In the case of the first event, the observed short-period (60–90 s) Doppler oscillations coincident with the magnetic fluctuations at observatories located at several longitudes and latitudes around dip equator, may be due to the effect of fields of disturbance of global origin. These magnetic fluctuations called micropulsations, might have occurred at the SC. Matsushita[1] suggested that the initial shock of SC may produce not only hydromagnetic waves responsible for SCs and SIs, but also smaller amplitude and short-period hydromagnetic waves. These waves may propagate simultaneously and oscillate the ionosphere, causing ionospheric currents. From the theory of micropulsations, when the hydromagentic wave moves through the plasmasphere along a flux tube, the varying magnetic field would compress and rarify the intervening plasma. This mechanism may create magnetic fluctuations as well as plasma motions. In a modelling work of Doppler osciallations due to micropulsations, Poole *et al.*[12] suggested that compressions and rarefractions of the plasma may be the dominant factor for the observed oscillations in the Doppler shifts, when compared to the effects due to refractive index variations. If this were to be considered, as the plasma motions may manifest in EXB drifts, the observed short-period oscillations in Vz (or in V_D) may be because of the effects of plasma motions due to hydromagnetic waves.

1. Matsushita, S., On geomagnetic sudden commencements, sudden impulses, and storm durations. *J. Geophys. Res.*, 1962, **67**, 3753–3777.
2. Araki, T., Iyemori, T., Tsunomura, S., Kamei, T. and Maeda, H., Detection of an ionospheric current for the preliminary impulse of the geomagnetic sudden commencements. *Geophys. Res. Lett.*, 1982, **9**, 341–344.
3. Araki, T., Global structure of geomagnetic sudden commencements. *Planet. Space Sci.*, 1977, **25**, 373–384.
4. Motoba, T., Kikuchi, T., Luhr, H., Tamihara, H., Kitamura, T. I. and Hayashi, K., Global Pc5 caused by a DP2-type ionospheric current system. *J. Geophys. Res.*, 2002, **107**,
5. Kikuchi T., Luhr, H., Kitamura, T., Saka, O. and Schlegel, K., Direct penetration of the polar electric field to the equator during a DP2 event as detected by the auroral and equatorial magnetometer chains and the EISCAT radar. *J. Geophys. Res.*, 2000, **105**, 23,251–23,261.
6. Kikuchi, T., Evidence of transmission of polar electric fields to the low latitude at times of geomagnetic sudden commencements. *J. Geophys. Res.*, 1986, **91**, 3101–3105.
7. Sastri, J. H., Visweswara Rao, J. V. S. and Ramesh, K. B., Penetration of polar electric fields to the nightside dip equator at times of geomagnetic sudden commencements. *J. Geophys. Res.*, 1993, **98**, 17,517.
8. Sastri, J. H., Huang, Y. N., Shibata, T. and Okuzawa, T., Response of equtorial-low latitude ionosphere to sudden expansion of magnetosphere. *Geophys. Res. Lett.*, 1995, **22**, 2649–2652.
9. Sastri, J. H., Luhr, H., Tachihara, H., Kitamura, T. I. and Rao, J. S. V. S., Electric field fluctuations (25–35 min) in the midnight dip equatorial ionosphere. *Ann. Geophys.*, 2000, **18**, 252–256.
10. Sastri, J. H. *et al.*, Preliminary impulse of the geomagnetic storm sudden commencement of 18 November 1993. *J. Geophys. Res.*, 2001, **106**, 3905–3918.
11. Motoba, T., Kikuchi, T., Shibata, T. F. and Yumoto, K., HF Doppler oscillations in the low-latitude ionosphere coherent with equatorial long-period geomagnetic oscillations. *J. Geophys. Res.*, 2004, **109**, A06214.
12. Poole, A., Sutcliffe, P. R. and Walker, A., The relationship between ULF geomagnetic pulsations and ionospheric Doppler oscillations: Derivation of a model. *J. Geophys. Res.*, 1988, **93**.

ACKNOWLEDGEMENTS. We thank Dr V. V. Somayajulu, Ex-Scientist, Vikram Sarabhai Space Centre, Thiruvananthapuram for providing useful research material and valuable suggestions. P.A. and N.L.D. are grateful to the management of Gandhi Institute of Technology and Management, Visakhapatnam, for encouragement. We also thank the 210 MM network and National Geophysical Research Institute, Hyderabad for providing geomagnetic data.

Received 17 February 2006; revised accepted 23 June 2006

Climatic variability and its impact on cereal productivity in Indian Punjab

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Dynamic crop growth simulation models CERES-Rice and CERES-Wheat for rice and wheat, respectively were used to study the effect of climate change on growth and yield of these crops under non-limiting water and nitrogen availability. Analysis of recent 30 year historical weather data from different locations in the state revealed that the minimum temperatures have decreased or increased (–0.02 to + 0.07°C/year), maximum temperatures decreased (–0.005 to –0.06°C/year) and rainfall increased (2.5–16.8 mm/year). Keeping in view the observed trends in climate variability, growth and yield of crops were simulated under plausible synthetic climatic scenarios of changes in temperature and solar radiation. In general, with an increase in temperature above normal, the phenological development in wheat was advanced, but that of rice was not much affected. With an increase in temperature up to 1.0°C the yield of rice and wheat decreased by 3 and 10%, respectively. On the other hand, crop yields decreased with 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°C while minimum temperature increased by 1.0 to 3.0°C from normal, the yield in rice and wheat decreased by 0.8 and 3.0%, respectively from normal.

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When the temperature increased by 1.0°C and solar radiation decreased by 5% from normal, the grain yield of rice and wheat decreased by 9 and 14%, respectively from normal. Under enhanced CO_2 concentration of 600 ppm, a temperature increase of 2.0°C from normal reduced the maximum LAI by 5.5%, biomass by 2.6% and grain yield by 2.8% from normal.

Keywords: Carbon dioxide, climate change, radiation, rice, simulation model, wheat.

RICE and wheat are the predominant cereal crops in northwest India, including the State of Indian Punjab. Although geographical area of Punjab is only 1.53% of the country, it contributes nearly 70% of wheat and 55% of rice to the central pool of food grains and hence is commonly referred to as the bread basket of the country. Productivity of wheat and rice which is highly dependent on climatic changes, will need to be maintained at a higher level to meet the future food demands of increasing population in India. Rao *et al.*[1] reported implications of climate change for India and concluded that cereal production is estimated to decrease and nutrition security of the population-rich but land-hungry regions of India would be hampered.

Climatic changes (temperature, radiation and rainfall) and carbon dioxide levels can affect the yields of rice and wheat 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[2]. The direct effects of increased levels of CO_2 are generally beneficial to vegetation[3], though global warming and other climatic changes may have a range of negative or positive impacts depending on complex interactions among managed and unmanaged ecosystems[4].

It is now well known that climate is changing worldwide. The past two decades have witnessed globally a rapid increase in the awareness about climatic changes and triggered widespread apprehension amongst scientists and governments about their global implications[5]. The major environmental concern regarding increased concentration of CO_2 and other trace gases is their greenhouse potential, i.e. their ability to trap solar energy in the atmosphere thereby causing global warming and other changes in the world's climate[6]. The Inter-Government Panel on Climate Change has recently compiled the magnitude of change in temperature, rainfall and carbon dioxide for different parts of the world[7], according to which CO_2 levels will increase to 397–416 ppm by 2010 and to 605–755 ppm by 2070. Wigley[8] reported a warming of 0.5°C by 1995–2005, 1.5°C by 2015–50 and 3.0°C by 2050–2100. Hume and Cattle[9] have reported that although the solar radiation received at the surface will be variable geographically, on an average it is expected to decrease slightly by about 1%. Recent studies on changes in climate predicted by global climate models (GCMs) suggest that in addition to thermal stress due to global warming, stress on water availability in tropical Asia is likely to be exacerbated in future[10].

In view of futuristic changes in climate, it is imperative to assess their impact on crop productivity for a given region. Simulation techniques are easy, time-saving and economical for studying the influence of climatic variability on growth and yield of the crops. Peart *et al.*[11] employed simulation technique for studying the effect of climate change on crop yields in southeastern USA. Several such attempts have been made for predicting yield of wheat[12] rice[13,14], and wheat, rice, maize and groundnut[15] under changing climatic conditions.

The CERES family of models has 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. Taking into account the anticipated regional climatic changes, the effects of changes in temperature, solar radiation and carbon dioxide and interaction of temperature, solar radiation and carbon dioxide on growth and yield of wheat and rice crops under Punjab conditions were studied using the CERES family of crop simulation models.

Daily historical weather data at different locations in the State (geographically extending from about 30°12′ to 31°37′N lat., 74°53′ to 76°28′E long. and 211 to 251 m amsl) were analysed to determine climatic variability trends by regressing five-yearly moving average weather parameter against time[16], and these are summarized in Table 1. Over a period of about 30 years rainfall for the five locations has increased from 2.5 to 16.8 mm/yr, the maximum temperature has decreased from 0.005 to 0.06°C/yr, minimum temperature has decreased or increased from –0.03 to +0.07°C/yr, while solar radiation has decreased or increased from –0.04 to +0.04 $MJ/m^2/yr$.

The central Punjab experiences semi-arid tropical climate with hot summers and cool winters. Rice and wheat are grown under irrigated conditions since crop season rainfall (630 mm for rice and 129 mm for wheat) is highly insufficient for successful growth of these crops.

On the basis of climatic variability trends observed in the State, plausible synthetic scenarios of normal and increase or decrease, and interactions of temperature (maximum and minimum) and solar radiation were generated for the simulation study.

The widely accepted approach to analyse possible effects of different climatic parameters on crop growth and yield by specifying the incremental changes to climatic parameter and applying these changes uniformly to baseline/normal climate[17], was employed in the present study.

In this study one variable at a time was modified and its effect on growth and yield of rice and wheat was studied, 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 inter-

Table 1. Stations and observed climatic variability trends

Station	Latitude, longitude and height amsl	Period of data	Maximum temperature change (°C/yr)	Minimum temperature change (°C/yr)	Solar radiation change (MJ/m^2/yr)	Rainfall (mm/yr)
Amristar	31°37′N, 74°53′E, 231 m	1970–98	–0.03 (R^2 = 0.48)	–0.03 (R^2 = 0.41)	+0.04 (R^2 = 0.38)	+2.5 (R^2 = 0.07)
Jalandhar	31°19′N, 75°34′E 238 m	1971–97	–0.01 (R^2 = 0.07)	–0.02 (R^2 = 0.32)	*	+11.2 (R^2 = 0.54)
Ludhiana	30°56′N, 75°48′E 247 m	1970–99	–0.02 (R^2 = 0.55)	+0.07 (R^2 = 0.87)	+0.003 (R^2 = 0.001)	+10.5 (R^2 = 0.80)
Patiala	30°20′N, 76°28′E 251 m	1970–98	–0.005 (R^2 = 0.04)	+0.02 (R^2 = 0.54)	–0.04 (R^2 = 0.20)	+12.3 (R^2 = 0.66)
Bathinda	30°12′N, 74°57′E 211 m	1977–98	–0.06 (R^2 = 0.61)	+0.02 (R^2 = 0.17)	*	+16.8 (R^2 = 0.68)

*Data not available.

Table 2. Effect of temperature change from normal on deviations in phenology (days) of crops

	Temperature change (°C)								
Phenological event	–3.0	–2.0	–1.0	–0.5	Normal temperature	+0.5	+1.0	+2.0	+3.0
Rice									
Heading	5	2	0	0	101*	0	0	1	4
Maturity	12	6	2	0	141*	1	1	1	5
Wheat									
Anthesis	25	17	8	3	95*	–3	–6	–12	–16
Maturity	22	15	8	4	135*	–3	–6	–12	–17

*Number of days after sowing.

actively modified to assess their combination effect on growth and yield of rice and wheat.

Growth and yield of rice and wheat were simulated with dynamic simulation models of CERES-Rice[18] and CERES-Wheat[19] respectively, using synthetic climatic scenarios. The CERES models were employed for simulation of crop response to climate change because they are physiologically based models and have already been validated over a wide range of climates all over the world and are not location-specific.

The CERES models simulate crop growth, development and yield taking into account the effects of weather, management, genetics, soil water, carbon and nitrogen[2]. The models describe the phenological development through the crop life cycle using the degree-day accumulation. The duration of growth stages in response to temperature and photoperiod varies between species and cultivars, efficiency approach as a function of daily irradiance for a full canopy which is then multiplied by factors ranging from 0 to 1 for light interception, temperature, leaf N status and water deficit. Cultivar differences in yield components, tillering and temperature tolerance are captured by the model using a set of cultivar-specific ccoefficients[20].

CERES-Rice and CERES-Wheat have been validated for commonly sown cultivars of rice[21] and wheat[22] under Ludhiana (Punjab) conditions. Since rice and wheat are grown under assured irrigated conditions in Punjab, optimum (non-limiting) moisture conditions were assumed.

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. Heading as well as maturity of rice was not much affected by increase or decrease in temperature of 1.0°C from normal (Table 2), but with a decrease in temperature by 3.0°C heading and maturity were delayed by 5 and 12 days respectively, from normal. On the other hand, anthesis and maturity of wheat revealed more drastic changes as the phenology was significantly advanced by increasing temperature, but was delayed by decreasing temperature (Table 2).

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 and wheat was advanced by as much as 1–8 days (Table 3). In rice, 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 was advanced by 1 to 4 days while the physiological maturity was advanced by 2 to 8 days from normal. In wheat, when the minimum temperature increased by 1.0 to 3.0°C and maximum temperature decreased by 0.25 to 1.0°C, both the anthesis and maturity were advanced by up to 8 days from normal.

Table 3. Effect of increasing minimum temperature above normal and decreasing maximum temperature below normal on deviations in phenology (days) of crops

		Minimum temperature change (°C)								
		+1.0			+2.0			+3.0		
		Maximum temperature change (°C)			Maximum temperature change (°C)			Maximum temperature change (°C)		
Phenological event	Normal (days after sowing)	–0.25	–0.5	–1.0	–0.25	–0.5	–1.0	–0.25	–0.5	–1.0
Rice										
Heading	101	–1	–1	–2	–2	–3	–3	–4	–4	–4
Maturity	141	–2	–2	–3	–4	–5	–4	–7	–8	–8
Wheat										
Anthesis	95	–2	–2	0	–6	–4	–3	–8	–8	–6
Maturity	135	–1	–1	1	–5	–4	–3	–8	–7	–6

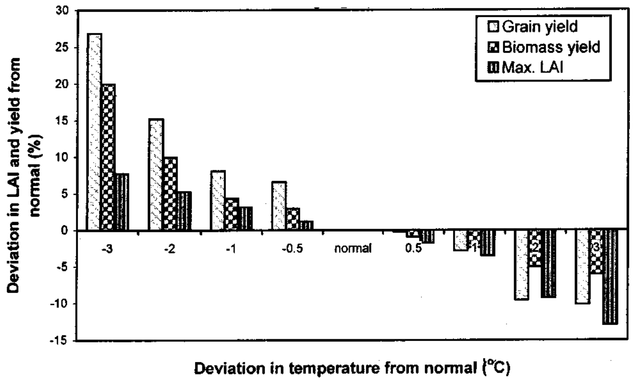

Figure 1. Effect of temperature change on growth and yield of rice.

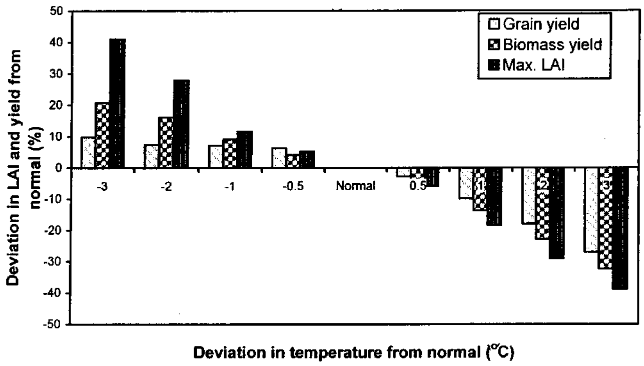

Figure 2. Effect of temperature change on growth and yield of wheat.

The effect of increase or decrease in temperature on growth and yield of rice and wheat is shown in Figures 1 and 2, respectively. An increase in temperature decreased but decrease in temperature increased the growth and yield of rice and wheat. Both the decrease and increase were more for wheat than for rice. With an increase in temperature by 1.0 to 2.0°C, the simulated maximum leaf area index (LAI) decreased by 3.5 to 9.2% in rice and by 18.4 to 29.2% in wheat; biomass yield decreased by 2.3 to 5.0% in rice and by 13.7 to 22.8% in wheat; grain yield decreased by 2.9 to 9.6% in rice and by 9.8 to 18.0% in wheat from normal. Similarly, with a decrease in temperature by 1.0 to 2.0°C, the simulated maximum LAI increased by 3.1 to 5.2% in rice and by 11.6 to 27.8% in wheat; biomass yield increased by 4.3 to 9.9% in rice and by 9.1 to 16.1% in wheat; grain yield increased by 8.1 to 15.1% in rice and by 7.2 to 7.4% in wheat from normal.

The effect of increase or decrease in solar radiation on growth and yield of rice and wheat are shown in Figures 3 and 4 respectively. In general, increase in solar radiation favoured increase in the growth and yield, whereas decrease in solar radiation favoured reduction in growth and yield of crops. However changes in growth and yield were generally below 6% for solar radiation changes imposed in this study.

The effect of increasing minimum temperature and decreasing maximum temperature on simulated maximum LAI, biomass yield and grain yield are shown in Figures 5 and 6 for rice and wheat respectively. In general maximum LAI, biomass yield and grain yield of both crops were adversely affected by increasing the minimum temperature from 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 were within 5% from normal and the yields were not affected significantly. At further higher levels of increase in minimum temperature, reduction in growth and yield was greater and more so in wheat than in rice.

The effect of increasing temperature by 1, 2 and 3°C, and decreasing radiation levels by 1, 2 and 5% on maximum LAI, biomass and grain yield is depicted in Table 4 for rice and wheat. When temperature increased by 1.0°C and radiation levels decreased by 1, 2.5 and 5% from normal, the maximum LAI of rice decreased by 4.0, 4.9 and 6.6% from normal respectively; and of wheat decreased by 19.2, 20.8 and 23.2% from normal respectively. Under the same levels of temperature and radiation, the grain yield

Table 4. Effect of increasing temperature above normal and decreasing radiation below normal on deviations (per cent) in maximum LAI, grain yield and biomass yield of crops

Growth and yield attribute	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

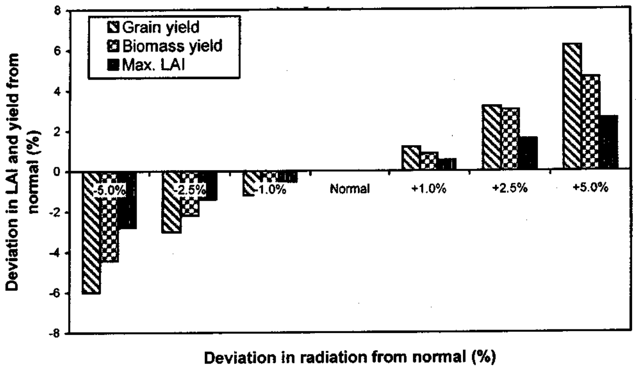

Figure 3. Effect of radiation change on growth and yield of rice.

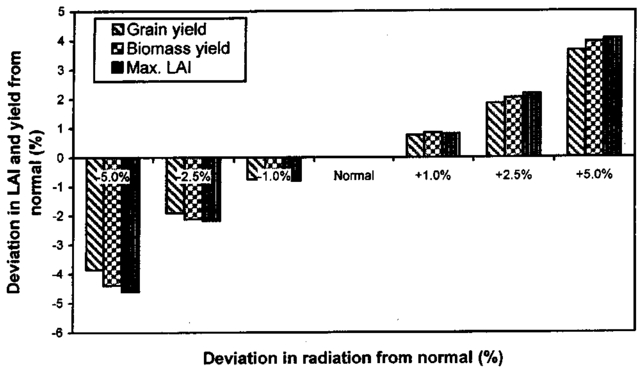

Figure 4. Effect of radiation change on growth and yield of wheat.

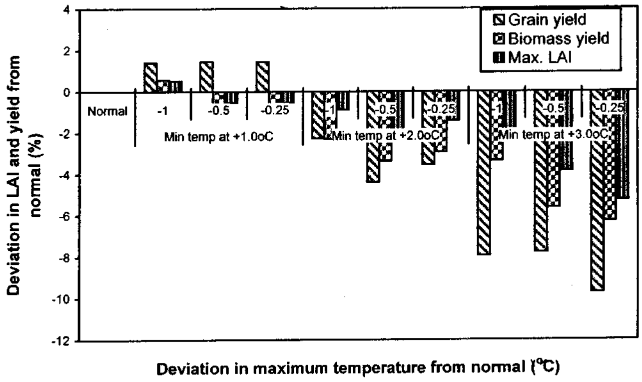

Figure 5. Effect of maximum × minimum temperature interaction on growth and yield of rice.

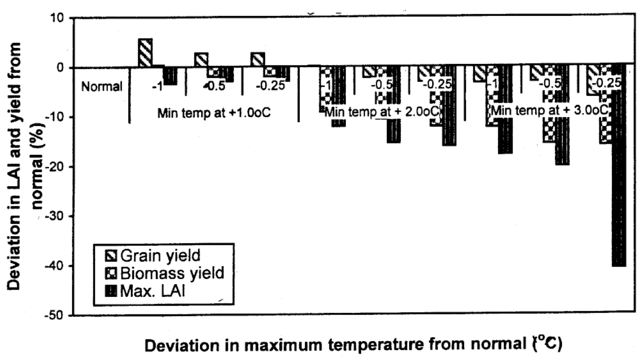

Figure 6. Effect of maximum × minimum temperature interaction on growth and yield of wheat.

of rice decreased by 4.1, 5.9 and 9.0% from normal respectively; and of wheat decreased by 10.7, 11.9 and 14.1% from normal respectively, whereas the biomass yield of rice decreased by 3.3, 4.7 and 7.1% from normal respectively, and that of wheat decreased by 14.7, 16.1 and 18.4% from normal respectively. The interactive effects of increasing temperature and decreasing radiation revealed a cumulative adverse effect on growth and yield of rice and wheat. In wheat the growth and yield was highly sensitive to temperature increase, while it was relatively less sensitive to decrease in radiation.

Rice crop is sensitive to changes in temperature and carbon dioxide concentration. Being a C_3 plant, rice holds an edge over C_4 plants due to increase in photosynthetic rates under expected enhanced CO_2 concentrations. The results of the simulation study for interactive effects of increasing temperature and CO_2 concentration revealed that the adverse effect of increase in temperature on growth and yield of crop was counter-balanced by favourable

Table 5. Effect of increasing temperature and CO_2 above normal on deviations (per cent) in maximum LAI, grain yield and biomass yield of rice

Growth and yield attribute	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
Maximum	–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

effect of increasing CO_2 levels up to some particular combination (Table 5). With temperature increase of 1.0°C from normal, CO_2 concentration of only more than 500 ppm was able to nullify the negative deviations in growth and yield, but when temperature increased by 2.0°C from normal, even 600 ppm CO_2 was unable to nullify the adverse effect of temperature.

The yield of a crop can be taken as a product of rate of biomass accumulation (solar radiation-dependent) and growth duration (ambient air temperature-dependent). Highest potential yield of a crop is therefore obtained in regions where crop duration is more under relatively low temperatures unless the radiation levels are low[23]. Increased shading associated with enhanced cloudiness may lead to spikelet sterility in rice. For a decrease in radiation by 25%, the reduction in yield[24] could be more than 30%. Hence an increase or decrease in temperature and solar radiation directly affects the yield of a crop.

Wheat being a cool season crop was affected by temperature changes to a greater extent compared to rice which is a warm season crop in Punjab (India). The results of the simulation indicate that these climatic variations could affect growth and yield of crops in the region. With an increase in temperature up to 1.0°C (other weather variables being normal), the yield of rice and wheat could decrease by 3 and 10% respectively. With further increase in temperature, the yield is progressively decreased. On the other hand, crop yields increased with an increase in radiation levels above the normal values and vice versa. Moreover, the reason for changing the variables independent of each other is that they help identify the relative sensitivities of the agriculture sector to changes in climate variables[25].

The interaction effect of increasing minimum temperature and simultaneously decreasing maximum temperature revealed that the growth and yield of crops were adversely affected by increasing minimum temperatures. However, the decreasing maximum temperatures were able to partially counteract only up to a certain limit. With increasing trend of rainfall in the region, more cloudy days leading to lower solar radiation could be expected. Thus the cumulative effect of increasing temperature and decreasing solar radiation would be more adverse. On the other hand, increasing temperature along with increasing CO_2 is expected to counter-balance the effects of each variable up to a certain range in the variable, beyond which the negative effect of climatic variables such as temperature will have an overriding effect and potential yields of crops will be reduced.

The objective of this simulation study using CERES-Rice and CERES-Wheat dynamic growth models was to assess the effect of probabilistic climate-change scenarios on growth duration and yield of rice and wheat.

Crop simulation models are able to analyse how weather and genetic traits can affect the potential productivity under a given set of management practices. But the major limitations of such simulation studies are listed below:

- The effect of nutrients other than nitrogen is not simulated.
- Rise in ambient air temperature coupled with enhanced precipitation levels may create favourable conditions for pest and disease infestation in tropical countries like India. The adverse effects of weed, insect-pest and disease damage are not considered in simulation models.
- 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 effects of increase in temperature and decrease in solar radiation.

Such simulation studies can guide us in determining the effect of climate changes on phenological development, growth and yield of crops, but the results should be viewed in light of such limitations.

1. Rao, G., Kelly, P., Hume, M. and Srinivasan, G., Working paper GEC 94–22. Centre for Social and Economic Research on the Global Environment, Univ. of East Anglia, UK, 1994.
2. Timsina, J. and Humphreys, E., Performance and application of CERES and SWAGMAN Destiny models for rice–wheat cropping systems in Asia and Australia: A review. CSIRO Land and Water Technical Report 16/03; CSIRO Land and Water, Griffith, Australia, 2003, p. 57.
3. Farquhar, G. D., Carbon dioxide and vegetation. *Science*, 1997, **278**, 1411.
4. Watson, R. T., Zinyowera, M. C. and Moss, R. H. (eds), Climate change 1995. In *Impacts, Adaptation and Mitigation of Climate Change: Scientific Technical Analyses*, Cambridge University Press, UK, p. 878.

5. Gadgil, S., Climate change and agriculture – An Indian perspective. In *Climate Variability and Agriculture* (eds Abrol, Y. P. *et al.*), Narosa Publishing House, New Delhi, 1996, pp. 1–18.
6. Houghton, J. T., Meira Filbo, L. G., Callander, B. A., Harris, N., Kattenberg, A. and Maskell, K., Climate change 1995. In *The Science of Climate Change*, Cambridge University, UK, 1996.
7. Watson, R. T., Zinyowera, M. C. and Moss, R. H. (eds). *The Regional Impacts of Climate Change: An Assessment of Vulnerability*, IPCC II Report, Cambridge University Press, 1998, p. 517.
8. Wigley, T. M. L., The greenhouse effect: Scientific assessment of climatic changes. Lecture presented at the Primer Minister's Seminar on Global Climate, London, 29 April 1989.
9. Hume, C. J. and Cattle, H., The greenhouse effect: Meteorological mechanisms and models. *Outlook Agric.*, 1990, **19**, 17–23.
10. IPCC (Intergovernmental Panel on Climate Change). In *Second Scientific Assessment of Climate Change* (eds Houghton, J. T. *et al.*), WMO-UNEP Report, Cambridge University Press, Cambridge, 1996, UK, p. 879.
11. Peart, R. M., Jones, J. W., Curry, R. B., Boote, K. J. and Allen Jr. L. H., Impact of climate change on crop yield in the southeastern USA – A simulation study. In *The Potential Effects of Global Climate Change in the United States, Appendix C Agriculture* (eds Smith, J. B. and Tripak, D. A.), EPA 230-05-89-053, US Environmental Protection Agency, Washington DC, 1989, vol. 1.
12. Mearns, L. O., Rosenweig, C. and Goldberg, R., The effects of changes in daily and Inter-annual climate variability on CERES-Wheat: a sensitivity study. *Climate Change*, 1996, **32**, 257–292.
13. Bachelet, D. and Gay, C. A., The impact of climate change on rice yield: A comparison of four model performances. *Ecol. Model.*, 1993, **65**, 71–93.
14. Olszyk, D. M., Centeno, H. G. S., Ziska, L. H., Kern, J. S. and Matthews, R. B., Global climate change, rice productivity and methane emissions: Comparison of simulated and experimental results. *Agric. For. Met.*, 1999, **97**, 87–101.
15. Hundal, S. S. and Prabhjyot-Kaur, Climate change and its impact on crop productivity. In *Climate Variability and Agriculture* (eds Abrol, Y. P. *et al.*), Narosa Publishing House, New Delhi, 1996, pp. 377–393.
16. Hundal, S. S. and Prabhjyot-Kaur, Annual and seasonal climate variability at different locations of Punjab state. *J. Agrometeorol.*, 2002, **4**, 113–125.
17. Rosenzweig, C. and Iglesias, A., Implications of climate change for international agriculture: Crop modelling study. United States Environmental Protection Agency, Policy Planning and Evaluation, 1994, INTRO 3-30.
18. Ritche, J. T., Alocilja, E. C., Singh, U. and Uehara, G., IBSNAT and CERES-Rice model: Weather and Rice. In Proceedings of The International Workshop on the Impact of Weather Parameters on Growth and Yield of Rice, 7–10 April 1986, pp. 271–281.
19. Godwin, D., Ritche, J. T., Singh, U. and Hunt, L., *A User's Guide to CERES-Wheat V2.10*, International Fertilizer Development Center, 1990, p. 94.
20. Ritchie, J. T., Singh, U., Godwin, D. and Bowen, W. T., Cereal growth, development and yield. In *Understanding Options for Agricultural Production* (eds Tsuji, G. Y., Hoogenboom, G. and Thornton, P. K.), Kluwer, Dordrecht, The Netherlands, 1998, pp. 79–98.
21. Hundal, S. S. and Prabhjyot-Kaur, Evaluation of agronomic practices for rice using computer simulation model, CEREC-Rice. *Oryza*, 1999, **36**, 63–65.
22. Hundal, S. S. and Prabhjyot-Kaur, Application of the CERES-Wheat model to yield prediction in the irrigated plains of the Indian Punjab. *J. Agric. Sci.*, 1997, **129**, 13–18.
23. Ritchie, J. T., Genetic specific data for crop modelling. In *Systems Approach for Agricultural Development* (ed. Penning de Vries, F. W. T.), Kluwer, Dordrecht, The Netherlands, 1993.
24. Sinha, S. K., Response of tropical ecosystems to climate change. In *International Science I*, Crop Science Society of America, Madison, WI, USA, 1993, pp. 281–289.
25. IPCC–TGCIA (International Panel on Climate Change – Task Group on scenario for Climate Impact Assessment). Guidelines on the use of scenario data for climate impact and adaptation assessment, 1999, p. 69.
26. Singh, U., Timsina, J. and Godwin, D. C., Testing and application of CERES-Rice and CERES-Wheat models to rice–wheat cropping systems. In *Modelling Irrigated Cropping Systems, with Special Attention to Rice-Wheat Sequences and Raised-Bed Planting* (eds Humphreys, E. and Timsina, J.), Proceedings of a Workshop at CSIRO Land and Water, Griffith, Australia, 25–28 February 2002, pp. 17–32.

ACKNOWLEDGEMENTS. The present study was partially funded by Indian Council of Agricultural Research, New Delhi under an adhoc research project, Climatic variability and its effects on crop production in Punjab. The study was carried out in the Department of Agricultural Meteorology, Punjab Agricultural University, Ludhiana.

Received 31 March 2006; accepted 24 July 2006

Surface-modified zeolite–A for sequestration of arsenic and chromium anions

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It is of immense practical importance to develop materials with tailored properties to sequester anionic pollutants in addition to cationic pollutants. Zeolites are alumino-silicate materials with properties to attract positive-charged ions and, therefore, are widely used for sequestration of cationic pollutants. Surface-modified zeolite materials have been developed from commercial zeolites and flyash-based zeolites by treating them with surface modifiers like hexadecyltrimethylammonium bromide and tetramethylammonium bromide. The adsorbent has been evaluated for removal of arsenic and chromate anions. High selectivity, faster kinetics and high adsorption capacity ensure-cost effectiveness of these materials compared to other conventional materials for de-arsenification.

Keywords: Arsenic, chromium, flyash-based zeolite, surfactant-modified zeolite, water treatment.

IN the backdrop of the widespread public concern about vast sections of population in West Bengal (India) and Bang-

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