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Simulating impact of climatic variability and extreme climatic events on crop production

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सार – भारतीय परिप्रेक्ष्य में अंतर-वार्षिक जलवायविक भिन्नता की विस्तृत अवधि और चरम जलवायविक घटनाओं के बार-बार घटित होना बहुत चिंता का विषय है। इन घटनाओं से कृषि उत्पादन पर पड़ने वाले प्रभाव का मूल्यांकन करने और इसके उपायों के लिए कृषि प्रबंधन की आवश्यकता है। कृषकों और अन्य स्टेकहोल्डरों के लिए समुचित क्षेत्र की विशिष्ट कृषि परामर्शी सेवाएं दिए जाने की आवश्यकता है। जलवायु से संबंधित इन घटनाओं का फसल पर पडने वाले प्रभाव का मूल्यांकन करने और अधिक कृषि उत्पाद सुनिशिचित करने के लिए समुचित प्रक्रियाओं को अपनाने हेतु फसल सिम्यूलेशन मॉडल प्रभावकारी उपाय है। फसल सिम्यूलेशन मॉडल और जैव भौतिक एवं सामाजिक आर्थिक पहलुओं के पारस्परिक डेटाबेस स्तरों को जोड़कर क्षेत्रीय स्तर पर कृषि परामर्शीयॉ तैयार करने में सुदूर संवेदी और जी आई एस प्रभावकारी टूल्स हो सकते है। प्रभावकारी कृषि परामर्शी सेवाओं के लिए आवश्यक है कि इसका संबंध अन्य जैविक (बायोटिक) एवं अजैविक (एबायोटिक) प्रभावों के साथ किया जाए जिससे कि कृषि प्रबंधन के समुचित उपाय किए जाएं और सही-सही आकलन किया जा सके। फसल सिम्यूलेशन मॉडल के द्वारा फसल की बदहाली एवं मृदा प्रक्रियाओं और अंततोगत्वा पैदावार की स्थितियों को प्रभावी रूप से समझा जा सकता है। इस समीक्षा लेख में हमने भारत में अंतर वार्षिक/ऋतुनिष्ठ जलवायविक भिन्नता और चरम जलवायविक परिघटनाओं के घटने का वर्णन किया है और इन परिघटनाओं (जिसमें जलवायु परिवर्तन शामिल है) से फसल के विकास और फसल की पैदावार तथा फसल लगाने की प्रणाली पर पड़ने वाले प्रभाव का आंकलन करने के लिए फसल मॉडल्स जैसे : INFOCROP, WTGROWS, DSSAT की क्षमता को दर्शाया है और इसकी पुष्टि के लिए समुचित उपायों को करने के लिए सुझाव दिया है। फसल की अवस्था का मूल्यांकन करने में सुदूर संवेदी की क्षमता और क्षेत्रीय / राष्ट्रीय स्तर पर पैदावार के पूर्वानुमान को दर्शाया गया है। भारत के लिए मौसम आधारित कृषि परामर्शी सेवाओं के इस विलक्षण प्रचालनात्मक मंच के निर्माण में जी आई एस के माध्यम से प्राप्त सुदूर संवेदी सूचनाओं के साथ फसल सिम्यूलेशन टूल्स की महत्वपूर्ण भूमिका हो सकती है।

ABSTRACT. Wide range of inter-annual climatic variability and frequent occurrence of extreme climatic events in Indian context is a great concern. There is a need to assess the impact of these events on agriculture production as well suggest the agri-management options for sustenance. The appropriate region specific agro-advisory needs to be established for the farmers and other stake holders. Crop simulation models are effective tools for assessing the crops' response to these climate related events and for suggesting suitable adaptation procedures for ensuring higher agricultural production. Remote sensing and GIS are effective tools in this regard to prepare the regional based agro-advisories, by linking with the crop simulation models and relational database layers of bio-physical and socio-economic aspects. For effective agro-advisory services, there is a need to link the other biotic and abiotic stresses for accurate estimates and generating window of suitable agri-management options. Crop simulation models can effectively integrate these stresses for crop and soil processes understanding and ultimate yield formation. In this review article, we have discussed about the inter-annual/ seasonal climatic variability and occurrence of extreme climatic events in India and demonstrated the potential of crop models *viz*., INFOCROP, WTGROWS, DSSAT to assess the impact of these events (also including climate change) on growth and yield of crops and cropping systems and thereby suggesting appropriate adaptation strategies for sustenance. The potential of remote sensing for crop condition assessment and regional/national yield forecast has been demonstrated. Crop simulation tools coupled with remote sensing inputs through GIS can play an important role in evolving this unique operational platform of designing weather based agro-advisory services for India.

Key words – Climate variability, Extreme climatic event, Climate change, Crop simulation tools, WTGROWS, INFOCROP, DSSAT, Adaptation, Sustainable production.

1. Climatic variability and extreme climatic events

Inter- annual and Intra-annual climate variability and climatic extreme events have increased in frequency, amplitude and duration over the past 30 years. In the recent past, there has been increase in events such as drought, flood, heat and cold waves, strong wind, hailstorm, cyclones etc. Natural hazards have caused extensive damage to national agricultural economies. Crop simulation models have been widely used to evaluate and assess the influence of weather and climate, agronomic management practices on crop growth, development and yield.

Few examples of extreme climatic events in India are: the occurrence of high temperature in March 2004, which adversely affected the crops across the State of Himachal Pradesh in India. Wheat and potato harvest was advanced by 15-20 days and the flowering of apple was early by 15 days. Maximum temperatures during March, 2010 were above normal by 4-8 °C over northwest, east, central India, significantly higher during grain filling period of wheat crop thus adversely affecting the grain filling process causing low yield. North-West and North-East States of India experienced severe cold wave from December 2002 to January, 2003. The crop yield loss varied between 10 and 100% in the case of horticultural crops and seasonal crops. However, temperate fruits like apple, perch, plum and cherry gave higher yield (Samra *et al*., 2004). The years 2002 and 2009 were a classical example to show how Indian food grain production depends on rainfall of July. Impact of daily rainfall anomalies on the total food grain production is significant (Venkataraman, 2012). Episodes of severe drought correlate with El Niño-Southern Oscillation (ENSO) events. Untimely rains and hailstorms destroyed wheat crop of 15,000 ha over UP, Haryana and Punjab in *rabi* season of 2007. In contrast, heavy snowfall over Kashmir valley was recorded during March, 2007 due to western disturbances. Torrential downpour in June, 2007 over Kerala, Karnataka, Andhra Pradesh and Maharashtra, while in July and August over Gujarat, West Bengal, Orissa, Bihar, Uttar Pradesh and Assam, led to floods. Heavy rains again in September in Andhra Pradesh, Karnataka and Kerala led to floods and thus the year 2007 can be declared as the flood year in India. A huge crop loss was noticed in several states of the Country due to floods in *kharif*, 2007. Frequent unseasonal rains and hailstorm in March 2015 made the damage to *rabi* crops across north, central and east India. Heavy downpour over Mumbai on 26 July, 2005 and 3rd September, 2005 over Bangalore; severe tropical storms in Andhra Pradesh in September; floods in Kerala, Karnataka, Maharashtra, Gujarat, Orissa and Himachal Pradesh during the Southwest monsoon (June-September), 2005 in India devastated cropped area to a large extent in addition to losses of thousands of human lives.

The extreme weather event like tropical cyclones varies abruptly from year to year in terms of frequency and intensity over all the cyclone basins. Indian seas comprise of Bay of Bengal and Arabian Sea, and are quite different than any other regions of the world as per the genesis and movements of the cyclonic storms are concerned. Uniqueness of the Indian region is mainly characterized to two cyclone seasons such as pre-monsoon (April-May) and post-monsoon (October-December) cyclones. Various studies shows an increasing trend for the Bay of Bengal cyclones, however a sharp increasing trend is observed for severe cyclonic storms, as the sea surface temperature of whole Bay is increased by 0.4 °C in both pre-monsoon and post-monsoon seasons. The Arabian Sea cyclones are also showing increasing trend in post-monsoon seasons, however the pre-monsoon systems shows decreasing trend, as the Arabian Sea is warmer in post- monsoon compared to pre-monsoon season.

Eastern Uttar Pradesh, in the foothills of the Nepal Himalayas, has been prone to floods for centuries. In the last 60 years, however, their frequency has increased dramatically. People living in the region have slowly developed ways to cope with the floods. The major factors helping people develop their adaptive capacities in agriculture can be Intensification & Diversification (farmers grow hemp and vegetables like okra with sugar cane, fish culture, fodder production, or livestock rearing); Value addition; Indigenous technical knowledge; Crop cycle management (cultivation under pre-flood, during-flood, post-flood. Traditional knowledge/expertise of the farmers is to be integrated within the decision support system for effective and relevant advisory to the farmers.

The monsoon, which provides 80 per cent of the total rainfall in the subcontinent and on which India is completely dependent for its agriculture, is witnessing disturbing changes. There has been a decline in the average total seasonal rain during the period 1980-2011, according to a study carried out by Stanford Woods Institute for the Environment. The study revealed that the intensity of rainfall in wet spells during 1981-2011 was significantly higher than during 1950-1980. At the same time, dry spells became 27 per cent more frequent during 1981-2011. Similar results have been reported from Indian Institute of Tropical Meteorology.

Frequency of occurrence of *drought* has increased over the past, which affects the agricultural production to a great extent. Meteorological drought is defined on the basis of the degree of dryness (in comparison to some "normal" or average amount) and the duration of the dry period. Hydrological drought is associated with the effects of periods of precipitation shortfalls on surface or subsurface water supply (*i.e*., stream flow, reservoir and lake levels, ground water). The frequency and severity of hydrological drought is often defined on a watershed or river basin scale. Agricultural drought links various characteristics of meteorological (or hydrological) drought to agricultural impacts, focusing on precipitation shortages, differences between actual and potential evapo-transpiration, soil water deficits, reduced groundwater or reservoir levels. Agricultural drought is able to account for the variable susceptibility of crops during different stages of crop development. *Rabi* food grain production in India depicts better adaptability to drought than *kharif* food grain production mostly due to better access to irrigation infrastructure. Sustenance of agri-production under drought can be through close monitoring of seasonal conditions, suggesting contingent crops on near real time basis, adopting different farm level options like changing the sowing dates, adopting different crop varieties and supplemental irrigation using micro irrigation. Large scale demonstrations of climate resilient agronomic practices to create awareness and promote widespread adoption by farmers at block level, *viz*., direct seeding options for short duration varieties in paddy for delayed situations, in situ moisture conservation practices and crop residue recycling and planting of millets, cotton, pulses and oilseed crops in ridge-furrow or raised bed systems to ensure adequate drainage in case of excess rains. Availability of inputs related to nutrient management (*e.g*., foliar spray of KCl or KNO_3 to partially alleviate moisture stress during drought) and inputs related to reduction of crop water demand (*e.g*., application of anti-transpirants or hormones) is an issue to be addressed to the farmers. Medium and long term strategies are critical and essential to tackle monsoon aberrations, *viz*., restoration and renovation of drains in flood prone delta areas and cyclone affected areas, rainwater harvesting works, water conservation through micro-irrigation systems, crop residue recycling, river bank protection, promotion of agro-forestry systems, introducing weather insurance. Advance weather information on occurrence of drought through extended range forecast/seasonal climate forecast and disseminating agromet advisories issued based on medium range forecast for mid-season corrections could be the effective way for ensured agri-production.

India Meteorological Department (IMD) monitors occurrence of drought through the variation of rainfall on different spatial scale (district, met sub-division, state and country) and temporal scale (daily, weekly, monthly and seasonal). Other effective indices used are aridity anomaly monitored every fortnight, standardized precipitation index (SPI) every week. IMD has developed Aridity Index based on rainfall, potential and actual evapo-transpiration, available soil moisture by using water balance approach. Aridity anomalies are worked out and these anomalies are classified into various categories of arid conditions like Mild Arid (Aridity anomaly 1 - 25%), Moderate Arid (Aridity anomaly 26 - 50%) and Severe Arid (Aridity anomalies more than 50%). These anomalies are used for near real time monitoring and assessment of agricultural droughts over the country on a weekly/fortnightly interval. Though its assessment and monitoring system is well established, the adaptation strategies to sustain agricultural production in diverse agro-ecologies and production environments remain challenging task. IMD generates district level weather forecast for rainfall, temperature, wind and humidity using multi-model super ensemble technique. Subsequently IMD, in collaboration with centres of Indian Council of Agriculture Research (ICAR) and State Agricultural Universities, provides district level Agromet Advisory Services (AAS) for the benefit of farmers. Advisories are generally prepared on the basis of experts' judgement, through use of technical coefficients/crop simulation tools. These advisories are timely disseminated in various agro-climatic zones and production environments. Agricultural scientists of developed countries have already accepted crop simulation approach as a viable tool for developing information on weather and climate dependent advisories for the farmers. IMD is intent on promotion of the use of crop growth model for different crops, *viz*., wheat, rice, sorghum, maize, soybean, groundnut, chickpea, mustard, sugarcane, cotton, potato, tomato, cabbage etc. at these Agro-Met Field Units (AMFUs).

Remote sensing technology provides an excellent strategic monitoring tool to assess crop growth condition on regional scale, stress discrimination by linking with the ground truth observation and providing the information to various stakeholders for value-added information flows to the farming community. Understanding through vegetation indices as derived from satellite images can identify the crops' type and associated stress (*viz*., drought, flooding, extreme heat/cold, nutrients' deficiency, insects/pests attack). A separate drought code using NDVI, irrigation and probabilities of meteorological drought needs to be developed for effective operational agro-advisory service.

National Centre For Medium Range Weather Forecasting (NCMRWF), set up by the Govt. of India, helped to establish the system for prediction of weather using Numerical Weather Predictions (NWP) models and establishment of several agro-advisory service units (AASUs) representing the respective agro-climatic zones of India. The AASUs issued final advisory twice a week widely circulated through mass media so that the farmers/agro-industrialist of the region may utilize the expert's advisories. Keeping great importance of South West (SW) monsoon and its impact on *Kharif* crops in consideration, IMD (earlier NCMRWF) started preparing medium range prediction of rainfall on Agro-Climatic Zone (ACZ) scale and actual observation based agro-advisory for farmers, near real time every week during the monsoon season. Singh *et al*., 1995 evaluated medium range forecast for its performance by linking with Wheat Growth Simulator (WTGROWS) and concluded the potential use of crop simulation models for developing appropriate agro-advisory service for the Indian farmers.

It is expected that there will be pronounced warming in future, particularly during the post monsoon period and winter, increased frequency of floods during the monsoon and a decrease in winter precipitation with a lower number of rainy days. As climate change becomes more dramatic, its effect on a range of climate extremes will become increasingly important. Crop yields in some areas have already started to decline due to warmer conditions compared to the expected yields without warming. A recent evaluation also concluded that future growing season temperatures increase for both tropical and subtropical regions will result in substantial potential implications on global food systems. Many crops, for example, are especially sensitive to extreme temperatures that occur just prior to or during the critical pollination phase of crop growth. Extreme temperatures can negatively impact grain yield and quality aspects. More frequent hot days are also likely to increase heat stress on human farm workers, animals and plants. The agriculture sector is a high emitter of methane and nitrous oxide, for example, through livestock and fertilisation. Greenhouse gas emission contributes to climate change phenomenon, and any delay in greenhouse gas mitigation is likely to lead to more severe and frequent climate extremes in the future. Mean global warming does not exclude the possibility of cooling in some regions and seasons. There is a need to understand the climate change and its variability on spatio-temporal scale, with precision and high resolution. Yield reductions are predicted in wheat and rice due to temperature rise in key growing regions. The length of the growing period in rainfed areas is likely to decrease, especially in peninsular regions. *Kharif* (autumn) crops in general are impacted more by rainfall variability while *rabi* (spring) crops by rise in minimum temperature. Wheat in general likely to be negatively impacted in *rabi* due to terminal heat stress. Rice gets affected both by temperature and water availability. Legume crops such as soybean and groundnut might benefit due to increased temperature/ CO_2, if water availability is not limited. There are more opportunities for rainwater harvesting due to high intensity rainfall but greater loss of topsoil due to erosion.

The purpose of mitigation and adaptation measures is to attempt a gradual reversal of the effects caused by climate change and sustain development. There are several mitigation and adaptation practices that can be effectively put to use to overcome the effects of climate change with desirable results. These methods fall into the broad categories of under crop/cropping system-based technologies, resource conservation-based technologies and socio-economic and policy interventions. There is a need of crops and varieties that fit into new cropping systems and seasons, specially for high temperature, drought, inland/coastal salinity, sea-water inundation and submergence tolerance. We also need varieties with high fertiliser and radiation use efficiency. Raised-bed planting of wheat in the Indo-Gangetic plains entails 20-25% saving in irrigation water and is suitable for mechanical weeding, and results in reduced herbicide use. We also need better water management and nutrient management for crops and cropping systems. Adaptation measures to reduce the negative effects of increased climatic variability as normally experienced in arid and semi-arid tropics may include changing the cropping calendar to take advantage of the wet period and to avoid extreme weather events during the growing season. Crop varieties that are resistant to lodging may withstand strong winds during the sensitive stage of crop growth. In addition, improved crop management through crop rotations and intercropping, integrated pest management, supplemented with agro-forestry and aforestation schemes will be important component in strategic adaptation to climate change in India. Grain-legume intercrops have many potential benefits such as stable yields, better use of resources, weeds, pest & disease reductions, increased protein content of cereals, reduced N leaching as compared to sole cropping systems.

2. Crop simulation models for climatic variability / extreme climate assessment through growth and yield of crops

Crop growth and yield is influenced by various biotic and abiotic factors. Among abiotic factors, inter-seasonal climatic variability is a concern, which is usually reflected in year to year fluctuations in crops' yields. Characterization of inter-annual climatic variability can be evaluated through growth and yield of crops and cropping systems (Kalra *et al*., 2008). Crop simulation tools (*viz*., WTGROWS, INFOCROP, DSSAT etc.) help in evaluating inter-annual variability through growth and yield of crops (Aggarwal *et al*., 1994; Aggarwal *et al*., 2006). These tools have successfully demonstrated the impacts through modifications in phenological development, water and nutrients requirement, assimilation & partitioning behavior, source-sink relationship & yield formation. Technical coefficients, as

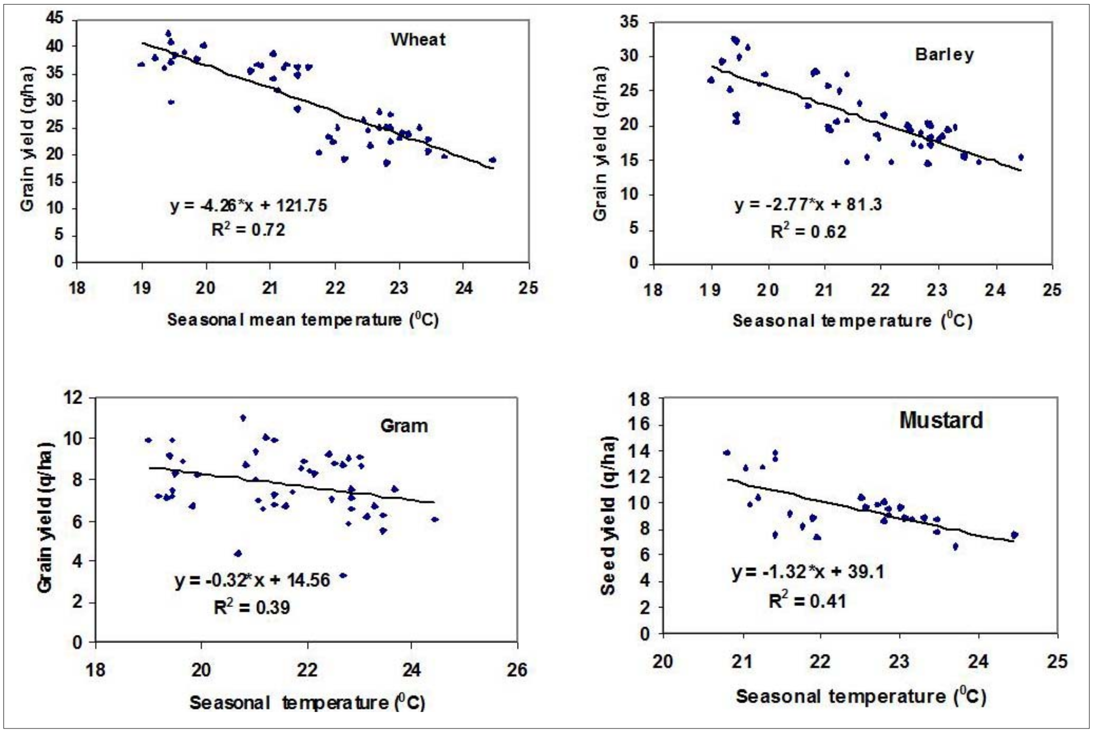

Fig. 1. Dependence of crop yields on seasonal temperature

generated through quantification of inter-annual climatic variability through growth and yield of important crops, could be joined with regional climate change scenarios for assessing the impact for defining the vulnerable regions. Simulation models can be used for defining suitable mitigation and adaptation strategies for sustaining agricultural productivity and also safe guarding the environment.

INFOCROP, is a decision support system based on crop models that has been developed by a network of scientists at Indian Agricultural Research Institute (IARI) to provide a platform to scientists to build their applications around it and to meet the goals of stakeholders need for information (Aggarwal *et al*., 2006). The models in this DSS have similar structure, and are designed to simulate the effects of weather, soils, agronomic management, nitrogen and water application and major pests on growth and yield of important crops and greenhouse gases emission. Its general structure is based on a large number of earlier models and the expertise of the scientists involved. In particular, it is based on MACROS, SUCROS and WTGROWS (Aggarwal *et al*., 1994) models. It is user-friendly, targeted to increase applications of crop models in research and development, and has simple and easily available input requirements. The crop models have been developed by the specialists in those crops and have been validated in major crop specific environments of India. The decision support system also includes databases of typical Indian soils, weather and varieties for applications.

Swain and Yadav (2009) assessed the impact of climate change on rice yield, using simulation model CERES-rice. The model was calibrated and well evaluated for medium and long duration varieties through field experimental data at Kharagpur, India. With increase in atmospheric CO_2 level by 100 ppm, the grain yield of rice was increased up to 6% under optimum supply of water and nutrients. The long duration variety showed better adaptability to climate change than the medium duration varieties under optimum input management condition.

Lal *et al.* **(**1998**)** examined vulnerability of wheat and rice crops in northwest India to the projected climate change by using CERES wheat and rice models. The sensitivity experiments with these models showed higher yields for both wheat and rice (28% and 15% respectively for a doubling of CO_2) under elevated CO_2 levels. In general, acute water shortage conditions combined with the thermal stress should adversely affect both the wheat and more severely the rice productivity in NW India even under the positive effects of elevated CO_2 in the future.

Aggarwal *et al.* (2010) carried out simulation for rice and wheat crops in upper Ganga Basin using InfoCrop and indicated that rice and wheat crops are likely to be affected more in the A2 scenario than in the B2 scenario for 2080 AD of PRECIS, IITM, Pune, India. Climate change is likely to benefit wheat crop in northern parts of the study region in districts Dehradun, Bijnor, Haridwar, JP Nagar and Muzaffarnagar. On the other hand, rice crop in the north of the study region is likely to be more affected by climate change as compared to the southern region.

Bhatia *et al.* (2008) evaluated potential yield of soybean in rainfed environments and evaluated the yield gap and association with the inter-annual climatic variability, which could subsequently be employed with the climate change impact analysis study. Singh *et al.* (2005) evaluated the CHIKPGRO (CROPGRO-Chickpea) model for chickpea cultivars JG 74 and K 850 at Baster plateau in Chhattisgarh of central India and used validated model to explore the possibility of chickpea as second crop in Bastar Plateau region of Chhattishgarh using DSSAT crop simulation model. Using Wheat Growth Simulator (WTGROWS), a strong linear decline in wheat yield was noticed with the increase in January temperature. For every degree increase in mean temperature, grain yield decreased by 428 kg/ha (Aggarwal and Kalra, 1994a).

Effect of increase in seasonal temperature on grain yield of different crops, evaluated on the basis of district wise data in north-west India, indicated differential response to crops (Kalra *et al*., 2008). The extent of reduction in wheat yield due to temperature rise was highest (4.29 q/ha/°C) in Haryana followed by Rajasthan (2.49), Punjab (0.62) and Uttar Pradesh (0.56). More or less, similar trend was noticed for barley crop. The extent of decrease in chickpea yield was maximum (3.01 q/ha/°C) in Haryana followed by 1.81, 1.27 and 0.53 in Punjab, Rajasthan and Uttar Pradesh, respectively. The yield of rapeseed mustard was reduced by 2.01 in Haryana, followed by 0.98 and 0.92 q/ha/°C in Uttar Pradesh and Rajasthan, respectively. By pooling of the datasets for all the locations, reduction in yield per degree rise in temperature were 4.26, 2.77, 0.32 and 1.32 q/ha/°C rise for wheat, barley, chickpea and mustard, respectively (Fig. 1). Regional based technical coefficients for yield dependence of crops on seasonal temperature could be developed. We should also aim at stage specific dependence through development of dated production functions, as commonly reported for water use-crop yield relationship. Effect of seasonal temperature change on yield of early, medium and late duration varieties of maize was evaluated, which showed a decreasing trend in yield with temperature rise. Differential reduction in yield was noticed for different duration class varieties of maize.

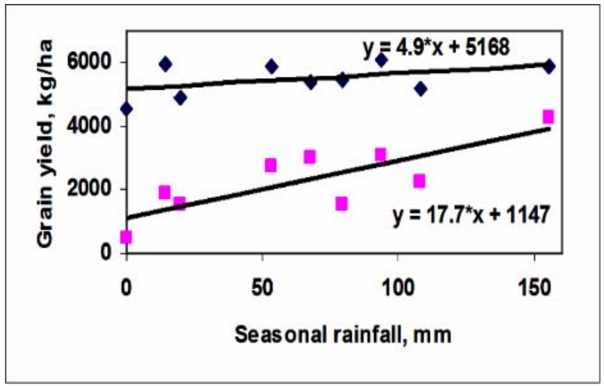

Fig. 2. Simulated wheat yields as a function of seasonal rains for irrigated and rainfed conditions in New Delhi environment

Decrease in yield was maximum (4.6 q/ha/°C) in late duration class, followed by medium duration class (4.3 q/ha/°C) and early duration class (3.2 q/ha/°C). In the last couple of decades, climate extremes and widening of the inter-annual climatic variability has been noticed, there is a strong need to identify suitable crops and cropping systems to ensure sustained agricultural production. If the inter-annual climatic variability (stage-wise) could be related to growth and yield of crops, the technical coefficients generated within the exercise could successfully be employed along with climate change scenario window to evaluate the impact.

The effect of change in rainfall during *rabi* and *kharif* seasons on national food production was analyzed. During *rabi* season, no correspondence was noticed when per cent change in food production from trend line was related with per cent change in rainfall from normal. It was due to the reason that most of the *rabi* crops are generally grown under irrigated condition, and the rainfall does not show any significant relationship with the food production on national scale, although intermittent rains (total around 2-5 cm) matching with critical stages of wheat growth in north-west India has pronounced effect on growth and yield. But the results can be different in different segments of the country, particularly the rainfed and dry land regions. During the *kharif* season, 0.64% increase in food production was noticed with 1 percent increase in *kharif* rainfall from the normal. Annual food production also had one to one correspondence with the annual rains. This exercise needs to be carried out for various agro-ecologies, production environments and crops/cropping systems.

Variation in amounts received in rains during winter, due to western disturbance, in the Indo-Gangetic Alluvial Plains has pronounced effect on growth and yield of wheat crop, specially under rainfed and limited water supply situation. WTGROWS model was used to evaluate the

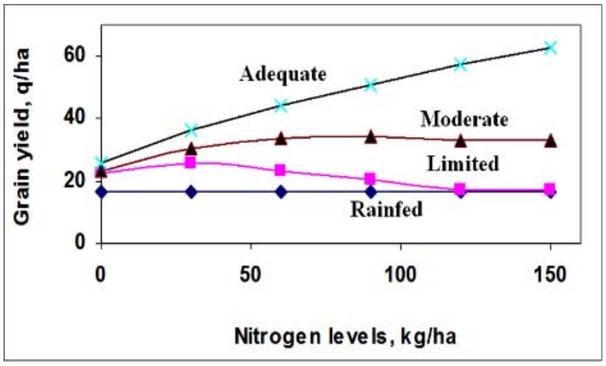

Fig. 3. Water nitrogen interaction in wheat at New Delhi environment (WTGROWS result)

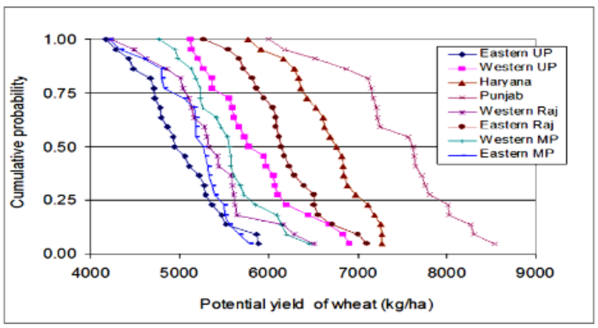

Fig. 4. Potential grain yield of wheat of meteorological sub-division (by using WTGROWS)

interaction of temperature rise and variations in amount of winter-rains in various production environments (Rai *et al*., 2004) and it could be concluded that the adverse-effect of temperature rise could be nullified through higher amounts of winter-rains received. Winter rains in north-west India due to western disturbance generally varies from 0-5 cm, but received intermittently in small amounts at critical growth stages of *rabi* crops, and thus are highly beneficial in terms of enhanced yields. Even the beneficial effects are noticed in well irrigated lands.

WTGROWS was run to evaluate the effect of variable amounts of winter rains on growth and yield of wheat grown under rainfed and optimally irrigated condition for New Delhi environment (Aggarwal and Kalra, 1994a, Fig. 2). The results clearly demonstrated one to one correspondence of the winter rains verses grain yield under rainfed environment, although the increase in trend with slower rate was even noticed under irrigated condition. Depending upon the amount of winter rains north-west India, the irrigation scheduling can be designed to avoid over-irrigation, which is a general practice for wheat in north-west India.

INFOCROP – Wheat was run for New Delhi environment to optimize the dose of nitrogen under

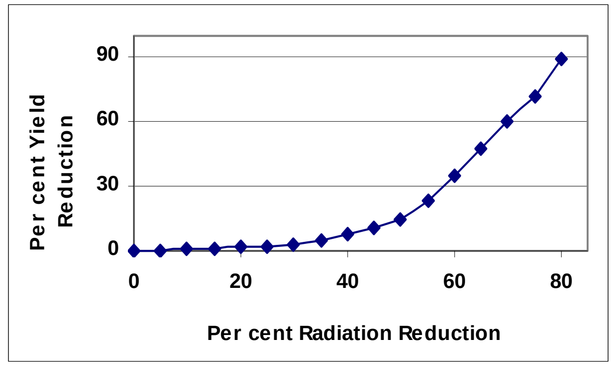

Fig. 5. Effect of radiation reduction on yield of wheat in New Delhi environment

variable water supply situation (Aggarwal and Kalra, 1994b) shown in (Fig. 3). Under one irrigation at CRI Stage, N application benefits could be noticed till 70 kg/ha application, whereas with two irrigation applied each at CRI and flowering, the benefits of N application could be noticed upto 110 kg/ha. With assured irrigation water availability, the benefits in wheat yield could be noticed at application rates higher than even 150 kg/ha. From the analysis, it was clear that N dose needs to be set on the basis soil moisture and irrigation water availability, which could be important under drought / limited water supply situation. Multi-nutrients interaction is also key for breaking the yield barriers, say for example N-use efficiency will increase if other nutrients deficient in soil test values are applied. Under condition of soil water availability, as dependent on the rainfall received, and the plant development and processes also influenced by climatic conditions, mainly temperature and radiation, the simulated yield could be computed, which could become one of the key inputs of nutrients' optimization model to work out the nutrients' management for sustainable agriculture.

Potential yield of wheat in different growing regions was simulated by the WTGROWS-model using the historic weather datasets on meteorological sub-division scales (Kalra *et al*., 2005). Results clearly showed the decrease in potential yield of wheat moving eastward and southward from Punjab, clearly indicating the dependence on prevailing temperature (Fig. 4). Variability range happened to be more for higher productive regions, showing the vulnerability of climate change to these areas. The results were subsequently pooled for developing relationship of potential wheat yield with seasonal temperature, which showed a decreasing yield trend due to rising temperature with a slope of 6.34 q/ha per degree rise in temperature, relatively higher than the reduction factor evaluated on district scales by using the actual productivity records.

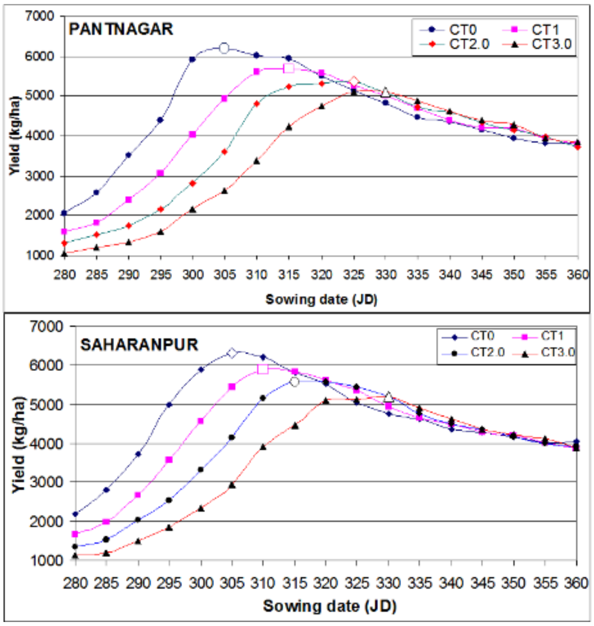

Fig. 6. Effect of sowing dates and temperature rise on attainable yield of wheat in different agro-environments

The effect of reduction in radiation on wheat yield in New Delhi environment was evaluated by using WTGROWS-model (Fig. 5). The optimal grown conditions were assumed for this exercise. The results indicated that reduction in radiation upto 15% was not having much effect on wheat yield. With 40% decrease in the radiation, the yields reduced by around 10%. Usually this problem of the radiation reduction happens in the months of December and January. But at that time, the crop is the early phases, *i.e.*, early jointing, where the extent of radiation requirement by the crop is generally low. This event is due to foggy weather or the aerosol layer at a height of 3-4 km. Though there is a reduction in the direct solar radiation, that also not exceeding by 10%, but the diffused radiation component increases. This diffused component compensates for the reduction of the direct part, as it also contributes to the photosynthetic activity. There is a need to work out the photosynthetic efficiency of the diffused radiation for the crops. Presently, this part has not been dealt in the model.

Effect of sowing date on wheat yield in various production environments was evaluated using WTGROWS-model (Rai *et al*., 2004). The model was run for optimally grown condition, *i.e.*, adequate inputs of water, fertilizer etc. Normal weather of the location was employed for this purpose. The cultivars' characters (through heat degree day requirement, genetic coefficients) were used for the respective locations. Results indicated that optimum date of sowing for wheat was spatially dependent, mainly due to prevailing climatic conditions. The large turnaround time due to late harvest of basmati rice and tillage options for subsequent wheat poses problem in the Punjab, Haryana and Western U.P. Excessive moisture at maturity stage of rice in eastern U.P. and Bihar delays its harvest and thereby delay in sowing of wheat crops. There is a need to reduce the turnaround time to match with the optimal dates for these regions, through adoption of zero/minimum tillage options, resulting in reduced turnaround time to the extent of 10-15 days for ensuring wheat sown in the optimal window. Simulation results indicated significant reduction over the optimal yields due to early or delay sowing of wheat from optimal dates. Usually there is 1% reduction in the wheat yield per day delay in the sowing of wheat from the optimal date (Aggarwal and Kalra, 1994b).

Delayed sowing of wheat with increased temperature is one of the adaptation strategies for sustaining yield, as reflected over locations by running WTGROWS model (Fig. 6, Kalra *et al*., 2008). The results clearly showed 5-7 days delay in sowing per degree rise in temperature for entering into optimal sowing window pane for wheat. Similar work has been carried out for crops in various production environment to suggest options for sustenance. Fig. 7 shows the optimal date of sowing with increase in temperature during growing period of wheat, which clearly establishes the delayed sowing of crop with increased temperature (Rai *et al*., 2004).

Water use verses yield relationship is water production function. Water use can be in terms of applied water (effective rainfall plus irrigation water) or evapo-transpiration (actual evaporation plus actual transpiration) or consumptive water use (actual evaporation + actual transpiration + drainage). Normally evapo-transpiration is related to grain yield or biomass. Water use efficiency is termed as grain yield (or biomass) per unit of water use, and can decide about the irrigation schedule for a set value of evapo-transpiration for a target yield. Dated production functions can assess the yield on the basis of water availability/water use in various stages of the crop growth. Under agricultural drought condition, the limited water supply could be scheduled to have the optimized grain/economic yield. Secondary dataset for north india were collated for seasonal water use - yield relationship function for important crops (wheat, rice, mustard, chickpea, sugarcane).

Running INFOCROP-Wheat for New Delhi environment (by using representative soil, crop and normal weather) under variable supply of irrigation water indicated that 3 irrigation (one each at CRI, Jointing, Flowering) could provide 5 t/ha of yield, which was 93% of the yield as obtained under 4-5 irrigation, whereas 2

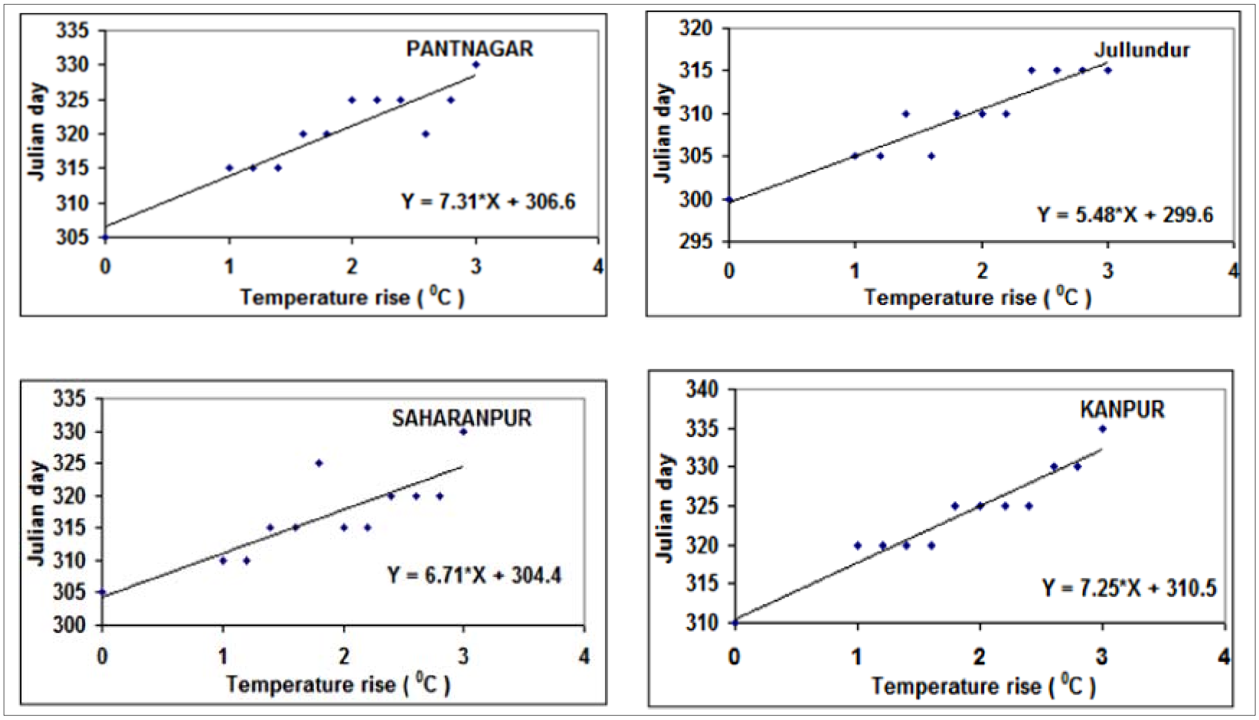

Fig. 7. Optimal date of sowing in various regions for wheat as influenced by temperature rise

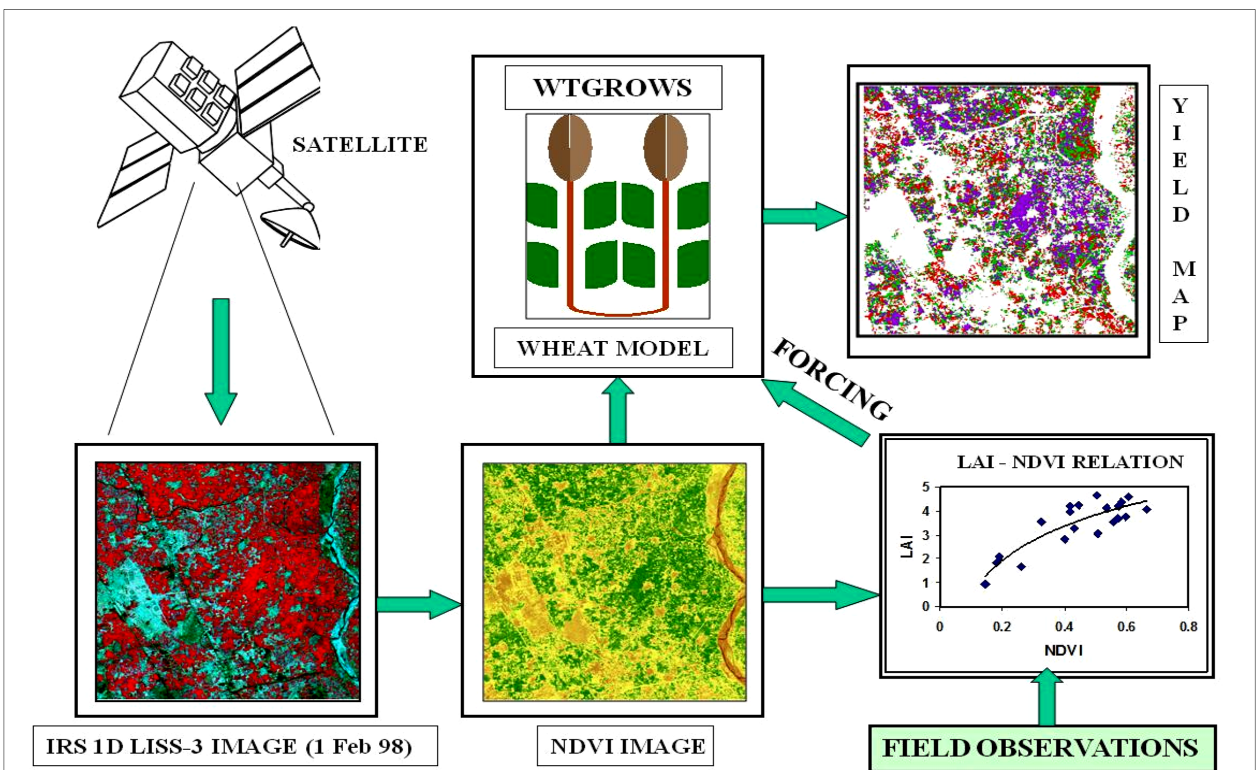

Fig. 8. Methodology development of wheat yield estimates by linking remote sensing inputs with crop growth model

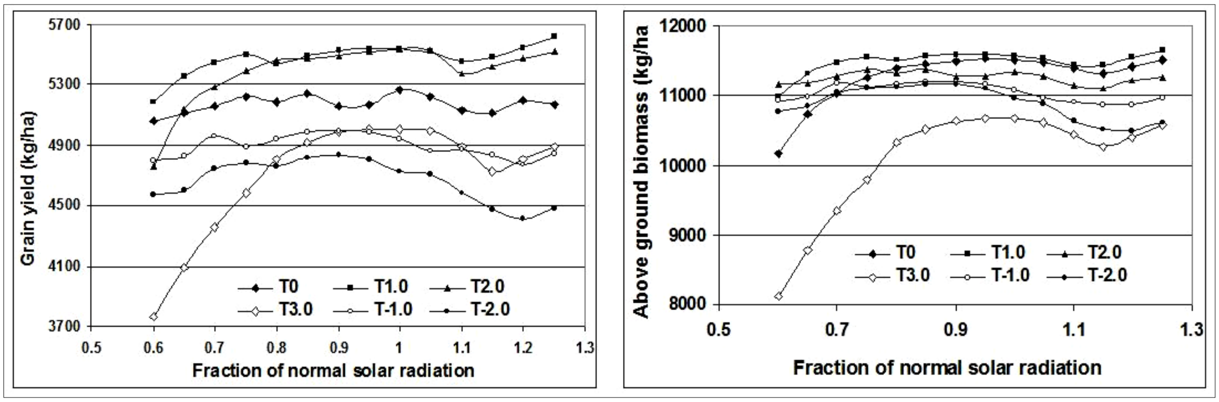

Fig. 9. Radiation and temperature change interaction on growth and yield of wheat at New Delhi environment

irrigation (CRI + Flowering) could simulate 4.1 t/ha, whereas one irrigation at CRI stage could provide 3.2 t/ha. The results clearly revealed that 3 irrigation in wheat is the optimal amount in New Delhi, where winter rains due to western disturbance matches with the critical stages of wheat growth (Kalra *et al*., 2008).

Methodology development for wheat yield forecast by linking remote sensing inputs with wheat growth model and relational data base layers was done under IARI-SAC joint project (Fig. 8). RS data, through spectrally derived indices such as IR/R, NDVI etc., were related to the leaf area index, which was then used as forcing variable in WTGROWS to subsequently forecast the yield. For this purpose, experiments in the farmers' fields at Alipur (two seasons), Bhopal (three seasons), Karnal (two seasons) and Hissar (two seasons) were conducted. The methodology of evaluating leaf area index near flowering on the basis of satellite driven NDVI was developed, and was then forced in the model on point scales for yield estimates. Since the range of growing condition covered a wide range, almost represented a very large region, the extrapolation of the decisions over a larger area could successfully forecast the yield on a large scale.

National wheat yield forecast was done for three seasons on meteorological sub-division scale by using WTGROWS, relational database layers and RS-based acreage obtained from concurrent running experiment (Kalra *et al*., 2005). WTGROWS was run for historic weather dataset (last 25 years), with the relational database inputs through their associated growth rates and compared with the wheat yield trends at the met-subdivision scale. Calibration factors, for each met-subdivision, were obtained to capture the other biotic and abiotic stresses and subsequently used to statistically adjust yields at each sub-division to observed level. Meteorological data for each-subdivision on weekly basis was used. WTGROWS was run with actual weather data obtained up to forecasting date, and weather normals were used for subsequent growing period, and the forecast was generated. This methodology could forecast the wheat yield during 1999-2000 well in advance with a high accuracy at national scale. This procedure could be adopted for Crop Growth Monitoring System (CGMS) for agri-production estimates in the country and various spatial layers in addition can be used for land use planning.

WTGROWS was used to evaluate the interaction of radiation with temperature for wheat in New Delhi and Patna environments (Kalra *et al*., 2008). Daily percent change in radiation from -40% to +25% was considered at 5% interval and temperature changes from -2.0 to +3.0, with an incremental value of 1 °C were considered. The range of variations among treatments for above ground biomass existed in a narrower range excepting for temperature rise of 3 °C, whereas the differences were wider in case of grain yield where the interaction effect was more pronounced. In general, the above ground biomass and grain yield reduced gradually with reduction in the radiation from the normal value, the trend was more consistent for Patna environment in comparison to New Delhi environment. Temperature rise of 1 °C had relatively positive effects compared to the control (no temperature rise) both for above ground biomass and grain yield for the New Delhi environment, which may not be consistent with different production environments and agro-ecologies. Subsequent rise in temperature reduced the biomass and yield over the control treatment and the extent of reduction was quite large for 3 °C rise (Fig. 9). Reduction in temperature by 1 & 2 °C enhanced the yield and biomass under Patna environment due to relatively higher temperatures during growth of wheat crops under normal conditions. The degree of reduction in yields associated with reduction in radiation amounts is not large till around 20% of the radiation decrease from the normal

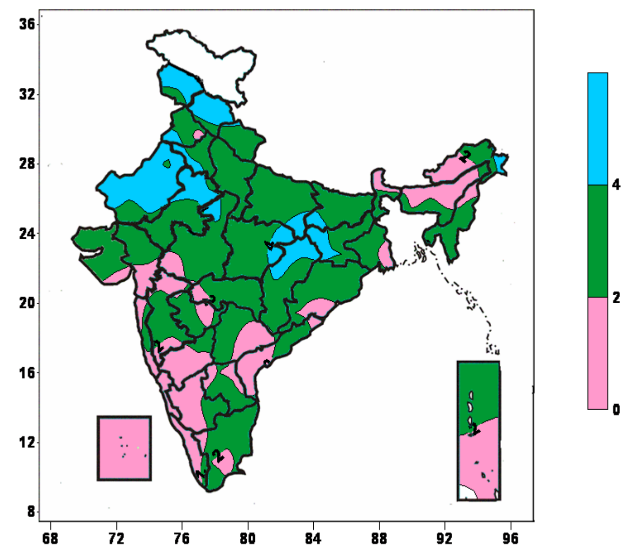

Fig. 10. Maximum temperature (°C) anomaly in India for the month of March 2010

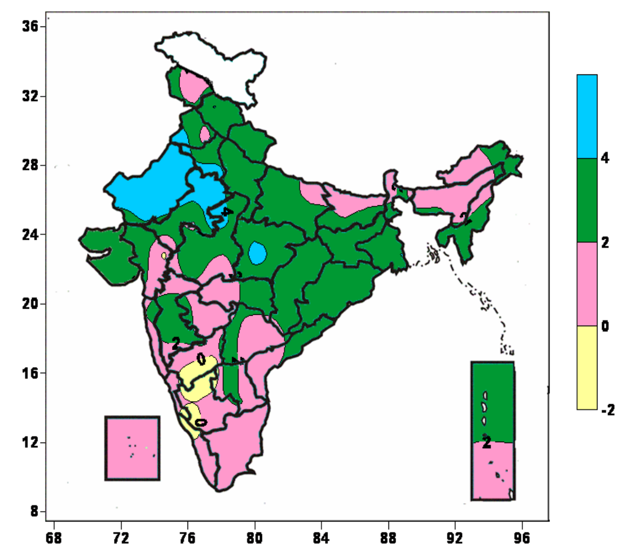

Fig. 11. Minimum temperature (°C) anomaly in India for the month of March 2010

values. Simulation results clearly indicate the significant interaction of radiation with temperature as far as growth and yield of crops are concerned. Under All India Coordinated Research Project on Agrometeorology, ICAR-CRIDA, Rao *et al*. (2015) has evaluated with three years experimental data from 2011 to 2013 at Akola for three different soybean varieties *viz.*, JS-335, JS-9305, TAMS 98-21 grown under different temperature environment. They found that the maximum temperature level raised by 1 °C, 2 °C and 3 °C decreased the yield level ranging from 3.2 to 28.4 % under 1 °C, by 14.3 to 38.9% under 2 °C and from 22.6 to 50.8% under 3 °C.

Simulating impact of low temperature in January 2010 and high temperature in March 2010 on wheat growth and yield

Over the last five years, the per hectare yield of wheat in India has fallen due to the temperature rising steadily in January, February and March, a time most crucial for the wheat crop. The year 2010 began with dense fog and cold day conditions prevailing over most parts of Indo-Gangetic Plains in the month of January. However February was near normal in respect of both maximum and minimum temperatures which was favorable and beneficial for the wheat productivity. In month of March, generally characterized by gradual increase in temperatures over the country, both maximum and minimum temperatures remained above normal almost throughout the month over most parts of the country. The Maximum temperatures increased considerably from the beginning of third week when they crossed 40° C mark at some places over Gujarat and south Rajasthan. Subsequently during the third week, the region of high maximum temperatures (40 °C and more) has extended into the remaining parts of Gujarat & Rajasthan and many parts of west Madhya Pradesh, Chhattisgarh, Jharkhand and south Uttar Pradesh. Maximum temperatures were above normal by 4-8 °C over northwest, east, central and adjoining peninsular India (Figs. 10 &11).

Wheat crop did not encounter increased temperature at booting and anthesis stages but the temperature was significantly higher than normal during grain filling period thus adversely affecting the grain filling process. In the present study, efforts are made to estimate the wheat yield for the year 2009-10 using DSSAT CERES-Wheat v4.0 crop growth simulation model. Simulations were made under irrigated condition using data base for 15 wheat-growing locations in India. As wheat cultivation is mostly irrigated and recommended NPK is applied, productivity of a given cultivar is primarily governed by the weather, particularly temperature and radiation.

Besides *rabi* season of 2009-2010, yield estimates are also made for previous wheat season 2008-2009, to compare crop attributes and yield. The deviation of yield estimates over previous year allowed to remove the model bias arising due to parameters not accounted in the crop simulation model and quantify effect of increased temperature in March on crop growth. Three sowing dates were considered representing early, normal and late condition for 3 regions, *viz*., NW India, Uttar Pradesh (U.P.) and East India. Commonly grown cultivars at different locations were considered in the study.

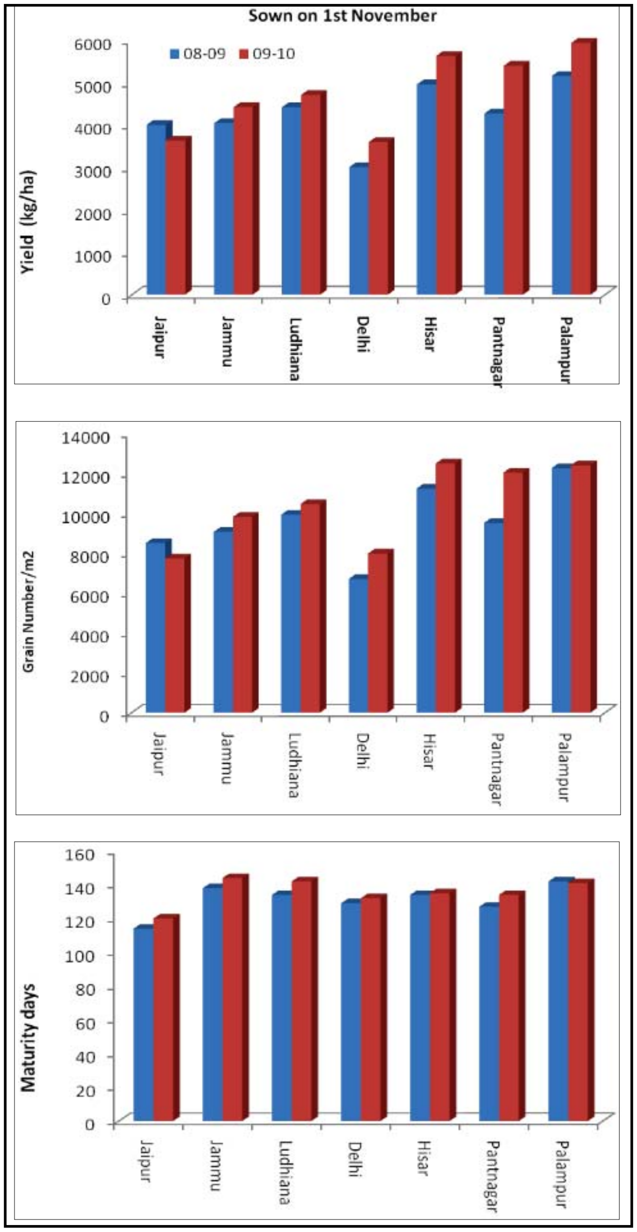

Fig. 12.1. Simulated grain yield, grain number and maturity period for 2009-10 and 2008-09 (early sown) : NW India

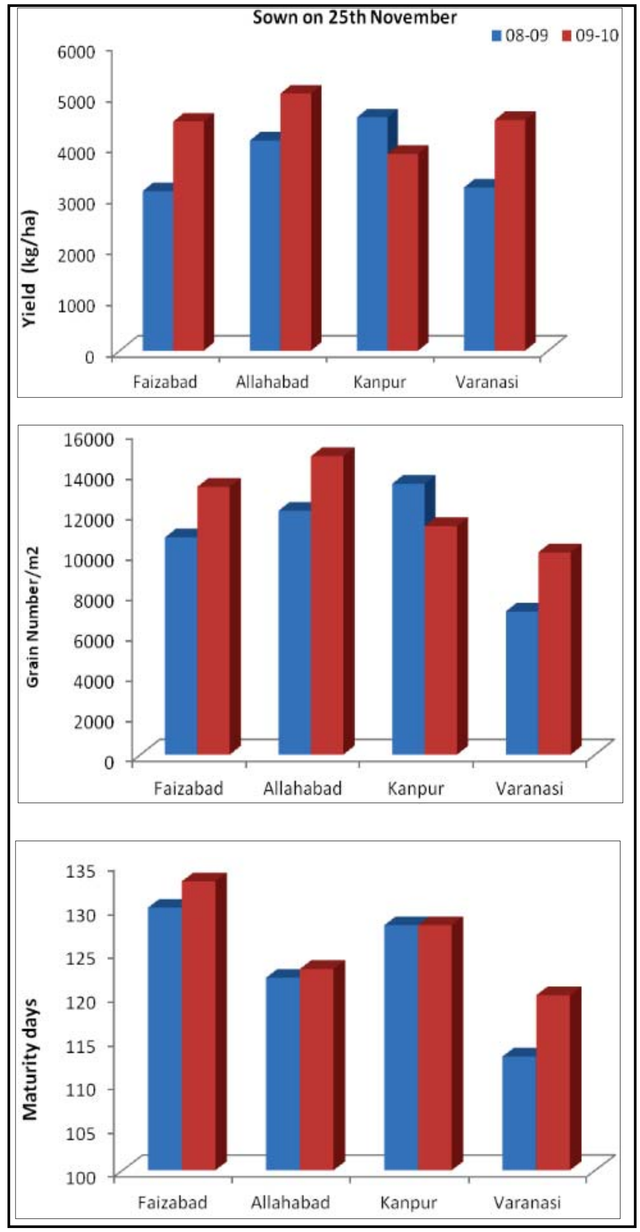

Fig. 12.2. Simulated grain yield, grain number and maturity period for 2009-10 and 2008-09 (early sown) : Uttar Pradesh

The simulated grain yield, grain number and maturity dates for the different locations and yield percentage deviation from year 2008 - 09 is shown in Figs. 12.1, 12.2, 12.3, 13.1, 13.2, 13.3, 14.1, 14.2, 14.3 & 15.

Early sown crop (1 Nov-NW India, 25 Nov-UP and 15 Nov-East India)

Figs. 12.1, 12.2 & 12.3 show that in NW India during crop season 2009-10 led to higher yield as compared to year 2008-09 due to cold day conditions prevailing over most parts of Indo-Gangetic Plains in the month of January. The day temperatures were below normal by 4-8 °C but the minimum temperature was above normal by 2-3 °C. However February was near normal in respect of both maximum and minimum temperatures with two to three good rainfall activities over NW plains and Central India. The simulated average yield for NW India is 42.7 and 47.7 q/ha for the year 2008-09 and 2009-10 respectively. Similarly for Uttar Pradesh yield is 37.5 and 44.7 and 32.8 and 42.0 q/ha for East

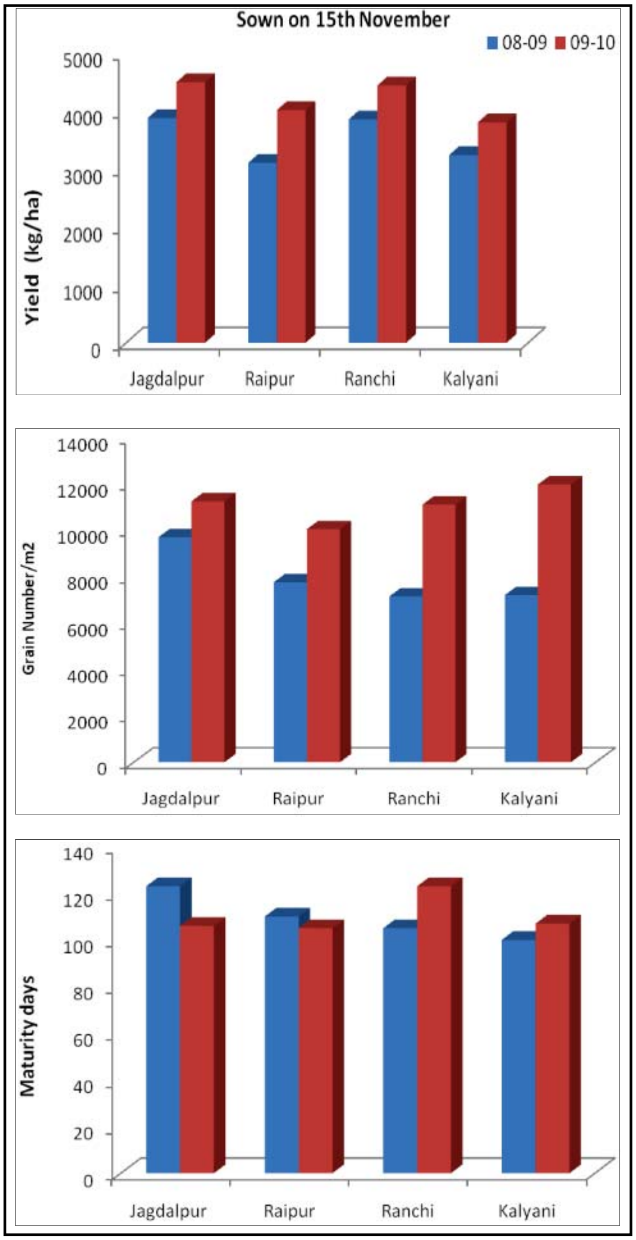

Fig. 12.3. Simulated grain yield, grain number and maturity period for 2009-10 and 2008-09 (early sown) : East India

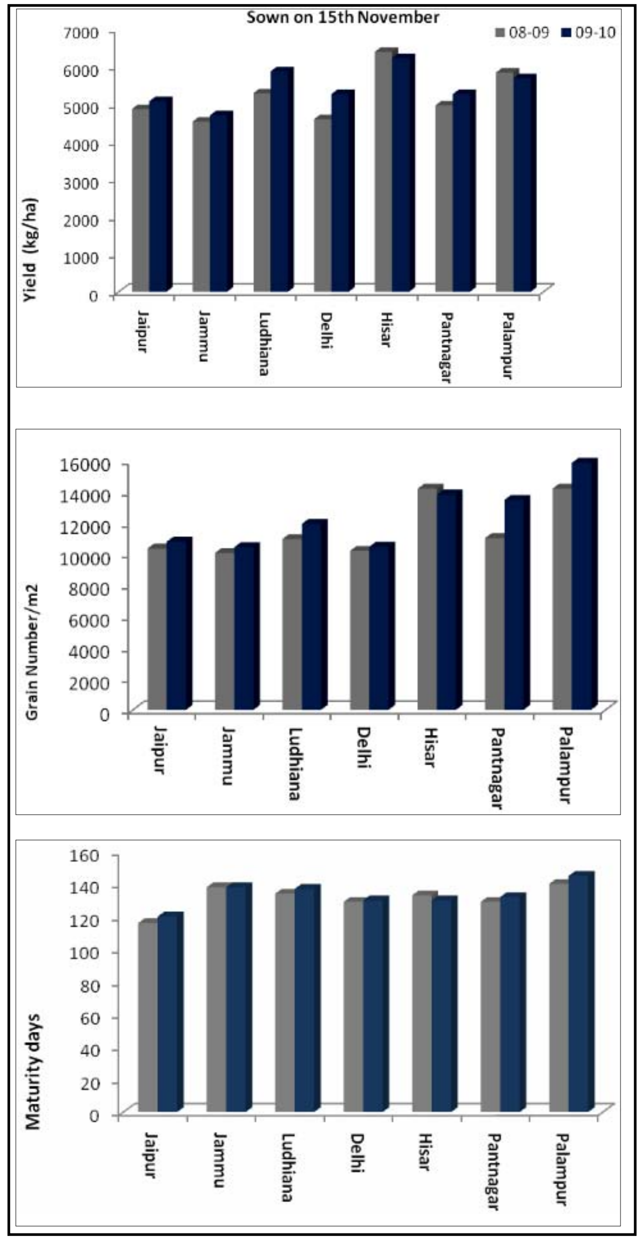

Fig. 13.1. Simulated grain yield, grain number and maturity period for 2009-10 and 2008-09 (normal sown) : NW India

India. Wheat yield production realized during 2009-10 is more compared to 2008-09. As a combined effect, Figs. 12.1, 12.2 & 12.3 depicts increase in grain yield by ~10% in NW India, ~16% in Uttar Pradesh and ~21 % in East India respectively.

Normal sown crop (15 Nov-NW India, 10 Dec-UP and 1 Dec-East India)

Figs. 13.1, 13.2 & 13.3 shows that the wheat crop in UP during the season 2009-10 was slightly affected due to rise in temperature in March encountered at grain filling stage. The simulated average yield for UP was 49.4 and 44.6 q/ha for the year 2008-09 and 2009-10 respectively. Similarly, the yields for year 2008-09 and 2009-10 were 34.7and 42.3 q/ha for East India and 52.2 & 54.5 q/ha for NW India. Wheat yield estimated during 2009-10 is ~10% less compared to 2008-09 in UP. As a combined effect, Figs. 13.1, 13.2 & 13.3 depicts increase in grain yield by ~4% in NW India and ~18% in East India respectively.

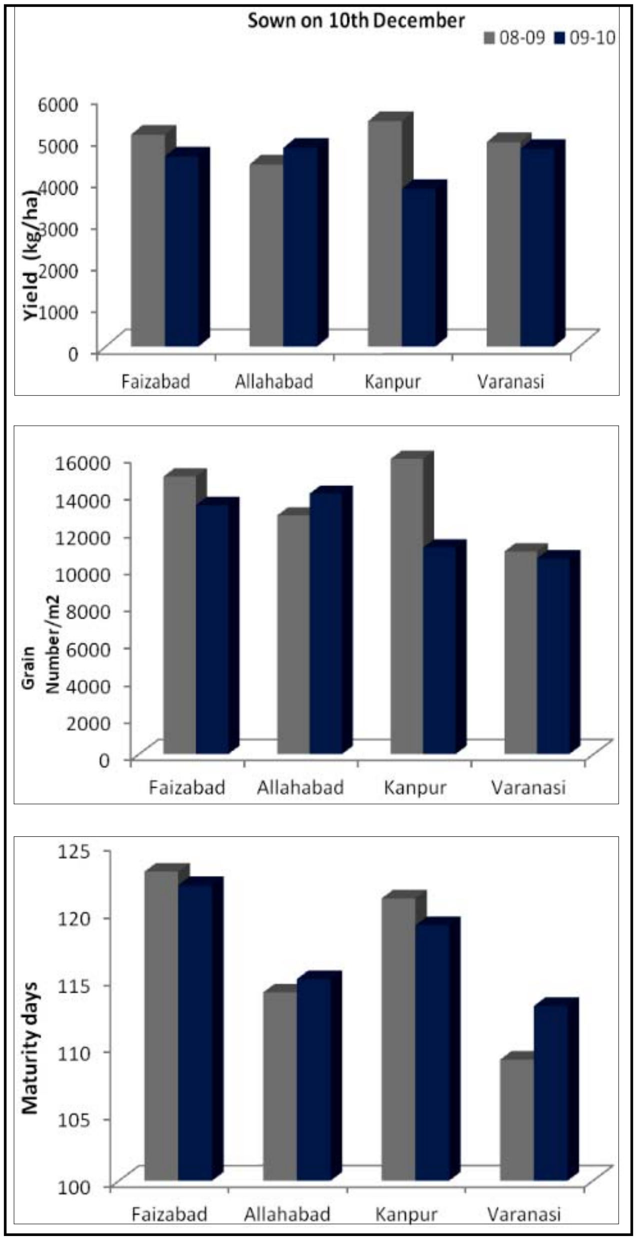

Fig. 13.2. Simulated grain yield, grain number and maturity period for 2009-10 and 2008-09 (normal sown) : Uttar Pradesh

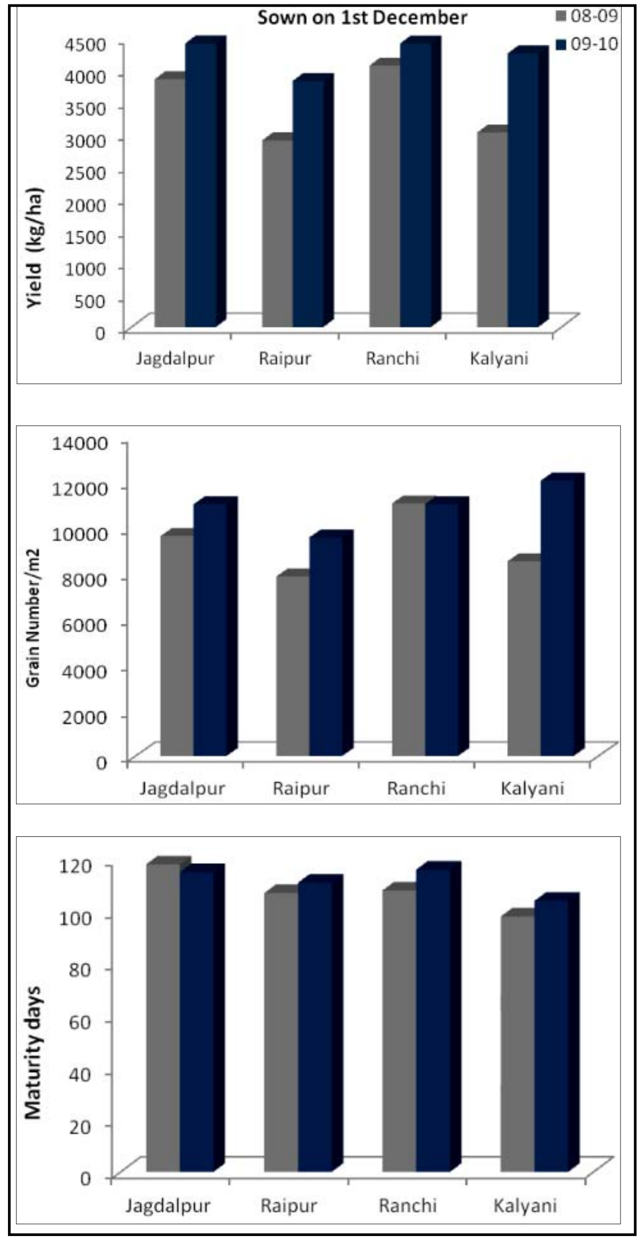

Fig. 13.3. Simulated grain yield, grain number and maturity period for 2009-10 and 2008-09 (normal sown) : East India

Late sown crop (25 Nov-NW India, 25 Dec-UP and 15 Dec-East India)

Figs. 14.1, 14.2 & 14.3 show that in NW India during crop season 2009-10 led to lower yield as compared to year 2008-09 except in East India. In the month of March, 2010, maximum and minimum temperatures remained above normal almost throughout the month over most parts of the country. Maximum temperatures were above normal by 4-8 °C over northwest, east, central and adjoining peninsular India. Daily temperature (maximum, minimum, mean) departures over western & central Himalayan region were even more than 10 °C on some days. The simulated average yield for the year 2008-09 and 2009-10 were 53.6 and 51.2 q/ha for NW India, 50.8 and 37.4q/ha for UP, 32.1 and 35.4 q/ha for east India. Figs. 14.1, 14.2, 14.3 and 15 indicated decrease in grain yield by ~36% in UP and ~4% in NW India while increase in east India.

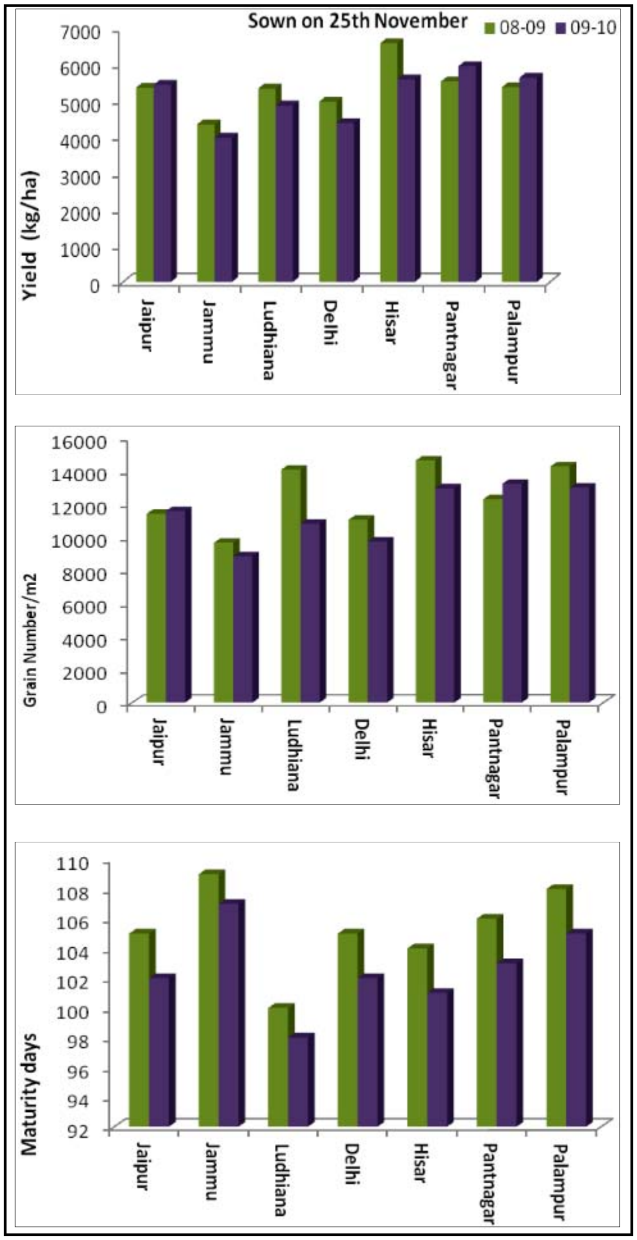

Fig. 14.1. Simulated grain yield, grain number and maturity period for 2009-10 and 2008-09 (late sown) : NW India

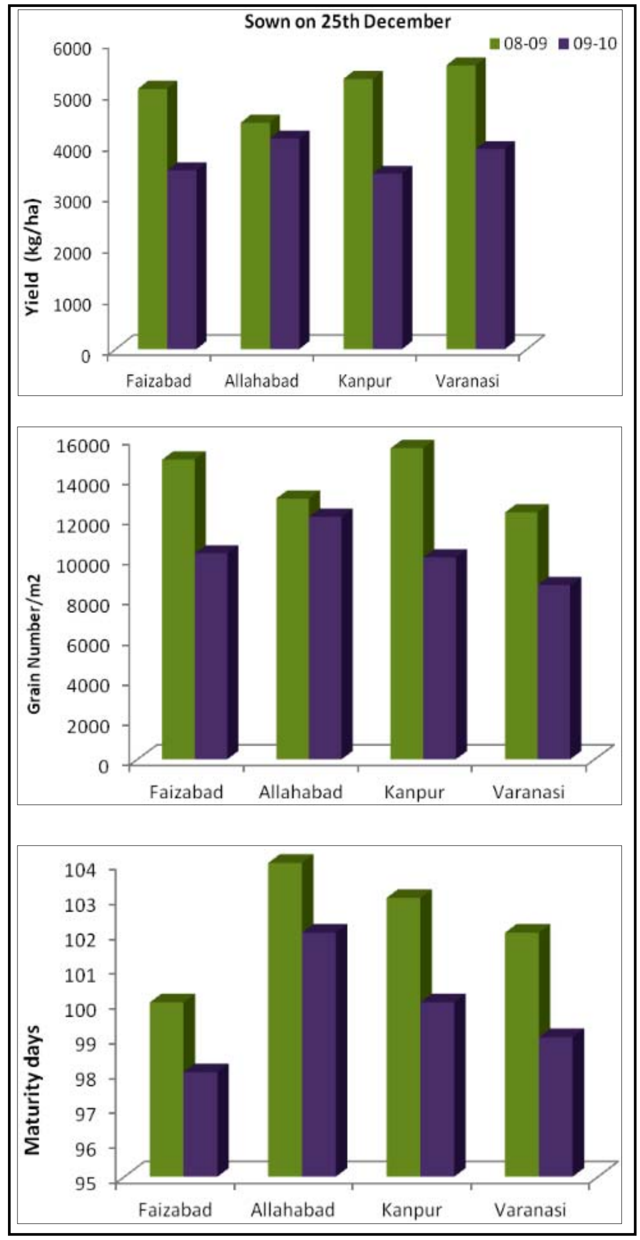

Fig. 14.2. Simulated grain yield, grain number and maturity period for 2009-10 and 2008-09 (late sown) : Uttar Pradesh

3. Aerosol mediated effects on weather and crops response

Increase in aerosols (atmospheric pollutants) due to emission of greenhouse gases including black carbon and burning of fossil fuels, chlorofluorocarbons (CFCs), hydro-chlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), Ozone depletion and UV-B filtered radiation, eruption of volcanoes, the "human hand" in deforestation in the form of forest fires and loss of wet-lands are one of the causal factors for weather extremes.

Thick haze and smoke originating from burning biomass in northwestern India and air pollution from large industrial cities in northern India often concentrate over the Ganges Basin. Prevailing westerlies carry aerosols along the southern margins of the sheer-faced Tibetan Plateau towards eastern India and the Bay of Bengal. Dust and black carbon, which are blown towards higher

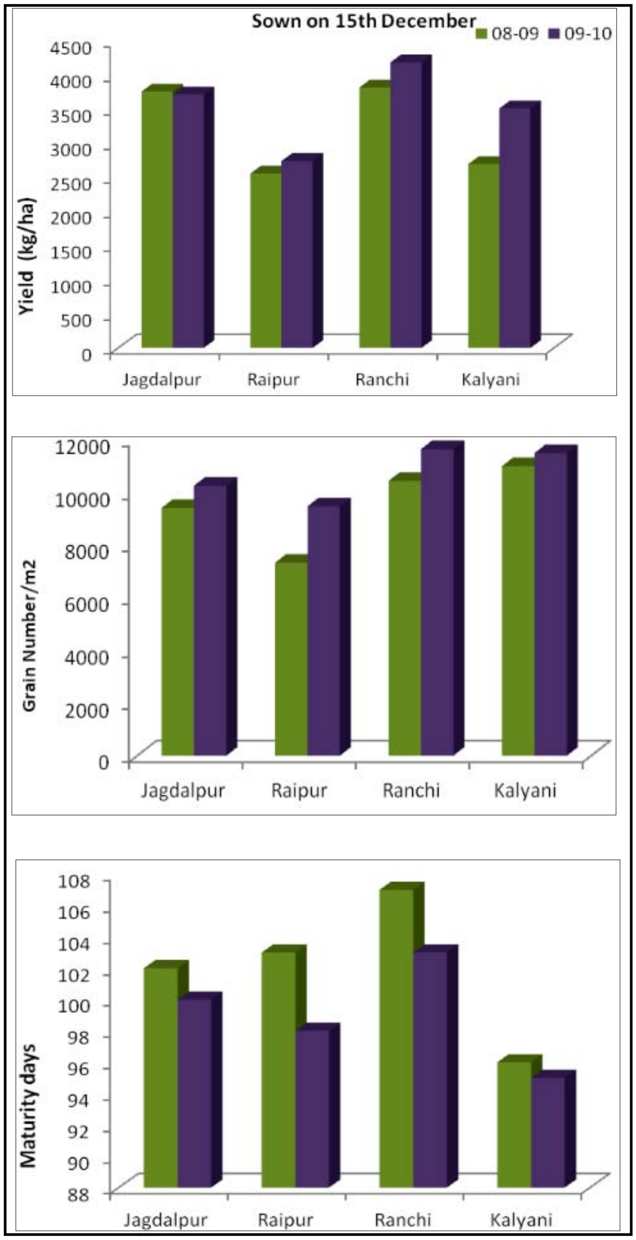

Fig. 14.3. Simulated grain yield, grain number and maturity period for 2009-10 and 2008-09 (late sown) : East India

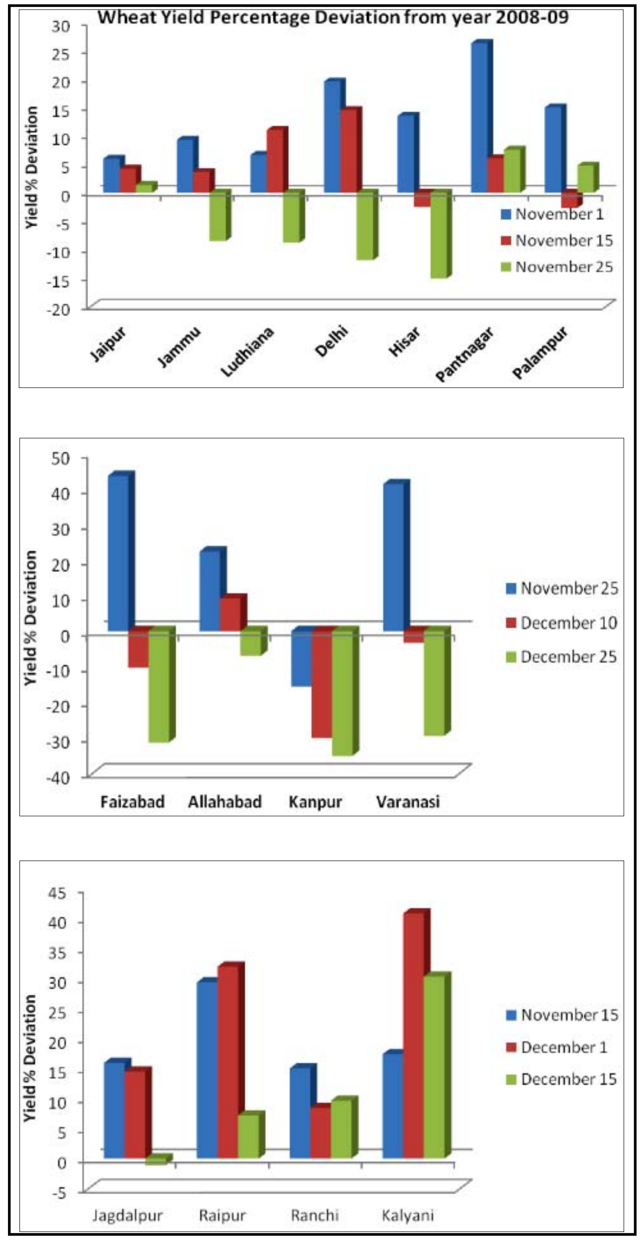

Fig. 15. Yield deviation for the different scenario for crop season 2008-09

altitudes by winds at the southern margins of the Himalayas, can absorb shortwave radiation and heat the air over the Tibetan Plateau. The net atmospheric heating due to aerosol absorption causes the air to warm and convect upwards, increasing the concentration of moisture in the mid-troposphere and providing positive feedback that stimulates further heating of aerosols.

During January-March 1999, a significant reduction in radiation occurred in north-west India due to aerosol presence. The values of radiation during this period reaching the earth's surface, with and without aerosol (filter = 500 nm) were used to evaluate the per cent reduction in the radiation due to aerosol. Aerosol presence influenced sunshine hours and the amount of radiation received. The extent of reduction in radiation during this extreme event was relatively less as the extent of the diffused radiation increased. During this time, the radiation reduction ranged from 5-12%. The associated weather changes (lowering of temperature, etc.) due to aerosol presence can benefit the crops through phenology modifications and other crop process activities. The extent of reduction in the radiation as well modifications in the other weather parameters due to aerosol presence were spatially and temporally different.

Impact of thick aerosol layer during this period was evaluated for wheat, rice and sugarcane. Crop growth models, WTGROWS for wheat, CERES Rice for rice and CANEGRO for sugarcane were used for this investigation (UNEP and C^4, 2002). Three scenarios were chosen for the study: evaluating the impact in terms of growth and yield of these crops under prevailing weather (thick aerosol layer), if the aerosol forcing was not present (radiation effect only) and if aerosol forcing was not present and the associated weather parameters, in terms of temperature and rainfall, were also included.

The model was run, with and without aerosols, for different wheat growing met-subdivisions. Reduction in growth and yield values were noticed by including the aerosol effects (radiation reduction only). But when the coupled weather changes, along with radiation reduction, were included, then the crop growth duration increased and the interaction effect of radiation-temperature nullified the negative-effects of the radiation reduction when taken alone. Usually the coupled weather change phenomenon occurs simultaneously.

During winter season, rice crop is generally grown in south India, where the annual range of variation in temperature is small, and the temperatures are generally high. CERES Rice of DSSAT was run for rice for Coimbatore and Hyderabad. If aerosol layer would not have existed, it might have resulted in enhanced yield of the order of 6-8%. But the radiation reduction alone does not take place, the coupled weather change phenomenon nullified the reduction of yields through cooling of the temperature, which enhanced the duration of the crop.

CANEGRO Module of DSSAT was employed for evaluating impact on sugarcane. The specific event, *i.e.*, aerosol presence during January-March, 1999 was evaluated for Delhi, Lucknow and Coimbatore, three diverse agro-climatic regions. The effect of three months aerosol presence was not significant in terms of cane yield (January sown) reduction, as without aerosol one would have achieved around 1% higher yield in all the locations. But the radiation reduction alone does not take place, the coupled weather change phenomenon nullified the reduction of yields through cooling of the temperature, which would enhance the duration of the crop.

There is a need to evaluate probability of occurrence of extreme aerosol events in south Asia, relate aerosol optical depth with the reduction in solar radiation reaching the earth surface, associated modifications in distribution of direct and diffused components, associated coupled weather parameters changes, plant processes as related to direct and diffused components of solar radiation, modifications in the existing crop simulation models to include aerosol mediated effects.

4. Conclusions

Inter-annual climate variability in Indian context is significant. Probability of occurrence of extreme climatic events has increased over the past few decades. Crop simulation models are effective tools for assessing the crops' yield as well suggests appropriate adaptation strategies for sustained agricultural production under wide range of inter-annual climatic variations and extreme climatic/episodic events. The simulation results by running INFOCROP/WTGROWS clearly indicated the effects of inter-seasonal climatic variability on growth and yield of crops. The growing season temperature has one-to-one correspondence with yield of major crops, which can aid in extrapolating the results for evaluating the impact of climate change and its variability as well addressing the extreme warming/cooling. Extreme climatic events has increased in recent past, and farmers have to learn to deal with them. There is a need to identify suitable resource and input' management strategies to sustain crops' yields under these extreme events, which is possible by linking the relational layers of bio-physical and socio-economic aspects along with the weather information to the crop simulation models for assessment of crop losses as well for suggestions of control options for sustained agri-production. The simulation results by using DSSAT model indicated the influence of episodic changes in temperature events on wheat growth and yield. There is a need to disseminate the agro-advisory well within time to the farming community, and India Meteorological Department is actively engaged in this regard through a well designed network. IMD is effectively using crop simulation models and remote sensing inputs for this purpose. Global climate change is noticed, and the growing rate has become faster in recent past. There is a need of evaluating impact of climate change on agriculture, for which crop simulation models play key role in understanding the crops and soil processes in relation to climate change and variability and subsequently assess the final growth and yield of crops. Through simulation models, vulnerable regions with the climate change/extreme climatic events could be identified. There is a need to link the crop growth models with the relational database layers through remote sensing and GIS platforms to assess agricultural production on regional scale and this service has to made operational. There is a strong need to develop integrated assessment model for evaluating agri-sector impact of extreme weather events and climate change, which should also include water, nutrients, soil health, insects-pests-microbes along with weather information. Crop simulation tools coupled with remote sensing inputs through GIS can play an important role in evolving this unique operational programmes.

References

Aggarwal, P. K., Naresh Kumar, S. and Pathak, H., 2010, "Impacts of climate change on growth and yield of rice and wheat in the upper Ganga Basin", *WWF India Studies*, p36.

Aggarwal, P. K., Kalra, N., Chander, S. and Pathak, H., 2006, "Infocrop : A dynamic simulation model for the assessment of crop yields, losses due to pests and environmental impact of agro-ecosystems in tropical environments", I. Model description, *Agricultural Systems*, **89**, 1-25.

Aggarwal, P. K., Kalra, N., Singh, A. K. and Sinha, S. K., 1994, "Analyzing the limitations set by climatic factors, genotype, water and nitrogen availability on productivity of wheat", I. The model description, parameterization and validation, *Field Crops Res*., **38**, 73-91.

Aggarwal, P. K. and Kalra, N., 1994a, "Simulating the Effect of Climatic Factors", *Genotype and Management on Productivity of Wheat in India*, IARI Publication, New Delhi, p156.

Aggarwal, P. K. and Kalra, N., 1994b, "Analysing the limitations set by climatic factors, genotype, water and nitrogen availability on productivity of wheat", II. Climatically potential yields and optimal management strategies. *Field Crops Res*., **38**, 93-103.

Bhatia, V. S., Piara Singh, Wani, S. P., Chauhan, G. S., Kesava Rao A. V. R., Mishra, A. K. and Srinivas, K., 2008, "Analysis of potential yields and yield gaps of rainfed soybean in India using CROPGRO-Soybean model", *Agricultural and Forest Meteorology*, **148**, 8-9, 1252-1265.

Kalra, N., Dadhwal, V. K., Aggarwal, P. K. and Parihar, S. S., 2005, "Forcasting of crop yield using remote sensing inputs and crop growth simulation models", IARI/SAC Publication.

Kalra, N., Chakraborty, D., Sharma, A., Rai, H. K., Jolly, M., Chander, S., Ramesh Kumar, P., Bhadraray, S., Barman, D., Mohan Lal and Sehgal, M., 2008, "Effect of increasing temperature on yield of some winter crops in north-west India", *Current Science*, **94**, 1, 82-88.

Lal, M., Singh, K. K., Rathore, L. S., Srinivasan, G. and Saseendran, S. A., 1998, "Vulnerability of rice and wheat yields in NW India to future changes in climate", *Agricultural and Forest Meteorology*, **89**, 2, 101-114.

Rai, H. K., Sharma, A., Soni, U. A., Khan, S. A., Kumari, K., Chander, S. and Kalra, N., 2004, "Simulating the impact of climate change on growth and yield of wheat", *J. of Agro-meteorology*, **6**, 1, 1-8.

Rao, V. U. M., Bapuji Rao, B., Sarath Chandran, M. A., Vijaya Kumar, P. and Subba Rao, A. V. M., 2015, "All India Coordinated Research Project on Agrmeterology, Annual Report (2014-15)", Central Reserarch Institute for Dryland Agriculture, Hyderabad, p92.

Samra, J. S., Singh, G. and Ramakrishna, Y. S., 2004, "Cold wave during 2002-03 over North India and its effect on crops", The Hindu dated 10th January, 2004. p6.

Singh, K. K., Baxla, A. K., Chaudhary, J. L., Kaushik, S. and Akhilesh Gupta, 2005, "Exploring the possibility of second crop in Bastar Plateau region of Chhattishgarh using DSSAT crop simulation model", *Journal of Agrometeorology*, **7**, 2, 149-160.

Singh, K. K., Kalra, N., Mohanty, U. C. and Rathore, L. S., 1995, "Performance evaluation of medium range weather forecast using crop growth simulator", *J. Environmental Systems*, **25**, 4, 397-408.

Swain, D. K. and Yadav, A., 2009, "Simulating the impact of climate change on rice yield using CERES-Rice model", *Journal of Environmental Informatics*, **13**, 2, 104-110.

UNEP and C^4, 2002, "The Asian Brown Cloud: Climate and other Environmental Impacts UNEP", Nairobi.

Venkatraman, P., 2012, "Impact of Monsoon rains on the total food Grain production over India", Climate Change Research team, APEC Climate Symposium (APCS) 2012, St Petersburg, Russia.