth. An increase in the atmospheric CO_2 concentration affects agricultural production by climate change and changes in photosynthesis and transpiration rate. The rise in atmospheric CO_2 concentration from pre-industrial level of about 280 ppm to about 377 ppm currently is well documented (Keeling and Whorf, 2005). It is therefore important to assess the combined effects of elevated atmospheric concentration and climate change on the productivity of a region's dominant crops (Haskett et al., 1997). The direct effects of increased concentrations of CO_2 are generally beneficial to vegetation (Farquhar, 1997), especially for C_3 plants (wheat, rice, barley, oats, peanut, cotton, sugar beet, tobacco, spinach, soybean and most trees), as elevated levels lead to higher assimilation rates and to an increase in stomatal resistance resulting in a decline in transpiration and improved water use efficiency of crops.

The rising temperature and carbon dioxide and uncertainties in rainfall associated with global climate change may have serious direct and indirect consequences on crop production and hence on food security (Sinha and Swaminathan, 1991; Kumar, 1998). It is, therefore, important to have an assessment of the direct and indirect consequences of global warming on different crops contributing to our food security. Future agricultural planning has to formulate a holistic approach on productivity, stability, sustainability, profitability and equity in Indian agriculture in coming decades. Simulation techniques are easy, time saving, economical and widely used for studying the influence of climatic variability on the growth and yield of crops. The effects of changes in temperature, precipitation and CO_2 concentrations on crop productivity have been studied extensively using crop simulation models (e.g., Bachelet and Gay, 1993; Olszyk et al., 1999; Timsina and Humphreys, 2003; Attri and Rathore, 2003; Parry et al., 2004; Hundal and Prabhjyot-Kaur, 2007; Pathak and Wassmann, 2009). Simulation studies have been conducted for predicting the plausible effects of elevated levels of CO_2 on the yield of crops (Olszyk et al., 1999; Tubeillo and Ewert, 2002). Lal et al. (1998) through sensitivity experiments found that under elevated CO_2 levels, the yields of rice and wheat increased by 15% and 28%, respectively for a doubling of CO_2 in Northwest India. Soybean yields have been reported to increase by nearly 50% for a doubling of atmospheric CO_2 from its current level of 330 ppm (Mall et al., 2004).

The combined effects of climate change have been found to have implications for dryland and irrigated crop yields (Rosenzweig and Iglesias, 1994). However, the effect on production is expected to vary by crop and location as well as by the magnitude of warming, and the direction and magnitude of precipitation change (Adams et al., 1998). Several such attempts have been made for predicting the yield of wheat (e.g., Mearns et al., 1996; Attri and Rathore, 2003; Pathak and Wassmann, 2009), rice (e.g., Bachelet and Gay, 1993; Olszyk et al., 1999) and wheat, rice, maize and groundnut (e.g., Hundal and Prabhjyot-Kaur, 1996) under changing climatic conditions.

The DSSAT-family of models have been used most extensively in predicting the effect of various climate change scenarios on crop yields as these models contain subroutines for examining the impact of climate change on crop yields (e.g., Lal et al., 1998; Attri and Rathore, 2003; Timsina and Humphreys, 2003; Mall et al., 2004; Hundal and Prabhjyot-Kaur, 2007). Keeping into account the anticipated regional climatic changes in India, the effects of changes in temperature, solar radiation and carbon dioxide and their interactions on the growth and yield of salient crops under the agro-climatic conditions of Punjab State were studied by using the CERES- and GRO-family of crop simulation models. The results of these simulation studies, together with an overview of climate change/variability in India are discussed in this chapter.

2. CLIMATE CHANGE AND CLIMATE VARIABILITY IN INDIA

An analysis of the mean annual surface air temperature over India indicates a significant warming of about 0.3-0.6 °C since the 1860's (Hingane et al., 1985; Pant, 2003). This warming trend in general is comparable to the global mean trend of 0.5 ^{o}C in last 100 years (Sathaye et al., 2006). Analysis of a representative rainfall series from different locations in India over past more than a century indicate a highly variable but trendless behavior of the rainfall with a prominent epochal nature of variability. However, it has been reported that there do exist some smaller sub-regions with statistically significant increasing and decreasing trends (Sontakke, 1990; Pant and Rupa Kumar, 1997). Some studies have indicated that the rainfall patterns in India are also set to change and the western and central areas could have up to 15 more dry days each year, while in contrast, the north and northeast are predicted to have 5 to 10 more days of rain annually. In other words, the dry areas will get drier and the wet areas will get wetter (Pant and Rupa Kumar, 1997; Pant, 2003).

Since there is a large spatial and temporal variability in weather factors in a region, it is desirable that more detailed scenarios are made available for different agro-climatic zones. There is also greater consensus now that in future climatic variability in India will increase leading to more frequent extremes of weather in the form of uncertain onsets of monsoons, and frequency and intensity of drought, flooding, etc. (Goswami et al., 2006).

3. CLIMATE CHANGE/VARIABILITY: A CASE STUDY IN PUNJAB

Agriculture is sensitive to short-term changes in weather as well as to seasonal, annual and longer-term variations in climate. The variations in the meteorological parameters, in combination with other parameters such as soil characteristic, cultivar, pest and diseases, etc., have paramount influence on the agricultural productivity (Pathak and Wassmann, 2009). In the northern India, though the geographical area of Punjab State is only 1.53 % of the country, it contributes nearly 70% of wheat and 55% of rice to the central pool of foodgrains and hence, is referred to as "Bread Basket" of the country. It is, therefore, of great importance to have an assessment of the variability in these climatic factors in Punjab State.

The climate variability analysis was carried out by analyzing historical data of maximum and minimum temperatures and rainfall for five locations in three agro-climatic zones of the state, i.e., Zone I (Ballowal Saunkhri), Zone III (Amritsar, Ludhiana and Patiala) and Zone IV (Bathinda) (Fig. 2). The daily temperature and rainfall data of past three decades for Ballowal Saunkhri (1984-2005), Amritsar (1970-2005), Ludhiana (1970-2005), Patiala (1970-2005) and Bathinda (1977-2005) were analyzed for annual, *kharif* (1 May to 31 October) and *rabi* (1 November-30 April) crop growing seasons. The results of the study are discussed below.

3.1 Temperature Variability Trends

The trend line obtained by regressing the five-yearly moving averages against time for annual, *kharif* and *rabi* season maximum and minimum temperatures are shown in Tables 1 and 2, respectively for the locations of Ballowal Saunkhri, Amritsar, Ludhiana, Patiala and Bathinda. In general, the maximum temperature has decreased from the normal at Ballowal Saunkhri and Bathinda; however, no trend could be established for the other locations. The *kharif* maximum temperature decreased at the rate of 0.04 °C/year at Ballowal Saunkhri and Bathinda.

The annual and seasonal minimum temperature has increased at the rate of 0.07 °C/year over the past three decades at Ludhiana. At Patiala, the annual and *kharif* minimum temperatures have increased at the rate of 0.02 °C/year and at Bathinda the annual, *kharif* and *rabi* minimum temperatures have increased at the rate of about 0.03, 0.02 and 0.05 °C/year, respectively. However no trend of change in the minimum temperature was observed at Ballowal Saunkhri and Amritsar.

Table 1. Time trend equations for maximum temperature (slope of regression in °C/calendar year) over the past three decades at different locations for annual, *kharif* and *rabi* seasons in Punjab

Station (Latitude, longitude and elevation above MSL)	*Annual*	*Kharif*	*Rabi*
Ballowal Saunkhri (31° 60′ N, 76° 23′ E, 355 m)	$y = 0.058x - 86.08$ $R^2 = 0.46$	$y = 0.045x - 56.17$ $R^2 = 0.46$	$y = 0.089x - 152.30$ $R^2 = 0.56$
Amritsar (31° 37′ N, 74° 53′ E, 231 m)	$y = -0.010x + 50.97$ $R^2 = 0.13$	$y = -0.018x + 73.07$ $R^2 = 0.32$	$y = 0.007x + 10.39$ $R^2 = 0.05$
Ludhiana (30° 56′ N 75° 48′ E 247 m)	$y = -0.0001x + 30.90$ $R^2 = 0.00$	$y = -0.014x + 62.67$ $R^2 = 0.21$	$y = 0.017x - 98.40$ $R^2 = 0.15$
Patiala (30° 20′ N 76° 28′ E 251 m)	$y = 0.004x + 21.10$ $R^2 = 0.04$	$y = -0.007x + 50.33$ $R^2 = 0.17$	$y = 0.020x - 16.39$ $R^2 = 0.26$
Bathinda (30° 12′ N 74° 57′ E 211 m)	$y = -0.023x + 77.42$ $R^2 = 0.21$	$y = -0.040x + 117.00$ $R^2 = 0.31$	$y = -0.001x + 29.41$ $R^2 = 0.00$

Table 2. Time trend equations for minimum temperature (slope of regression in °C/calendar year) over the past three decades at different locations for annual, *kharif* and *rabi* seasons in Punjab

Station (Latitude, longitude and elevation above MSL)	*Annual*	*Kharif*	*Rabi*
Ballowal Saunkhri (31° 60′ N, 76° 23′ E, 355m)	$y = -0.022x + 61.80$ $R^2 = 0.06$	$y = -0.011x + 45.87$ $R^2 = 0.02$	$y = -0.008x + 27.25$ $R^2 = 0.006$
Amritsar (31° 37′ N, 74° 53′ E, 231 m)	$y = -0.004x + 25.17$ $R^2 = 0.017$	$y = -0.002x + 28.13$ $R^2 = 0.004$	$y = -0.006x + 21.01$ $R^2 = 0.02$
Ludhiana (30° 56′ N 75° 48′ E 247 m)	$y = 0.071x - 125.00$ $R^2 = 0.92$	$y = 0.076x - 129.00$ $R^2 = 0.94$	$y = 0.067x - 125.00$ $R^2 = 0.86$
Patiala (30° 20′ N 76° 28′ E 251 m)	$y = 0.015x - 13.34$ $R^2 = 0.43$	$y = 0.022x - 20.81$ $R^2 = 0.59$	$y = 0.010x - 9.803$ $R^2 = 0.15$
Bathinda (30° 12′ N 74° 57′ E 211 m)	$y = 0.038x - 59.57$ $R^2 = 0.59$	$y = 0.025x - 27.30$ $R^2 = 0.25$	$y = 0.053x - 97.18$ $R^2 = 0.71$

3.2 Rainfall Variability Trends

The trend lines obtained by regressing the five-yearly moving averages against time for annual, *kharif* and *rabi* season rainfalls are shown in Table 3 for the locations of Ballowal Saunkhri, Amritsar, Ludhiana, Patiala and Bathinda. In general, no significant change was noted for the annual and seasonal rainfalls at different locations over the past three decades. At Ballowal Saunkhri, the annual, *kharif* and *rabi* rainfalls have decreased at a rate of 16, 12 and 3 mm/year, respectively. At Bathinda, the *rabi* season rainfall has decreased at a rate of 2 mm/year over the past three decades.

Table 3. Time trend equations for rainfall (slope of regression in mm/calendar year) over the past three decades at different locations for annual, *kharif* and *rabi* seasons in Punjab

Station (Latitude, longitude and elevation above MSL)	*Annual*	*Kharif*	*Rabi*
Ballowal Saunkhri (31° 60′ N, 76° 23′ E, 355m)	$y = -16.11x + 3314$ $R^2 = 0.39$	$y = -12.50x + 25948$ $R^2 = 0.34$	$y = -3.26x + 6675$ $R^2 = 0.36$
Amritsar (31° 37′ N, 74° 53′ E, 231 m)	$y = -1.94x + 4579$ $R^2 = 0.06$	$y = -1.32x + 3210$ $R^2 = 0.04$	$y = -1.18x + 2493$ $R^2 = 0.06$
Ludhiana (30° 56′ N 75° 48′ E 247 m)	$y = 3.193x - 5602$ $R^2 = 0.12$	$y = 3.26x - 5860$ $R^2 = 0.13$	$y = -0.476x + 1077$ $R^2 = 0.02$
Patiala (30° 20′ N 76° 28′ E 251 m)	$y = 1.08x - 1358$ $R^2 = 0.007$	$y = 2.25x - 3824$ $R^2 = 0.038$	$y = -1.462x + 3044$ $R^2 = 0.054$
Bathinda (30° 12′ N 74° 57′ E 211 m)	$y = -3.015x + 6562$ $R^2 = 0.034$	$y = -0.276x + 1009$ $R^2 = 0.00$	$y = -2.976x + 6025$ $R^2 = 0.54$

The earlier study conducted by Hundal and Prabhjyot-Kaur (2002) revealed an overall increase in rainfall over a period of 1970-1998 at different locations (Amritsar, Ludhiana, Patiala and Bathinda). However, during the period from 1999 to 2005, below normal rainfall was received at all the five locations during the years 1999, 2002, 2004 and 2005. During the year 2000, below normal rainfall was recorded at Ludhiana and Patiala and during year 2001, below normal rainfall was recorded at all the four locations except Ludhiana. This resulted in arresting the increasing trend of rainfall at different locations in the state. Hence, no significant trend in increase/decrease of rainfall was observed at all the locations except Ballowal Saunkhri where a significant decreasing trend was observed.

4. EFFECT OF CLIMATE CHANGE ON CROP PHENOLOGY, GROWTH AND YIELD: A CASE STUDY

Crop growth and yield were simulated with DSSAT (Decision Support System for Agrotechnology Transfer) models of CERES-Rice (Ritchie et al., 1986), CERES-Wheat (Godwin et al., 1990), PNUTGRO (Boote et al., 1989), SOYGRO (Jones et al., 1988) and CHICKPGRO (Singh and Virmani, 1996) for rice, wheat, groundnut, soybean and gram, respectively under anticipated synthetic climatic scenarios. These models require weather, soil and crop data for simulating the crop phenology, growth and various yield characteristics. The crop models used in this study were: CERES-Rice (Prabhjyot-Kaur and Hundal, 2001), CERES-Wheat (Hundal and Prabhjyot-Kaur, 1997), PNUTGRO (Prabhjyot-Kaur and Hundal, 1999) and SOYGRO (Prabhjyot-Kaur and Hundal, 2002). These models have been validated under Ludhiana (Punjab) environmental conditions for the commonly sown cultivars.

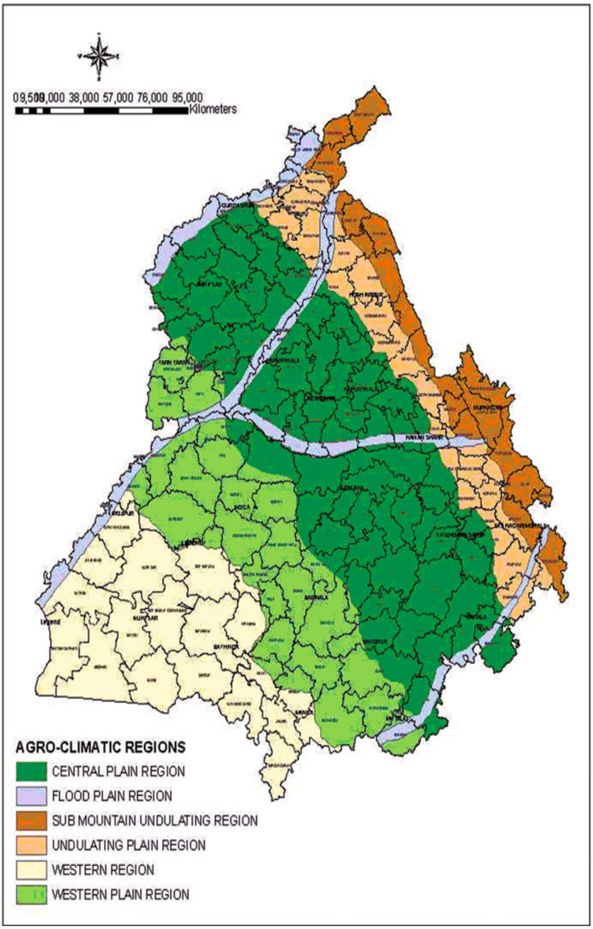

Fig. 2 Agro-climatic map of Punjab State, northern India.

The soil and weather data used in the study were collected from Punjab Agricultural University, Ludhiana, India. It is located at 30° 54′N latitude and 75° 48′E longitude at an elevation of 247 m above mean sea level. This location represents the central irrigated plains of the Indian Punjab in which crops are grown under assured irrigation conditions and hence optimum (non-limiting) moisture conditions were assumed. The simulations were made with the assumption that nutrition was non-limiting and there were no losses from insect-pests.

On the basis of climatic variability trends observed in the state, anticipated synthetic scenarios of increase or decrease from normal temperature, interactions of maximum and minimum temperatures, solar radiation, carbon dioxide levels and intra-seasonal temperature change were generated for the simulation study. One variable at a time was modified and its effect on crop growth and yield was simulated while taking all the other climate variables to be normal. The major reason for using incremental variable scenarios is that they capture a wide range of potential changes. Subsequently, the combination of two variables was interactively modified to assess their combined effect on crop growth and yield.

4.1 Effect of Changes in Temperature

The phenological development, growth and yield attributes of crops were simulated when both maximum and minimum temperatures were increased or decreased by 0.5, 1.0, 2.0 and 3.0 °C from normal while keeping the other climate variables constant. Phenological development of *kharif* crops, i.e., rice, groundnut and soybean was not much affected by increase or decrease in temperature of 1.0 °C from normal (Table 4). On the other hand, phenological development of wheat and gram (*rabi* crops) revealed more drastic changes as the phenology was significantly advanced by increasing temperature but was delayed by decreasing temperature.

The growth and yield of crops was reduced by an increase in temperature, but increased with a decrease in temperature from normal (Table 5). Both the reduction and the increase were more for *rabi* crops (wheat and gram) than for *kharif* crops (rice, groundnut and soybean). With an increase in temperature by 1.0 to 2.0 °C, the simulated maximum leaf area index (LAI) in rice decreased by 3.5 to 9.2%, in wheat by 18.4 to 29.2%, in groundnut by 3.4 to 5.8% and in soybean by 0.3 to 3.0% from normal; biomass yield in rice decreased by 2.3 to 5.0%, in wheat by 13.7 to 22.9%, in groundnut by 2.7 to 5.4%, in soybean by

Table 4. Effect of increase or decrease in temperature from normal on deviations in the phenology (days) of crops

Phenological stages	*Temperature level*								
	–3.0 °C	*–2.0 °C*	*–1.0 °C*	*–0.5 °C*	*Normal**	*+0.5 °C*	*+1.0 °C*	*+2.0 °C*	*+3.0 °C*
Rice									
Heading date	+5	+2	0	0	223	0	0	+1	+4
Maturity date	+12	+6	+2	0	263	+1	+1	+1	+5
Wheat									
Anthesis date	+25	+17	+8	+3	41	–3	–6	–12	–16
Maturity date	+22	+15	+8	+4	81	–3	–6	–12	–17
Groundnut									
Flowering date	0	0	–1	0	197	0	0	+3	+4
Podding date	0	0	–1	0	218	0	+1	+5	+4
Maturity date	+6	+2	–1	0	285	0	+2	+5	+9
Soybean									
Flowering date	0	0	–1	–1	239	+1	+2	+3	+4
Podding date	0	0	0	0	260	+1	+2	+3	+3
Maturity date	+2	+1	0	0	294	+1	+1	+2	+2
Gram									
Flowering date	+35	+22	+11	+4	08	–4	–7	–19	–23
Podding date	+34	+23	+12	+5	30	–4	–9	–16	–22
Maturity date	+27	+18	+9	+4	99	–5	–8	–16	–24

*Julian day.

Table 5. Effect of increase or decrease in temperature from normal on deviations (%) in the growth and yield attributes of crops

Growth/Yield attributes	*Temperature level*								
	–3.0 °C	*–2.0 °C*	*–1.0 °C*	*–0.5 °C*	*Normal*	*+0.5 °C*	*+1.0 °C*	*+2.0 °C*	*+3.0 °C*
Rice									
Maximum LAI	+7.69	+5.24	+3.15	+1.22	5.72•	–1.75	–3.50	–9.26	–12.94
Grain yield	+26.81	+15.15	+8.07	+6.56	6692♦	–0.16	–2.82	–9.59	–10.14
Biomass yield	+19.93	+9.92	+4.35	+2.93	11717♦	–0.94	–2.35	–5.02	–6.06
Wheat									
Maximum LAI	+41.08	+27.84	+11.62	+5.14	3.70•	–5.94	–18.38	–29.19	–38.90
Grain yield	+9.85	+7.38	+7.16	+6.26	4932♦	–2.75	–9.87	–18.02	–27.03
Biomass yield	+20.84	+16.07	+9.12	+4.11	13304♦	–4.60	–13.76	–22.87	–32.35
Groundnut									
Maximum LAI	+17.10	+11.65	+6.02	+3.76	5.32•	–1.13	–3.38	–5.82	–7.70
Seed yield	+27.75	+16.53	+6.21	+5.31	998♦	–4.01	–4.51	–10.62	–13.13
Biomass yield	+20.50	+12.33	+4.98	+4.37	11467♦	–2.19	–2.79	–5.42	–7.91
Soybean									
Maximum LAI	+3.05	+3.21	+0.76	–0.15	6.55•	–0.31	–0.31	–3.05	–7.63
Seed yield	–11.60	–4.38	–1.61	+0.02	1982♦	+3.98	+2.37	+2.42	–5.60
Biomass yield	–1.93	+1.14	+0.89	+0.80	7369♦	+0.09	–1.25	–3.42	–8.12
Gram									
Maximum LAI	–30.30	–21.30	–10.11	–7.86	0.89•	+7.86	+17.97	+37.08	+47.19
Seed yield	–17.87	–13.94	–7.24	–7.04	1449♦	+0.21	+8.14	+16.01	+17.87
Biomass yield	–23.50	–16.17	–7.51	–6.14	3808♦	+2.25	+8.85	+15.15	+14.20

• Maximum LAI (dimensionless); ♦ Grain/Seed/Biomass Yield (kg/ha).

1.2 to 3.4% and in gram by 8.8 to 15.1% from normal; grain/seed yield in rice decreased by 2.8 to 9.6%, in wheat by 9.8 to 18.0% and in groundnut by 4.5 to 10.6% from normal. However, in gram crop, with an increase in temperature by 1.0 to 2.0 °C, the simulated maximum leaf area index (LAI) increased by 17.9 to 37.0%, biomass yield increased by 8.8 to 15.1%, seed yield increased by 8.1 to 16.0%, while seed yield in soybean also increased by 2.3 to 2.4% from normal.

A decrease in temperature by 1.0 to 2.0 °C led to an increase in the simulated maximum leaf area index (LAI) in rice by 3.1 to 5.2% and in wheat by 11.6 to 27.8% from normal; simulated biomass yield in rice by 4.3 to 9.9%; in wheat by 9.1 to 16.1%, in groundnut by 4.9 to 12.3% and in soybean by 0.8 to 1.1%; grain/seed yield in rice by 8.0 to 15.1%, in wheat by 7.2 to 7.4% and in groundnut by 6.2 to 16.5% from normal. On the other hand, with a decrease in temperature by 1.0 to 2.0 °C, the simulated maximum LAI in gram decreased by 10.1 to 21.3%, biomass yield decreased by 7.5 to 16.1%, seed yield decreased by 7.2 to 13.9%, while seed yield in soybean also decreased by 1.6 to 4.3% from normal.

4.2 Effect of Changes in Solar Radiation

The effects of increase or decrease in solar radiation on growth and yield of crops are shown in Table 6. In general, increase in solar radiation favored the growth and yield of crops, whereas the decrease in solar radiation favored reduction in growth and yield of crops. With an increase in solar radiation by 5.0%, the simulated maximum LAI increased in rice by 2.6%, in wheat by 4.0%, in groundnut by 5.8%

and in gram by 2.2% from normal; biomass yield increased in rice by 4.6%, in wheat by 3.9%, in groundnut by 7.4%, in soybean by 1.0% and in gram by 3.6% from normal; grain/seed yield increased in rice by 6.2%, in wheat by 3.6%, in groundnut by 7.7%, in soybean by 2.3% and in gram by 3.5% from normal. On the other hand, with a decrease in solar radiation by 5.0%, the simulated maximum LAI decreased in rice by 2.7%, in wheat by 4.5% and in groundnut by 1.1%, from normal; biomass yield decreased in rice by 4.4 %, in wheat by 4.3%, in groundnut by 2.7%, in soybean by 2.8% and in gram by 4.0% from normal; grain/seed yield decreased in rice by 6.0%, in wheat by 3.8%, in groundnut by 3.1%, in soybean by 2.8% and in gram by 4.0% from normal.

Table 6. Effect of increase or decrease in radiation from normal on deviations (%) in the growth and yield attributes of crops

Growth/Yield attributes	*Radiation level (Percent deviation from normal)*						
	–5.0	*–2.5*	*–1.0*	*Normal*	*+1.0*	*+2.5*	*+5.0*
Rice							
Maximum LAI	–2.79	–1.39	–0.52	5.72•	+0.52	+1.57	+2.62
Grain yield	–6.00	–3.00	–1.19	6692♦	+1.19	+3.19	+6.20
Biomass yield	–4.44	–2.19	–0.86	11717♦	+0.86	+3.03	+4.63
Wheat							
Maximum LAI	–4.59	–2.16	–0.81	3.70•	+0.81	+2.16	+4.05
Grain yield	–3.85	–1.90	–0.75	4932♦	+0.75	+1.84	+3.65
Biomass yield	–4.38	–2.12	–0.83	13304♦	+0.83	+2.02	+3.95
Groundnut							
Maximum LAI	–1.13	+0.56	+1.69	5.32•	+3.01	+4.13	+5.82
Seed yield	–3.11	–0.40	+1.30	998♦	+3.41	+5.01	+7.72
Biomass yield	–2.78	–0.20	+1.33	11467♦	+3.37	+4.89	+7.40
Soybean							
Maximum LAI	0.00	0.00	0.00	6.55•	–0.15	–0.31	–0.61
Seed yield	–2.87	–1.36	–0.50	1982♦	+0.55	+1.26	+2.32
Biomass yield	–2.89	–1.39	–0.05	7369♦	+0.53	+0.91	+1.03
Gram							
Maximum LAI	0.00	–1.12	0.00	0.89•	0.00	0.00	+2.25
Seed yield	–4.00	–1.93	–0.76	1449♦	+0.69	+1.79	+3.59
Biomass yield	–4.02	–1.94	–0.76	3808♦	+0.76	+1.89	+3.68

• Maximum LAI (dimensionless); ♦ Grain/Seed/Biomass Yield (kg/ha).

4.3 Effect of Interactions between Maximum and Minimum Temperatures

When the maximum temperature decreased by 0.25 to 1.0 °C from normal and minimum temperature increased simultaneously from 1 to 3 °C from normal keeping the other climate variables constant, the phenology of rice, wheat and gram were advanced by as much as 1 to 15 days (Table 7). When the minimum temperature increased by 1.0 to 3.0 °C and maximum temperature decreased by 0.25 to 1.0 °C from normal, the heading in rice was advanced by 1 to 4 days, while the physiological maturity was advanced by 2 to 8 days from normal; in groundnut physiological maturity was advanced by 1 to 3 days from normal; in wheat both the anthesis and maturity were advanced by up to eight days from normal; and in gram flowering was advanced by 2 to 11 days while podding and physiological maturity were

Table 7. Effect of increasing minimum temperature and decreasing maximum temperature on deviations (days) in the phenology of crops

Phenological stages	*Minimum temperature*								
	At +1.0 °C			*At +2.0 °C*			*At +3.0 °C*		
	Maximum temperature			*Maximum temperature*			*Maximum temperature*		
	–0.25 °C	*–0.5 °C*	*–1.0 °C*	*–0.25 °C*	*–0.5 °C*	*–1.0 °C*	*–0.25 °C*	*–0.5 °C*	*–1.0 °C*
Rice									
Heading date	–1	–1	–2	–2	–3	–3	–4	–4	–4
Maturity date	–2	–2	–3	–4	–5	–4	–7	–8	–8
Wheat									
Anthesis date	–2	–2	0	–6	–4	–3	–8	–8	–6
Maturity date	–1	–1	+1	–5	–4	–3	–8	–7	–6
Groundnut									
Flowering date	0	0	–1	0	0	0	+1	0	0
Podding date	0	0	–1	0	0	0	+1	0	0
Maturity date	–2	–2	–3	–2	–2	–3	–1	–2	–3
Soybean									
Flowering date	+1	+1	+1	+1	+1	+1	+3	+3	+2
Podding date	+1	+1	+1	+1	+1	+1	+2	+2	+2
Maturity date	0	0	0	0	0	0	+1	+1	+1
Gram									
Flowering date	–3	–3	–2	–5	–5	–6	–11	–10	–9
Podding date	–4	–4	–2	–10	–10	–7	–15	–14	–13
Maturity date	–4	–4	–2	–10	–9	–8	–15	–14	–13

advanced by 2 to 15 days from normal. On the other hand, under similar interactive scenario of decreasing maximum temperature and increasing minimum temperature, the phenological development of soybean was either not affected or was delayed by 1 to 3 days from normal.

The effect of increasing minimum temperature and decreasing maximum temperature on simulated maximum LAI, biomass yield and grain/seed yield for crops are shown in Table 8. It is apparent from this table that generally, the maximum LAI, biomass yield and grain/seed yield of crops were adversely affected by increasing the minimum temperature from normal. However, these adverse effects were partially counteracted by decreasing maximum temperature from normal. When minimum temperature increased by 1.0 °C and maximum temperature decreased by 0.25 to 1.0 °C from normal, the deviations in the growth and yield attributes were low and the yields were not affected significantly. At further higher levels of increase in minimum temperature, reductions in growth and yield were greater and more so in *rabi* season crops (wheat and gram) than in *kharif* season crops (rice, groundnut and soybean).

4.4 Effect of Interactions between Temperature and Solar Radiation

The effect of increasing temperature (by 1, 2 and 3 °C from normal), and decreasing radiation levels (by 1, 2 and 5%) on maximum LAI, biomass and grain/seed yield of crops are shown in Table 9. When temperature increased by 1.0 °C and radiation levels decreased by 1, 2.5 and 5% from normal, the maximum LAI decreased respectively in rice by 4.0, 4.9 and 6.6%, in wheat by 19.2, 20.8 and 23.2% and

Table 8. Effect of increasing minimum temperature and decreasing maximum temperature on deviations (per cent) in the growth and yield attributes of crops

Growth/Yield attributes	*Minimum temperature*								
	At +1.0 °C			*At +2.0 °C*			*At +3.0 °C*		
	Maximum temperature			*Maximum temperature*			*Maximum temperature*		
	–0.25 °C	*–0.5 °C*	*–1.0 °C*	*–0.25 °C*	*–0.5 °C*	*–1.0 °C*	*–0.25 °C*	*–0.5 °C*	*–1.0 °C*
Rice									
Maximum LAI	–0.52	–0.52	–0.52	–1.39	–2.45	–0.87	–5.24	–3.84	–2.45
Grain yield	+1.45	+1.45	+1.40	–3.55	–4.38	–2.25	–9.71	–7.94	–7.78
Biomass yield	–0.82	–0.82	–0.58	–2.94	–3.36	–2.29	–6.28	–5.60	–3.35
Wheat									
Maximum LAI	–2.97	–2.97	–3.51	–16.21	–15.40	–12.16	–40.81	–20.27	–17.84
Grain yield	+2.67	+2.67	+5.61	–3.22	–2.27	+0.06	–6.33	–3.38	–3.22
Biomass yield	–2.02	–2.02	+0.28	–12.19	–10.68	–9.18	–16.02	–15.59	–12.38
Groundnut									
Maximum LAI	+0.18	+0.18	+0.94	–0.93	–1.13	–1.13	–2.25	–1.32	–1.50
Seed yield	–1.90	–1.90	–0.90	–4.20	–3.11	–4.41	–6.8	–6.81	–6.51
Biomass yield	–0.18	–0.18	–0.29	–2.27	–1.70	–1.58	–2.44	–2.87	–2.87
Soybean									
Maximum LAI	+0.15	+0.15	+0.61	–1.22	–0.92	–0.61	–0.92	–0.61	–0.76
Seed yield	+2.22	+2.22	+3.33	+2.37	+2.97	+4.18	+5.09	+5.8	+7.87
Biomass yield	–0.23	–0.03	+0.35	–1.64	–1.32	–0.62	–1.97	–1.52	–0.76
Gram									
Maximum LAI	+3.37	+7.87	+7.87	+16.85	+17.97	+2.25	+30.34	+34.83	+33.7
Seed yield	–4.62	–0.21	–0.21	+0.48	+5.11	+5.79	+7.18	+9.87	+9.32
Biomass yield	–1.71	+18.64	+18.64	+3.72	+5.93	+7.58	+8.69	+11.24	+10.5

Table 9. Effect of increasing temperature above normal and decreasing radiation below normal on deviations (percent) in the growth and yield attributes of crops

Growth and yield attributes	*Temperature change +1 °C*			*Temperature change +2 °C*			*Temperature change +3 °C*		
	Radiation change (%)			*Radiation change (%)*			*Radiation change (%)*		
	–1.0	*–2.5*	*–5.0*	*–1.0*	*–2.5*	*–5.0*	*–1.0*	*–2.5*	*–5.0*
Rice									
Maximum LAI	–4.02	–4.90	–6.64	–9.97	–11.19	–13.29	–13.81	–15.73	–18.88
Grain yield	–4.05	–5.89	–8.97	–10.82	–12.64	–15.69	–11.39	–13.28	–16.42
Biomass yield	–3.27	–4.69	–7.08	–6.03	–7.58	–10.25	–7.14	–8.84	–11.73
Wheat									
Maximum LAI	–19.19	–20.81	–23.24	–30.00	–31.35	–33.78	39.73	–41.08	–43.24
Grain yield	–10.69	–11.94	–14.05	–18.86	–20.11	–22.26	–27.86	–29.70	–31.22
Biomass yield	–14.67	–16.06	–18.40	–23.76	–25.10	–27.36	–33.19	–34.48	–36.64

Contd...

(*Contd.*)

Growth and yield attributes	*Temperature change +1 °C*			*Temperature change +2 °C*			*Temperature change +3 °C*		
	Radiation change (%)			*Radiation change (%)*			*Radiation change (%)*		
	–1.0	*–2.5*	*–5.0*	*–1.0*	*–2.5*	*–5.0*	*–1.0*	*–2.5*	*–5.0*
Groundnut									
Maximum LAI	–1.31	–2.25	–3.94	–3.20	–4.32	–6.01	–5.63	–6.57	–8.27
Seed yield	–2.71	–4.25	–6.89	–8.71	–10.22	–12.7	–11.22	–12.6	–15.03
Biomass yield	–0.91	–2.41	–4.96	–3.16	–4.64	–7.13	–5.26	–6.7	–9.12
Soybean									
Maximum LAI	0.00	–0.15	–0.31	–3.05	–3.05	–3.05	–7.63	–7.63	–7.79
Seed yield	+1.82	+0.95	–0.55	+1.87	+1.01	–0.55	–6.1	–6.91	–8.37
Biomass yield	–1.79	–2.63	–4.13	–3.95	–4.77	–6.24	–8.63	–9.43	–10.83
Gram									
Maximum LAI	+16.85	+15.73	+14.61	+35.96	+34.83	+32.50	+46.06	+43.82	+41.57
Seed yield	+7.25	+5.79	+3.38	+14.91	+13.25	+10.35	+16.63	+14.83	+11.73
Biomass yield	+7.9	+6.49	+3.99	+14.08	+12.39	+9.53	+13.02	+11.26	+8.22

in groundnut by 1.3, 2.2 and 3.9% from normal. Under same levels of temperature and radiation, the grain/seed yield decreased respectively in rice by 4.0, 5.8 and 8.9%, in wheat by 10.7, 11.9 and 14.1% and in groundnut by 2.7, 4.2 and 6.8% from normal, whereas the biomass yield in rice decreased by 3.3, 4.7 and 7.1%, in wheat by 14.7, 16.1 and 18.4% and in groundnut by 0.9, 2.4 and 4.9% from normal. The interactive effects of increasing temperature and decreasing radiation revealed a cumulative adverse effect on growth and yield of rice, wheat, groundnut and soybean. However, similar response was not observed for the gram crop.

4.5 Effect of Interactions between CO_2 and Temperature

The direct effects of increased concentrations of CO_2 are generally beneficial to vegetation as elevated levels lead to higher assimilation rates. The interactive effects of increasing CO_2 concentration and increasing temperature on crop growth and yield are shown in Table 10. The results of the simulation study revealed that increasing CO_2 levels were able to counteract the adverse effects of temperature increase on growth and yield of crops to some extent. A temperature increase of 2.0 °C from normal and doubled CO_2 concentration of 600 ppm in rice crop reduced the maximum LAI by 5.5%, biomass yield by 2.6% and grain yield by 2.8% from normal. However, a temperature increase of 2.0 °C from normal and doubled CO_2 concentration of 600 ppm increased the maximum LAI of wheat, groundnut, soybean and gram by 2.8, 35.6, 25.6 and 64.4% from normal, respectively; biomass yield of wheat, groundnut, soybean and gram by 3.9, 31.4, 28.6 and 58.4% from normal, respectively and grain yield of wheat, groundnut, soybean and gram by 5.6, 30.1, 35.2 and 55.7% from normal, respectively.

4.6 Effect of Intra-Seasonal Temperature Change

Wheat is a major winter cereal crop in northern India and it requires cool climate during its early growth stages for potential productivity. Any abrupt changes in weather parameters, especially an increase in

Table 10. Effect of increasing temperature and CO_2 above normal on deviations (percent) in the maximum LAI, grain yield and biomass yield of crops

Growth and yield attributes	*Temperature change from normal +1 °C*				*Temperature change from normal +2 °C*			
	CO_2 concentration (ppm)				*CO_2 concentration (ppm)*			
	330 (Normal)	*400*	*500*	*600*	*330 (Normal)*	*400*	*500*	*600*
Rice								
Maximum LAI	–9.3	–6.1	–4.0	+0.8	–12.3	–11.9	–7.8	–5.5
Grain yield	–6.6	–4.3	–2.8	+0.5	–7.5	–7.2	–4.4	–2.8
Biomass yield	–6.0	–4.0	–2.9	+0.8	–7.3	–7.1	–4.0	–2.6
Wheat								
Maximum LAI	–18.3	–11.2	–2.3	+7.8	–29.1	–17.6	–4.5	+2.8
Grain yield	–9.9	–5.6	+2.1	+10.4	–18.0	–10H.4	–1.4	+5.6
Biomass yield	–13.7	–10.7	–1.4	+8.6	–22.9	–12.5	–3.3	+3.9
Groundnut								
Maximum LAI	–3.4	+17.3	+34.5	+47.2	–5.8	+15.4	+28.3	+35.6
Seed yield	–4.5	+14.1	+29.0	+38.4	–10.6	+12.0	+25.7	+30.1
Biomass yield	–2.8	+14.9	+29.9	+40.6	–5.4	+12.1	+25.6	+31.4
Soybean								
Maximum LAI	–0.3	+12.3	+23.3	+27.8	–3.0	+11.4	+19.6	+25.6
Seed yield	+2.4	+12.5	+25.9	+35.0	+2.4	+12.6	+25.9	+35.2
Biomass yield	–1.2	+11.6	+23.4	+31.6	–3.4	+11.4	+22.9	+28.6
Gram								
Maximum LAI	+17.9	+24.4	+51.2	+64.5	+27.1	+33.9	+51.2	+64.4
Seed yield	+8.1	+21.1	+43.3	+58.8	+16.0	+22.5	+44.2	+55.7
Biomass yield	+8.8	+21.8	+45.0	+57.9	+15.1	23.5	+45.7	+58.4

maximum/minimum temperature from normal at any growth stage of crop adversely affects the growth and ultimately the potential yield of wheat. A 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 (Prabhjyot-Kaur et al., 2007). The simulation study was carried out with the assumption that weather remained normal in rest of the crop growth period, and the crop remained free from 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 (Table 11). A further scrutiny revealed that the temperature increase mostly affected the early (October) sown crop during 4th week of January, February and up to 1st fortnight of March; the timely (November) sown crop during February and March; the late (4th week of November) sown crop during March; and very late (December) sown crop during March and 1st week of April.

The analysis revealed that an increase of temperature from normal decreased the grain yield of wheat at the following rates (Table 12):

- Temperature increase in the 4th week of January decreased the grain yield by 0.99, 0.66 and 0.70% per degree Celsius for wheat sown in the 4th week of October, 1st week of November, and 2nd week of November, respectively.
- Temperature increase in the 1st fortnight of February decreased the grain yield by 2.88 and 1.87% per degree Celsius for wheat sown in the 4th week of October, and 1st week of November, respectively.

Table 11. Effect of intra-seasonal temperature increase from normal on the grain yield (% deviation) of wheat sown on different dates

Month	*Time period*	*Temperature increase from normal*					
		+1.0 °C	*+2.0 °C*	*+3.0 °C*	*+4.0 °C*	*+5.0 °C*	*+6.0 °C*
Early sown (28th October)							
January	Last week	–3.0	–3.1	–3.1	–6.3	–6.8	–7.1
February	1st fortnight	–3.4	–3.7	–7.6	–11.5	–13.0	–17.2
	2nd fortnight	–2.4	–2.8	–5.2	–8.1	–10.9	–13.8
March	1st fortnight	–2.3	–4.6	–6.8	–13.8	–8.2	–10.4
Normal sown (8th November)							
January	Last week	+1.9	+0.1	+0.4	–1.5	–2.0	–1.1
February	1st fortnight	+1.7	–1.6	–1.8	–3.9	–7.7	–7.3
	2nd fortnight	–0.4	–4.1	–5.1	–9.9	–14.2	–16.4
March	1st fortnight	–2.7	–3.3	–6.0	–9.5	–9.5	–13.0
	2nd fortnight	+1.1	–1.5	–0.5	–0.1	–1.9	–1.5
Normal sown (15th November)							
January	Last week	+1.8	+1.7	+1.4	+0.5	–0.2	–1.8
February	1st fortnight	–0.5	–2.7	–1.5	–2.0	–1.3	–1.9
	2nd fortnight	–2.0	–5.8	–6.0	–8.7	–9.7	–14.2
March	1st fortnight	–4.8	–9.3	–10.1	–14.2	–16.0	–20.8
	2nd fortnight	–2.5	–1.6	–4.3	–6.9	–5.9	–8.1
Late sown (25th November)							
January	Last week	+0.1	+3.7	+3.5	+3.4	+3.4	+7.2
February	1st fortnight	+0.5	+2.4	+2.8	+4.7	+4.9	+7.0
	2nd fortnight	+2.5	+1.1	+3.4	–0.6	–2.6	–3.3
March	1st fortnight	–0.5	–5.4	–6.7	–3.3	–16.0	–19.4
	2nd fortnight	–0.1	–4.7	–5.6	–9.2	–10.1	–11.2
Late Sown (2nd December)							
January	Last week	0.0	+0.6	+0.6	+0.5	+0.6	+3.4
February	1st fortnight	+0.7	+0.6	+0.6	+3.4	+3.6	+3.7
	2nd fortnight	–0.5	–0.4	–1.7	–2.3	–3.1	–3.6
March	1st fortnight	–2.3	–1.6	–6.8	–7.6	–12.5	–17.7
	2nd fortnight	–5.5	–6.6	–12.3	–14.5	–19.1	–21.4
April	1st week	–1.4	–1.8	–2.6	–2.2	–3.5	–3.1

Table 12. Rate of change (increase/decrease) from normal in the grain yield of wheat sown on different dates due to intra-seasonal temperature increase from normal

Time period of temperature increase	*Date of sowing*	*Rate of change in grain yield (Percent/°C)*
Fourth week of January	Early sown (28th October)	–0.99
	Normal sown (8th November)	–0.66
	Normal sown (15th November)	–0.70
	Late sown (25th November)	+0.98
	Late sown (2nd December)	+0.48

Contd...

(*Contd.*)

First fortnight of February	Early sown (28th October)	–2.88
	Normal sown (8th November)	–1.87
	Normal sown (15th November)	–
	Late sown (25th November)	+1.19
	Late sown (2nd December)	+0.76
Second fortnight of February	Early sown (28th October)	–2.40
	Normal sown (8th November)	–3.30
	Normal sown (15th November)	–2.15
	Late sown (25th November)	–1.26
	Late sown (2nd December)	–0.69
First fortnight of March	Early sown (28th October)	–2.40
	Normal sown (8th November)	–2.10
	Normal sown (15th November)	–2.98
	Late sown (25th November)	–3.51
	Late sown (2nd December)	–3.15
Second fortnight of March	Normal sown (15th November)	–1.24
	Late sown (25th November)	–2.15
	Late sown (2nd December)	–3.40
First week of April	Late sown (2nd December)	–0.38

- Temperature increase in the 2nd fortnight of February decreased the grain yield by 2.40, 3.30, 2.15, 1.26 and 0.69% per degree Celsius for wheat sown in the 4th week of October, 1st week, 2nd week, 4th week of November, and 1st week of December, respectively.
- Temperature increase in the 1st fortnight of March decreased the grain yield by 2.40, 2.10, 2.98, 3.51 and 3.15% per degree Celsius for wheat sown in the 4th week of October, 1st week, 2nd week, 4th week of November, and 1st week of December, respectively.
- Temperature increase in the 2nd fortnight of March decreased the grain yield by 1.24, 2.15 and 3.40% per degree Celsius for wheat sown in the 2nd week, 4th week of November, and 1st week of December, respectively.

5. CONCLUSIONS

Crop productivity is constrained by the inter- and intra-seasonal variation of the weather parameters through their direct effect as well as indirect effects such as weather induced changes in incidence of pests and diseases, and requirement or availability of water for irrigation (Timsina and Humphreys, 2003). The given uncertainties in regional climates are even aggravated by global warming, which may have serious direct and indirect consequences on crop production and hence on food security. It is, therefore, important to have an assessment of the consequences of climatic variability on crops especially cereals and possible adaptation strategies (Pathak and Wassmann, 2009). This chapter has highlighted the climate change/variability in India and as well as assessed the effect of probabilistic climate change scenarios on the growth duration and yield of crops using simulation models for rice, wheat, groundnut, soybean and gram by presenting a case study in Punjab State of northern India.

Crop simulation models are able to analyze how weather and genetic traits can affect the potential productivity under a given set of management practices. They are very useful tools to evaluate the impacts of climate change/variability in a region or country on the direction of changes in phenological development, growth and yield of crops, which in turn help address the food security issue in the face of global climate change. However, the results of such simulation should be viewed in light of the model limitations. The major limitations of such simulation studies are as follows:

- The effects of nutrients other than nitrogen are not simulated.
- The temperatures are increasing as a consequence of greenhouse gases including carbon dioxide. The positive role of carbon dioxide in enhancing photosynthesis and yield of C_3 crops is expected to counteract the negative impacts of increase in temperature and decrease in solar radiation. Such interactive effects of carbon dioxide increase are not accounted for in some simulation studies (Attri and Rathore, 2003; Mall et al., 2004; Pathak and Wassmann, 2009).
- The adverse effects of extreme weather hazards, weeds, insect-pests and disease damage are not considered in the existing crop simulation models.
- Moreover, rise in ambient air temperature coupled with enhanced precipitation levels may create favorable conditions for pest and disease infestation in tropical countries like India. Such interactions are presently not accounted for in simulation studies as the available dynamic simulation models do not simultaneously simulate the interactive effect of the crop and pest.

The results of the case study presented in this chapter revealed that with an increase in temperature above normal, the phenological development in *rabi* season crops (wheat and gram) was advanced, but that of *kharif* season crops (rice, groundnut and soybean) was not much affected. On the other hand, the growth and yield of all the crops was reduced by increase in temperature and decrease in radiation and vice-versa. The interaction effects of simultaneous increase/decrease in parameters were also simulated. When the maximum temperature decreased by 0.25 to 1.0 ^{o}C while minimum temperature increased by 1.0 to 3.0 ^{o}C from normal, reductions in growth and yield were greater and more so in *rabi* season crops (wheat and gram) than in *kharif* season crops (rice, groundnut and soybean). The enhanced concentrations of CO_2 were able to counteract the adverse effects of temperature increase on growth and yield of crops to some extent. The simulation study conducted to assess the effect of intra-seasonal increase of temperature from normal on yield of wheat sown on different dates 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.

India is a large developing country with nearly two-thirds of the population depending directly on the climate sensitive sectors such as agriculture, fisheries and forests. The projected climate change under various greenhouse gas emission scenarios is likely to have implications on food production, water supply, biodiversity and livelihoods (Sinha and Swaminathan, 1991; Sathaye et al., 2006). It is, therefore, important to assess direct and indirect consequences of global warming on different crops (Attri and Rathore, 2003; Pathak and Wassmann, 2009). This necessitates improved scientific understanding, capacity building, networking and broad consultation processes. Thus, future agricultural planning has to take note of the overall goal of attaining congruence in productivity, stability, sustainability, profitability and equity in Indian agriculture in coming decades in order to ensure food security in the country.

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