

RICE YIELD PREDICTION USING CROP GROWTH SIMULATION AND AGROMETEOROLOGICAL MODELS IN GUJARAT

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ABSTRACT

Among the various production commodities of basic importance, agricultural production is the one which is subjected to wide and irregular fluctuations of output. The importance of timely and reliable prediction of yield of principal crops need to be emphasized for the country like India where, the economy is mainly dependent on rainfed agriculture.

Various yield prediction models are very much useful to the government agencies, trade and industry for planning about the distribution, storage, processing, and export/import of crop produce besides taking timely policy decisions on fixing levy prices as they provide accurate advance estimation of yields. Besides this, these models have facilitated identification of production constraints and for assisting in agro-technology transfer.

The present study was undertaken to predict the rice yield using crop simulation models and to develop an appropriate agrometeorological model for prediction of rice yield in Gujarat. Crop growth simulation models viz. DSSAT and WOFOST were calibrated and validated under Gujarat conditions. Suitable

agrometeorological model for predicting the yield of rice was also developed by using combined effects of different weather parameters viz. rainfall, bright sunshine hours, maximum and minimum temperature and morning and afternoon relative humidity on rice yield. For the present investigation the major rice growing districts of Gujarat viz., Ahmedabad, Baroda, Bulsar, Kheda, Panchmahal, Sabarkantha and Surat were considered.

The simulation results of DSSAT model for different districts revealed that the performance of the model for grain yield for all the districts was found highly significant with coefficient of determination values of 98.3% and 95.6% during the years 2004 and 2005 respectively.

Various test criteria were applied to validate the performance of the model. The simulation performance of grain yield was found better in 2004 than in 2005. The error per cent during the year 2004 was 9.9% and it was 10.3% in 2005. The average error as computed by MAE was 139.3 and 135.6 with 173.3 and 186.4 RMSE during 2004 and 2005 respectively. The respective MBE was found to be 89.0 and -94.7 and index of agreement was 0.98 and 0.97.

Sensitivity study of DSSAT revealed that 3°C elevation in mean ambient temperature decreased the yield by 4 to 41%. The 3°C down scaled ambient temperature increased the yield by 7 to 76%.

The solar radiation increase from 1 to 3 MJm⁻² day⁻¹ resulted in 2 to 26% yield increase. In case 3 MJm⁻² day⁻¹ reduction in solar radiation, 1 to 42% decrease in yield was observed.

Elevation of 300 ppm in CO₂ concentration over its base value increased yield by 4 to 29%.

The simulation results of WOFOST model simulation in both the years for different districts revealed that the simulated values of grain yield were found in perfect agreement with corresponding observed yield. Error per cent of WOFOST was 6.83% and 7.34% during 2004 and 2005 respectively. The coefficient of determination was 99.6% and 97.1%; MAE was 93.85 and 91.14, RMSE was 116.98 and 134.60 and MBE was found to be 50.14 and -66.57, respectively during the year 2004 and 2005.

Three approaches using original observed weather variables (1) weekwise, (2) stagewise and (3) periodwise average weather variables and two approaches using generated weather variables (1) week number as weight and (2) correlation coefficient as weight were used for fitting of the agrometeorological models. Approaches using shorter interval i.e. weekly weather variables either original or generated were found superior to the approaches using longer period averaged weather variables i.e. stagewise and periodwise approaches.

The results revealed that the effects of all the weather variables in relation to their quantum and direction differed over the approaches. However, they were found important for prediction point of view in rice productivity. The effect of weather variables also differed within the crop stage and period, indicating that small interval of crop period results in significantly higher R² value and thereby minimizes the error of predicting the rice yield. Different approaches were found superior over others in different districts.

In Ahmedabad district week number as weight approach provided suitable yield prediction model, eight week before expected harvest which explained > 75% variation in productivity. The 12 week model fitted with week number as weight approach is recommended as rice yield prediction model for Ahmedabad district

$$Y = 6304.22 + 3.80 RHE^1 - 0.69 RHM^2 + 0.26 (RF \cdot RHE)^0 - 2.37 (MINT \cdot RHE)^0 + 4.36 (MAXT \cdot RHM)^2 \quad (\text{Adjusted } R^2 = 90.6\%)$$

Weekwise approach provided suitable yield prediction model in Baroda district, 8 weeks before harvest which explained > 75% variability. The 12 week model fitted with weekwise approach is recommended as rice yield prediction model for Baroda district

$$Y = -5050.94 - 0.33 RF_2 + 19.06 BSS_6 + 37.45 RHM_9 - 42.51 BSS_{10} + 178.41 BSS_{11} + 24.46 RHM_{11} \quad (\text{Adjusted } R^2 = 99.4\%)$$

The 18 week model fitted with weekwise approach which provided earlier rice yield prediction (2 weeks before harvest) and explained > 75% variability is recommended as rice yield prediction model for Bulsar district

$$Y = 5788.42 - 23.63 BSS_3 - 0.15 RF_3 - 69.95 MAXT_5 + 59.49 MINT_5 - 86.85 BSS_6 + 106.21 BSS_7 + 2.47 RF_7 + 103.57 MAXT_8 - 33.49 BSS_9 + 25.88 BSS_{11} + 3.73 RF_{11} - 0.84 RF_{12} - 170.01 MAXT_{13} - 70.32 MINT_{13} - 106.46 BSS_{14} - 41.87 RHE_{14} + 0.60 RF_{16} + 41.80 RHM_{17} \quad (\text{Adjusted } R^2 = 99.8\%)$$

The 20 week model fitted with weekwise approach which explained > 75% variability is recommended as rice yield prediction model for Kheda district

$$Y = 8682.13 + 317.72 \text{ MINT}_{10} + 12.87 \text{ RHE}_{10} - 202.97 \text{ MINT}_{12} - 59.17 \text{ MAXT}_{18} - 79.21 \text{ BSS}_{19} - 32.92 \text{ RHM}_{19} \quad (\text{Adjusted } R^2 = 99.8\%)$$

The 12 week model fitted with weekwise approach which provided earlier prediction of the rice yield (8 weeks before harvest) and explained > 75% variability is recommended as rice yield prediction model for Panchmahal district

$$Y = 8881.23 - 105.44 \text{ BSS}_2 + 105.02 \text{ MAXT}_2 - 164.14 \text{ MINT}_2 - 8.90 \text{ RHE}_2 - 54.41 \text{ RHM}_7 + 2.78 \text{ RF}_8 - 80.16 \text{ MINT}_{10} \quad (\text{Adjusted } R^2 = 96.0\%)$$

The 14 week model which provided earlier prediction (6 weeks before harvest) and explained > 75% variability is recommended rice yield prediction model for Sabarkantha district

$$Y = -1075.72 + 37.25 \text{ RHM}_1 + 2.68 \text{ RHM}_3 + 8.99 \text{ RHE}_4 + 28.55 \text{ RHM}_5 - 34.24 \text{ RHM}_6 - 6.40 \text{ RHE}_{10} - 59.89 \text{ MAXT}_{11} + 68.84 \text{ MAXT}_{13} \quad (\text{Adjusted } R^2 = 99.8\%)$$

The 20 week model fitted with weekwise approach which explained > 75% variability is recommended as rice yield prediction model for Surat district

$$Y = 2851.46 + 72.40 \text{ MINT}_1 + 57.63 \text{ MAXT}_4 - 17.24 \text{ MAXT}_5 - 0.06 \text{ RF}_8 - 2.83 \text{ RHM}_9 - 1.38 \text{ RF}_{11} - 18.61 \text{ MINT}_{16} - 2.75 \text{ RF}_{18} - 1.66 \text{ RF}_{19} - 89.51 \text{ MAXT}_{20} - 6.24 \text{ RHE}_{20} \quad (\text{Adjusted } R^2 = 99.8\%)$$

The developed agrometeorological models were equally comparable to the crop growth simulation models viz. DSSAT and WOFOST in all the districts except in Baroda district where the performance of WOFOST and DSSAT respectively was found superior to the developed agrometeorological model.

The average performance of the models was adept in yield prediction for all the districts. The percent deviation for DSSAT was ± 0.9 to $\pm 9.9\%$, for WOFOST from ± 0.2 to ± 6.1 and for agrometeorological model it was ± 0.1 to $\pm 16.8\%$.

The developed agrometeorological models could efficiently predict the rice yield upto 8 weeks i.e. two months before the actual harvest of the crop with very high accuracy ($>90\%$). Thus these developed agrometeorological models can help the government and various other agencies to take appropriate steps in case of ensuing scarcity or glut situation.

The DSSAT and WOFOST also predicted the rice yield in reasonable limit with additional advantage to project yield fluctuation with reasonable accuracy in fluctuating weather particularly temperature, solar radiation and CO_2 concentration.

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CERTIFICATE

This is to certify that the thesis entitled **“Rice yield prediction using Crop Growth Simulation and Agrometeorological models in Gujarat”** submitted by **Shri Vikram Singh Chauhan** in partial fulfilment of the requirements for the degree of **Doctor of Philosophy in Agricultural Meteorology** of the Anand Agricultural University is a record of bonafide research work carried out by him under my guidance and supervision. The thesis has not previously formed the basis for the award of any degree, diploma or other similar title.

Place : Anand
Date :15-12-2007

(A.M. Shekh)
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**Rice yield prediction using Crop Growth
Simulation and Agrometeorological models in
Gujarat**

A
THESIS
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FOR THE AWARD OF THE DEGREE

OF

**DOCTOR OF PHILOSOPHY
IN
AGRICULTURAL METEOROLOGY**

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1. INTRODUCTION

1.1 PREAMBLE

Among the various production commodities of basic importance, agricultural production is the one which is subjected to wide and irregular fluctuations of output.

Indian economy is mainly based on agriculture. Growth rate for overall GDP of India during 2006-2007 is estimated 9.2% whereas for agriculture and allied sectors it is estimated 2.7% (Anon., 2007). India has made considerable progress in agriculture since independence in terms of production, productivity and area under cultivation with respect to many crops. The demand of any staple food is inelastic for long term whereas, supply of agricultural production for short term is elastic.

Rice is the staple food for over half of the world's population but its production faces many constraints under conditions of increasing world population and diminishing resources of water and land. On its own, the Food and Agriculture Organization (FAO) of the United Nations had declared 1966 the Year of Rice. The United Nations launched the International Year of Rice 2004 on 31 October 2003. This was the second time that the United Nations has paid such a special tribute to rice, the only food crop honoured twice. Rice is the single most important employment and income source for the rural poor. Besides being an essential food, rice is also an important factor in enriching culture, lifestyles,

and ecosystem functions. Rice is a symbol of cultural identity, global unity, and life (Toriyama *et al.*, 2005).

Rice is grown in more than 100 countries in the world. Asia contributes to about 90% of world rice production. It can grow at altitudes ranging from 10 feet below sea level to 10000 feet above sea level. The rice tribe *Oryzeae* consists of 12 genera and more than 70 species distributed in tropical and temperate regions worldwide (Ge *et al.*, 2005).

The genus *Oryza* has two cultivated and 22 wild species. Of the two cultivated species, *O. sativa* (2n=24 AA), commonly referred to as Asian rice, is grown worldwide, whereas *O. glaberrima* (2n=24 AA), “African rice,” is cultivated in a limited area in West Africa. (Brar, 2005)

Rice grown in Asia has two subspecies *Oryza sativa* L. subsp. *indica* and *Oryza sativa* L. subsp. *japonica*. Rice grown in India belongs to *Oryza sativa* L. subsp. *indica* (Sharma, 2003). Rice is a major food crop that is grown in dryland (or upland) conditions on mountain slopes as well as in wetland conditions in valley bottoms and in terraced fields. It is a subsistence crop for most farmers. (Pandey *et al.*, 2006).

Rice and rice-based products derived from rice grain and rice flour include parboiled rice; quick-cooking rice and ready-to-eat convenience foods; rice flours; rice starch; cakes and puddings; baked breads and crackers; breakfast cereals and expanded rice products; extrusion-cooked and puffed rice snacks; noodles, paper, and pasta; baby/weaning foods; fermented foods and beverages; pet foods; and bran products (Juliano, 2005).

Rice is processed and used as various kinds of foodstuffs besides direct food use, such as parboiled rice, fermented rice wine, rice noodles, rice crackers, rice cakes, rice snacks, rice flour, and other fermented rice products (Ohtsubo *et al.*, 2005).

1.2 AREA AND PRODUCTION

India ranked first in area and second in production over the world (FAO, 2007, IRRI, 2007). Among the major rice growing states, Gujarat ranked 15th in area (0.66 million hectare) as well as in production (1.73 million ton) and 11th in productivity (2.61 t/ha) (IRRI, 2007). Rice in Gujarat is mainly grown in seven districts. These districts are Ahmedabad, Baroda, Bulsar, Kheda, Panchmahal, Sabarkantha and Surat.

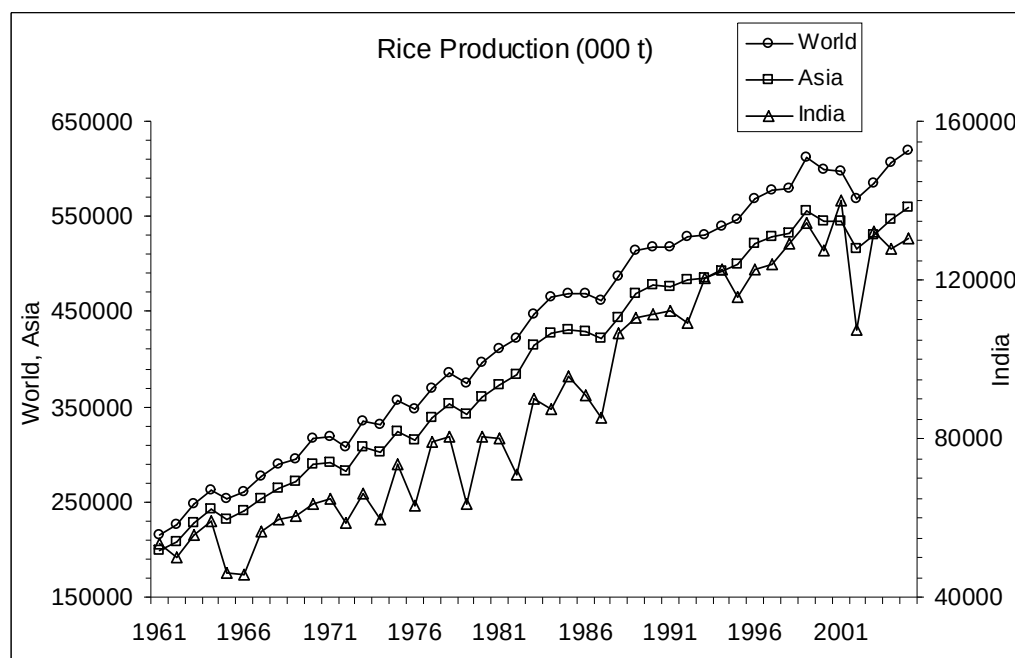


Fig. 1.1: Rice production of world, Asia and India (IRRI, 2007)

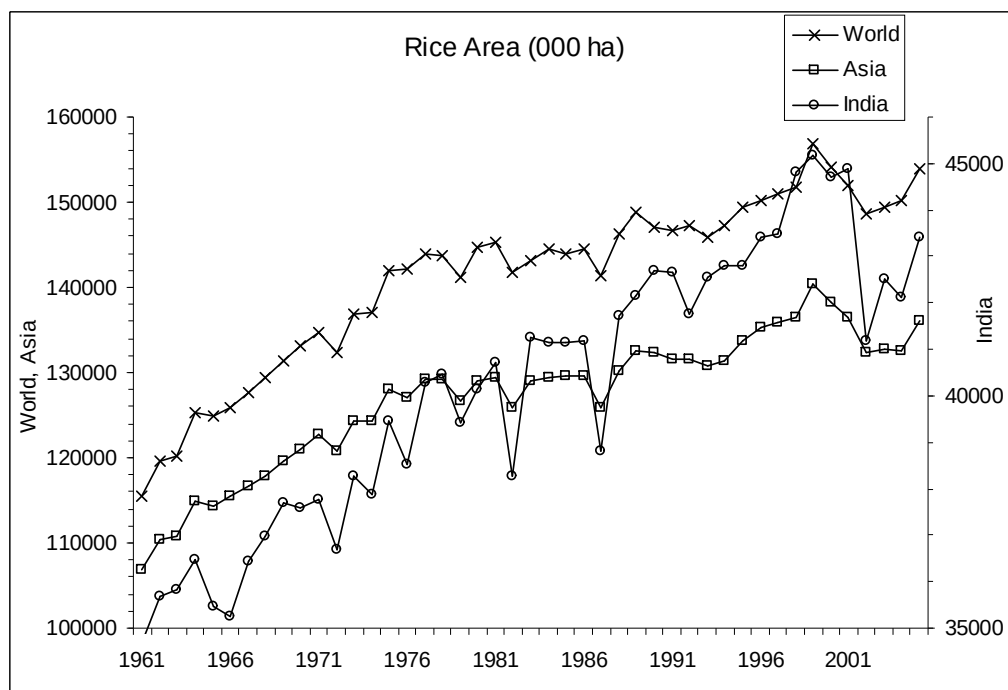


Fig. 1.2: Rice area of world, Asia and India (IRRI, 2007)

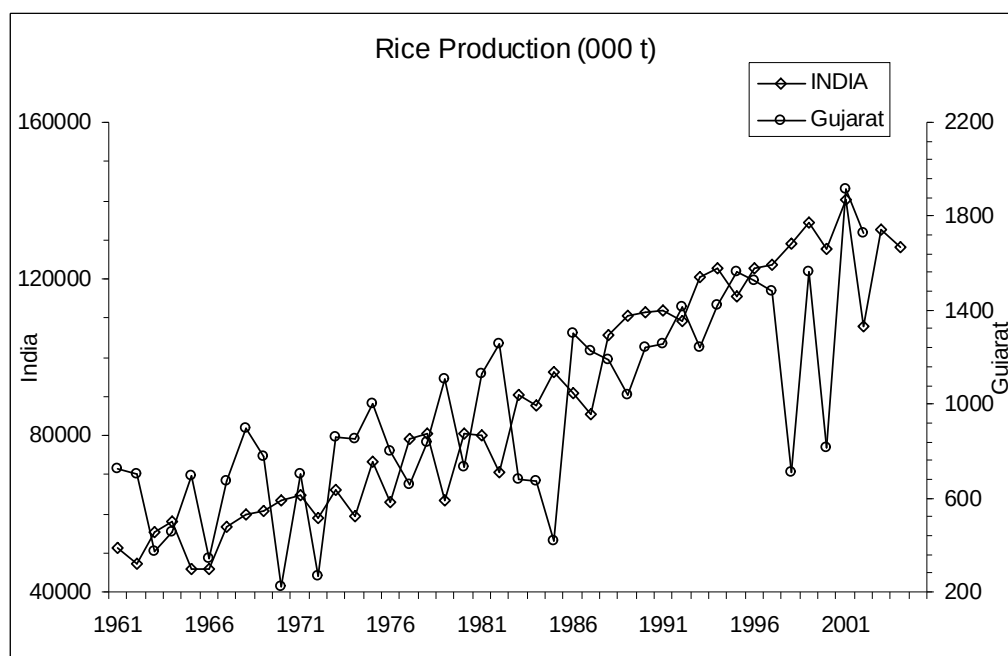


Fig. 1.3: Rice production of India and Gujarat (IRRI, 2007)

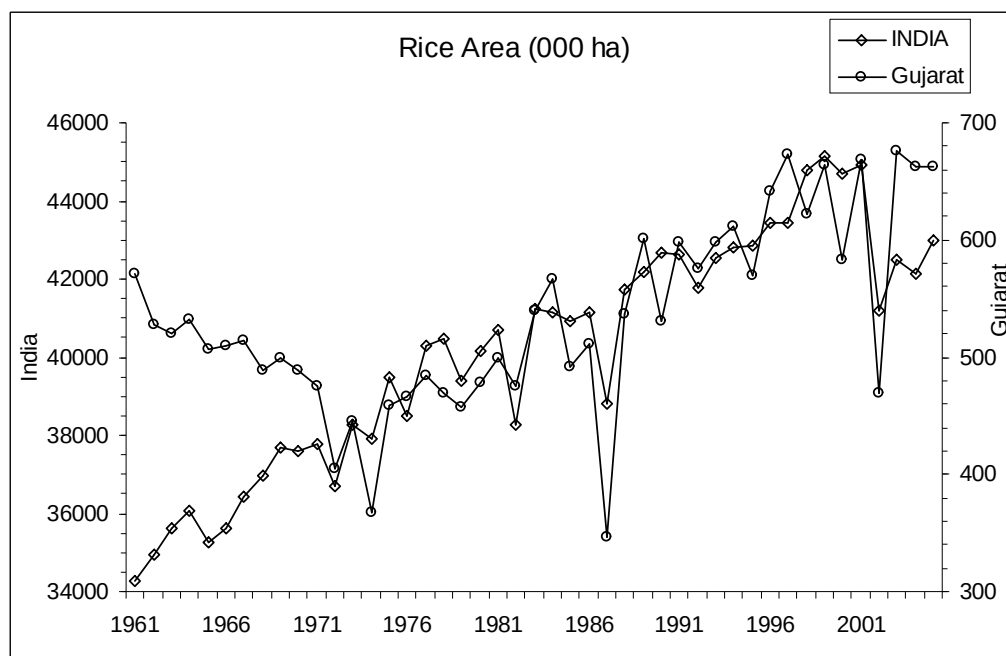


Fig. 1.4: Rice area of India and Gujarat (IRRI, 2007)

Rice production increased with time, this might be due to technological advances and more efficient use of inputs coupled with increased area under cultivation. Still there are few downfalls which clearly states that prevailing weather has significant effect on yield of rice. The rice is a staple food and continuous supply is to be maintained to the consumers. To ensure regular supply of the foodgrain proper steps are required to be taken in advance. If supply is not maintained uninterrupted than there are chances of a large number of human population drowning in perpetual hunger. About 1 billion households depend on rice cultivation for employment and their main source of livelihood. As the rice consuming population continues to grow, and the land and water resources needed for rice production diminish, we may face a potential crisis. World rice production has been less than rice

consumption since 2000. This insufficiency has been addressed by drawing on rice from buffer stock. In this context, advances in science and technology, as well as rice research, are increasingly critical to enhance rice production and sustainable agricultural development. Ensuring an increase in sustainable rice production will require innovation and cooperation within the scientific community, as well as commitment and shared responsibility among all stakeholders (Toriyama *et al.*, 2005).

1.3 WEATHER INFLUENCE ON RICE YIELD

Rice can be grown as a transplanted or direct sown crop during kharif season depending on the availability of water if other environmental conditions are not limiting. High rainfall, low radiation and high pest incidence are detrimental to high crop production (Chatterjee and Mandal, 1988). The crop development from sowing/ transplanting to harvest responds to environmental fluctuations that are predominantly weather induced. The important weather variables which drive crop growth and its development are rainfall, solar radiation, vapour pressure deficit and maximum and minimum temperatures. The effects of these weather elements on crop development finally decides rice production (Rao, 2003). The individual effect of different weather parameters is outlined below

1.3.1 SOLAR RADIATION

The intensity of solar radiation has a profound influence on rice yield. Its role in photosynthesis, photoperiodism and photonasty are well known. The amount of solar radiation received during the period of 45 days before the harvest

is important on which the final crop yield depends. The grain weight per spikelet can be improved if the solar radiation is optimum during maturity (Rao, 2003).

Increase in radiation up to $500 \text{ cal cm}^{-2} \text{ d}^{-1}$ increases spikelets number (Yoshida and Parao, 1976), which is an important indicator of dry weight at heading. Solar radiation in the range of 300 to $600 \text{ cal cm}^{-2} \text{ d}^{-1}$ in the post-flowering period is positively related to number of filled grains per panicle. Solar radiation in the ripening phase influences both the percentage of well-filled grains and weight per grain. For equivalent yields the radiation requirement in the ripening phase is lower than that of the reproductive phase as (i) the drymatter produced in the ripening phase is lesser than that at the start of the ripening phase (ii) substantial portion of photosynthates formed in the reproductive phase is used in grain yield and (iii) when photosynthesis gets restricted in the ripening phase about 70% of the stored carbohydrates at the start of the phase are translocated to grain. A cumulative solar radiation of $14000 \text{ cal cm}^{-2}$ in the ripening phase preceded by 6 to 7 hours of bright sunshine per day in the reproductive phase is optimum for rice grain yield. Reduction in solar radiation will lead to an equivalent reduction in rice yields (Venkataraman *et al.*, 2007).

1.3.2 RAINFALL

Based on premonsoon and monsoon rainfall, 37% of yield variability can be explained during kharif season in case of the rice crop. Premonsoon rainfall determines the germination and survival of seedlings. If premonsoon rainfall is inadequate or erratic, germination and survival of seedlings are doubtful and crop suffers heavy loss initially which leads to poor grain yield. The wet spells are

detrimental from flowering to maturity (Rao, 2003). Considering the percolation and consumptive use needs of puddled rice an amount of 50 mm of rain per week would be needed by an established, rainfed transplanted rice. Moisture stress in the vegetative stage reduces plant height, tiller number and leaf area but the crop can recover without much loss in yield if moisture adequacy is restored before flowering. Rice is most sensitive to moisture stress in the reduction division stage (Panicle initiation to flowering) that leads to high spikelet sterility. The yield reduction due to submergence is two times higher under muddy than clear water. Panicle formation stage and ripening phase are the most and least vulnerable to submergence (Venkataraman *et al.*, 2007).

1.3.3 TEMPERATURE

Temperature influences the growth, development and yield of rice. The three cardinal temperature points for rice are: Minimum 10 °C, Optimum 30 °C and Maximum 38 °C. Rice generally requires high temperatures above 20 °C but not above 35 – 40 °C. The optimum temperature is near 30 °C for the maximum and near 20 °C for the minimum. The crop duration varies with the maximum temperature. If the maximum temperature is high, the number of days required for crop maturity is proportionally less (Rao, 2003).

For delineating specific time-periods suitable for maximal production of rice at a given location it is necessary to know the cardinal (high, low and optimal) temperature requirements of various rice growth stages. From the literature cited by Venkataraman *et al.*, (2007) the low, high and optimal temperatures requirements of important rice growth stages are given below in Table 1.1:

Table 1.1: Cardinal temperature requirements of various rice growth stages

Growth Stage	Cardinal Temperatures(°C)		
	Low	High	Optimum
Germination	10	45	20 to 35
Emergence & Establishment	12	35	25 to 30
Transplanting	> 18	-	-
Rooting	16	35	25 to 28
Leaf Emergence & Elongation	7	45	30 to 31
Tillering	16	33	25 to 31
Flower Initiation	15	-	24 to 29
Anthesis	22	35	30 to 33
Ripening	12	30	20 to 25
Fertility	14	38	-

1.3.4 RELATIVE HUMIDTY

Rice is subjected to unusual stresses due to continuous high water vapour content in the atmosphere during the crop season. Such humid conditions are favourable for the development and spread of many fungal and bacterial diseases. It is also conducive for various crop insect pests (Rao, 2003).

Flowering in rice is best when RH is 70 to 80%, RH below 40% inhibit flowering. RH of 60% lead to faster senescence of leaves. Increasing RH increases stomatal aperture and lead to higher photosynthesis irrespective of the solar radiation regime (Venkataraman *et al.*, 2007).

1.4 RICE YIELD PREDICTION

The importance of timely and reliable prediction of yield of principal crops need to be over-emphasized for the country like India where, the economy is mainly based on agricultural production. The pre-harvest estimates of crop yields are considered mainly as an aid to conjecture the final production and therefore, sufficient attention needs to be paid towards their prediction. Pre-harvest yield

forecasts can help in taking policy decisions with greater confidence in the food procurement and distribution, price policies, export-import policies and for exercising several administrative measures for storage and marketing of agricultural commodities.

Frequently there is a time lag between awareness of an important event or need and occurrence of that event. This lead time is the main reason for planning and forecasting. In management and administrative situations the need for planning is of great importance because the lead time for decision taking ranges from several years to a few days. Forecasting is an important aid in effective and efficient planning. A wide variety of forecasting methods are available. These range from the most naïve methods, such as use of the most recent observation as a forecast, to highly complex approaches such as neural networks and econometric systems of simultaneous equations (Makridakis *et al.*, 2003).

There are broadly three approaches that are used for forecasting the crop yields (Singh *et al.*, 1976). They are,

I. Based on weather data

II. Based on biometrical characters

III. Based on eye observations on the growing crop

These approaches are complementary to one another and may be combined. The last two approaches, utilizes information collected over space by sample survey in the year for which the forecast is to be made. This naturally involves, time and money. Moreover the eye observations are subjective in nature and thus result in biased forecasts. In case of weather variables, the historical data of crop yields and weather are utilized to study crop weather relationship and the forecast

based on such relationship is objective in nature and do not require survey. Hence different types of models are used for forecasting depending upon the objective of forecast and availability of data.

1.5 MODEL

Model may be defined as a functional relationship between dependent observable plant response such as weight, height, number of leaves etc. and the pertinent variable influencing the plant (Walker and Splinter, 1971). Crop model can also be defined as a quantitative scheme to predict the growth, development and yield of a crop, given a set of genetic coefficients and relevant environmental variables. It is a simplified representation of the system, usually in mathematical or computable form.

A model is a schematic representation of the conception of a system or an act of mimicry or a set of equations, which represents the behaviour of a system. Also, a model is “A representation of an object, system or idea in some form other than that of the entity itself”. Its purpose is usually to aid in explaining, understanding or improving performance of a system. A model is, by definition “A simplified version of a part of reality, not a one to one copy”. This simplification makes models useful because it offers a comprehensive description of a problem situation. However, the simplification is, at the same time, the greatest drawback of the process. It is a difficult task to produce a comprehensible, operational representation of a part of reality, which grasps the essential elements and mechanisms of that real world system and even more

demanding, when the complex systems encountered in environmental management (Murthy, 2005).

Methods of predicting crop yields range from statistical approaches to crop simulation models. Despite several classifications put forth by the research workers, it is more convenient to categorize the crop models broadly into two categories viz. empirical/ regression models and simulation models (Patel, 2004).

1.5.1 CROP SIMULATION MODEL

A crop simulation model is a computer model used to simulate reality. These models are designed to predict the effect of a future land use scenario on a suite of plant indicators (growth, yield, productivity, etc.). Crop simulation models are state of the art technology that allows a user to estimate crop growth and yield as a function of weather conditions and management scenarios. Crop simulation models are able to provide an answer for "if then" type of questions. These models are used as the basis for decisions. Various crop simulation models are used nowadays viz. DSSAT (Decision Support System for Agrotechnology Transfer), WOFOST (WOld FOod STudy), WTGROWS (WheaT GROWth Simulator), INFOCROP (INFOrmation on CROP), BACROS (BASic CROp growth Simulator), CROPSYS (CROP SYStems), SUCROS (Simple and Universal CROp growth Simulator), SWAP (Soil Water Atmosphere Plant), etc.

The simulation models could be used for identifying crop production constraints under field conditions in different agroclimatic zones. These models could be a substitute to multilocational field trials for introducing a variety in different agroclimatic zones and thus saving time and money. Hence crop

simulation modelling is felt necessary for maximising the agricultural production through better crop management practices. The tools required for running a crop simulation model are the software for the crop chosen and a PC/AT with knowledge in computers (Rao, 2003).

Two models viz. DSSAT and WOFOST were used for the present study. These models are widely used by various researchers for more than 15 and 10 years respectively. Brief detail about them is given below.

1.5.1.1 DSSAT

Decision Support System for Agrotechnology Transfer (DSSAT) documented by Jones *et al.*, (2003) provides easy access to data bases and crop models so that the user may "test" on screen the performance of new cultivars, sites, or management practices. This system allows user to screen new technology packages, such as a new cultivar or fertilizer management strategy, without spending excess time on expensive, time consuming field trials. By simulating outcomes of strategies on the computer screen, user can ask "what if" questions and explore the options on screen. Sustainable agriculture requires tools that enable decision makers to explore the future.

DSSAT was designed primarily for user groups in agriculture, but owing to its break with traditional ways of diagnosing and prescribing solutions, it has been adopted by other types of users. The emergence of issues which require assessment of conditions not in the past or present, but in the future calls for the systems approach to problem solving encompassed by DSSAT, which includes:

Global climate studies, Use with geographic information systems, Whole-farm system models, Pest-crop interaction models, Fertilizer strategies, Plant breeding.

The model requires daily weather data of air temperature, irradiation and rainfall to simulate crop yield.

1.5.1.2 WOFOST

World Food Study (WOFOST) is a member of the family of models developed in Wageningen by the school of C.T. de Wit and documented by Boogaard *et al.*, (1998). WOFOST was originally developed as a crop growth simulation model for the assessment of the yield potential of various annual crops in tropical countries.

WOFOST has been applied as a tool for the analysis of yield risk and interannual yield variability, of yield variability over soil types, or over a range of agrohydrological conditions, of differences among cultivars, of relative importance of growth determining factors, of sowing strategies, effects of climate change and critical periods for use of agricultural machinery. The model has also been used for predictive purposes, in quantitative land evaluation, such as regional assessments of crop yield potential in the form of maximum yield levels, estimation of maximum benefits from irrigation or from fertilizer use, detection of adverse growing conditions by simulation-monitoring the agricultural season, and regional yield forecasts.

The model requires daily weather data of air temperature, irradiation, vapour pressure and rainfall to simulate crop yield. The model can also be run using monthly climatic normal data.

1.5.2 AGROMETEOROLOGICAL MODEL

Crop growth is often described by an empirical model, consisting of a regression equation. Sometimes, environmental variables, such as radiation and rainfall, are incorporated in the regression. These models can generate accurate yield predictions, especially when the regression parameters are estimated on the basis of extensive sets of experimental data. These predictions are restricted to the environment on which the regression is based. (Diepen *et al.*, 1989).

Various agro-meteorologically based models are generally crop-weather relationship models which may be defined as a simplified representation of the complex relationship between weather or climate and crop performance (such as growth, occurrence of phenological events, yield or yield components) using established mathematical and/or statistical techniques (Baier, 1977). Generally, multiple and stepwise regression techniques are employed using more than one variable. Apart from meteorological variables, other variables such as soil characteristics, biometric observation, growth indices, derived meteorological parameters (e.g. available soil moisture, actual evapotranspiration, water stress indices and temperature based indices) and a technological trend have been correlated with crop yields. Statistical models for simulating yield as a function of important climatic variables such as rainfall were started since Fisher's (1924) work. Later numerous studies were carried out to use crop-weather relationships for the development and applications of crop-weather models suitable for monitoring and predicting crop yields.

India Meteorological Department (IMD) has developed many crop-weather models at operational and experimental level (Das *et al.*, 1971; Chowdhary and Sarwade, 1985; Sarwade, 1988). For operational purpose, they used 20 to 50 years district yields as dependent variables whereas daily values of meteorological parameters like rainfall, temperature, cloud cover, relative humidity etc. were used as independent variables. In addition, derived parameters like rainy days, radiation, mean temperature, soil moisture, evapotranspiration, moisture index, generalized monsoon index etc. were also used.

Use of models which give accurate predictions of productivity help government/ authority to procure food grains in the surplus area to maintain price stability and plan its distribution patterns during the preharvest period in areas where low productivity was anticipated (Hamid, 1993).

The combination of natural resources, genes, weather and management systems largely determines maximum crop yields (Sheehy *et al.*, 2004).

Crop growth, development and yield are affected by climatic, edaphic, hydrologic, biotic, agronomic and socioeconomic factors. Analysing the effects of some specific factors without consideration of interactions and feedbacks from other controlling elements can often be misleading. Progress in crop modelling in India has been constrained in past due to lack of trained manpower, difficulty in 'calibrating' available models and accessibility to soil and weather databases (Aggarwal, 2002).

1.6 ROLE OF WEATHER IN DECISION MAKING

Weather is a major factor affecting crop production in advanced agricultural systems. Weather is a primary determinant of agricultural production. There are many weather variables like rainfall, temperature, relative humidity, wind speed and sunshine hours that constitute the major climatic influence contributing to the growth and development of the crop directly or indirectly. The resultant response is manifested in the final yield. Other factors which are not related to weather are variation in seed, fertilizer application, cultural practices and management techniques. They are summed up as effects of technological advances. These effects are also of paramount importance in the crop productivity.

The variable weather conditions discourage farmers from using modern inputs (Pal, 1979). The paddy crop is highly sensitive to weather risk under the given soil/crop complex (Awasthi *et al.*, 1987). High rainfall, low radiation and high pest incidence are detrimental to high crop production (Chatterjee and Mandal, 1988). The degree of vulnerability of crops to climate variability depends mainly on the development stage of the crops at the time of weather aberration (Lansigan *et al.*, 2000).

As with all crops, climatological factors such as temperature, precipitation, solar radiation (intensity, photoperiod, and quality), and wind are important in influencing rice production. While these and many other factors influence yield, the close association between yearly/seasonal weather and yield has often been noted.

Decisions based solely upon mean climatic data are likely to be of limited use for at least two reasons. The first is concerned with definition of success and the second with averaging and time scale. In planning and analyzing agricultural systems it is essential not only to consider variability, but also to think of it in terms directly relevant to components of the system. The principal effects of weather on crop growth and development are not well understood and need investigation. Crop simulation models can predict responses to large variations in weather with certain degree of accuracy. At every point of application weather data are the most important input. The main goal of most applications of crop models is to predict commercial output (Murthy, 2005).

Since little work has been reported regarding rice yield prediction in Gujarat, therefore, the present study was undertaken with a view to predict the rice yield using crop simulation models and develop appropriate agrometeorological model for prediction of rice yield in Gujarat. The specific objectives of present study were,

- (1) To calibrate DSSAT and WOFOST models for Gujarat
- (2) To validate DSSAT and WOFOST models for Gujarat
- (3) To explore the possibility of developing appropriate agrometeorological model for rice yield prediction in Gujarat.

2. REVIEW OF LITERATURE

Several studies have been carried out in the past in India and abroad on crop weather relationship using different approaches to predict crop yield.

Reliable and timely prediction provides important and useful input for proper, foresighted and informed planning in agriculture which is full of uncertainties. Agriculture, now a days has become highly input and cost intensive. Under the changed scenario today, forecasting of various aspects relating to agriculture are becoming essential. But in spite of strong need for reliable and timely prediction, the current status is far from satisfactory. For most of the sectors, there is no organised system of prediction. The official predictions/forecasts (advance estimates) of major cereal and commercial crops are issued by Directorate of Economics and Statistics. Prediction of crop production before harvest is required for various policy decisions relation to storage, distribution, pricing, marketing, import-export, etc. The advance estimates provided by Directorate of Economics and Statistics are subjective. Thus, there is a need to develop sound objective forecasts of crop production (Aggarwal, 2002).

The review is divided in two parts

2.1 Review of work related to Crop Growth Simulation Modelling

2.2 Review of work related to Agrometeorological Modelling

2.1 Review of work related to Crop Growth Simulation Modelling

Crop growth simulation models are a combination of mathematical equations and logic used to conceptually present a simplified crop production

system. With the advancement in understanding of the processes involved in crop production the crop growth simulation models are used for solving problems particularly yield prediction. Well known concepts viz. thermal time to predict plant development, radiation interception to predict mass accumulation for a population of plants, potential evaporation to predict plant and soil evaporation, and radiation use efficiency for predicting dry matter production, grain yield and transpiration relations have laid sound basis for development of crop simulation models (Shekh *et al.*, 1999).

Crop growth simulation modelling aims at simulation of day to day assimilation of photosynthetic material, based primarily on the exchange of energy and mass among the various growth processes taking place in a plant.

Crop growth simulation models are useful tool to quantify the environment limits to crop production. Their application minimise the requirement for costly inputs and lengthy experimentation. Crop growth simulation models are useful in defining research priorities, technology transfer, estimating production potential, strategic and tactical decisions and for predicting the effects of climatic change and climatic variability. A detailed and realistic prediction is possible by simulation models, provided that day-wise and precise weather data are available (Ramasamy, 2000).

McMennamy (1980a, 1980b) developed a simple RICE production MODEL (**RICEMOD**), responsive to daily weather parameters and based on selected functional relationships found in rice for dynamic simulation of irrigated rice crop growth and yield. RICEMOD is an ecophysiological model for irrigated rice

production. It includes a number of physical parameters, including accommodation of subroutines dealing with soil and plant chemistry as well as physical processes of the atmospheric environment. The model is very sensitive to soil parameters and has been expanded to consider soil water deficit. Model components include maximum leaf area index, timings of plant growth initiation and harvest, radiation-use efficiency (RUE), and harvest index (HI). He suggested that only reasonably accurate results could be expected using daily rather than hourly weather data for forecasting of irrigated rice crop growth and yield in Philippines.

Whisler (1983) carried out sensitivity tests of the environmental variables in rice crop simulation model **RICEMOD** for sensitivity to the input environmental variables at IRRI, Philippines. They reported that the model was most sensitive to the climatic variables of day length, solar radiation, pan evaporation, and a factor relating pan evaporation to daily plant transpiration, and least sensitive to maximum and minimum temperature and rainfall.

Lin (1988) calibrated and validated Crop Environment Resource Synthesis (CERES) **CERES-Rice** simulation model at Honolulu. He reported that high day and night temperature hastened maturation, resulted in lower filled grain percentage, 1000 grain weight and grain yield. He also reported that the model adequately predicted phenological development and final biomass for a wide range of environments and it was sensitive to seasonal variation and altitude and could mimic the high sensitivity of rice to temperature and solar radiation.

Sadasivam *et al.*, (1989) conducted productivity studies on 6 lowland varieties at Coimbatore using the Modules of an Annual CROp Simulator (**MACROS**) simulation model devised by IRRI, which takes into account dry matter accumulation, physiological characteristics and weather conditions. They stated that yield production can be reasonably estimated on varietal physiological characteristics and weather conditions. They reported that the calculated and measured grain yield agreed satisfactorily (within 10%).

Herrera *et al.*, (1990) used **MACROS** model to simulate physiological and physical processes by which meteorological variables affect the growth, development and production of rice in Phillipines. They reported that weather conditions during the reproductive phase of development significantly affect grain yield.

Jansen (1990) studied the effects of future climate change on potential yields of rice cv. IR36 grown at present and in 2020 and 2100 in China, India, Indonesia, Thailand and South Korea were estimated using the crop growth simulation model **MACROS** which combines the effects of temperature, radiation, wind speed, air humidity and crop status on physiological processes. Historic weather data of these sites were adapted to possible changes in temperature and CO₂ level, to mimic climate change. They reported that simulated yields rose in low and middle temperature change scenarios, but decreased in the high temperature scenario. Water use efficiency decreased in the high temperature scenario irrespective of CO₂ scenario, and increased otherwise.

A dynamic model for simulating rice growth and yield in relation to weather and climate (**SIMRIW**) was developed and used by Horie (1991) in Japan. The model does not predict actual yield, but gives potential yield that may be expected under a given climate from the physiology of a given cultivar grown under optimal conditions. He reported that there was close correlation between predicted and actual grain yields.

Matthews *et al.*, (1995) used an ecophysiological model for irrigated rice production (**ORYZA1**) for modeling the impact of climate change on rice production in 11 countries of Asia. They found negative effect of temperature increase on rice yields. They reported that temperature increases of 1, 2, and 4 °C decreased yields by 6.7, 14.1 and 29.4%, respectively.

Singh and Padilla (1995) used **CERES-rice** for simulating rice response to climate change in Philippines. They reported that high temperature induced spikelet sterility, and longer growth duration, particularly longer grain filling duration. They suggested that with improved varieties and good management, climate change could have positive effects on rice production.

Rao and Subash (1996) used **CERES-Rice** model to assess potential yield of rice at Pilicode. They simulated rice yield for both *kharif* and *rabi* seasons. They reported that simulated and actual yields agreed well in the 1993, while simulated yield was higher than that observed during 1994.

Mahmood (1997) used a physically based parametric model (**YIELD**) to study the impacts of air temperature variations on the *boro* rice phenology in Bangladesh. Model applications showed that an increase in air temperature

provides longer and more stable thermal conditions for *boro* rice maturing stage. The planting date plays an important role in the *boro* rice phenology. This effect was most noticeable during initial growth stages. A non-linear relationship was found between decreasing air temperature and the length of the initial growth stage and a predominantly linear relationship was found with other growth stages. Model applications showed that an increase in air temperature provides longer and more stable thermal conditions for *boro* rice maturing stage. A 5% increase and a 4% decrease in seasonal total evapotranspiration occurs under each 1 °C cooler and warmer air temperature conditions, respectively. Furthermore, variations in the percent of time required for the completion of different growth stages under various air temperature conditions will demand a reorganization of irrigation schedules.

Mahmood (1998) used **YIELD** and **CERES-Rice** models to estimate *boro* rice productivity under normal and abnormal climate scenarios in Bangladesh. *Boro* rice productivity at Mymensingh predicted by YIELD was higher than the prediction by CERES-Rice. Productivity estimates for *Barisal* by these two models were almost identical. Assumptions of non-identical management practices, different soil characterization procedures, different methods for calculation of dry matter production by these two models and the range of diurnal temperature variations played an important role in productivity estimates. The YIELD model predicted shorter lengths of the growing season under normal and abnormal thermal climate conditions than the lengths predicted by the CERES-Rice model, due to the YIELD model's assumption of higher threshold

temperature and a relatively simple relationship between phenology and air temperature. He pointed that the complex data required by CERES-Rice were an impediment for its extensive use. He further reported that in absence of input data for the CERES-Rice, the YIELD model could be considered as a possible tool for various applications in crop-environment relationships

Saseendran *et al.*, (1998) used CERES-Rice and ClimProb for determining the optimum transplanting dates for rice in Kerala. Optimal transplanting dates were derived based on two approaches: (i) probabilities of rainfall events using ClimProb, a PC-based software package, and (ii) target yields simulated by the CERES-Rice crop growth simulation model. They reported that the under rainfed conditions optimum transplanting dates were from the 23rd to 26th week for multiple cropping in a year, and from the 26th to 32nd week for a rainfed monocrop.

An experiment was conducted to study the effect of photoperiod on interval between panicle initiation and flowering in rice using CERES-Rice model in Netherlands by Yin and Kropff (1998). In a greenhouse experiment, plants of 12 rice (*Oryza sativa*) cultivars were grown under three short-day (SD) conditions (10, 11 or 12 h day⁻¹) or under three long-day (LD) conditions (13, 14 or 15 h day⁻¹) until panicle initiation (PI), after which half of the plants at SD were transferred to a 3-h longer photoperiod and half of the plants at LD were moved to a 3-h shorter photoperiod. Duration from PI to flowering was positively correlated with the photoperiod experienced after PI; the effect of a 3-h change in photoperiod varied from negligible in some cases to more than 10 days in others. No

consistent carryover effect of photoperiod before PI on the PI-to-flowering duration was detected. As expected, the total main-culm leaf number was influenced by photoperiod before PI, but not thereafter. Although the leaf number varied greatly both among cultivars and among pre-PI photoperiods, the number of unexpanded leaves at PI was nearly constant, with an average of about three leaves. They pointed towards the inadequacy of the assumption in crop simulation model CERES-Rice that the panicle initiation to flowering duration was influenced only by a carryover effect of pre panicle initiation photoperiod.

The agronomic evaluation was carried out by Hundal and Kaur (1999) at Ludhiana through CERES-Rice model. The effects of various dates of transplanting, age of seedlings at transplanting, number of seedlings hill⁻¹ and plant population on rice (cv. PR-106) yields were simulated. The simulation results showed that the optimum date of transplanting for rice was 15 June. However, earlier transplanted (1 June) rice performed better when seedling age was reduced from 40 to 30 days. Young seedlings (20- and 30- days old), irrespective of date of transplanting, proved better than older (40 days) seedlings, when other variables were kept constant. An increase in plant population from 11 to 44 hills m⁻² and an increase in number of seedlings hill⁻¹ from 1 to 6, showed an increasing trend in rice yields as simulated by the model.

Casanova *et al.*, (2000) tested the performance of an explanatory model ORYZA1 for rice growth simulation for Mediterranean conditions at Nicaragua. The model was calibrated and validated with field data for a short-grain (cv. Tebre) and a long-grain rice cultivar (L-202) grown in 1994-96 in the Ebro Delta

of Spain. Phenological development, daily dry matter production and leaf area development were calibrated. There were no significant differences between the cultivars for the total length of the growth period. However, the pre-heading period was longer and the post-heading period shorter in L-202 than in Tebre. This resulted in differences in translocation characteristics, spikelet number per unit area, weight of the grains and harvest index. The crop characteristics viz. extinction coefficient, dynamics of nitrogen distribution, partitioning of assimilates, relative death rate of leaves, relative growth rate of leaf area during exponential growth, specific leaf area and specific stem green area were similar in the 2 cultivars. The simulated curve fitted the observations much better when leaf area index was considered as comprising the leaf blade area only, without a photosynthetic contribution by the stem green area. The model simulated rice growth very accurately until flowering. After flowering, however, divergences appeared and increased especially at the yellow ripe stage. This reduction of growth rate was usually accompanied by an increase in the relative death rate of leaves and the drying of the grains. They reported that the main source of error might be a limited understanding of the ripening and sink limitation processes. A considerable yield gap between potential and observed yield remained. A climatic variability assessment over 10 years showed a small but correlated variation in both simulated and measured rice yields.

Mathauda *et al.*, (2000) applied **CERES-Rice** in determining rice crop responses (yield attributes) to temperature variations, as indications of the potential effects of projected climatic changes on food production in Punjab. They

reported that global warming would have adverse effects on rice production through advancement of maturity, reduction of source size, and poor sink strength.

Ramasamy (2000) used **ORYZA1** model to determine the yield potential of the standard rice cultivar, cv. IR 72, throughout India utilising historical mean weather data. The potential grain yields varied from 9.34 to 13.98 t/ha between 9° 08' and 31° 25'N latitude. The potential yield of rice increased with increasing latitude (9° to 23° N) and elevation (0 to 900 m above sea level). Growth duration varied from 100 to 146 days depending on geographical location. Suitable sowing times varied from all 12 months in the South to a short period of only 4 months in the North. Optimum time of sowing for most of the locations in India was worked out to be on 15 June. This study suggests that a detailed and realistic prediction is possible by simulation models, provided that day-wise and precise weather data are available.

Saseendran *et al.*, (2000) studied the effects of climate change on rice production in the tropical humid climate of Kerala using **CERES-Rice**. The temperature sensitivity experiments showed that for a positive change in temperature there was a continuous decline in the yield. For every one degree increment the decline in yield was about 6%. Rainfall sensitivity experiments showed that increase in rice yield due to increase in rainfall above the observed values was near exponential. Decrease in rainfall resulted in yield loss at a constant rate of about 8% per 2 mm/day, up to about 16 mm/day.

Aggarwal and Mall (2002) compared two popular rice growth models, **CERES-Rice** and **ORYZA1N** for climate change and rice yields in diverse agro-environments of India. The results showed that the direct effect of climate change on rice crops in different agroclimatic regions in India would always be positive irrespective of the various uncertainties. Rice yields increased between 1.0 and 16.8% in pessimistic scenarios of climate change depending upon the level of management and model used. These increases were between 3.5 and 33.8% in optimistic scenarios. At current and improved levels of management, southern and western parts of India, which had relatively lower temperatures compared to northern and eastern regions showed greater sensitivity in rice yields under climate change. The response to climate change was small at low N management compared to optimum management. The magnitude of this impact could be biased up to 32% depending on the uncertainty in climate change scenario, level of management and crop model used. These conclusions were highly dependent on the specific thresholds of phenology and photosynthesis to change in temperature used in the models. They concluded that caution was needed in using the impact assessment results made with the average simulated grain yields and mean changes in climatic parameters.

Mall and Aggarwal (2002) compared two popular rice growth models, **CERES-Rice** and **ORYZA1N** for climate change and rice yields in diverse agro-environments of India. A dataset of 32 experiments consisting of 98 treatments was assembled. These experiments were conducted over the period of 1980-1993 in diverse Indian locations from 11 to 33°N. The treatments varied in N

management, sowing dates, cultivars and seasons. The flowering duration in the dataset varied between 37 and 86 days and grain yields between 2587 and 8877 kg ha⁻¹. Seven treatments from this dataset, one for each cultivar, were selected for calibration. The genetic coefficients of different cultivars used in the analysis for both models were estimated from this short-listed dataset by repeated iterations until a close match between simulated and observed phenology and yield was obtained in these treatments. Similarly, 11 treatments with zero or low N applications were used for calibration of initial soil N for different locations. The remaining 80 treatments were used for validation of the models. Both models predicted satisfactorily the trends of leaf area and dry matter growth, grain number, days to flowering and grain yields. Simulated yields were within +15% of the measurements. Considering that the field measurements also generally have 10-15% error and that the treatments widely varied in weather conditions, particularly in temperature, it was concluded that both models were adequate to simulate the effects of climate change on rice yields in diverse agro-environments of India that were free from all pests

Gaouna *et al.*, (2003) used **FAO-CROPWAT** model to estimate crop water requirement (CWR), soil moisture deficit (SMD) and yield reduction in a study area in southern Chad during February-July 2002. Spatially distributed climate, pluviometric crop and soil data were used to assess millet, sorghum and rice sensitivity to water deficit. Simulations were run for 2 sowing dates for each crop to represent early and late sowing. It was assumed that no irrigation was available and water for plant growth was provided only by rainfall. Four types of SMD

curves were identified and described as a function of the climate, soil, crop and sowing date. The latter appeared to be the most influential parameter, which affected water deficit. The results in terms of yield reduction showed a little effect of water deficit on crop productivity. Only the soils characterized by the presence of an iron cemented hardpan and soils characterized by extremely low permeability rate showed a reduction that should be taken into consideration. The analyses of yield reduction per growth stage showed that the first and the last stages were definitely the most sensitive to water deficit thus contributing the most to total yield reduction estimated over the entire plant cycle.

Kropff *et al.*, (2003) used **ORYZA1** simulation model to evaluate the effects of improved crop management on the rice yield potential in dry season at the IRRI Research Farm (IRF) from 1980 to 2001 based on actual climate data from planting to maturity. Comparisons of simulated and actual data were based on the yield of the best entry in a continuous cropping experiment at IRF from 1979 to 2001, and the highest recorded yields of IR72 in replicated agronomic trials under optimum crop management systems during 1992-2001. Simulation results based on actual data of solar radiation and temperature for 1979-2001 indicated a gap of 3 t/ha between potential dry season yield and the yield of the best entry in the long-term continuous cropping experiment before 1992. The simulated yield potential was much closer to the best entry yield in the long-term continuous cropping experiment (difference of approximately 1.5 t/ha). However, the average difference between simulated yield and the highest recorded yields of IR72 was approximately 0.6 t/ha. These results suggested that improved crop management

effectively reduced the gap between simulated and actual yields. The simulated model estimated that the climatic yield potential in 1998-2001 was, on average, 12% lower than the yield potential in 1992-97. Thus, they concluded that the yield decline was mainly associated with reduced solar radiation and increased night temperature.

Poussin *et al.*, (2003) used **RIDEV** simulation model for finding the determinants of irrigated rice yield in the Senegal River valley during 2 years in both wet and dry growing seasons. Grain yields were highly variable, ranging from 0 to 9.5 t ha⁻¹, with an average yield over years and seasons of 5 t ha⁻¹, indicating an average yield gap of about 4-5 t ha⁻¹ between actual farmers' yields and potential yields. Average yield levels for three out of the four seasons were not significantly different. However, cold temperatures at the onset of the dry season induced slower development rate and lower aboveground biomass despite higher plant and tiller density at panicle initiation (PI). Analysis of growth cycle and spikelet sterility levels in the sample fields showed that yield losses due to cold or heat stress around flowering could be neglected. Yield variability was, therefore, assumed to be mostly due to differences in crop management (other than choice of sowing and harvest dates) at the farmer level.

Tsvetsinskaya *et al.*, (2003) used **CERES** for assessing the effect of spatial scale of climatic change scenarios on simulated maize, winter wheat, and rice production in the Southeastern United States. Three different cases were considered for each scenario viz. climate change alone, climate change plus elevated CO₂, and the latter with adaptations. On the state level, for most cases,

significant differences in the climate changed yields for corn were found, the coarse scale scenario usually producing larger modeled yield decreases or smaller increases. For wheat, however, which suffered large decreases in yields for all cases, very little contrast in yield based on scale of scenario was found. They reported that scenario scale resulted in significantly different rice yields mainly because of low variability in yields. Their results indicated that spatial resolution of climate change scenarios could be an important uncertainty in climate change impact assessments, depending on the crop and management conditions.

Yun (2003) calibrated **CERES-Rice** for predicting regional rice production in South Korea using spatial data. The simulation was done with the past weather data as of September 15 each year, which was about a month earlier than the actual harvest date. Simulated yields of the 1455 CZUs (cultivation zone units) were aggregated into the corresponding 162 crop reporting districts by acreage-weighted summation, and compared with the reported yield and production. He reported that the forecasted yields were less sensitive to the inter-annual climate variation than the reported yields, and there was a relatively weak correlation between the forecasted and the reported yields. Projected production of rice for each crop reporting district, which was the product of yield and acreage, was close to the reported production with the R^2 values over 0.97.

Abou *et al.*, (2004) used a rice growth simulation model **ORYZA1** for Rice yield estimation by integrating with remote sensing data in China. The main objective of this research was to combine a rice growth simulation model with remote sensing data to estimate rice grain yield for different growing seasons

leading to an assessment of rice yield at regional levels. Integration between NOAA (National Oceanic and Atmospheric Administration) AVHRR (Advanced Very High Resolution Radiometer) data and the rice growth simulation model ORYZA1 to develop a new software, which was named as Rice-SRS Model, resulted in accurate estimates for rice yield in Shaoxing, with an estimation error reduced to 1.03% alongwith 0.79% overestimation and 0.79% underestimation for early, single and late season rice, respectively. Selecting suitable dates for remote sensing images was an important factor which could influence estimation accuracy. They reported that estimating rice yield using two or three images was possible if images were obtained during the panicle initiation and heading stages.

Hundal and Kaur (2004) used **CERES-Rice** model to study climate change and their effect on crop productivity in Punjab. They found negative effect of increasing temperature on rice yield. They reported that change in climate may bring about changes in population dynamics, growth and distribution of insect and pests. The onset of summer monsoon over India might be delayed and become more uncertain resulting in reduced availability of irrigation water due to tremendous competition for domestic and other uses.

Kumar and Sharma (2004) validated **CERES-Rice** model to simulate the growth, development and yield of 4 rice cultivars (RP 2421, HPR 927, HPR 957 and Kasturi) in Palampur during the rainy season of 1998 and 1999, in relation to transplanting date (23 June and 12 July in 1998, and 24 June and 9 July in 1999). The model was efficient in predicting the phenology of all cultivars, and the association between actual and simulated data on number of days to flowering and

physiological maturity was significant. The model failed to simulate the number of panicles/m². However, the number of grains/m², single grain weight, grain yield, straw yield and harvest index were satisfactorily simulated, and the association between simulated and actual data on these parameters was significant. The model did not correctly predict biomass yield at maturity. The model was validated for grain yield over 5 years using data from other experiments conducted in different locations with different management schemes. The simulated grain yields were very close to the actual grain yields, and the goodness of fit between simulated and actual data was significant.

Akula and Shekh (2005) and Akula *et al.*, (2005) evaluated and calibrated **WTGROWS** and **INFOCROP** models for wheat crop at Anand. They reported that model proved to be valuable tool for predicting wheat growth and yield. Both the models exhibited their robustness in predicting yields by explaining more than 90 per cent of variation in yield and total dry matter on an overall basis. The estimated RMSE for yield by WTGROWS was 318 kg ha⁻¹, while that for yield by InfoCrop was 360 kg ha⁻¹. The estimated average district potential yield by the models was 5.9 t ha⁻¹ on overall bases. This was 2.36 times higher than the average actual state yield and was due to favourable thermal regimes where the estimated thermal time requirement (TTVG) explained 87 per cent of variation in the potential yield and indicated significant linear positive trend. The attainable wheat yields were found to decrease in all the districts irrespective of the agro climatic zone. The estimated attainable yield for the state as whole was 4.8 t ha⁻¹ on the basis of the ten districts considered in the study. The average sowing gap

between potential and attainable yield varied from 863 to 1205 kg ha⁻¹. Reduction in yield due to delayed sowing in the districts of Saurashtra, middle Gujarat, north Gujarat and south Saurashtra was to the tune of 60, 59, 49 and 44 kg ha⁻¹ per day delay in sowing, respectively. They further reported that more than two fold increase in potential wheat yield as compared to the actual indicated the scope of harvesting better yields in middle Gujarat agroclimatic zone subject to biotic and abiotic stress free conditions.

Chaudhari *et al.*, (2005) validated SPAW model for soil moisture and evapotranspiration under wheat crop at Anand. They reported that this model could be used in deciding irrigation scheduling of wheat under irrigated conditions. The model overestimated the soil moisture under the wheat crop with 0.71 R² and RMSE value of 1.77. There was reasonable agreement between simulated and observed soil moisture. The differences between measured and computed AET of wheat were less than 9%. They concluded that SPAW model could be used for predicting the moisture content of the soil profile under irrigated wheat crop.

Easterling and Apps (2005) assessed the consequences of climate change for food and forest resources in USA using State Pressure Response Adaptation (SPRA) model. Findings suggested that for rice, CO₂ benefits might decline quickly as temperatures warm beyond optimum photosynthetic levels. However, crop plant growth might benefit relatively more from CO₂ enrichment in drought conditions than in wet conditions. Modelling studies suggested that warming above current temperatures diminish crop yields in the tropics while up to 2-3 °C

of warming in the mid-latitudes may be tolerated by crops, especially if accompanied by increasing precipitation.

Motha and Baier (2005) used **SPRA** model to assess the impact of present and future climate change and climate variability on agriculture in the temperate regions at Washington. The potential impact of climate variability and climate change on agricultural production in the United States and Canada varied by latitude. Largest reductions were projected in southern crop areas due to increased temperatures and reduced water availability. Agricultural livestock and rice cultivation were leading contributors to methane emission into the atmosphere. The application of fertilizers was also a significant contributor to nitrous oxide emission into the atmosphere. They suggested that forest and land management were effective tools in mitigating the greenhouse effect.

Rai and Kushwaha (2005) validated **CERES-Rice** model for prediction of upland rice yield in Pantnagar. Rice cv. Pant Dhan-4 seedlings were transplanted on 15 June or 1 or 15 July in a field experiment during 1997-98 to determine the optimum transplanting date for rice and validate the suitability of CERES rice model in simulating the growth and yield of upland grown rice. The simulated and observed values for number of days to panicle initiation and 50% flowering coincided, whereas the estimated value for number of days to maturity was higher than the simulated value. A high correlation between the observed and simulated value for yield and yield components including number of panicles, number of grains per panicle and 1000-grain weight was recorded, indicating the suitability

of the CERES-Rice model in simulating the development, yield and yield components of upland rice.

Singh *et al.*, (2005) explored possibility of second crop in Chhattishgarh using CERES-Rice simulation model. They reported that rice should be sown on 15th or 22nd May under upland rainfed conditions. They further reported that rainfall in vegetative stage has positive effect on yield and maximum temperature has negative effect during juvenile phase. They concluded that chickpea cultivars K-850 and JG-47 should be sown on 4th October to get higher yields.

Yajima (2005) developed a rice crop model (Yajima) to construct the initial version of a climatic early warning system against cool summer damage of rice under changing climate for monitoring rice growth and development on large scale in Japan. The approach involved using the development stage and spikelet sterility and yield models, and crop and geo-climatic data sets to develop a prediction system. With the use of mesh-weather data, rice models were developed and varietal characteristics of rice planted in the monitored area, spatial distribution of mean air temperature, and its deviation from climatic normals, as well as spikelet sterility caused by cool temperature, were determined. A significant linear correlation was obtained between the estimated spikelet sterility and yield. The results suggest the importance of using a crop model to monitor and forecast rice development stages and spikelet sterility at the regional level or in areas affected by cool temperature damage. With this method, extension staff could easily provide information on the possible occurrence of spikelet sterility in

particular areas, which could enable rice growers to take necessary countermeasures to minimize the yield reduction from cool temperature.

Patel and Shekh (2006) calibrated **CERES-Wheat** for genetic coefficients at Anand. The linear trend of total yield gap showed non-significant results with the rate of change $-14 \text{ kg ha}^{-1}\text{day}^{-1}$ because of decreasing trend of potential yield. The quantified sowing gap was found to be $65 \text{ kg ha}^{-1}\text{day}^{-1}$. They observed high CV percent in total yield gap due to weather variability particularly in temperature.

Sharma and Kumar (2006) parameterised and validated **CERES-Rice** model in Himachal Pradesh based on several independent sets of yield data. Optimum time of transplanting of RP-2421 was worked out to be May 15 – June 25 whereas for HPE – 1064 and HPE – 2027 it was worked out to be second fortnight of May to first fortnight of June. The cultivar Naggar Dhan required early transplanting during May 7 – 15 as compared to other varieties. The model performed well in predicting grain yield of all the four varieties and the association between simulated and observed values was significant with $R^2 = 0.78$. They concluded that yield decreased with delayed transplanting.

Das *et al.*, (2007) evaluated **ORYZA200** model for assessing the impact of climate change on rice production in Gangetic West Bengal. The potential production was more even than the highest reported value (9 t ha^{-1}). Application of fertiliser under nitrogen limited situations assured more yields. In water limited situation predicted yield components were less. They stressed the importance of proper care in irrigation management towards better production of yield

components. Model varification indicated that model estimation was higher than the observed values. They concluded that the study area will experience a warming climate in 2025 resulting in reduction of yield components.

2.2 Review of work related to Agrometeorological Modelling

Weather affects crop differently during different stages of crop growth. Thus extent of weather influence on crop yield depends not only on the magnitude of weather variables but also on the distribution pattern of weather over the crop season which calls for the necessity of dividing the whole crop season into fine intervals. This will increase number of variables in the model and in turn a large number of parameters will have to be evaluated from the data. This will require a long series of data for precise estimation of the parameters which may not be available in practice. Thus, a technique based on relatively smaller number of manageable parameters and at the same time taking care of entire weather distribution may solve the problem.

Agrometeorological models are defined as the product of two or more weather factors each representing functioning between yield and weather. These models do not require hypothesis of the plant and environment process. Thus the input requirement are less stringent but the output information is more dependent on the input data. Thus agrometeorological models are a practical tool for the analysis of crop response to weather and estimating the yield.

Fisher (1924) and Hendricks and Scholl (1943) have done pioneering work in crop weather relationship. They have given models which require small number

of parameters to be estimated while taking care of distribution pattern of weather over the crop season.

Fisher (1924) assumed that the effects of change in weather variables in successive weeks would not be an abrupt or erratic but an orderly one that follows some mathematical law. He assumed that these effects A_w , ($w = 1, 2, \dots, n$) are composed of the terms of a polynomial function of time. Further, value of weather variable in w^{th} week X_w ($w = 1, 2, \dots, n$) was also expressed in terms of orthogonal functions of time. substituting the expressions for A_w and X_w in regression equation

$$Y = A_0 + A_1X_1 + A_2X_2 + \dots + A_nX_n$$

(where Y denoted yield) and utilising the properties of orthogonal and normalised functions, he obtained

$$Y = A_0 + a_0 r_0 + a_1 r_1 + a_2 r_2 + \dots + a_k r_k$$

where $A_0, a_0, a_1, \dots, a_k$ are constants to be determined and r_i are the distribution constants of X_w .

Fisher has suggested to use $k = 5$ for most of the practical situations. In fitting this technique for $k = 5$, the number of constants to be evaluated will remain 7, no matter how finely growing season is defined. He used this model to study the influence of rainfall on the yield of wheat.

The Fisher's technique was modified by Hendricks and Scholl (1943). They divided the crop season into n weekly intervals and have assumed that a second degree polynomial in week number would be sufficiently flexible to express the relationship.

Mathematically, it can be expressed as

$$A_w = a_0 + a_1 w + a_2 w^2$$

Substituting the expression for A_w in regression equation, the model was obtained as

$$Y = A_0 + a_0 \sum_{w=1}^n X_w + a_1 \sum_{w=1}^n w X_w + a_2 \sum_{w=1}^n w^2 X_w$$

In this model, number of constants to be determined reduces to 4, irrespective of n . This model was extended for two weather variables to study joint effects of temperature and precipitation on corn yield. Since the data for such studies extended over a long period of years, an additional variate T representing the year was included to make allowance for time trend.

Hendricks and Scholl (1943), Stacy *et al.* (1957) and Runge (1968) have used this model to study joint effects of temperature and rainfall on crop yields.

Many other workers in India and abroad have studied crop weather relationships, however, a very few have used such relationship for forecasting of crop yields.

The model suggested by Hendricks and Scholl has been modified by various workers (Agrawal *et al.*, 1980, 1983 and Jain *et al.*, 1980) by expressing effects of changes in weather variables on yield in the w^{th} week as second degree polynomial in respective correlation coefficients between yield and weather variables. This explain the relationship in a better way as it gives appropriate weightage to different periods. The model was developed using partial crop season data considering all weather variables.

The model was further modified by Agrawal *et al.*, (1986) and the finally recommended model was of the form.

$$Y = A_0 + \sum_{i=1}^p \sum_{j=0}^1 a_{ij} z_{ij} + \sum_{i \neq i'=1}^p \sum_{j=0}^1 a_{ii'} z_{ii'} + cT + e$$

where

$$z_{ij} = \sum_{w=1}^m r_{iw}^j X_{iw} \quad \text{and} \quad z_{ii'} = \sum_{w=1}^m r_{ii'w}^j X_{iw} X_{i'w}$$

Y is crop yield, T is year number, X_{iw} is the value of i^{th} variable in w^{th} week, $r_{iw} / r_{ii'w}$ is correlation coefficient of Y with i^{th} weather variable / product of i^{th} and i'^{th} weather variable in w^{th} week, m is week of forecast, p is number of variables used and e is error term distributed as $N(0,1)$.

These models were used to forecast yield of rice and wheat in different situations. The results revealed that reliable forecasts can be obtained using this approach when the crops are 10 – 12 weeks old. In Raipur where 25 years data were available, forecasts could be obtained with 5% deviation from actual observed yield whereas for other situations where data were not adequate percentage deviations of yield forecast from observed yields were about 10%.

The results further revealed that reliable forecast was possible when the crop is 12 week old. Appropriate models can be developed for various crops in different agroclimatic zones if weekly data for about 10 – 15 years are available for various districts within these zones and using this methodology a reliable forecast of yields for the zones can be obtained well in advance of harvest with about 5% deviation from actual yield. Further state, or national level forecast can be obtained with a still more degree of reliability.

Das (1970) studied the forecasting of rice yield in India on the basis of weather. He developed separate regression equation for each region. He found that rainy days from 16th September to 15th October and maximum temperature from 16th August to 15th September had significant effect on yield in West Bengal, while in Andhra Pradesh, rainy days and rainfall distribution in August and September were highly correlated with yield.

Das and Sajnani (1970) investigated critical periods on the basis of weather elements having significant influence on crop yield at Pune. They concluded that the precipitation at different stages of growth of rice crop in Telengana region of Andhra Pradesh had significant contribution in prediction of yield.

Barany (1971) demonstrated the contribution to the climatological study of rice-growing in the region of Szeged (Hungary) using data on rice yields and weather conditions during 1951-70. The sunshine and heat requirements of the rice crop were especially high in July and August, the periods of stem formation, flowering and panicle formation. He found that average grain yields were correlated with mean temperature and duration of sunshine.

Das and Ramachandran (1971) developed a forecasting model for bajra yield for Ahmedabad district of Gujarat using regression analysis. They reported that it could be possible to give final estimate of yield of bajra by third week of October.

Das *et al.*, (1971) evolved formulae for forecasting the yield of autumn paddy in Mysore State using meteorological factors by means of regression analysis. They found that restricted rainy days from July to 15 September and

frequent droughts and floods during August and September were the principal factors having significant effects on yields in coastal Mysore. The corresponding factor for interior North Mysore was drought during July-September. In interior South Mysore, June and September rainfall have a significant effect on yield. The formulae agreed well with reported yields for 1965-1968.

Ghosh *et al.*, (1973) studied the effects of weather factors on yield attributes of rice at CRRI Cuttack using regression technique. They reported that high maximum temperature (29 - 31.5°C) and high total sunshine hours 3 weeks after flowering favoured panicle number and grain weight in the midseason cultivar T-141. They also reported that the absence of rainy days during the ripening phase was not beneficial to grain weight.

Ishizuka *et al.*, (1973) conducted a research in Japan on the effects of cold weather on the rice plant and countermeasures which could be taken to avoid or reduce the severity of cold damage in Taiwan. They stressed the importance of continuing research into rice production in cool climates even during periods when climatic conditions were more favourable.

Venkataraman and Narasimhamurthy (1973) studied the flowering behaviour of the rice crop at Pune to examine the presence or absence of photoperiodic response and the likely alternate flowering month for photosensitive cultivars in South India. Several rice cultivars with a wide range of sowing dates at several stations in South India were examined.

Bhargava *et al.* (1974) studied the recurrence of rainfall deficiency in relation to rice crop in Raipur. They reported that, rainfall during July, September

and the total rainfall during the crop season in the district was highly correlated with yield of paddy.

Van (1974) studied the effects of climate on rice yields in Malaysia during both the off-season and main-season rice crop. The off-season crop yielded better than the main-season crop but no significant differences were detected. He found that the performance of the rice crop was affected by the number of rainy days particularly during the growth phase between floral initiation and ripening. He suggested that the off-season crop and the main crop be redesignated the first and second crop, respectively.

Huda *et al.* (1975) studied the contribution of climatic variables in predicting rice yield in Pantnagar. They used a second degree polynomial multiple regression equation. They reported that average weekly total rainfall is beneficial during the nursery period and detrimental during vegetative and ripening phases. Above-average maximum daily temperature was beneficial during the 1st 3 weeks of establishment and slightly detrimental during the next 2 weeks, then had an increasing adverse effect which was greatest at maximum tillering and ear initiation and was still severe during flowering; a decrease of 1 °C was beneficial. A 1 °C increase in average minimum daily temperature was beneficial during establishment and had a progressively increasing adverse effect throughout flowering and ripening. Grain yields were decreased by increased maximum and minimum relative humidity and increased at low relative humidity.

IRRI (1975) reported that sunlight was more critical for grain yield during the reproductive than the ripening phase. Similarly, Robertson (1975) at WMO

discussed the methods of forecasting paddy yield and distribution of rice cultivation throughout the world with particular reference to climate and weather. Growth and development of the rice plant were detailed with its environmental requirements and problems of irrigation discussed in detail. Numerous data were presented on the climatic zonation of rice in monsoon regions and the bioclimatic conditions in rice-producing areas.

Keulen (1976) developed a model for calculating the potential grain production of rice from temperature and solar radiation in Indonesia. Despite the difficulties of achieving potential production, there was general agreement between the actual and estimated potential values of grain production of Surinam and Indonesian rice crops for which experimental and climatological data were available. He suggested that the model could be applied for screening yield potential in breeding programmes.

Munakata (1976) studied the joint effects of radiation and temperature on rice growth and yield in by the non-linear multiple regression model, using data obtained annually in major rice-producing areas in Japan Japan. He stated that the effect was not linear and varied with growth stage of the crop. He found that the number of spikelets/m² was strongly influenced by temperature at (a) 45 and (b) 20 days before heading, and by solar radiation at (c) 40 days prior to heading, when the effect of temperature + radiation on the number of spikelets/m² was greatest. The grain yield/number of spikelets quotient (ripening grade) was governed by the climatic factors at (b) and at (e) 20 days after heading. Solar radiation had a positive effect throughout the reproductive stage. Low temperature

at (b) and at (f) 10 days after heading, and high temperature at heading proved negative to ripening grade, with normal solar radiation. Multiple regression equations were fitted to study relation of temperature and spikelet numbers, grain yield and climatic factors, and grain yield and light alongwith temperature.

Yoshida and Parao (1976) studied climatic influence on yield and yield components of lowland rice in the tropics at Philippines. They reported that the grain yields were highly correlated positively with average daily solar radiation and negatively with average daily mean temperature during the reproductive stage, i.e. the 25-day period before flowering. Controlled-environment and field studies demonstrated that variations in temperature and solar radiation within ranges commonly encountered during the vegetative stage did not have any overall effects on yield and yield components. Relatively low temperature and high solar radiation during the reproductive stage had remarkable effects on increasing spikelet number and hence grain yield. Solar radiation during the ripening period influenced grain filling. Yield and yield components data collected from various locations in the tropics indicated that the probability of weather conditions before or after flowering having a greater effect on yield was location- or season-specific. A 3-year average annual production from 4 crops/year was 23.7 t/ha. Hence, total DM production was estimated at about 35 t/ha year. They concluded that on a yield/crop basis, the tropical environment may not necessarily be more productive than the temperate region, but it has a greater potential in terms of annual production.

IRRI (1977) reported that rainfall distribution was a major factor affecting the performance of rainfed rice crops.

Strommen (1977) outlined a modelling approach which gives a qualitative estimate of potential crop yields using agrometeorological data for an early warning system for food crops including rice in India, Haiti, Pakistan, Bangladesh, USSR and China. The merit of this approach was that it utilized an existing data system; it could be implemented with limited resources and in a short time span; and a large and detailed historical yield database was not required. The model was especially recommended for maize, rice, soyabeans and wheat.

Rao (1978) fitted a regression equation for yield and significant weather parameters to study the effects of weather on productivity of rice in Kenya and found positive effects of mean temperature and a negative effect of radiation on yield. Due to altitude (1159 m) the effect of weather conditions was significantly different from other places around the equator and at near sea level.

Chaudhary and Sodhi (1979) studied the effect of weather factors on growth of rice cv. Taichung (Native) 1 sown at 14 days intervals from 15 May to 30 April and transplanted after 14-21 days at Kharagpur. They reported that the growth duration varied with air temperature and increased in proportion to the length of time the plants experienced low temperature during vegetative growth and flowering. Temperature accounted for 86% of the variation in growth duration. Winter sown plants produced the largest number of tillers and highest straw yield. Minimum spikelet sterility (12-18%) was found in November sown plants which

experienced temperature of 27-28 °C during flowering. Sterility increased when plants were exposed to higher or lower temperature during flowering. Highest yields were in plants sown from 13 November to 11 December.

IRRI (1979) developed an evapotranspiration model of a rice crop based on solar radiation and water balance for rice under wetland conditions. Model revealed that evapotranspiration was greatest during early growth and declined as growth advanced under conditions where the level of incident solar radiation remained constant. It was argued that measured evapotranspiration was highest during the reproductive stage due to high evaporative demand and incident solar radiation. Increased evapotranspiration in the generative phase was attributed to climatic changes and not changes in growth demands of the rice crop.

Mandac and Herdt (1979) developed a differential yield response equation, incorporating physical factors viz. weather, soil, water stress, pest and disease and input factors viz. fertilizer, insect control and weed control in Phillipines. The estimated production function was used to account for the yield differences among low and high yield farm groups. About 70 and 97% of the total yield differences between high and low yields with farmers' inputs was explained by the production function during the wet and dry season, respectively. About 80% of the differences in yields with high inputs was explained by the function during the wet season. Some 50% of the yield differences was accounted for by differences in the environment during both seasons.

Agrawal *et al.* (1980) developed two models for forecasting of rice yield using corresponding weighted averages and correlation coefficients instead of

original weekly weather data at Raipur. Forecast equations showed that the 11th week after sowing was most suitable for forecasting rice yields. In Raipur where 25 years data were available, forecasts were obtained with 5% deviation from actual observed yield whereas for other situations where data were not adequate percentage deviations of yield forecast from observed yields were about 10%. The results further revealed that appropriate models can be developed for various crops in different agroclimatic zones if weekly data for about 10 – 15 years are available for various districts within these zones and using this methodology a reliable forecast of yields for the zones can be obtained well in advance of harvest with about 5% deviation from actual yield.

Angus and Zandstra (1980) developed a growth and development model for wetland rice that accounts for the effects of radiation, temperature, water supply and Nitrogen nutrition in Australia. The model quantitatively accounted for the yield interaction between radiation and N supply in a flooded environment and qualitatively simulated the interaction of drought and N response in rainfed rice. They reported that water balance and rice yield could not be accurately simulated for sloping fields in Australia.

Chen (1980) developed a technique for improving the forecasting performance of ARIMA model for rice in Taiwan, which involves constructing a separate model for the random error term of each equation. The technique was found to work effectively in improving the forecasting power of regression equations.

Jain *et al.* (1980) studied the effect of climatic variables on rice yield and its forecast in Raipur district, M.P. for the period from 1947 to 1971. The effect of total weekly rainfall was found beneficial throughout the crop season. The reliable forecast was possible after about two months of sowing, assuming that weather would be remaining normal thereafter.

Mota and Silva (1980) developed an empirical-statistical rice yield/weather/technology model in Brazil using data on yields, crop phenology and monthly weather. They reported that the absolute difference between observed and predicted yields ranged from 37 to 193 kg/ha for an average yield of 3.91 t/ha.

Ramdoss and Subramaniam (1980) studied the influence of weather parameters during the last 45 days of crop growth on rice yield at Coimbatore. They reported that the maximum temperature and number of sunshine hours had a positive effect on paddy yield and a negative effect on straw yield.

Sarker (1980) described methodology of acquisition and analysis of rice and weather data and techniques for yield forecasting using meteorological data and water needs of the rice crop at Pune. Techniques for measuring evapotranspiration and percolation losses for rice fields were also described.

Stansel (1980) and Stansel and Fries (1980) conceptualised an agromet rice yield prediction model based on the effects of agrometeorological variables on different growth stages. The model identifies stress parameters allowing precise yield evaluation in Texas. He reported that world production could be decreased

19% by a temperature reduction of 2 °C in combination with a precipitation reduction of 15%.

Shanker and Gupta (1981) conducted a correlation study of the height of the paddy crop with some weather elements viz. maximum, minimum and mean air temperature, amounts of rainfall and evaporation, and duration of sunshine. Statistically significant but negative correlations were obtained between the crop height and maximum, minimum and mean temperature and rainfall. Significant positive correlations were obtained between the crop height and evaporation and duration of sunshine.

Agrawal and Jain (1982), developed composite model for forecasting the yield of rice in Raipur district. The additional contribution of agricultural inputs over the trend was found negligible, suggesting that inclusion of trend as a variable in the model takes care of agricultural inputs and change in technology. The weather variables along with time trend explained more than 70 % of the variation in yield at about 2.5 months before the harvest in comparison to weather variables alone.

Takami and Kumashiro (1982) studied response of crop photosynthesis of rice to climatic conditions as affected by the canopy architecture in Japan. Rates of crop photosynthesis were calculated using a model for erect-leaved, horizontally-leaved and ideally-leaved (upper leaves vertical and lower leaves horizontal) crops at 8 sites in various parts of the world. They reported that the canopy architecture was important at high LAI and improved canopy architecture

could make a significant contribution to increasing grain yield especially in areas where the solar radiation level is high.

Agrawal *et al.* (1983) studied the joint effects of climatic variables on rice yield at different stages of crop growth in Raipur district. Beneficial effect was observed on yield for above average maximum temperature with rise in humidity during active vegetative phase while detrimental effect was observed in other phases of crop growth. The rise in humidity has small beneficial effect in general throughout the crop season. The effect increased with increase in temperature. Rise in temperature associated with high rainfall had beneficial effect during growth phase of the crop.

Lomas and Herrera (1985) studied weather and rice yield relationships in tropical Costa Rica. They reported that the rice yield were most variable due to low rainfall. They concluded that rainfall during August when rice was in the reproductive stage could be used to assess rice yields.

Prabhakaran (1985) carried out correlation analysis of data on rainfall and number of rainy days on two PTB varieties of rice in Kerala. He reported that the correlations between grain yield and number of rainy days and rainfall were both positive and negative depending upon the growth stage of the crop and differed with the variety. He reported that the correlations between grain yield and rainfall during the 8th WAS and number of rainy days during the 12th WAS and ripening were negative and that between number of rainy days during the 7th WAS and yield was positive for PTB 1. For PTB 5, correlations between rainfall in the 11th WAS or early tillering and yield were negative.

Agrawal *et al.* (1986) developed two regression models to forecast paddy yield at Raipur. They observed that above average maximum daily temperature had beneficial effect during ripening stage and detrimental effect during reproductive stage of the rice crop while in the initial growth, active and lag vegetative phase effects were fluctuating. The effect of increase in minimum temperature was beneficial during initial, lag vegetative and reproductive stages, detrimental during ripening stage and fluctuating during active vegetative stage. Above average relative humidity and rainfall had beneficial effect throughout the growth phase and detrimental effects during ripening phase of the crop in general. Effects of increase in sunshine hours were detrimental during initial growth, active vegetative and reproductive stages, fluctuating during lag vegetative and beneficial during ripening stage of the crop.

Khan and Chatterjee (1987) studied the influence of weather on forecasting the yield of autumn rice in West Bengal through multiple linear regression technique. The data of rice yield of 25 years (1958-1982) were taken as dependent variable and the data of weekly rainfall covering the growing period from 18th to 35th standard week as the independent variables. Prediction model developed by selected rainfall variables was helpful in forecasting the yield of rice within a deviation of 12 % from actual yield. The coefficient of determination was 0.95.

Viswambharan *et al.*, (1987) developed linear regression models to predict yields of rice cultivars in relation to weather components in Kerala. In field trials conducted during 1983-86, rice cv. Jaya and IR8 were transplanted on 7 dates between 22 August and 12 November. Grain yield was positively correlated with

total solar radiation during 5-15 days before the 50% heading stage, and negatively correlated with the number of rainy days 15-30 days before the 50% heading stage. Adverse effects of weather on yield were more pronounced in crops transplanted from 18 September to 17 October.

Wang and Zhang (1987) used a classification method AID (automatic interaction detection) to establish a statistical model consisting Circulation-Weather-Harvest system to simulate a long sequence of annual harvests of rice yields in Yangtze Delta of China based on rainfall from June to September and temperature in July. Based on the simulated result, an analysis of the frequency of rice harvest fluctuation in the Yangtze Delta showed that good harvests comprise 45%, bad and disastrous years 25%, and normal years 30%. The distribution was not homogenous and phases of good and bad harvest alternate, the length of one period of long-term fluctuation being about 36 years.

Chatterjee and Mandal (1988) reported that high rainfall, low radiation and high pest incidence were detrimental to high crop production in West Bengal, Orissa, Bihar and East Uttar Pradesh. They reported that under rainfed conditions in the kharif season high rainfall, low radiation and high pest incidence were detrimental to high crop production. They stressed that efforts were needed to compensate for low production in the kharif season by increasing the productivity of rabi (winter season) crops, under both rainfed and irrigated conditions.

Dua and Garrity (1988) tested different models for predicting rice flowering using mean temperature and photoperiod in Phillipines. Data from 43 experiments conducted at 23 irrigated sites in Asia, Africa and South America (latitudes 0°9'S

to 37°16'N) were evaluated for relationships between mean temperature, photoperiod and flowering date. Cultivars IR9729-67-3 (very early), IR36 and BG35-2 (early) and Taichung Sen Yu 285 (medium) were tested for best fit to generalized thermal or photoperiod models. A simple model using accumulated thermal units accurately estimated the rate of progress to flowering in IR36. Best fit models included a quadratic photoperiod term that accounted for day length effects. Models for the other cultivars also gave similar performances.

Ravi *et al.* (1988) conducted field experiments in the wet season of 1984-85 in order to develop yield models in terms of spectral (remote sensing) data such as radiance values in different wavelength bands, viz. visible and near infrared (NIR) and meteorological parameters for rice crops at Nawagam. The cultivars and dates of sowing variables were included to induce variability in yield and to arrive at a model that can be used to predict yield under a wide range of growing conditions. Spectral data such as radiance values in different wavelength bands, viz. visible and near infrared (NIR), and biometric data on LAI, wet biomass and dry biomass were collected at weekly intervals. A linear relation between LAI and NIR:red irradiance ratio was observed. Linear relations were also found between spectral parameters and paddy yield. A linear regression relationship incorporating the irradiance ratio and a multilinear regression relationship incorporating integrated irradiance ratio and accumulated temperature degree days were tried to estimate yield. They concluded that combination of both the spectral or meteorological variables gave better estimation of yield than when only the spectral or meteorological variables were used.

Shanker and Gupta (1988) used multiple regression technique for forecasting paddy yield in Bihar and Orissa states based on weather parameters viz. temperature, sunshine, rainfall and evaporation. Meteorological and yield data from the phenological periods in which weather elements showed significant correlation with crop yield were used in the derivation. Actual and estimated yields for all sites agreed well for both collected and independent data. They concluded that the multiple regression technique could be used for yield forecasting in other regions.

Viswambharan *et al.*, (1989) delineated climatic constraints of high-yielding photo-insensitive winter rice in Kerala. They reported that excessive wind velocity during flowering and maturation, low solar radiation and the occurrence of rainy days during maturation phase produced high spikelet sterility and low yields.

Chakravarty (1990) studied the crop-weather interactions in cereal and pulse crops at IARI. He analysed results of field experiments carried out at various locations in India to understand quantitatively the crop-weather interactions in cereals (rice, pearl millet, sorghum, maize, wheat and barley), legumes (groundnuts, mung beans and gram) and raya. He reported that PAR interception and utilization by the crop, distribution of rainfall and phenological stage at which it occurs and accumulated heat sums had a linear relationship in cereal crops including rice.

Pandey and Gupta (1990) studied the influence of weather variables on sorghum yield in Surat district. They observed that weather variables like rainfall,

maximum and minimum temperature, relative humidity and duration of sunshine influenced the sorghum yield significantly.

Shi and Shen (1990) studied the effect of high humidity and low temperature on spikelet fertility in 12 varieties of indica rice in China during 1989. They reported that spikelet fertility was reduced with increasing RH and decreasing temperature. RH was the most significant meteorological factor affecting spikelet fertility followed by mean temperature at 3 days after heading. Spikelet fertility also varied with variety.

Takami *et al.*, (1990) proposed a mathematical expression (Quantitative method) to describe the effects of drought during the grain-filling stage on grain yield in rice which could serve as a submodel for yield prediction in a mechanistic crop production model in Japan. The expression predicts the grain yield as a function of the total DM production during grain filling with 2 parameters: potential yield, and amount of mobilizable reserves at anthesis. The proposed relation states that grain yield equals the potential yield when the total assimilate supply is equal to, or greater than the potential yield. Below this level of assimilate supply, grain yield decreases in proportion to the total DM produced during grain filling. The model was tested in an experiment in which the yield response of rice cv. Nipponbare and Tachiminori to 6 levels of water availability was measured. The theoretical generalization fitted the experimental results. It was concluded that the model was useful in predicting the yield response of rice when the crop encountered drought stress during grain filling, provided the 2 parameters cited above could be measured or estimated at anthesis.

Murai *et al.*, (1991) studied relation between cool temperature damage at booting stage and water depth in four dwarf lines of rice in Japan. They reported that cool temperature was prime cause of spikelet sterility. The reduction in spikelet fertility was observed from 31.9 to 58.3% in different lines. Sterility of variety D-47 was not reduced owing to its high sensitivity to cool temperature.

Reddy and Reddy (1992) used correlation co-efficients for establishing crop weather relationships in rice at Rajendranagar. They correlated grain yield with number of rainy days, sunshine hours, humidity and maximum temperatures during the pre- and post-flowering stages. They reported that the grain yield was negatively correlated with number of rainy days and humidity during the vegetative stage and with maximum temperatures and humidity during the reproductive stage, but was positively correlated with sunshine hours during the pre- and post-flowering stages.

Summerfield *et al.*, (1992) studied photothermal responses of flowering in rice in UK. They assumed linear relationship between the rate of progress towards panicle emergence and mean temperature. They recorded the time from sowing to panicle emergence in 16 diverse rice cultivars in 13 different controlled environments comprising constant and diurnally alternating temperatures between 16 and 32°C and photoperiods between 10.5 and 15.0 h/d. In 11.5-h days and at suboptimal temperatures, relations between the rate of progress towards panicle emergence and mean temperature were linear in all cultivars, and amongst these the base temperature at that photoperiod varied between 6.6 and 11.9°C. In most cases progress was most rapid at 24-26°C. They concluded that both temperature

and photoperiod had considerable effect on panicle emergence. Differences among cultivars in relative sensitivity of rate of progress towards panicle emergence to both temperature and to photoperiod were considerable; japonica cultivars tended to be more sensitive to temperature and less sensitive to photoperiod than indica cultivars.

Hoa and Singh (1993) developed regression model to forecast rice yield based on weather parameters at Pantnagar. They reported that the effect of maximum temperature, minimum temperature and relative humidity was beneficial at the end of the seedling stage. During the vegetative growth stage, relative humidity and total rainfall were found beneficial, while increase in minimum temperature was found harmful. The forecasting model using weather data upto 13th week (the third week of August) was appropriate for forecasting rice yield as it explained 85 % variation in yield.

Mandal and Kar (1993) estimated yield of rainfed upland rice cv. MW 10 grown during the rainy seasons from weather parameters at Kharagpur. They reported that when available soil water was low, the model underestimated yields at or near the harvesting date and when the available soil water was higher, the yields were overestimated around the same period. Except for about a month before harvesting, the model predicted DM yields with reasonable accuracy.

Pandey and Singh (1993) developed pre-harvest forecasting model for wheat at Pantnagar. The forecasting model based on week numbers as weight was found superior as it explained 87 % variation in the yield. It was possible to forecast yield in 15th week after sowing the crop i.e. February, almost two months before

the harvest. The weather index based on correlation coefficient as weights was also found superior and explained more variation in the yield.

Jacobs and Pearson (1994) used a mathematical model based on the daily cycle of temperature on development of rice in Australia. They reported that the daily impact of cold varies with the phenology of the crop and total or cumulative impact depends on the summation of thermal time below a critical minimum temperature for cold damage. They noted that owing to exposure to suboptimal ($<20^{\circ}\text{C}$) temperatures, cold damage took the form of reduced yield, abnormal spikelet development, and reduced spikelet fertility.

Yang and Yang (1994) studied effect of solar radiation and air temperature on rice cv. Tainung 67 yield in Taiwan at 5 different levels of water deficit. They found that rice yield increased with increasing total solar radiation and heat sums, decreased with increased water stress, but was not significantly affected by total sunshine hours or rainfall.

Collinson *et al.*, (1995) studied the relative importance of air and floodwater temperatures on the development of rice cv. IR36 in both a growth cabinet and a glasshouse at Reading. They found that the rate of floral development was enhanced by warmer nutrient solution temperatures at the same air temperature and times to panicle emergence were reduced by an average of 17 days with increase in the nutrient solution temperature from 20 to 28°C . They stressed on the importance of determining water/root temperature as well as air temperature when investigating the effect of environment on development of the rice plant.

Dingkuhn and Miezani (1995) and Dingkuhn *et al.*, (1995) studied the climatic determinants of irrigated rice performance in the Sahel. They reported that locally grown varieties were mostly of medium duration and comparatively thermo- and photoperiod-insensitive. They further reported that minimum temperatures below 18°C at booting stage resulted in near total spikelet sterility and a specific delay in heading.

Kawakata and Yajima (1995) used nonparametric methods to develop an equation describing the number of days required from emergence to flowering as a function of air temperature, photoperiod and sowing date in Japan. Six rice cultivars were sown at 2-weekly intervals during 1 year, in a greenhouse maintained at a constant air temperature (average 24.4°C). The number of days required from emergence to flowering was constant for rice plants sown between August and February, while those sown between March and July required more time. On the basis of these results, an equation describing the cumulative water temperature over the time required for flowering as a function of photoperiod ($f(P)$) and sowing date, was derived. The value of $f(P)$ was almost zero when the photoperiod was shorter than the critical photoperiod (P_0); when the photoperiod was longer, however, the value of $f(P)$ increased proportionally. The function was simplified to represent the effective photoperiod. The equations of this model were able to analyse quantitatively the photoperiod sensitivity of rice plants, and the observed flowering time was accurately estimated.

Khan *et al.*, (1995) used multiple regression analysis to predict the yields of winter rice and rape and mustard from the rainfall distribution before sowing and

during the growing season in West Bengal. The models developed were able to account for more than 70% of the total variation in rice yield in most of the districts. The range was 23-98%. For rape and mustard, agronomic inputs (cultivar choice in particular) affected the prediction equation greatly without which the coefficient of determination (R^2) was reduced. Of the 9 districts, the regression models developed for 6 accounted for more than 70% variability in yield and their R^2 values were significant at 5% level. The models could be used for pre-harvest forecast of winter rice and mustard in West Bengal by 21 October and 31 December which were quite earlier than the final forecasts made on 31 January and 13 April by the State agencies.

Pamplona *et al.*, (1995) used regression method to study the effect of radiation and temperature on rice yield in Philipines. Based on field data from 1989 to 1993, grain yield was highly correlated with solar radiation and minimum temperature. Several regression runs gave the best fit model $YIELD = 0.23 * RAD - 0.0281 * (TEMPMIN)^2 + 15.78$ with $R^2 = 0.97$. The model showed that the high yield observed especially during the dry season (DS), was not due mainly to higher solar radiation but also due to lower minimum temperature. Also, yield response to different levels of nitrogen varied with solar radiation and minimum temperature. Results suggest that the crop's responsiveness to nitrogen fertilizer application could be associated with higher solar radiation. They stressed that regression models are appropriate to quantify crop responses to environmental factors but still inadequate to provide proper understanding of the interaction of the components of the system. Therefore, current strategies in crop production,

particularly nitrogen management, should be complemented with knowledge-based and mechanistic simulation models capable of integrating site-specific climatic data.

Samui (1995) studied the influence of variations in rainfall on rice yield in Gangetic West Bengal with 10-year moving averages. He found marked variation between years in rainfall and rice yield. He reported that yield increase were due to improved management practices and not due to rainfall.

Yin *et al.*, (1995) developed a nonlinear model for crop development as a function of temperature. The Beta function, commonly used as a skewed probability density function in statistics, was introduced to describe the effect of temperature on the rate of crop development, using data from rice, cassava and maize to illustrate the models ability to describe the shape of the temperature response. The framework was set by three cardinal temperatures, namely the base (T_b), the optimum (T_o) and the ceiling (T_c) temperature. The model parameters T_b and T_c and three other coefficients micro, alpha and beta were used to derive the value of T_o and the maximum development rate. Parameter alpha also characterized the curvature of the relationship with temperatures between T_b and T_o , and parameter beta described the curvature between T_o and T_c . The developed model had one parameter less than the Rice Clock Model (RCM) and in contrast to the RCM, it ensures that the maximum development rate occurs exactly at T_o . The model accurately described the response to temperature of several developmental processes, and was superior to two widely used thermal time approaches in predicting rice flowering time.

Panda *et al.*, (1996) studied the management of rice cv. Lalat for the aberrant weather situations of the coastal plains of Orissa taking 4 transplanting dates at 10-d intervals starting from 20 August and three spacings (10 x 10, 15 x 10 and 20 x 10 cm). They outlined contingent planting of rice for aberrant weather situations in Coastal Plains of Orissa. They reported that late transplanting decreased grain yield significantly from 50.05 q/ha (20 August) to 20.0 q (19 September). Reduction in cumulative temperature of 195.9, 302.5 and 534.9 °C in the main field decreased the grain yield by 18.22, 33.41 and 60.03%, respectively. Spacing at 10 x 10 cm produced the highest mean yield of 38.84 q/ha.

Singh *et al.*, (1996) studied the influence of agroclimatic elements on the yield of rice at Raipur. The crop period was divided into different phenological phases of rice. The bright sunshine hours, maximum and minimum temperature were negatively correlated with yield in all the phases. The yield variation explained by afternoon relative humidity was maximum, followed by those of rainfall, maximum temperature, bright sunshine hours, minimum temperature and morning relative humidity.

Yin *et al.*, (1996a, 1996b) used a nonlinear model (**m-RCM**) to study differential effects of day and night temperature amplitude on development to flowering in twenty four cultivars of rice in Philippines, under 5 diurnally constant (22, 24, 26, 28 and 32 °C) and 4 fluctuating (26/22, 30/22, 22/26 and 22/30 °C) temperatures imposed between 0600 and 1800 hours. Time of panicle emergence was recorded. Treatments were selected to enable the separation of

effects of day temperature (TD) and night temperature (TN) on development rate (DR). The response of DR to constant temperatures was typically nonlinear. This non-linearity could not explain the difference in flowering dates between fluctuating and constant temperatures with the same mean daily value but opposite TD/TN differences. In most cases, TD exerted a greater influence than TN. The data were further analysed by a non linear model which separated the effects of TN and TD. The estimated value for the optimum TN was generally 25-29 °C. Differential effects of TN and TD on DR were found in all but one cultivar and were interactive in some. The model accurately predicted cultivar and site-specific variation in rice flowering date. They suggested that these results form a new basis for modelling flowering dates in rice. This model was used by Yin *et al.*, (1996b) to study differential effects of day and night temperature on development to flowering in twenty four cultivars of rice in Netherlands. They reported that the response of development rate to constant temperatures was typically nonlinear and day temperature exerted a greater influence than night temperature. Yin *et al.*, (1997a, 1997b) evaluated the **m-RCM** and a logistic model for photothermal responses of flowering in rice in Philippines. The performance of the nonlinear models was similar although the logistic model overpredicted days to flowering.

Chaurasia and Minakshi (1997) studied wheat crop yield and climatological data. Yearly fluctuations were discussed and regression equations were developed to predict the wheat yield in the central part of Punjab state. The multiple regression equation using maximum and minimum temperature, morning and

evening relative humidity, sunshine hours and wind speed resulted in high coefficient of determination.

Mahmood (1997) studied the impacts of air temperature variations on the rice phenology in USA. He reported that the prevailing air temperature determined the length of crop growth stages. He reported that the planting date plays an important role in the boro rice phenology. This effect was most noticeable during initial growth stages. A non-linear relationship was found between decreasing air temperature and the length of the initial growth stage and a predominantly linear relationship was found with other growth stages. Model applications showed that an increase in air temperature provides longer and more stable thermal conditions for boro rice maturing stage. A 5% increase and a 4% decrease in seasonal total evapotranspiration occurs under each 1 degrees C cooler and warmer air temperature conditions, respectively.

Rai and Chandrahas (1997) used composite weather index for the forecast of rice yield. They reported that relative humidity and number of rainy days were beneficial upto early growth phase whereas sunshine and maximum temperature in addition to relative humidity contributed positively towards rice yield upto the vegetative phase. During the reproductive phase, minimum temperature and rainfall had the deleterious effect on the yield of rice.

Caton *et al.*, (1998) developed, validated and evaluated a temperature-based model of stand establishment for rice direct-sown into flooded fields in California. The best performing stand density model used sowing rate and total degree-days (adjusted $R^2 = 65\%$). The model is widely applicable and is useful either alone or

as a submodel in rice growth and management models. No problems were detected with this model's assumptions or statistical adequacy, and alternate models performed worse or were invalidated.

Samui *et al.*, (1998) used curvilinear technique to investigate the relationship between weather and rice yield at Pattambi. They reported that yield fluctuated with change in average daily temperature, bright sunshine hours and total rainfall during different growth stages of the crop. The yield increased as the average daily temperature increased from 21.5 °C; yield decreased as the average daily temperature increased from 29.1 °C; yield slowly decreased as the total bright sunshine hours during planting to harvesting increased from 300 to 450 h (beyond 450 h the fall was rapid); and yield decreased with increase in total rainfall during planting to maturity from 900 to 1100 mm.

Sie *et al.*, (1998) developed and tested an empirically based model for estimating rice crop duration and leaf appearance rate in a variable thermal environment in Senegal. They reported that the rate of leaf appearance was dependent on the temperature above base temperature. Mean daily water temperature (T_w) varied from 13 to 35 °C. After seed soaking, the rate at which the first leaf (L1) appeared was linearly related with T_w , with a base temperature (T_{base}) of about 10 °C. Appearance rates of the subsequent three leaves (L2-L4) had a similar T_{base} , and presented a distinct temperature optimum (T_{opt}) at about 23 °C, beyond which development rates decreased. No significant temperature response was observed for the leaf appearances between L5 to the flag leaf (L12 to L20). Crop duration to flowering varied from 45 (IR64) to 63 days (Jaya).

These variations were associated with highly variable leaf numbers in all cultivars, including photoperiod-insensitive IKP. One-third of the variable duration was due to a variable basic vegetative phase (BVP), caused by variable germination and leaf appearance rates, and two-thirds due to variable duration of panicle induction after BVP. Water temperature was the main determinant of both sources of variability. The model was used to identify phenological-stage and cultivar-specific causes of variable crop duration.

Jain and Agrawal (1999) evaluated various statistical models for crop yield forecasting at IASRI, New Delhi. They utilised various models viz. Fisher's technique, Hendricks and Scholl's model, IASRI model (modified Hendricks and Scholl's model), IMD approach, Principal component model, Markov chain model, Logistic growth model and Modified logistic growth model. They concluded that Fisher's model was useful for studying influence of single variable on crop yield. Hendricks and Scholl's model, IASRI model and IMD models gave yield with 5 – 10% deviation from actual observed yield when the crop was 12 weeks old. Principal component model gave yield forecasts one month before harvest with 3% deviation from observed yield. Markov chain model could forecast crop yield with 2 – 4% deviation from observed yield about 3 months before harvest. Logistic growth model and Modified logistic growth model could forecast yield one month before harvest with 5% deviations from observed yield.

Kaladevi *et al.*, (1999) evaluated the effect of agrometeorological factors (maximum and minimum temperature, relative humidity, solar radiation, wind speed, evaporation, and total rainfall) on the yield of *rabi* rice in Tamil Nadu.

They reported that increased lower minimum temperatures resulted in higher dry matter production (dry matter produced for a degree difference between maximum and minimum temperature).

Rai and Chandrahas (1999) used linear discriminate score of weather parameters and input variables for forecasting of rice yield. observed that temperature (maximum and minimum) and sunshine hours were effective at the growing phase whereas sunshine hours found ineffective during early growth phase. All the variables under study at active vegetative phase explained about 87% of the total variation in rice yield.

Samui (1999) used curvilinear technique to examine the influence of meteorological parameters on the yield of rice at some stations in India. He reported that highest yield was obtained when average rainfall ranged between 100 and 115 cm. Maximum and minimum temperature ranges of 29-32 °C and 23-25 °C, respectively, gave optimum yield.

Tripathi *et al.*, (1999) developed crop weather models to predict the growth and yield of rice and wheat under rice-wheat cropping system at Faizabad. They simulated dry matter and grain yield of rice and compared them with actual observations for the commonly grown cultivar Sarjoo-52. The simulated value of dry matter was within the range of 88 – 100% with a mean of 94% of the actual value after vegetative stage. Growing degree days (GDD) was found the best weather parameter for yield prediction and predicted yields in the range of 2 – 3 q/ha with observed yield. They concluded that GDD could be fairly used to predict the yield before the crop maturity.

Gupta *et al.*, (2000) correlated the effect of rainfall, number of rainy days and length of rainy season with productivity of rice in Jabalpur. They reported that rice yields were significantly correlated with quantum of rainfall, length of rainy season and number of rainy days. They concluded that for obtaining higher productivity of rainfed rice either surplus rain water be efficiently managed to overcome moisture stress during reproductive phase or to minimise the risk of moisture stress during grain filling, short duration varieties be selected which were better in water use efficiency and drought tolerant.

Kokate *et al.*, (2000) developed a statistical model for forecasting the yield of rice in Ratnagiri district of Maharashtra for three varieties viz. Jaya, Ratna and RTN-1 using ancillary characters and weather variables. Seven ancillary characters and weather variables were considered for the study. Results revealed that, use of either plant characters or climatological parameters alone could not fulfill the requirement of prediction model for forecasting yield of rice. However, integrating plant characteristics and climatological factors together in the same model gave reliable and predictive model for forecasting yield in rice which was evident from increased R^2 values.

Lalitha *et al.*, (2000) studied the influence of temperature on duration of tillering in lowland rice varieties in Andhra Pradesh. They reported that temperature prevailing during tillering period controlled its duration. Daily mean temperature exceeding 26 °C during period of tillering restricted the durations to 5 weeks after planting whereas the temperature in the range 22.9 to 25.8 °C

increased the duration upto 8 weeks. They concluded that the period taken to attain maximum tillering stage could be predicted by using degree day concept.

Lansigan *et al.*, (2000) studied agronomic impacts of climate variability on rice production in the Philippines. Typhoons, floods, and droughts caused 82.4% of the total Philippine rice losses from 1970 to 1990. Long-term climate variability influenced sowing date, crop duration, crop yield, and the management practices adapted in rice production. Short-term weather episodes affected yield by inducing changes in temperature, potential evapotranspiration, and moisture availability. They reported that degree of vulnerability of crops to climate variability depends mainly on the development stage of the crops at the time of weather aberration. The vulnerability and risk of crop production due to weather fluctuations and climate variability could be minimized if future weather variation could be adequately predicted and a suitable process-based ecophysiological crop yield forecasting model used to produce real-time yield forecasts.

Sahu *et al.*, (2000) studied the effect of rainfall on groundnut productivity in Junagadh region. The rainfall data for 32 years (1968-99) of Junagadh was analysed critically to reveal the rainfall pattern of the region where groundnut was predominantly grown in the monsoon season. The effect of rainfall on the groundnut productivity of the district was analysed and discussed. They reported that all the rainfall features except the monthly variability significantly influenced the yield of groundnut when long period rainfall was considered. In drought years the total rainfall had significant effect on yield, whereas in wet years only weekly rainfall and rainy days had significant effect on the yield of groundnut.

Shrivastava *et al.*, (2000) analysed rainfall data for annual, seasonal, monthly and weekly periods to evolve a rainfall-based cropping system with minimum risks which utilizes rainfall efficiently for increased production for Jabalpur region. They reported that the 2nd or 3rd week of June was the best period for sowing of early paddy and maize crops.

Agrawal *et al.*, (2001) used multiple regression to develop yield forecast models based on weather variables and agricultural inputs on agro-climatic zone basis for wheat and rice in Madhya Pradesh. The results indicated that reliable yield forecasts could be obtained using 15 years data when crops were 12 weeks old, i.e. 2 months before harvest. The methodology worked even if partial data for various districts or complete data for some districts within the zone were missing.

Campbell *et al.*, (2001) studied seasonal variation in radiation use efficiency of irrigated rice at Texas. Field experiments were conducted in 1998 and 1999 to evaluate RUE as a function of growth and development in a commercial rice field in Texas. Post-anthesis RUE was lower than pre-anthesis RUE. They concluded that RUE must be changed for differing LAI and for pre- and post-anthesis periods to use it as a model parameter.

Sarangi *et al.*, (2001) developed a regression model to forecast transplanted summer rice grain yield using growth and environmental parameters in Orissa. They reported that the grain yield was positively and significantly correlated with growth characters. The grain yield was poorly correlated with temperature sum from flowering to ripening but strongly correlated with sum of bright sunshine hours during entire growth period. They concluded that on the basis of data

available till flowering, this regression model could predict the yields of rice grain with 90-95% confidence.

Sarmah and Handique (2001) utilised multiple regression approach for preharvest forecasting of winter rice productivity for Jorhat district of Assam. They reported that weekly total rainfall, average weekly maximum temperature, average weekly bright sunshine hours, average weekly morning and evening relative humidity exhibited positive effect on rice yield. They also reported that the best time for rice yield forecasting was in the 43rd standard meteorological week, i.e. 4th week of October.

Fu *et al.*, (2002) developed a forecasting model for air temperature, through the time series analysis, and applied it in predicting the water requirements of well irrigated rice in China.

Kandiannan *et al.*, (2002) developed crop-weather model for prediction of rice yield using an empirical-statistical technique at Coimbatore. Four predictors were retained in the final model with an R^2 value of 0.92. The model with minimum parameters $Y = 22119.5758 + 19.6898 X_1 - 150.9261 X_2 - 1126.7501 X_4 + 0.7179 X_7$ could be used to predict the first season rice yield at Coimbatore. They reported that inclusion of solar radiation enhanced the R^2 value considerably.

Yu *et al.*, (2002) simulated rice biomass accumulation by an extended logistic model $X = f(p, t)$ including influence of meteorological factors in China. They reported that the model accounted for 96.6% of the variance of rice biomass

on the basis of sowing dates, developmental stage, solar radiation and temperature.

Goswami *et al.*, (2003) calculated growing degree days for rice and wheat in Ludhiana by summing mean daily temperature above base temperatures. The base temperature for wheat was 4.4 °C and 10 °C for rice. The sowing of rice nursery was done on May 12 and the transplanting was undertaken 30 DAS. Tillering started 39 DAS. The two rice varieties (PR 111 and PR 114) attained the physiological maturity on 124 and 128 DAS respectively. They reported that the phenological events followed the same trend irrespective of variety. GDD for PR 114 were relatively higher due to longer duration of the variety.

Jaybhaye *et al.*, (2003) studied the relationship of monsoon rainfall with yield of rice crop at Igatpuri. Rice yields showed significant correlations with quantum of monsoon rainfall ($r = 0.48$) and monsoon rainy days ($r = 0.80$). They reported that precipitation received during critical anthesis and reproductive stage was related with yield.

Mahale and Dhane (2003) analysed rainfall to evolve rainfall based profitable cropping system in relation to paddy at Panvel. Weibull formula was used for calculating rainfall probability. They reported that planning should be done to sow paddy crop in 23rd or 24th week. They suggested direct sowing or *rabi* crop immediately after the harvest of *kharif* crop to make use of residual moisture.

Mandal and Ghosh (2003) developed and validated a model based on correlation of thermal time indices with yield of four varieties of hybrid rice in

Terai zone of West Bengal. There was an increasing trend in grain yield for each cultivar with delay in planting from 5th July to 5th August. They reported that summation of bright sunshine hours and GDD during the ripening period (flowering to maturity) had positive and negative effects, respectively, on grain yield. They also reported that grain yield was positively correlated with GDD, HTU, PTU, and summation of BSS during the fourth leaf emergence and flowering stages for all sowing dates.

Nigam and Mishra (2003) studied the correlation between weather factors and rice grain yield in the tarai region of Pantnagar. They reported that effect of weather variables vary according to the time of transplanting. Under early transplanting conditions, the number of sunshine hours was significantly correlated with rice yield. Minimum temperature, maximum relative humidity, minimum relative humidity and rainfall were negatively correlated with yield, whereas the number of rainy days, wind velocity and evaporation were positively correlated with yield. Under timely transplanting conditions, the number of sunshine hours and maximum temperature showed a significant correlation with yield. Yield was negatively correlated with minimum temperature, maximum relative humidity, minimum relative humidity and rainfall, but was positively correlated with the number of rainy days, wind velocity and evaporation. Under late transplanting conditions, only the number of sunshine hours was significantly correlated with yield.

Patel and Vaishnav (2003) evaluated different statistical approaches to study the effect of rainfall on groundnut yield in dry farming areas of Gujarat at Anand.

Maximum variation (34%) in yield was accounted for by cubic curve fitting. None of the regression coefficients in any model were significant. They reported that rainfall at pegging stage had significant influence on yield. They further reported that a period of 7 days consisting 36-42 and 43-49 days after sowing was significantly associated with yield. They also suggested a model to predict groundnut yield of bunch varieties grown in dry farming areas of Saurashtra.

Pathak *et al.*, (2003) studied the trends of climatic potential and on farm yields of rice and wheat in the Indo-Gangetic plains. They reported that maximum temperature had detrimental effect during reproductive stage of the crop. The decrease in radiation and increase in minimum temperature were the reasons for the yield decline. They concluded that rise in maximum temperature above normal has beneficial effect in general. They also reported that increase in bright sunshine was beneficial in general throughout the crop growth period.

Ramakrishna *et al.*, (2003) developed regression model based on weather indices to estimate annual foodgrain production of India at Hyderabad. They reported that model using monthly rainfall indices and southern oscillation index gave more accurate estimates than those based on all India monsoon seasonal rainfall amounts alone. The above model predicted the annual foodgrain production in October, nearly eight months before the final official estimates.

Rao *et al.*, (2003) developed a simple model based on weather indices to obtain accurate estimates of annual rice production before the crop harvest at Hyderabad. The model could be used for advance estimation of rice production in India using weather indices.

Singh (2003) studied the effect of planting time and varieties (Ashwini, Pant V4 and Mahsoori) on the growth and performance of rice at IARI. Thermal time requirement was found positively associated with the duration of variety. The superiority of variety varied differently with individual parameters of growth and development. Longer duration variety Mahsoori proved greater producer of biomass. He reported that time taken to attain various phenological stages was shortened by delay in planting. He also reported that delay in planting caused reduction in yield parameters.

Yang and Damme (2003) analysed soil and climatic data from the 6 ecological regions for an environmental factor evaluation of crop growing in different agro-ecological zones in China. They reported that daytime temperature in most farming regions was suitable for the growth and production of the existing crops. Available soil water was the most limiting factor for crop growth in most regions except the moistest part of southern China. The growing period and temperature did not limit crop growth in most regions of China except in the Qinghai-Xizang Plateau. A comparison of the four crop development stages showed that in most areas of water stress, mid-season water stress was the most serious, followed by water stress at the initial stage of growth. During the last stage of growth, water stress was lightest or sometimes absent.

Chandran and Prajneshu (2004a, 2004b) used multiple linear regression (MLR) technique for modelling effect of sunshine hours and mean temperature on rice tiller production and rice productivity of Faizabad district. They reported that additive non-parametric regression approach could also be used to model the

individual effects of sunshine hours and mean temperature on rice tiller production. Comparison with conventional multiple linear regression approach showed superiority of proposed methodology over conventional techniques for the data under consideration

Dixit *et al.*, (2004a, 2004b) studied the influence of sowing time on phenology and growth of rice in Maharashtra. They reported that late sown crop matured early because panicle initiation and flowering was delayed in early sown crop. They further reported that late sown crop produced highest yield as it experienced higher GDD during flowering stage. They concluded that rice should be sown on 20th and 25th June for best performance with regard to yield and yield attributing characters in South Konkan region of Maharashtra.

Jeyaraman and Balasubramanian (2004) studied the effect of flood water on rice at Coimbatore. They suggested to adjust cropping schedule such that flowering do not coincide with cyclone/ rainfall period. They also suggested cyclone flood management at various growth stages for rice crop which should be followed to minimise the loss and thereby maximising the economic benefits.

Khistaria *et al.*, (2004) used regression models to forecast wheat yield from weather variables in Rajkot district. They used four approaches for forecasting yield. Among the different models fitted under four approaches, two models were identified as preharvest forecast models for Rajkot district, first from using weekwise original weather variables of 14 weeks and the second using generated variables (correlation coefficients as weight) of 14 weeks. Both the models provided forecast 6 weeks before expected harvest of wheat crop. Among these

two models, the model using original weekwise weather variables was found to be superior because of minimum standard error and high R^2 (>95%) and less deviation of simulated forecast from actual yields.

Parmar *et al.*, (2004) used regression technique to develop preharvest forecast models for groundnut using rainfall variable for Saurashtra at Junagadh. They developed five different models using weekly rainfall for five districts of Saurashtra which exhibited R^2 values more than 0.80. They reported that the quantum of influence of the rainfall variable differed over the districts. They further reported that sufficient rainfall during flowering and peg initiation was very crucial for obtaining high crop yield.

Paswan *et al.*, (2004) fitted three mechanistic growth models, i.e. logistics, Gompertz and monomolecular for rice productivity in Bihar. They reported that the logistic growth model was better than the other two models in analysing rice productivity in Bihar.

Patel and Sastri (2004) studied the effect of drought on rice yield in Madhya Pradesh. In broadcast system there was competition among the rice plants for water and nutrition and hence the yield decreased. Under prolonged drought condition weeding the field increased the crop yield by reducing the evapotranspiration losses. They reported that weeding at the beginning of reproductive stage increased the yield by about 0.30 t ha^{-1} .

Peng *et al.*, (2004) studied the effect of higher night temperature from global warming on rice yield decline in Philippines. They reported that the grain yield declined by 10% for each 1°C increase in growing season minimum temperature

in the dry season, whereas the effect of maximum temperature on crop yield was insignificant. They concluded that increased nighttime temperature associated with global warming decreased rice yields.

Reddy *et al.*, (2004) conducted an experiment to assess the temperature requirement in terms of degree days to attain various growth phases in rice at Hyderabad. A uniform package of practices were adopted by leaving only weather as variable. They reported that delayed planting resulted in lower GDD for flowering and maturity. Though total duration widely varied within variety, they came to maturity by accumulating certain amount of growing degree days regardless of the date of planting. They concluded that the important phenophases of rice could be assessed by using growing degree days.

Saha *et al.*, (2004) studied rainfall distribution pattern and its implication in rainfed rice planning for coastal Orissa at Mohanpur. They reported that the total amount and distribution pattern of monsoon rain was the most critical weather component in rainfed rice. The long duration varieties could be sown in lowlands by direct seeding during 21st to 22nd MSW as rain received during this period was sufficient for land preparation and sowing of rice crop. Sowing of upland rice should be done in 24th MSW as early monsoon rain might help for quick establishment of rice crop. They suggested for a second crop of horsegram or mustard immediately after the harvest of upland rice.

Shimono *et al.*, (2004) studied the responses of leaf photosynthesis and plant water status in rice to low water temperature at different growth stages in Japan. They reported that the light-saturated leaf photosynthesis during the reproductive

growth period had a significant positive correlation with water temperature. They also reported that no significant relation between them was observed during the vegetative growth period.

Subrahmaniyan *et al.*, (2004) studied the effect of relative temperature disparity (RTD) on rice yield using correlation technique at Coimbatore. The higher RTD value was an indication of a higher mean maximum temperature and relatively low mean minimum temperature. There was strong correlation between RTD and rice grain yield at reproductive stage ($r = 0.60^{**}$) and at maturity ($r=0.72^{**}$). They reported that higher RTD do not have any influence during vegetative stage but during reproductive and maturity stages it had positive influence on yield.

Tripathi (2004) designed a low cost lysimeter to study evapotranspiration and crop coefficients for rice in tarai region of Uttaranchal. The fifth degree polynomial that fitted the data accounted for 97% of the variability in ET. A high crop coefficient under shallow water tables was a result of both high ET and underestimation of ET. He reported that rice yield was correlated with evapotranspiration. He concluded that crop coefficient depended more on canopy growth characteristics than on water table.

Varmola *et al.* (2004) fitted a pre-harvest forecast model for wheat yield based on weather parameters using stepwise regression technique at Junagadh. Models based on original weather variables with week-wise and the crop stage-wise approach and the generated variables taking week number and correlation coefficient as weight were tried. They proposed the 14 weeks model based on

generated weather variables using correlation coefficient as weight to predict the wheat yield to forecast the yield 5-6 weeks before the harvest of the crop in the district.

Varmora *et al.*, (2004) fitted a pre-harvest forecast model for wheat yield based on weather parameters using stepwise regression technique to study the influence of weather parameters and time trend on wheat crop yield of Junagadh district. The stepwise regression approach was used taking weekwise, stagewise original weather parameters and time trend as independent variables and crop productivity as dependent variable. They observed positive and significant influence of time trend, total rainfall, maximum temperatures of 7th and 10th weeks and morning relative humidity of 10th week. Negative significant influence of maximum temperatures of 3rd, 5th and 9th weeks and sunshine hours of 9th week was observed on wheat yield. The R² value was 98%. The predicted yield showed 5.85 to 9.05 per cent deviations from observed yield of Junagadh district.

Confalonieri *et al.*, (2005) calibrated and validated two micrometeorological models (a mechanistic and an empirical one) for the simulation of thermal profile related to water and near water temperatures in some rice fields located near Milano, Italy. Both the models need as input data only daily values of maximum and minimum temperatures and therefore are suitable for agroecological operational purposes. The comparison between measured and simulated temperature values indicated that both the models were able to reproduce the effect of water on temperature with RMSE of 14% for the mechanistic model and 7% for the empirical one and modelling efficiency was always positive.

Hundal *et al.*, (2005) developed regression models for prediction of growth and yield of rice using temperature, photoperiod and sunshine duration at Ludhiana. Leaf area index, dry matter accumulation and grain yield were related with accumulated GDD, HTU and PTU in linear as well as exponential relationships. They observed positive relationship between GDD, HTU, PTU and total dry matter. They obtained exponential regression equation between LAI and three agroclimatic indices and linear regression equation obtained between TDM and three agroclimatic indices which could be used for predicting periodic LAI and TDM accumulation of rice using daily information on temperature, photoperiod and sunshine duration during the crop season.

Khan and Bhagat (2005) studied the effects of sowing date and weather on the growth and yield of rice cv. Annanda in Madhya Pradesh. Correlation coefficients were positive between leaf area index and crop growth rate and sunshine hours at the vegetative phase and rainfall at the reproductive phase. They reported that the yield and yield attributes were positively correlated with rainfall and sunshine hours at the reproductive and grain filling stages, and negatively correlated with maximum and minimum temperature at the grain filling stage.

Khan *et al.*, (2005) developed regression model to predict grain yield of kharif rice cultivars (Kshitish, IET-4094; Lal Swarna; and IR36) based on thermal, heliothermal and photothermal units prevailing during different phases of growth at Mohanpur. They reported that among the models developed, the one that measures the linear function of accumulated heliothermal units from

transplanting to 100% anthesis, and photothermal unit from transplanting to 50% anthesis to the variation in the yield was the best model.

Murthy *et al.*, (2005) studied resource capture mechanism to promote nursery growth in paddy for higher yield at Hyderabad. They reported that increased night temperature resulted in vigorous and tall seedlings. Modifications of environmental resource of nursery not only produced robust seedlings but these modifications enhanced the mean production by 5 quintals ha⁻¹. They concluded that significant increase in rice could be attained by capturing the resources and storing them within the canopy for increased ambient canopy temperature through modified nursery management.

Patel (2005) used stepwise regression technique for preharvest forecasting of rice yield in Kheda district. He used models based on original weather variables with weekwise and the crop stagewise approach and the generated variables taking week number and correlation coefficient as weight were also tried. Weekwise approach using original weather variables was found superior over the other approaches. This approach provided suitable pre-harvest forecasting model of Kheda district, four week before expected harvest (i.e. 3rd week of September).

Ray and Butala (2005) built empirical relations between crop yield and rainfall parameters using stepwise regression technique to study quantitative relationship between rainfall based parameters and district level yield of groundnut, cotton and bajra in Gujarat. They reported that number of rainy days and seasonal rainfall were mostly related to crop yield. They concluded that the

rainfall based parameters were very efficient in predicting yields for *kharif* crops in Gujarat. The empirical based models predicted the yield trends correctly.

Roel *et al.*, (2005) evaluated two alternative thermal unit models threshold water temperature (TNHB) T_b and IDD for the quantification of low water temperature effects on rice yield in California. Results showed that the effect of low water temperature were much greater than were apparent from the visual appearance of the rice plants. A logistic curve model based on TNHB 20 °C provided the best fit to the aggregated data.

Sreenivas *et al.*, (2005) studied the influence of weather parameters on yield of lowland rice using correlation technique at Rajendranagar. They reported that grain yield was positively correlated with accumulated growing degree-days at the reproductive phase during *kharif* and with bright sunshine hours during all the 3 phenological phases of rice during *rabi*. They concluded that an accumulated growing degree days of 422 °C day and 9.9 hours of bright sunshine during reproductive phase for *kharif* and *rabi* seasons were optimum for realising higher grain yield.

Panduranga *et al.*, (2006) studied effect of climate change on yield of food crops including rice. Both changes in amount and distribution of rainfall had resulted in changes in cropped area and production in the state. The productivity of paddy, jowar and groundnut increased while redgram remained same. They concluded that increase in rainfall resulted in increased paddy yield in Tumkur district of Karnataka.

Saha (2006) characterised rainwater deficit at different growth stages of rice crop for timely and delayed transplanting at Mohanpur. He reported that delayed transplanting from 28th week resulted in rainwater deficit in vegetative, reproductive and maturity stages resulting in low yield. Temporal pattern of rainfall distribution during crop growth stages was similar across all the stations.

Singh *et al.*, (2006) studied spatial and temporal changes in area, production and productivity of rice in Punjab. The average productivity of the crop during the 30 year period (1970-71 to 1999-2000) was highest in the district of Ludhiana (3498 kg ha⁻¹) followed by Sangrur (3296 kg ha⁻¹). The increase in both area and production was more conspicuous in the middle decade of 1980-81 to 1989-90 as compared to other two decades. They reported that increase in production was due to increase in area as well as enhanced productivity.

Parmar *et al.*, (2007) developed regression model for groundnut productivity in Junagadh district. He used five different approaches viz., seasonal rainfall, monthly rainfall, fortnightly rainfall, weekly rainfall and crop phasewise rainfall. They inferred that rainfall during presowing, flowering and peg initiation and full pegging to pod development crop phases had significant positive effect and therefore identified as most critical periods of rainfall for good groundnut yield in Junagadh district. The model using weekly rainfall upto 15th week variables as a set of predictor variables had the highest predictability with $R^2=0.68$. They concluded that rainfall received during shorter interval (weekwise) had higher influence as compared to seasonal, monthly, fortnightly and stagewise criteria.

Pandey *et al.*, (2007) carried out correlation study to assess influence of environmental parameters on mustard yield and quality. Results revealed that bright sunshine hours and maximum temperature had significant positive correlations during flowering and pod development phases while minimum temperature had significant negative correlations. Flowering and pod development phases were found to be highly sensitive to weather parameters. Based on significant association between weather parameters and seed yield of mustard a regression equation was developed for yield prediction. The model developed with temperature range during P2 phase was preferred as it explained highest (92%) variation in the seed yield.

Sahu *et al.*, (2007) determined sowing time for chickpea in Saurashtra using thermal indices. Three thermal use efficiencies such as HUE, HTUE and PTUE were correlated with grain yield. They concluded that chickpea varieties viz. Dahod yellow, GG-1 and KAK-2 should be sown from 15th to 25th October for higher yield due to higher efficiencies of utilising available heat and sunlight during the growth period.

The research work carried out by various workers on effect of different weather parameters on rice growth and yield is summarised below in Table 2.1.

Table 2.1: Research work on effects of weather during different phenological stages of rice crop

S. No.	Crop stage	Sensitive to weather variable					
		BSS	RF	MaxT	MinT	RHM	RHE
1	Seedling	Jain <i>et al.</i> , (1980), Aggrawal <i>et al.</i> , (1986), Viswambharan <i>et al.</i> , (1989), Summerfield <i>et al.</i> , (1992), Mandal & Ghosh (2003), Gaouna <i>et al.</i> , (2004), Sreenivas <i>et al.</i> , (2005)	Das (1971), Huda <i>et al.</i> , (1975), Prabhakaran (1985), Aggrawal <i>et al.</i> , (1986), Reddy & Reddy (1992), Saha (2006)	Huda <i>et al.</i> , (1975), Munakata (1976), Jain <i>et al.</i> , (1980), Aggrawal <i>et al.</i> , (1986), Collinson <i>et al.</i> , (1995), Yin <i>et al.</i> , (1996b), Mahmood (1997), Haloi & Dey (2000)	Huda <i>et al.</i> , (1975), Dingkuhn <i>et al.</i> , (1995), Yin <i>et al.</i> , (1996b), Murthy <i>et al.</i> , (2005)	Aggrawal <i>et al.</i> , (1986), Reddy & Reddy (1992)	Jain <i>et al.</i> , (1980), Aggrawal <i>et al.</i> , (1986), Haloi & Dey (2000)
2	Active tillering	Barany (1971), Munakata (1976), Jain <i>et al.</i> , (1980), Aggrawal <i>et al.</i> , (1986), Kawakata & Yajima (1995), Yin & Kropff (1996), Rai and Chandras (1997), Haloi & Dey (2000), Yu <i>et al.</i> , (2001)	Prabhakaran (1985), Aggrawal <i>et al.</i> , (1986), Viswambharan <i>et al.</i> , (1987), Jansen (1990), Murai <i>et al.</i> , (1991)	Huda <i>et al.</i> , (1975), Munakata (1976), Jain <i>et al.</i> , (1980), Aggrawal <i>et al.</i> , (1986), Shi (1990), Summerfield <i>et al.</i> , (1992), Collinson <i>et al.</i> , (1995), Yin <i>et al.</i> , (1996b), Mahmood (1997), Haloi & Dey (2000), Mandal & Ghosh (2003)	Munakata (1976), Murai <i>et al.</i> , (1991), Dingkuhn <i>et al.</i> , (1995), Yin <i>et al.</i> , (1996b), Kandinan <i>et al.</i> , (2002)	Aggrawal <i>et al.</i> , (1986), Shi (1990)	Jain <i>et al.</i> , (1980), Aggrawal <i>et al.</i> , (1986), Haloi & Dey (2000)
3	Vegetative lag	Barany (1971), Jain <i>et al.</i> , (1980), Aggrawal <i>et al.</i> , (1986), Kawakata & Yajima (1995), Gaouna <i>et al.</i> , (2004), Sreenivas <i>et al.</i> , (2005)	Das (1971), Huda <i>et al.</i> , (1975), Aggrawal <i>et al.</i> , (1986), Reddy & Reddy (1992), Saha (2006)	Jain <i>et al.</i> , (1980), Aggrawal <i>et al.</i> , (1986), Mahmood (1997), Haloi & Dey (2000)	Kandinan <i>et al.</i> , (2002)	Aggrawal <i>et al.</i> , (1986)	Jain <i>et al.</i> , (1980), Aggrawal <i>et al.</i> , (1986), Haloi & Dey (2000)
4	Flowering	Barany (1971), Ghosh <i>et al.</i> , (1973), IRRI (1975), Munakata (1976), Yashida & Parao (1976), Aggrawal <i>et al.</i> , (1986), Viswambharan <i>et al.</i> , (1989), Kawakata & Yajima (1995), Haloi & Dey (2000), Yu <i>et al.</i> , (2001), Kandinan <i>et al.</i> , (2002), Mandal & Ghosh (2003), Khan & Bhagat (2005), Sreenivas <i>et al.</i> , (2005)	Das (1971), Van (1974), Lomas (1985), Prabhakaran (1985), Aggrawal <i>et al.</i> , (1986), Viswambharan <i>et al.</i> , (1989), Saha (2006)	Ghosh <i>et al.</i> , (1973), Huda <i>et al.</i> , (1975), Yashida & Parao (1976), Chaudhary & Sodhi (1979), Aggrawal <i>et al.</i> , (1986), Reddy & Reddy (1992), Singh & Padilla (1995), Yin <i>et al.</i> , (1996a), Mahmood (1997), Shimono <i>et al.</i> , (2004), Sreenivas <i>et al.</i> , (2005)	Huda <i>et al.</i> , (1975), Yashida & Parao (1976), Chaudhary & Sodhi (1979), Jacob & Pearson (1994), Dingkuhn <i>et al.</i> , (1995), Yin <i>et al.</i> , (1996a), Kandinan <i>et al.</i> , (2002), Yajima (2005)	Aggrawal <i>et al.</i> , (1986), Reddy & Reddy (1992)	Jain <i>et al.</i> , (1980), Aggrawal <i>et al.</i> , (1986), Haloi & Dey (2000)
5	Grain development	IRRI (1975), Yashida & Parao (1976), Jain <i>et al.</i> , (1980), McMennamy (1980), Aggrawal <i>et al.</i> , (1986), Viswambharan <i>et al.</i> , (1989), Haloi & Dey (2000), Yu <i>et al.</i> , (2001), Kandinan <i>et al.</i> , (2002), Mandal & Ghosh (2003), Gaouna <i>et al.</i> , (2004), Khan & Bhagat (2005), Sreenivas <i>et al.</i> , (2005)	Ghosh <i>et al.</i> , (1973), Van (1974), Huda <i>et al.</i> , (1975), IRRI (1977), Aggrawal <i>et al.</i> , (1986), Viswambharan <i>et al.</i> , (1989), Saha (2006)	Jain <i>et al.</i> , (1980), Aggrawal <i>et al.</i> , (1986), Lin (1988), Jansen (1990), Mahmood (1997), Haloi & Dey (2000), Mandal & Ghosh (2003)	Huda <i>et al.</i> , (1975), Lin (1988)	Huda <i>et al.</i> , (1975), Jain <i>et al.</i> , (1980), Haloi & Dey (2000), Sarmah & Handique (2001), Nigam & Mishra (2003)	Huda <i>et al.</i> , (1975), Jain <i>et al.</i> , (1980), Aggrawal <i>et al.</i> , (1986), Haloi & Dey (2000), Sarmah & Handique (2001), Nigam & Mishra (2003)

3. MATERIALS AND METHODS

The present study was undertaken with a view to predict the rice yield using crop simulation models and develop appropriate agrometeorological model for prediction of rice yield in Gujarat. Two crop growth simulation models viz. DSSAT and WOFOST were used for calibration and validation under Gujarat conditions. The efforts were also made to develop suitable agrometeorological model for predicting the yield of rice by using combined effects of different weather parameters viz. rainfall, bright sunshine hours, maximum and minimum temperature and morning and afternoon relative humidity on rice yield. For the present investigation the major rice growing districts of Gujarat viz., Ahmedabad, Baroda, Bulsar, Kheda, Panchmahal, Sabarkantha and Surat were selected.

Weather is a major factor affecting crop production in advanced agricultural systems. Weather is a primary determinant of agricultural production. There are many weather variables like rainfall, temperature, relative humidity, wind speed and sunshine hours that constitute the major climatic influence contributing to the growth and development of the crop directly or indirectly. The resultant response is manifested in the final yield. Other factors which are not related to weather are summed up as effects of technological advances. These effects are also of paramount importance in the crop productivity.

Crop simulation models can predict responses to large variations in weather. At every point of application weather data are the most important input. The main goal of most applications of crop models is to predict commercial output

3.1 DATA ACQUISITION

Considering the specific objectives of the study, rice yield data for Ahmedabad, Baroda, Bulsar, Kheda, Panchmahal, Sabarkantha and Surat districts for the years 1980 to 2005 were extracted from District wise Area, Production & Yield of Important Food & Non-food Crops in Gujarat State, Directorate of Agriculture, Gujarat. The complete meteorological data set of same periods of Arnej, Khandha, Navsari, Anand, Godhara, Khedbrahma and Surat stations, a representative centre of each district were collected from the data bank maintained by the Department of Agricultural Meteorology, Anand Agricultural University, Anand for the present study.

The meteorological records for the years 1980 to 1988 for Arnej, 1980 to 1993 for Khandha, 1980 to 1988 for Godhara, 1980 to 1991 for Khedbrahma and 1980 to 1987 for Surat were not available and hence, were not included in the study. Weekly averaged data of weather variables viz., (1) bright sunshine hours (2) maximum temperature (3) minimum temperature (4) morning relative humidity (5) afternoon relative humidity and (6) weekly total rainfall were collected for the period of the growing season of rice in Gujarat for the years under consideration. Daily weather data of all the stations for 2004 and 2005 were collected for crop simulation modelling. Details regarding availability of yield and meteorological parameters is given in Table 3.1.

Table 3.1: Details regarding yield and meteorological data availability

S. No.	District	Station	Yield data available	Meteorological data available
1	Ahmedabad	Arnej	1980 – 2005	1989 – 2005
2	Baroda	Khandha	1980 – 2005	1994 – 2005
3	Bulsar	Navsari	1980 – 2005	1980 – 2005
4	Kheda	Anand	1980 – 2005	1980 – 2005
5	Panchmahal	Godhara	1980 – 2005	1989 – 2005
6	Sabarkantha	Khedbrahma	1980 – 2005	1992 – 2005
7	Surat	Surat	1980 – 2005	1988 – 2005

3.2 EVALUATION OF CROP GROWTH SIMULATION MODEL

Crop growth is often described by an empirical model, consisting of a regression equation (e.g. a logistic function). Sometimes, environmental variables, such as radiation and rainfall, are incorporated in the regression. These models can generate accurate yield predictions, especially when the regression parameters are estimated on the basis of extensive sets of experimental data. These predictions however, are restricted to the environment on which the regression is based. Furthermore, these empirical/descriptive models give little insight into causes of the observed yield variation.

Schematic overview of crop growth monitoring system is presented in Figure 3.1.

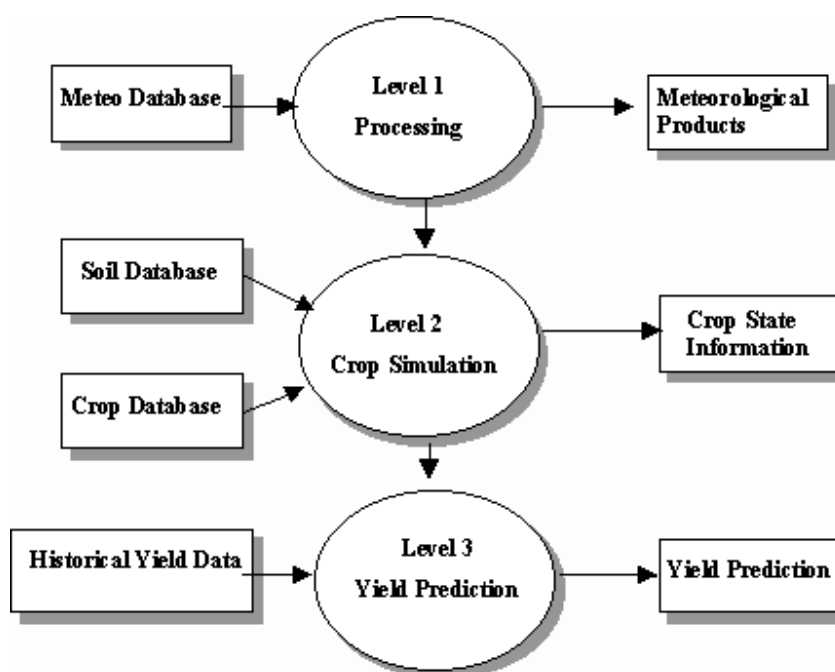


Figure 3.1: Schematic overview of the Crop Growth Monitoring System

Two crop growth simulation models were also evaluated for testing their worth for forecasting yield. The crop growth simulation models Decision Support System for Agrotechnology Transfer (DSSAT) documented by Jones *et al.*, (2003) and the WO^lrd FO^od STudy (WOFOST) developed by Diepen *et al.* (1989) at Wageningen were evaluated for the said purpose. The DSSAT and WOFOST models are described in detail.

3.2.1 DSSAT (Decision Support System for Agrotechnology Transfer)

DSSAT was developed through collaboration between scientists at the University of Florida, the University of Georgia, University of Guelph, University of Hawaii, the International Center for Soil Fertility and Agricultural Development, Iowa State University and other scientists associated with International Consortium for Agricultural Systems Applications (ICASA).

The Decision Support System for Agrotechnology Transfer (DSSAT) has been in use for more than 15 years by researchers in over 100 countries worldwide. DSSAT is a microcomputer software program combining crop soil and weather data bases and programs to manage them, with crop models and application programs, to simulate multi-year outcomes of crop management strategies. As a software package integrating the effects of soil, crop phenotype, weather and management options, DSSAT allows users to ask "what if" questions and simulate results by conducting, in minutes on a desktop computer, experiments which would consume a significant part of an agronomist's career.

DSSAT also provides for validation of crop model outputs; thus allowing users to compare simulated outcomes with observed results. Crop model validation is accomplished by inputting the user's minimum data, running the model, and comparing outputs. By simulating probable outcomes of crop management strategies, DSSAT offers users information with which to rapidly appraise new crops, products, and practices for adoption.

3.2.1.1 MINIMUM DATA SET

The minimum data set (MDS) refers to a minimum set of data required to run the crop models and validate the outputs. Validation requires:

1. Site weather data for the duration of the growing season,
2. Site soil data, and
3. Management and experimental data for the experiment.

3.2.1.1.1 MDS WEATHER DATA

The minimum weather data required includes:

1. Latitude and longitude of the weather station,
2. Daily values of incoming solar radiation (MJ/m²-day),
3. Maximum and minimum air temperature (°C), and
4. Rainfall (mm).

Dry and wet bulb temperatures and wind speed may also be included as optional data.

The length of weather records for validation must, at minimum, cover the duration of the experiment and preferably should begin a few weeks before planting and continue a few weeks after harvest so that "what-if" type analyses may be performed.

Complete set of daily weather data of all the stations for 2004 and 2005 were collected from the databank maintained by the Department of Agricultural Meteorology, Anand Agricultural University, Anand. Daily values of incoming solar radiation were computed from observed value of bright sunshine hours using solar radiation calculator (Glarner, 2006) which uses following formula.

$$Q_I = 1.974 * N (0.25 + 0.5 n/N)$$

Where

Q_I = incoming solar radiation at a place (MJ/m²-day)

n = bright sunshine duration (hours)

N = maximum possible sunshine duration of a place (hours)

Details regarding latitude and longitude of different weather stations and availability of daily weather data for DSSAT is given in Table 3.2.

Table 3.2: Details regarding daily weather data

S. No.	District	Station	Latitude (°)	Longitude (°)	Altitude (m)	Meteorological data available
1	Ahmedabad	Arnej	22.35	72.17	32	2004 – 2005
2	Baroda	Khandha	22.02	73.00	28	2004 – 2005
3	Bulsar	Navsari	20.57	72.54	10	2004 – 2005
4	Kheda	Anand	22.35	72.58	45	2004 – 2005
5	Panchmahal	Godhara	20.57	72.54	110	2004 – 2005
6	Sabarkantha	Khedbrahma	24.03	73.04	218	2004 – 2005
7	Surat	Surat	20.12	72.52	12	2004 – 2005

3.2.1.1.2 MDS SOIL DATA

Desired soil data includes soil classification (SCS), surface slope, color, permeability, and drainage class. Soil profile data by soil horizons include:

1. Soil depth (cm),
2. Lower limit of soil moisture ($\text{cm}^3 \text{cm}^{-3}$),
3. Upper limit of drained soil moisture ($\text{cm}^3 \text{cm}^{-3}$),
4. Upper limit of saturated soil moisture ($\text{cm}^3 \text{cm}^{-3}$),
5. Root growth factor (0.0 to 1.0),
6. Saturated hydraulic conductivity of macropore (cm hr^{-1}),
7. Bulk density of moist soil (g cm^{-3}),
8. Organic carbon (%),
9. Clay ($<0.002 \text{ mm}$) (%),
10. Silt ($0.05 \text{ to } 0.002 \text{ mm}$) (%),
11. Coarse fraction ($>2 \text{ mm}$) (%),
12. Total nitrogen (%),
13. pH in water,
14. pH in buffer, and
15. Cation exchange capacity (cmol kg^{-1})

The soil data of inbuilt default file in the model for deep sandy loam soil IBSNAT No. IB00000007 code: SL and soil depth of 210 cm was used.

3.2.1.1.3 MANAGEMENT AND EXPERIMENTAL DATA

Management data includes information on planting date, dates when soil conditions were measured prior to planting, planting density, row spacing,

planting depth, crop variety, irrigation, and fertilizer practices. This data are needed for both model validation and strategy evaluation. In addition to site soil and weather data, experimental data includes crop growth data, soil water and fertility measurements. This data are needed for model validation.

Details regarding MDS management data including recommended package of practices for the rice crop are presented in Table 3.3.

Table 3.3: Details regarding management data for DSSAT

Crop variety	Rice, GR-11
Initial conditions measurement date	190 (09 th July)
Planting date	196(15 th July)
Planting density	75
Row spacing	20 cm
Planting depth	5 cm
Planting Method	Transplanting
Date of irrigation	196 (15 th July) 230 (18 th August) 264 (21 st September) 276 (3 rd October)
Date of fertiliser application	196 (15 th July) 230 (18 th August) 264 (21 st September)

3.2.1.2 MODULES

The Cropping System Model (CSM) incorporates all crops as modules using a single soil model and a single weather module. The cropping system model now contains models of 17 crops derived from the old DSSAT CROPGRO and CERES models. The major modules are:

1. **Land Module**
2. **Management Module**

3. **Soil module** - A soil water balance sub-module and two soil nitrogen / organic matter modules.
4. **Weather module** - Reads or generates daily weather data
5. **Soil-Plant-Atmosphere module** - Deals with competition for light and water among the soil, plants, and atmosphere
6. **CROP GROwth (CROPGRO) plant growth module**
 - 6.1. Grain Legumes - Soybean, peanut, drybean, chickpea, cowpea, velvetbean, and faba bean
 - 6.2. Vegetables - Pepper, cabbage, tomato
 - 6.3. Grasses – Bahia, brachiaria
7. **Crop Environment REsource Synthesis (CERES) Plant Growth Module**
 - 7.1. Grain Cereals -Rice, maize, millet, sorghum, wheat, and barley
8. **SUBSTOR Plant Growth Module**
 - 8.1. Potato

CERES-Rice plant growth module was used for the present investigation.

3.2.1.3 CALIBRATION OF THE MODEL

Model calibration involves the modification of some model parameters such that data simulated by the error-free model fit the observed data. In many instances, even if a model is based on observed data, simulated values do not exactly comply with the observed data and minor adjustments have to be made for some parameters. Non-compliance may arise from sampling errors as well as from incomplete knowledge of the system. Alternatively, it may arise when the model is used in a situation that is markedly different from the one under which it was developed.

Table 3.4: Categorization of genetic coefficients for rice cv. GR-11

Parameter	Description of parameter
P1	Time period (expressed as growing degree days [GDD] in °C above a base temperature of 9°C) from seedling emergence during which the rice plant is not responsive to changes in photoperiod. This period is also referred to as the basic vegetative phase of the plant.
P20	Critical photoperiod or the longest day length (in hours) at which the development occurs at a maximum rate. At values higher than P20 developmental rate is slowed, hence there is delay due to longer day lengths.
P2R	Extent to which phasic development leading to panicle initiation is delayed (expressed as GDD in °C) for each hour increase in photoperiod above P20.
P5	Time period in GDD °C) from beginning of grain filling (3 to 4 days after flowering) to physiological maturity with a base temperature of 9°C.
G1	Potential spikelet number coefficient as estimated from the number of spikelets per g of main culm dry weight (less lead blades and sheaths plus spikes) at anthesis. A typical value is 55.
G2	Single grain weight (g) under ideal growing conditions, i.e. nonlimiting light, water, nutrients, and absence of pests and diseases.
G3	Tillering coefficient (scalar value) relative to IR64 cultivar under ideal conditions. A higher tillering cultivar would have coefficient greater than 1.0.
G4	Temperature tolerance coefficient. Usually 1.0 for varieties grown in normal environments. G4 for japonica type rice growing in a warmer environment would be 1.0 or greater. Likewise, the G4 value for indica type rice in very cool environments or season would be less than 1.0.

Calibration of model involves adjusting certain model parameters or relationships to make the model work for any desired location. When using a crop model, one has to estimate the cultivar characteristics if they have not been previously determined. The model requires eight cultivar specific genetic coefficients. The details of these coefficients are given in Table 3.4. These coefficients were obtained by using available input parameters for other genotype (Jaya) with similar phenology and running the model iteratively till the predicted

yield of the district showed variation less than 10% of the observed values. The details of calibrated genetic coefficients for rice cv. GR-11 are given in Table 3.5.

Table 3.5: Calibrated Genetic coefficients for rice cv. GR-11

Parameters	P1	P2R	P5	P2O	G1	G2	G3	G4
Genetic coefficients	570.0	100.0	480.0	11.4	36.0	0.0280	1.00	0.80

3.2.2 WOFOST

WOFOST (WOrld FOod STudy) is a member of the family of crop growth models developed in Wageningen by the school of C.T. de Wit. Related models are SUCROS (Simple and Universal CROp growth Simulator), MACROS (Modules of an Annual CROp Simulator) and ORYZA1. All these models follow the hierarchical distinction between potential and limited production and share similar crop growth submodels, with light interception and CO₂ assimilation as growth driving processes and crop phenological development as growth controlling process. However, the submodels describing the soil water balance and the crop nutrient uptake may vary much in approach and level of detail.

Development of WOFOST has been driven by its applications in several studies. WOFOST was originally developed to assess yield potential of various annual crops in tropical countries. WOFOST has been used to assess the effect of climate change on crop growth. The model is particularly suited to quantify the combined effect of changes in CO₂, temperature, rainfall and solar radiation, on crop development, crop growth and crop water use, as all the relevant processes

are simulated separately while taking due account of their interactions. A simplified algorithm used by WOFOST is depicted in Figure 3.2.

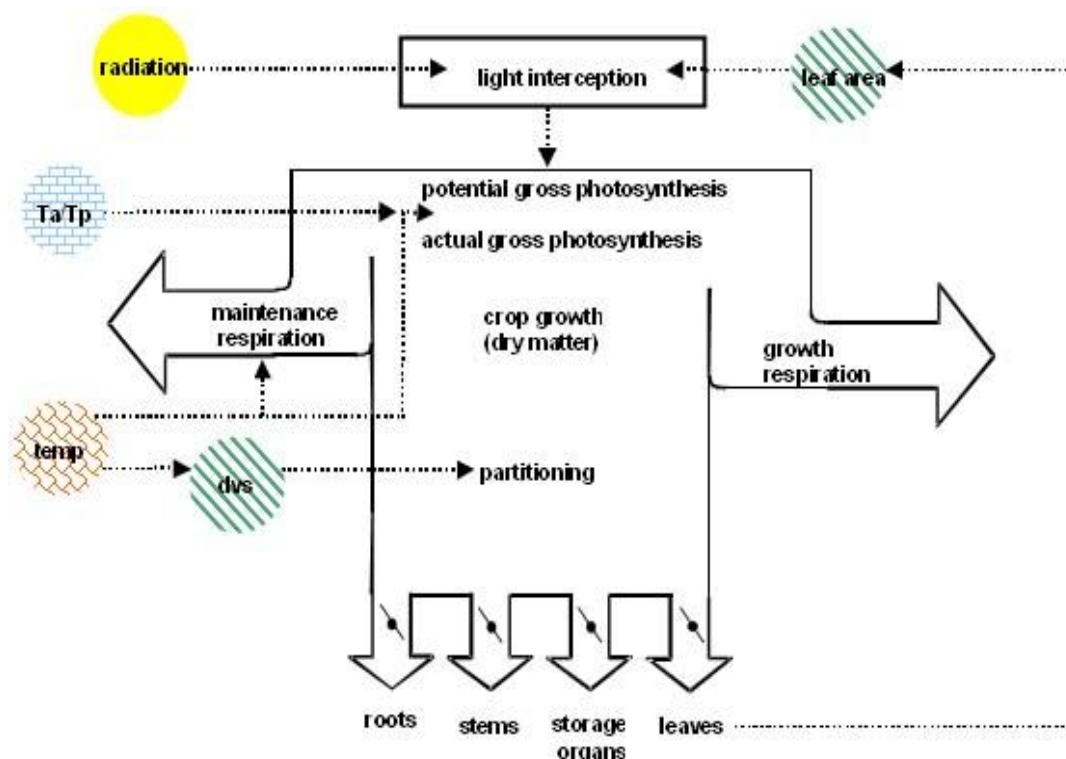


Figure 3.2: Algorithm used by WOFOST

3.2.2.1 FUNCTIONALITY

WOFOST is a mechanistic model that explains crop growth on the basis of the underlying processes, such as photosynthesis, respiration and how these processes are influenced by environmental conditions. The predictive ability of mechanistic models does not always live up to its expectation. It should be realized that each parameter estimate and process formulation has its own inaccuracy and that these errors accumulate in the prediction of final yield.

3.2.2.2 WEATHER

The meteorological parameters used by WOFOST are: maximum temperature, minimum temperature, global radiation, wind speed, vapour pressure, evapotranspiration and rainfall. The meteorological data are often measured on a daily basis.

The minimum input data required for WOFOST are listed in Table 3.6.

Table 3.6: Minimum input data required for WOFOST

Input	Description
STATION_NAME	station name for identification
LATITUDE	latitude (°)
LONGITUDE	longitude (°)
ALTITUDE	altitude (m)
ANGSTROM_A	calculated Angstrom A
ANGSTROM_B	calculated Angstrom B
WMO_NO	the reference number of the station
DAY	day of year [d]
MINIMUM_TEMPERATURE	minimum temperature [°C]
MAXIMUM_TEMPERATURE	maximum temperature [°C]
CALCULATED_RADIATION	daily global radiation in KJ/m ² /day
WINDSPEED	daily windspeed at 10 m [m s ⁻¹]
RAINFALL	daily rainfall [mm]
VAPOUR_PRESSURE	daily vapour pressure [hPa]

Station name, latitude, longitude and altitude values were as described in Table 3.2 and Angstrom A and B value were 0.18 and 0.55 respectively. The Penman method is used to calculate the evapotranspiration. The Penman-Monteith equation is given under

$$L_v \rho_w E = \frac{\Delta (R_n - S) + c_p \rho D_a / r_a}{\Delta + \gamma + \gamma (r_c / r_a)}$$

Where

E = evaporation rate in volume of water per unit area per unit time (mm)

L_v = latent heat of vaporization for water

ρ_w = density of water

Δ = rate of change of vapor pressure with temperature

R_n = net radiation above the surface

S = subsurface heat flux

c_p = heat capacity of air

ρ = density of air

D_a = vapor pressure deficit in the air

γ = psychrometric constant

r_c = canopy resistance

r_a = aerodynamic resistance

Global radiation is estimated by the model using the Ångström formula when no actual data are available. The Ångström formula uses the sunshine duration as input. The Ångström formula is as under

$$Q/Q_A = a + b n/N$$

where

Q = total solar radiation on a horizontal space (Wm^{-2})

Q_A = extra terrestrial radiation (1367 Wm^{-2})

a = 0.18

b = 0.55

Actual rainfall data are used as input, however, it is also possible to use generated rainfall from climatic normal data of the station. Actual wind speed and vapour pressure data were used.

3.2.2.3 CROP GROWTH

Crop growth depends on the daily net assimilation, which on its turn depends on the intercepted light. The intercepted light is determined by the level of incoming radiation and the leaf area of the crop. From the absorbed radiation and the photosynthetic characteristics of single leaves, the daily rate of potential gross photosynthesis can be calculated. Reduction of the transpiration due to water or oxygen stress results in a reduced production of assimilates. The assimilates are partitioned over the various plant organs. The instantaneous gross assimilation is calculated using the formula

$$A_L = A_m \left(1 - e^{-\frac{\varepsilon PAR_a}{A_m}} \right)$$

where

A_L = Instantaneous gross assimilation rate per unit leaf area at relative depth

L ($\text{kg ha}^{-1} \text{h}^{-1}$)

A_m = Instantaneous gross assimilation rate at light saturation ($\text{kg ha}^{-1} \text{h}^{-1}$)

ε = Initial light use efficiency [$(\text{kg ha}^{-1} \text{h}^{-1})/(\text{J m}^{-2} \text{s}^{-1})$]

PAR_a = Absorbed amount of the total radiation flux ($\text{J m}^{-2} \text{s}^{-1}$)

3.2.2.4 WATER BALANCE

A crop growth simulation model also has to keep track of the soil moisture content to determine when and to what degree a crop is exposed to water stress.

WOFOST uses a water balance, which compares for a given period of time, incoming water in the rooted zone with outgoing water and quantifies the difference between the two as a change in the stored soil moisture amount. WOFOST distinguishes three different situations. The first situation occurs when the soil moisture is at field capacity and the crop growth reaches its potential level. In the second situation, the influence of evapotranspiration and percolation on the availability of soil moisture are considered. Production is diminished by the reduced availability of soil moisture. In the last situation not only evapotranspiration and percolation are regarded but also influence of groundwater is taken into account. The actual soil moisture content in the root zone is calculated using following formula:

$$\theta_t = \frac{IN_{up} + (IN_{low} - T_a) \Delta t}{RD}$$

where

$$IN_{up} = P + I_s - E_s + SS_t / \Delta t - SR$$

$$IN_{low} = CR - Perc$$

Where

θ_t = Actual soil moisture content in rooted zone at time step t ($\text{cm}^3 \text{cm}^{-3}$)

IN_{up} = Rate of net influx through the upper root zone boundary (cm d^{-1})

IN_{low} = Rate of net influx through the lower root zone boundary (cm d^{-1})

T_a = Actual transpiration rate of crop (cm d^{-1})

RD = Actual rooting depth (cm)

P = Precipitation intensity (cm d^{-1})

I_e = Effective daily irrigation (cm d^{-1})

E_s = Soil evaporation rate (cm d^{-1})

SS_t = Surface storage (cm)

SR = Rate of surface runoff (cm d^{-1})

CR = Rate of capillary rise (cm d^{-1})

$Perc$ = Percolation rate (cm d^{-1})

θ_{wp} = Soil moisture content at wilting point ($\text{cm}^3 \text{cm}^{-3}$)

Δt = Time step (day)

Z_t = Depth of groundwater table (cm)

3.2.2.5 NUTRIENT BALANCE

Influence of nutrients (nitrogen, phosphate and potassium) on the yield and the yield statistics are calculated on a yearly basis. The routine consist of four successive steps. First the potential supplies of nitrogen, phosphorus and potassium are calculated, applying relationships between chemical properties of the soil layer 0-20 cm and the maximum quantity of those nutrients that can be absorbed by maize. It is assumed that the yield is not limited by nutrients and growth factors. In the second step, the actual uptake of each nutrient is calculated as a function of the potential supply of that nutrient, taking into account the potential supply of the other two nutrients. The third step compromises the establishment of three yield ranges as depending on the actual uptakes of nitrogen, phosphorus and potassium, respectively. In step four these yield ranges are combined in pairs, and the yields estimated for pairs of nutrients are averaged to obtain an ultimate yield estimate.

3.2.2.6 PARAMETER DESCRIPTION

WOFOST model requires 14 different input parameters. Different model parameters that were required to run the WOFOST model are summarised below in table 3.7.

Table 3.7: Different model parameters required for WOFOST

Name	Description	Unit
CVL	efficiency of conversion into leaves	kg kg ⁻¹
CVO	efficiency of conversion into storage organs	kg kg ⁻¹
CVR	efficiency of conversion into roots	kg kg ⁻¹
CVS	efficiency of conversion into stems	kg kg ⁻¹
DLO	optimum daylength for development	hr
RML	relative maintenance respiration rate leaves	kg CH ₂ O kg ⁻¹ d ⁻¹
RMO	relative maintenance respiration rate storage organs	kg CH ₂ O kg ⁻¹ d ⁻¹
RMR	relative maintenance respiration rate roots	kg CH ₂ O kg ⁻¹ d ⁻¹
RMS	relative maintenance respiration rate stems	kg CH ₂ O kg ⁻¹ d ⁻¹
SPAN	life span of leaves growing at 35 Celsius d	
TBASE	lower threshold temperature for ageing of leaves	°C
TDWI	initial total crop dry weight	kg ha ⁻¹
TSUM1	temperature sum from emergence to anthesis	° C
TSUM2	temperature sum from anthesis to maturity	° C

3.2.2.7 CALIBRATION OF THE MODEL

Model calibration involves the modification of some model parameters such that data simulated by the error-free model fit the observed data. In many instances, even if a model is based on observed data, simulated values do not exactly comply with the observed data and minor adjustments have to be made for some parameters. Non-compliance may arise from sampling errors as well as from incomplete knowledge of the system. Alternatively, it may arise when the model is used in a situation that is markedly different from the one under which it

was developed. Calibration of model involves adjusting certain model parameters or relationships to make the model work for any desired location. When using a crop model, one has to estimate the cultivar characteristics if they have not been previously determined. The model requires fourteen parameters. These parameters were obtained by running the model iteratively till the predicted yield of the district showed variation less than 10% of the observed values. The details of these input model parameters are given in Table 3.7.

Table 3.8: Model parameters used for calibration of WOFOST

Parameter	Value
TSUM1	1753
TSUM2	480
DLO	11.4
TDWI	25.0
SPAN	23.0
TBASE	9.0
CVL	0.754
CVO	0.584
CVR	0.754
CVS	0.754
RML	0.020
RMO	0.030
RMR	0.010
RMS	0.015

3.2.3 VALIDATION OF THE MODEL

The model validation stage involves the confirmation that the calibrated model closely represents the real situation. The procedure consists of a comparison of simulated output and observed data that have not been previously

used in the calibration stage. Ideally, all mechanistic models should be validated both at the level of overall system output and at the level of internal components and processes. The latter is an important aspect because due to the occurrence of feedback loops in biological systems, good prediction of system's overall output could be attributed to compensating internal errors. However, validation of all the components is not possible due to lack of detailed datasets and the option of validating only the determinant ones is adopted.

Validation procedures involve both qualitative and quantitative comparisons. Before starting the quantitative tests, it is advisable to qualitatively assess time-trends of simulated and observed data for both internal variables and systems outputs.

Before any model can be used with confidence, adequate validation or assessment of the magnitude of the errors that may result from its use should be performed. Model validation, in its simplest form is a comparison between simulated and observed values.

Beyond comparisons, there are several statistical measures available to evaluate the association between predicted and observed values. Among them correlation coefficient (r) and its square, the coefficient of determination (R^2) are widely used parameters. The main problem with this analysis is that the magnitudes of r and R^2 are not consistently related to the accuracy of prediction where accuracy is defined as the degree to which model predictions approach the magnitudes of their observed counterparts.

Test criteria have been separated into two groups, called summary measures and difference measures. Summary measures include the mean of observed values ($\bar{O}$) and predicted values ($\bar{P}$), the standard deviation of observations (S_o) and the predictions (S_p), the slope (b) and intercept (a) of the least square regression ($P_i = a + b + O_i$).

Index of agreement (D) was calculated by using following formula

$$D = 1 - \left[\frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (|P_i'| + |O_i'|)^2} \right]$$

$$0 \leq (D) \leq 1$$

where,

$$P_i' = P_i - \bar{P} \text{ and } O_i' = O_i - \bar{O}.$$

The summary measures describe the quality of simulation while the difference measures try to locate and quantify errors. The latter include the mean absolute error (MAE), the mean bias error (MBE) and the root mean square error (RMSE). They were calculated as follows and were based on the terms ($P_i - O_i$) :

$$MAE = \frac{\sum_{i=1}^n |P_i - O_i|}{n}$$

$$MBE = \frac{\sum_{i=1}^n [P_i - O_i]}{n}$$

$$RMSE = \left[\frac{\sum_{i=1}^n (P_i - O_i)^2}{n} \right]^{1/2}$$

MAE and RMSE indicate the magnitude of the average error, but provide no information on the relative size of the average difference between (P) and (O). The statistic MBE describes the direction of the error bias. The value of MBE is

related to the magnitude of the values under investigation. A negative MBE indicates that the predictions are smaller in values than those of the corresponding observations. Varshneya (1999), who gave a simple indication of error in prediction defined the percent Error (PE). PE is defined as ratio of RMSE to mean observed value expressed as percentage.

$$PE = \frac{RMSE}{\bar{O}} \times 100$$

The entire procedure as described above was carried out and pertinent results are described in the next chapter.

3.3 DEVELOPMENT OF AGROMETEOROLOGICAL MODEL

Various agro-meteorologically based models are generally crop-weather relationship models which may be defined as a simplified representation of the complex relationship between weather or climate and crop performance (such as growth, occurrence of phenological events, yield or yield components) using established mathematical and/or statistical techniques. Generally, multiple and stepwise regression techniques are employed using more than one variable. Statistical models for simulating yield as a function of important climatic variables such as rainfall were started since Fisher's (1924) work. Later numerous studies were carried out to use crop-weather relationships for the development of crop-weather models suitable for monitoring and predicting crop yields.

The sowing of rice is mainly concentrated around the second week of June in Gujarat (Anon, 2004). Hence, the data pertaining to weather parameter for the

period 23rd to 42nd meteorological standard weeks (MSW) were included in the present investigation.

For studying the effect of weather variables on the crop effectively, the 20 weeks of crop growth period was divided into six different phenological stages (Anon, 2004). The correlation and regression were tried for first five stages only as there are less chances of variability in yield during maturity stage. The details on MSW, periods and their corresponding phenological stages are given in Table 3.8.

Table 3.9: Meteorological standard weeks (MSW) and phenological stages of rice crop

Week No.	MSW	Month	Date	Crop stage description	Crop stage code
1	23	June	4-10	Seedling	S
2	24		11-17		
3	25		18-24		
4	26		25-1 July		
5	27	July	2-8	Active tillering	A
6	28		9-15		
7	29		16-22		
8	30	July - August	23-29	Vegetative lag	V
9	31		30-5 Aug.		
10	32		6-12		
11	33		13-19		
12	34	August - September	20-26	Flowering	F
13	35		27-2 Sept.		
14	36		3-9		
15	37		10-16		
16	38	September - October	17-23	Grain development	G
17	39		24-30		
18	40		1-7 Oct.		
19	41	October	8-14	Maturity	M
20	42		15-21		

3.3.1 METHODOLOGY FOR DEVELOPMENT OF AGROMETEOROLOGICAL MODEL

For developing appropriate agrometeorological model for prediction of rice yield in Gujarat. Following weather variables were considered based on the reported work by various workers in India and abroad.

Table 3.10: Description of variables used for agrometeorological modelling

Variables	Description
Y	Average rice yield of the district in kg/ha
X ₁	Bright sunshine hours/day
X ₂	Rainfall (mm)
X ₃	Maximum temperature (°C)
X ₄	Minimum temperature (°C)
X ₅	Morning relative humidity (%)
X ₆	Afternoon relative humidity (%)

For selecting the best regression equation among number of independent variables, the stepwise regression procedure was adopted (Draper and Smith, 1966). Statistical Package for the Social Sciences (SPSS) computer software was used for the analysis of the data with probability level of 0.05 to enter and 0.1 to remove the variables. The sets of multiple linear regression equations were obtained separately of each district using data upto year 2005 for each model. A regression model was fitted considering the entered variables obtained from

individual stepwise regression analysis to predict rice yield for the subsequent years.

The various approaches were tried to find out the suitable interval which can satisfactorily forecast the rice yield in a given year. The various approaches employed were as under.

3.6.1.1 Weekwise approach using original weather variables

3.6.1.2 Crop stagewise approach using original weather variables

3.6.1.3 Periodwise approach using original weather variables

3.6.1.4 Week number as weight using generated weather variables

3.6.1.5 Correlation coefficient as weight using generated weather variables.

These approaches are adoption of the models developed by Aggrawal *et al.*, (1986) and are mostly used by various workers in India. Patel (2005) used model developed by Aggrawal *et al.*, (1986) for preharvest forecasting of rice yield based on weather parameters in Kheda district of Gujarat.

3.3.1.1 WEEKWISE APPROACH USING ORIGINAL WEATHER VARIABLES

In this approach, weekly averaged data of different weather variables were considered in original form from 23rd to 42nd meteorological standard weeks. With a view to have forecasts before actual harvest, different models based on 12, 14, 16, 18 and 20 weeks crop duration were fitted. The descriptions of variables included in the model upto 20 weeks of crop period are given in Table 3.9.

Table 3.11: Description of weather variables included in weekwise approach

MSW	Crop week No.	Bright sunshine hours (X_{1j})	Rainfall (X_{2j})	Temperature		Relative humidity	
				Maximum (X_{3j})	Minimum (X_{4j})	Morning (X_{5j})	Afternoon (X_{6j})
23	1	X_{101}	X_{201}	X_{301}	X_{401}	X_{501}	X_{601}
24	2	X_{102}	X_{202}	X_{302}	X_{402}	X_{502}	X_{602}
25	3	X_{103}	X_{203}	X_{303}	X_{403}	X_{503}	X_{603}
26	4	X_{104}	X_{204}	X_{304}	X_{404}	X_{504}	X_{604}
27	5	X_{105}	X_{205}	X_{305}	X_{405}	X_{505}	X_{605}
28	6	X_{106}	X_{206}	X_{306}	X_{406}	X_{506}	X_{606}
29	7	X_{107}	X_{207}	X_{307}	X_{407}	X_{507}	X_{607}
30	8	X_{108}	X_{208}	X_{308}	X_{408}	X_{508}	X_{608}
31	9	X_{109}	X_{209}	X_{309}	X_{409}	X_{509}	X_{609}
32	10	X_{110}	X_{210}	X_{310}	X_{410}	X_{510}	X_{610}
33	11	X_{111}	X_{211}	X_{311}	X_{411}	X_{511}	X_{611}
34	12	X_{112}	X_{212}	X_{312}	X_{412}	X_{512}	X_{612}
35	13	X_{113}	X_{213}	X_{313}	X_{413}	X_{513}	X_{613}
36	14	X_{114}	X_{214}	X_{314}	X_{414}	X_{514}	X_{614}
37	15	X_{115}	X_{215}	X_{315}	X_{415}	X_{515}	X_{615}
38	16	X_{116}	X_{216}	X_{316}	X_{416}	X_{516}	X_{616}
39	17	X_{117}	X_{217}	X_{317}	X_{417}	X_{517}	X_{617}
40	18	X_{118}	X_{218}	X_{318}	X_{418}	X_{518}	X_{618}
41	19	X_{119}	X_{219}	X_{319}	X_{419}	X_{519}	X_{619}
42	20	X_{120}	X_{220}	X_{320}	X_{420}	X_{520}	X_{620}

*First figure in subscript is variable number and rest two are week number

The mathematical expression of this model was,

$$Y = A_0 + \sum_{i=1}^p \sum_{j=1}^w a_{ij} X_{ij}$$

where,

Y = Average rice yield of the district (kg/ha)

A_0 = Constant

X_{ij} = Observed value of i^{th} weather variable in j^{th} week, $i=1, 2, \dots, p=6$ and $j=1, 2, \dots, w=12, 14, 16, 18$ and 20

a_{ij} = partial regression coefficients associated with each X_{ij}

3.3.1.2 CROP STAGewise APPROACH USING ORIGINAL WEATHER VARIABLES

The 18 weeks of crop period were divided into 5 important crop stages and average value for the respective stages were considered to fit the model. The crop stagewise variables included in the model are given in Table 3.10.

Table 3.12: Description of weather variables included in crop stagewise approach

MSW	Crop week No.	Bright sunshine hours (X_{1j})	Rainfall (X_{2j})	Temperature		Relative humidity		Crop stage code
				Maximum (X_{3j})	Minimum (X_{4j})	Morning (X_{5j})	Afternoon (X_{6j})	
23-26	1-4	X_{11}	X_{21}	X_{31}	X_{41}	X_{51}	X_{61}	S
27-29	5-7	X_{12}	X_{22}	X_{32}	X_{42}	X_{52}	X_{62}	A
30-33	8-11	X_{13}	X_{23}	X_{33}	X_{43}	X_{53}	X_{63}	V
34-37	12-15	X_{14}	X_{24}	X_{34}	X_{44}	X_{54}	X_{64}	F
38-40	16-18	X_{15}	X_{25}	X_{35}	X_{45}	X_{55}	X_{66}	G

*First figure in subscript is variable number and second is stage number

Five models were fitted considering the data upto 1st, 2nd, 3rd, 4th, and 5th crop stages i.e. seedling (S), active tillering (A), vegetative lag (V), flowering (F) and grain development (G) stages, respectively.

The mathematical model for this approach was

$$Y = A_0 + \sum_{i=1}^p \sum_{j=1}^s a_{ij} X_{ij}$$

where,

Y = Average rice yield of the district (kg/ha)

A_0 = Constant

X_{ij} = Observed value of i^{th} weather variable in j^{th} crop stage $i=1, 2, \dots, p=6$
and $j=1, 2, \dots, s=1, 2, 3, 4 \text{ \& } 5$

a_{ij} = partial regression coefficients associated with each X_{ij}

3.3.1.3 PERIODWISE APPROACH USING ORIGINAL WEATHER VARIABLES

In this approach, monthly averaged data of different weather variables were considered in original form from 6th to 10th meteorological standard periods. With a view to have forecasts before actual harvest, different models based on 1, 2, 3, 4 and 5 periods crop period were fitted. The descriptions of variables included in the model are given in Table 3.11.

Table 3.13: Description of weather variables included in periodwise approach

MSP	Crop period No.	Bright sunshine hours (X_{1j})	Rainfall (X_{2j})	Temperature		Relative humidity	
				Maximum (X_{3j})	Minimum (X_{4j})	Morning (X_{5j})	Afternoon (X_{6j})
6	1	X_{11}	X_{21}	X_{31}	X_{41}	X_{51}	X_{61}
7	2	X_{12}	X_{22}	X_{32}	X_{42}	X_{52}	X_{62}
8	3	X_{13}	X_{23}	X_{33}	X_{43}	X_{53}	X_{63}
9	4	X_{14}	X_{24}	X_{34}	X_{44}	X_{54}	X_{64}
10	5	X_{15}	X_{25}	X_{35}	X_{45}	X_{55}	X_{66}

*First figure in subscript is variable number and second is period number

The mathematical expression of this model was,

$$Y = A_0 + \sum_{i=1}^p \sum_{j=1}^m a_{ij} X_{ij}$$

where,

Y = Average rice yield of the district (kg/ha)

A_0 = Constant

X_{ij} = Observed value of i^{th} weather variable in j^{th} period, $i=1,2,\dots,p=6$

and $j=1,2,\dots,m=1,2,3,4$ and 5

a_{ij} = partial regression coefficients associated with each X_{ij}

Generated weather variables were also tried to explain the relationship in a better way as it gives appropriate weightage to different periods. These models were successfully used for forecasting yield of various crops at district and zone level (Agrawal, 2007).

3.3.1.4 WEEK NUMBER AS WEIGHT APPROACH USING GENERATED WEATHER VARIABLES

Here in this approach new variables (Z_{ij}) and ($Q_{ii'j}$) were generated from original weekly averaged weather variable data (Agrawal *et al.*, 1986) as per the formula given below

$$Z_{ij} = \frac{\sum_{w=1}^n w^j \cdot X_{iw}}{\sum_{w=1}^n w^j} \text{ and } Q_{ii'j} = \frac{\sum_{w=1}^n w^j \cdot X_{iw} \cdot X_{i'w}}{\sum_{w=1}^n w^j}$$

Z_{ij} and $Q_{ii'j}$ are generated first and second order variables defined as,

where,

n = number of weeks up to the time of forecast

w = week identification ($w=1,2,\dots n=12, 14, 16, 18$ and 20)

X_{iw} = value of the i^{th} weather variable in the w^{th} week ($i \neq i' = 1,2,\dots,6$ and $j=0,1,2$)

The weighted averages of weekly weather variables and their interactions using powers (0, 1 and 2) of week number as a weight were used. The details of first order (Z_{ij}) and second order ($Q_{ii'j}$) generated variables included in the analysis are presented in Table 3.12.

Table 3.14: First and second order generated variables using week number as weight

First order generated variables (Z_{ij})

Z_{ij}	Z_{1j}	Z_{2j}	Z_{3j}	Z_{4j}	Z_{5j}	Z_{6j}
Z_{i0}	Z_{10}	Z_{20}	Z_{30}	Z_{40}	Z_{50}	Z_{60}
Z_{i1}	Z_{11}	Z_{21}	Z_{31}	Z_{41}	Z_{51}	Z_{61}
Z_{i2}	Z_{12}	Z_{22}	Z_{32}	Z_{42}	Z_{52}	Z_{62}

Second order generated variables ($Q_{ii'j}$)

$Q_{ii'j}$	$Q_{ii'0}$	$Q_{ii'1}$	$Q_{ii'2}$	$Q_{ii'j}$	$Q_{ii'0}$	$Q_{ii'1}$	$Q_{ii'2}$
Q_{12j}	Q_{120}	Q_{121}	Q_{122}	Q_{13j}	Q_{130}	Q_{131}	Q_{132}
Q_{14j}	Q_{140}	Q_{141}	Q_{142}	Q_{15j}	Q_{150}	Q_{151}	Q_{152}
Q_{16j}	Q_{160}	Q_{161}	Q_{162}	Q_{23j}	Q_{230}	Q_{231}	Q_{232}
Q_{24j}	Q_{240}	Q_{241}	Q_{242}	Q_{25j}	Q_{250}	Q_{251}	Q_{252}
Q_{26j}	Q_{260}	Q_{261}	Q_{262}	Q_{34j}	Q_{340}	Q_{341}	Q_{342}
Q_{35j}	Q_{350}	Q_{351}	Q_{352}	Q_{36j}	Q_{360}	Q_{361}	Q_{362}
Q_{45j}	Q_{450}	Q_{451}	Q_{452}	Q_{46j}	Q_{460}	Q_{461}	Q_{462}
Q_{56j}	Q_{560}	Q_{561}	Q_{562}				

Sixty three explanatory generated variables along with time trend variable were subjected to stepwise regression analysis for developing forecasting model.

The mathematical expression of the fitted model was

$$Y = A_0 + \sum_{i=1}^p \sum_{j=0}^2 a_{ij} Z_{ij} + \sum_{i \neq i'=1}^p \sum_{j=0}^2 b_{ii'j} Q_{ii'j}$$

where,

Y = Average rice yield of district kg/ha

A_0 = Constant

p = No. of weather variables ($p=1,2,\dots,6$)

a_{ij} , and $b_{ii'j}$ are partial regression coefficients associated with each Z_{ij} and

$Q_{ii'j}$, respectively ($ii' = 1,2,\dots,p$ and $j=0,1,2$)

Using these variables, forecasting models were developed for 12, 14, 16, 18 and 20 weeks crop periods to explore the possibility of early forecast before harvest.

3.3.1.5 CORRELATION COEFFICIENTS AS WEIGHT APPROACH USING GENERATED WEATHER VARIABLES

The correlation coefficients between rice yield and different weather variables were worked out weekwise and they were used as weight and new variables Z'_{ij} and Q'_{iij} (taking interaction of variables) were generated (Agarwal *et. al.*, 1986) using following formula

$$Z'_{ij} = \frac{\sum_{w=1}^n r_{iw}^j \cdot X_{iw}}{\sum_{w=1}^n r_{iw}^j} \text{ and } Q'_{iij} = \frac{\sum_{w=1}^n r_{i'iw}^j \cdot X_{iw} \cdot X_{i'w}}{\sum_{w=1}^n r_{i'iw}^j}$$

Z'_{ij} and Q'_{iij} are generated first and second order variables defined as,

where,

n = number of weeks up to the time of forecast

w = week identification ($w=1,2,\dots n=12, 14, 16, 18$ and 20)

X_{iw} = value of the i^{th} weather variable in the w^{th} week ($i \neq i' = 1,2 \dots p$ and $j=0,1,2$)

r_{iw} = correlation coefficient of yield with the i^{th} weather variable in the w^{th} week

$r_{i'iw}$ = correlation coefficient of yield with the product of the i^{th} and i'^{th} weather variable in the w^{th} week.

The details of first order (Z'_{ij}) and second order (Q'_{iij}) generated variables obtained from this way and included in analysis are given in Table 3.13.

Table 3.15: First and second order generated variables using correlation coefficients as weight

First order generated variables (Z'_{ij})						
Z'_{ij}	Z'_{1j}	Z'_{2j}	Z'_{3j}	Z'_{4j}	Z'_{5j}	Z'_{6j}
Z'_{i0}	Z'_{10}	Z'_{20}	Z'_{30}	Z'_{40}	Z'_{50}	Z'_{60}
Z'_{i1}	Z'_{11}	Z'_{21}	Z'_{31}	Z'_{41}	Z'_{51}	Z'_{61}
Z'_{i2}	Z'_{12}	Z'_{22}	Z'_{32}	Z'_{42}	Z'_{52}	Z'_{62}

Second order generated variables (Q'_{iij})							
Q'_{iij}	Q'_{i0}	Q'_{i1}	Q'_{i2}	Q'_{ij}	Q'_{i0}	Q'_{i1}	Q'_{i2}
Q'_{12j}	Q'_{120}	Q'_{121}	Q'_{122}	Q'_{13j}	Q'_{130}	Q'_{131}	Q'_{132}
Q'_{14j}	Q'_{140}	Q'_{141}	Q'_{142}	Q'_{15j}	Q'_{150}	Q'_{151}	Q'_{152}
Q'_{16j}	Q'_{160}	Q'_{161}	Q'_{162}	Q'_{23j}	Q'_{230}	Q'_{231}	Q'_{232}
Q'_{24j}	Q'_{240}	Q'_{241}	Q'_{242}	Q'_{25j}	Q'_{250}	Q'_{251}	Q'_{252}
Q'_{26j}	Q'_{260}	Q'_{261}	Q'_{262}	Q'_{34j}	Q'_{340}	Q'_{341}	Q'_{342}
Q'_{35j}	Q'_{350}	Q'_{351}	Q'_{352}	Q'_{36j}	Q'_{360}	Q'_{361}	Q'_{362}
Q'_{45j}	Q'_{450}	Q'_{451}	Q'_{452}	Q'_{46j}	Q'_{460}	Q'_{461}	Q'_{462}
Q'_{56j}	Q'_{560}	Q'_{561}	Q'_{562}				

In order to explore the possibility of early forecasts before 8, 6, 4 and 2 weeks of harvest of rice crop, four models were fitted using generated weather variables for the period of 12, 14, 16, 18 and 20 weeks crop periods.

Sixty three explanatory variables comprising of 18 first order generated variables (Z'_{ij}), 45 second order generated variables (Q'_{iij}) were subjected to stepwise regression analysis using following model.

$$Y = A_0 + \sum_{i=1}^p \sum_{j=0}^2 a_{ij} Z'_{ij} + \sum_{i \neq 1}^p \sum_{j=0}^2 b_{iij} Q'_{iij}$$

where,

Y = Average rice yield of the district kg/ha

A_0 = Constant

a_{ij} , and b_{iij} are partial regression coefficients associated with each Z'_{ij} and

Q'_{iij} respectively. ($i \neq i' = 1, 2 \dots p$ and $j = 0, 1, 2$)

p = No. of weather variables ($p=1, 2, \dots, 6$)

3.3.2 SELECTION OF MODEL

The model was selected as the suitable preharvest forecast model based on these two criteria viz. (i) earliness in forecast before harvest of rice crop and (ii) higher coefficient of determination (adjusted R^2). The nomenclature used for different adjusted R^2 (%) values is presented in Table 3.14.

Table 3.16: Nomenclature used for adjusted R^2 (%) values for selection of models

Adjusted R^2 (%)	Nomenclature
> 90	Very high
75 – 90	High
50 – 75	Moderate
50 – 30	Low
< 30	Very low

3.3.3 VALIDATION OF THE MODEL

The developed agrometeorological models were also tested using different criteria similar to those for crop growth simulation modelling and given in section 3.5.

3.4 COMPARATIVE EVALUATION OF THE MODELS

All the above models (Crop Growth Simulation and Agrometeorological) were evaluated for their suitability as an appropriate prediction model based on two criteria viz. (i) higher degree of agreement (D) (ii) lower prediction error (PE).

4. RESULTS AND DISCUSSION

The present study was undertaken with a view to predict the rice yield using crop simulation models and to develop an appropriate agrometeorological model for prediction of rice yield in Gujarat. Two crop growth simulation models were evaluated for testing their worth for forecasting yield. The crop growth simulation model Decision Support System for Agrotechnology Transfer (DSSAT) documented by Jones *et al.*, (2003) and the WO^Wld FO^Wd STudy (WOFOST) developed by Diepen *et al.* (1989) at Wageningen were evaluated for the said purpose. The crop growth simulation models viz. DSSAT and WOFOST were calibrated and validated under Gujarat conditions. The efforts were also made to develop suitable agrometeorological model for predicting the yield of rice by using combined effects of different weather parameters viz. rainfall, bright sunshine hours, maximum and minimum temperature and morning and afternoon relative humidity on rice yield. For the present investigation the major rice growing districts of Gujarat viz., Ahmedabad, Baroda, Bulsar, Kheda, Panchmahal, Sabarkantha and Surat were considered.

The plant growth is a complex phenomenon, which involves both the qualitative and quantitative characteristics of the rice crop depending upon different prevailing weather conditions, agronomical practices and crop management during the different phenological phases of the rice crop. So, to have an insight, the effects of weather parameters were studied and discussed in the following paragraphs.

4.1 GENERAL WEATHER CONDITION OF STUDY AREA

The variable weather conditions discourage farmers from using modern inputs. The paddy crop is highly sensitive to weather risk under the given soil/crop complex. High rainfall and low radiation are detrimental to high crop production. The degree of vulnerability of crops to climate variability depends mainly on the development stage of the crops at the time of weather aberration.

The weather condition prevailed during the crop growing season i.e. from 23rd to 42nd meteorological standard weeks were studied and are presented graphically through different figures. The average of available data was worked out for rainfall, bright sunshine hours, maximum and minimum temperature, and morning and afternoon relative humidity for graphical presentation. The different meteorological parameters are averaged over the standard meteorological weeks along with different phenophases of the crop growth. The weather parameters discussed here under are bright sunshine hours, rainfall, maximum and minimum temperature, and morning and afternoon relative humidity.

Obviously, it is very difficult to separate out the effect of any particular meteorological parameters for describing their influence on the growth and development of the rice crop. However efforts had been made to identify the effects of important weather parameters on the growth and development of rice crop as well as yield either individually or jointly.

4.1.1 BRIGHT SUNSHINE HOURS

Stagewise average (23rd to 42nd meteorological standard week) of the bright sunshine hours during the study period are depicted in Table 4.1 and plotted

graphically in Figure 4.1. The results presented in the Figure 4.1 revealed that large variation was observed in duration of average bright sunshine hours during the crop growth period in all the districts. Highest variation was observed in Sabarkantha (48.2%) followed by Baroda (44.7%), whereas lowest variation was observed in Surat (21.8%). The bright sunshine hours of Ahmedabad ranged from 3.4 to 8.0, Baroda from 2.5 to 7.3, Bulsar from 3.6 to 7.2, Kheda from 3.7 to 8.3, Panchmahals from 3.7 to 7.3, Sabarkantha from 2.3 to 7.4 and for Surat from 3.9 to 6.5 hours.

Table 4.1: Average bright sunshine hours during the crop growth period (hr)

Stage*	Ahmedabad	Baroda	Bulsar	Kheda	Panchmahals	Sabarkantha	Surat
S	7.2	5.4	6.7	7.8	7.3	5.2	6.0
A	4.1	3.0	4.5	4.5	4.3	2.5	4.1
V	3.4	2.5	3.6	3.7	3.7	2.3	3.9
F	5.9	3.9	5.1	5.8	5.0	4.6	5.3
G	8.0	7.3	7.2	8.3	7.3	7.4	6.5
SEM	0.4	0.4	0.3	0.4	0.3	0.4	0.2
CV(%)	34.4	44.7	27.9	33.4	31.1	48.2	21.8
SD	2.0	2.0	1.5	2.0	1.7	2.1	1.1

*S = Seedling, A = Active tillering, V = Vegetative lag, F = Flowering stage and G = Grain development stage

Highest bright sunshine hours during seedling stage were observed in Kheda district followed by Panchmahals, Ahmedabad, Bulsar, Surat, Baroda and Sabarkantha. During flowering stage highest bright sunshine hours were observed in Ahmedabad followed by Kheda, Surat, Bulsar, Panchmahals, Sabarkantha and Baroda in decreasing order. Data further revealed that the bright sunshine hours were decreasing from seedling to vegetative lag stage and thereafter it showed an increasing trend.

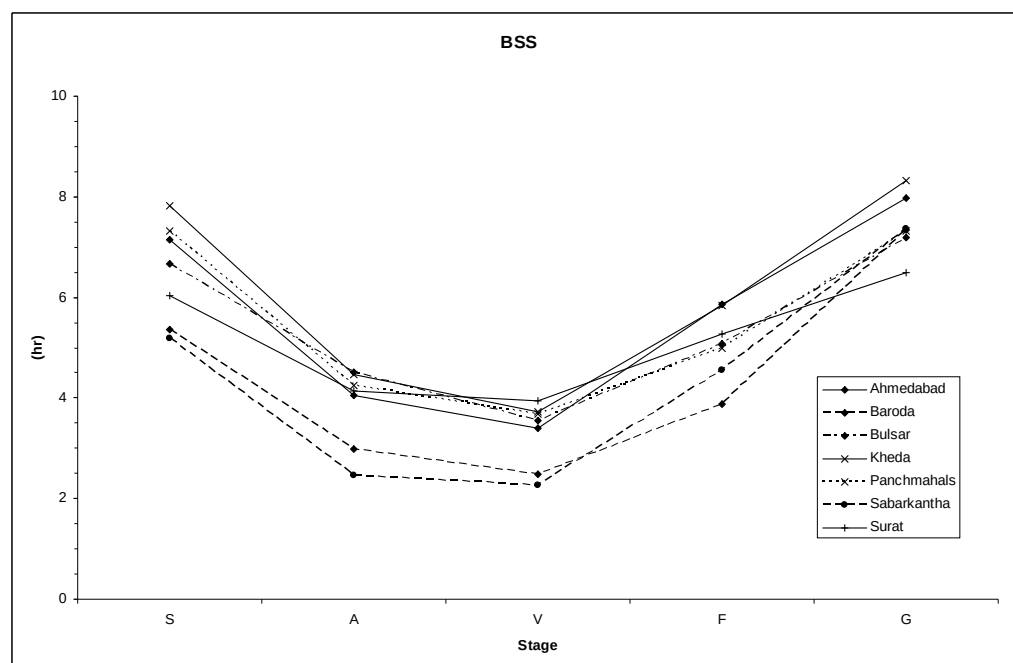


Figure 4.1: Variation in bright sunshine hours during the crop growth period

4.1.2 RAINFALL

Crop stagewise average rainfall during the study period (23rd to 42nd meteorological standard week) is presented in Table 4.2 and plotted graphically against various phenophases of rice crop in Figure 4.2.

Table 4.2: Average rainfall during the crop growth period (mm)

Stage	Ahmedabad	Baroda	Bulsar	Kheda	Panchmahals	Sabarkantha	Surat
S	122.9	266.4	297.2	136.8	136.7	113.8	307.2
A	139.2	220.8	395.3	187.0	184.2	171.0	312.8
V	177.5	215.8	392.6	254.7	277.7	203.4	254.8
F	141.0	225.4	228.4	160.0	204.4	157.8	146.8
G	44.8	82.1	106.2	46.6	39.8	42.5	50.9
Total	625.4	1010.5	1419.7	785.1	842.8	688.5	1072.5
SEM	09.8	14.0	24.3	15.2	17.6	12.4	22.6
CV(%)	39.3	34.6	42.8	48.3	52.2	45.1	52.8
SD	49.1	70.0	121.5	75.9	88.1	62.2	113.2

The results revealed that there was large variation in amount of rainfall during the crop growth period in all the districts. Rainfall of Ahmedabad was

from 44.8 to 177.5, Baroda from 82.1 to 266.4, Bulsar from 106.2 to 395.3, Kheda from 46.6 to 254.7, Panchmahals from 39.8 to 277.7, Sabarkantha from 42.5 to 203.4 and of Surat from 50.9 to 312.8 mm during different stages of crop.

Data further revealed that the amount of rainfall increased from seedling to vegetative lag stage and decreased thereafter. Maximum variation in amount of rainfall was observed in Surat (52.8%) followed by Panchmahals (52.2%) and minimum in Baroda (34.6%). Highest rainfall was observed in Bulsar during active tillering stage and least in Panchmahals during grain development stage.

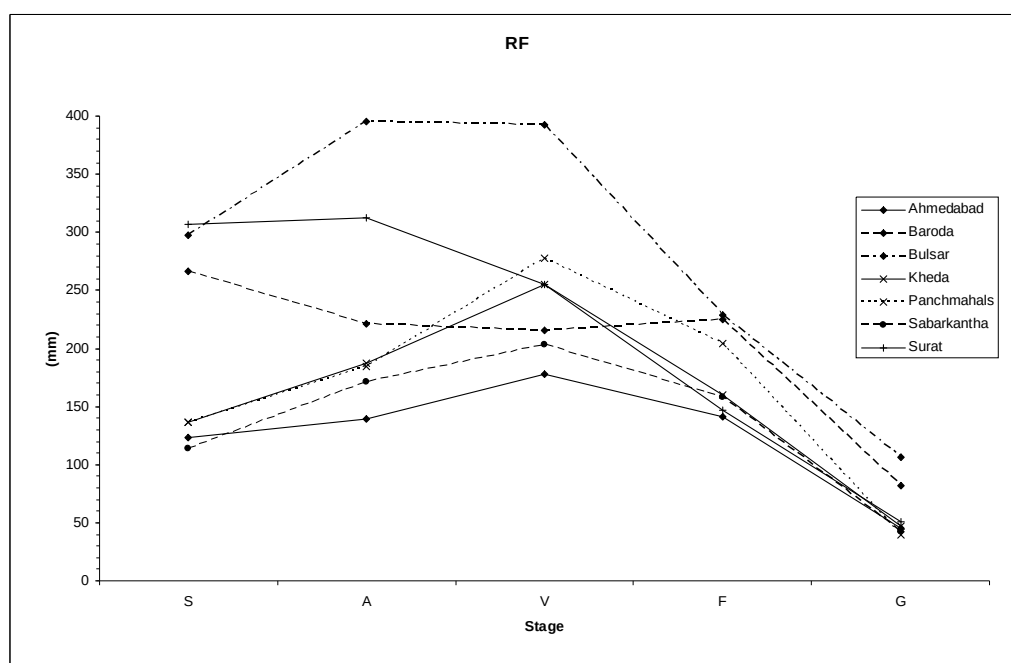


Figure 4.2: Variation in amount of rainfall during the crop growth period

4.1.3 MAXIMUM TEMPERATURE

Stagewise average of maximum temperature during the study period (23rd to 42nd meteorological standard week) is presented in Table 4.3 and plotted graphically against various phenophases of rice crop in Figure 4.3. The results revealed that very little variation was observed in stagewise maximum

temperature during the crop growth period in all the districts. Highest variation was observed in Sabarkantha (7.4%) and least in Surat (3.6%). Crop stagewise average maximum temperature of Ahmedabad ranged from 32.6 to 38.7, Baroda from 31.3 to 36.2, Bulsar from 30.0 to 33.0, Kheda from 31.4 to 36.6, Panchmahals from 30.7 to 36.6, Sabarkantha from 31.1 to 37.5 and of Surat from 30.4 to 32.9 °C.

Table 4.3: Average maximum temperature during the crop growth period (°C)

Stage	Ahmedabad	Baroda	Bulsar	Kheda	Panchmahals	Sabarkantha	Surat
S	38.7	36.2	32.8	36.6	36.6	37.5	32.9
A	34.5	32.7	30.8	32.8	32.2	33.4	30.9
V	32.6	31.3	30.0	31.4	30.7	31.1	30.4
F	32.9	32.2	30.4	32.1	31.4	32.0	30.5
G	34.9	34.4	33.0	34.6	33.7	34.8	32.3
SEM	0.5	0.4	0.3	0.4	0.5	0.5	0.2
CV(%)	7.0	5.9	4.5	6.2	7.1	7.4	3.6
SD	2.4	2.0	1.4	2.1	2.3	2.5	1.1

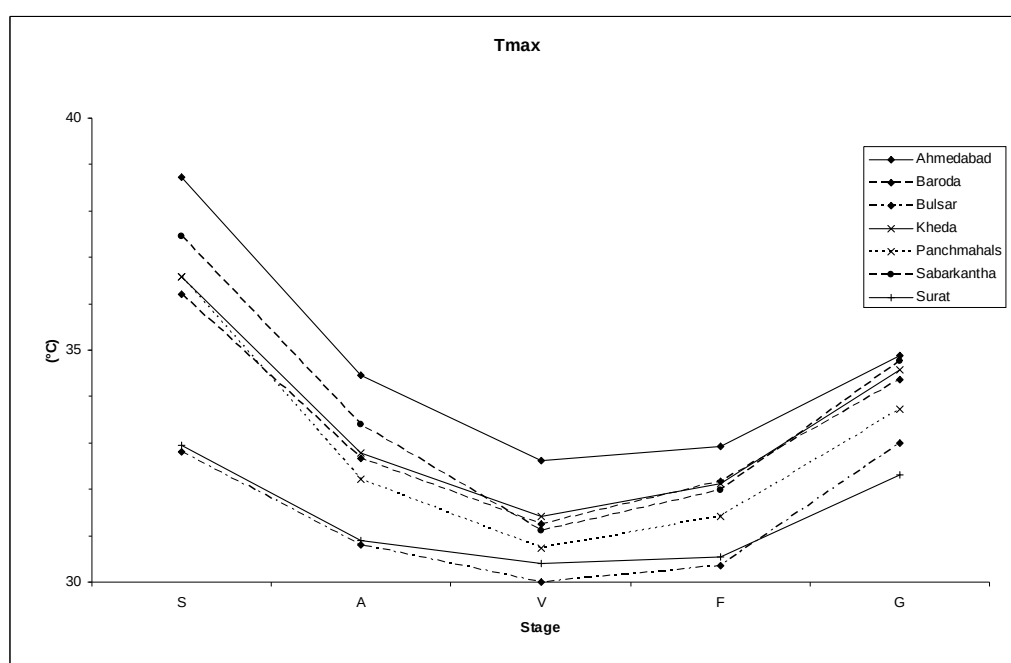


Figure 4.3: Maximum temperature variation during the crop growth period

Data further reveal that the maximum temperature decreased drastically from seedling to vegetative lag stage and gradually increased thereafter. Highest maximum temperature during crop growth period was recorded in Ahmedabad and lowest in Bulsar.

4.1.4 MINIMUM TEMPERATURE

Stagewise minimum temperature prevailed during the study period (23rd to 42nd meteorological standard week) is presented in Table 4.4 and plotted graphically against various phenophases of rice crop in Figure 4.4.

Table 4.4: Average minimum temperature during the crop growth period (°C)

Stage	Ahmedabad	Baroda	Bulsar	Kheda	Panchmahals	Sabarkantha	Surat
S	27.0	24.7	26.8	27.0	26.3	26.3	26.5
A	25.9	23.8	25.9	25.9	24.7	25.2	25.5
V	25.0	23.1	25.4	25.3	24.4	24.4	25.5
F	25.0	22.8	24.7	24.7	24.3	23.9	24.8
G	24.7	22.9	24.3	24.0	23.5	22.5	25.3
SEM	0.2	0.2	0.2	0.2	0.2	0.3	0.1
CV(%)	3.6	3.4	3.8	4.6	4.2	5.9	2.4
SD	0.9	0.8	1.0	1.2	1.0	1.4	0.6

Very little variation was observed in stagewise minimum temperature during the crop growth period in all the districts. Highest variation was observed in Sabarkantha (5.9%) and least in Surat (2.4%). Crop stagewise average minimum temperature of Ahmedabad ranged from 24.7 to 27.0, Baroda from 22.8 to 24.7, Bulsar from 24.3 to 26.8, Kheda from 24.0 to 27.0, Panchmahals from 23.5 to 26.3, Sabarkantha from 22.5 to 26.3 and of Surat from 24.8 to 26.5 °C.

Data further reveal that the minimum temperature decreased gradually during crop growth period. Highest minimum temperature during crop growth period was recorded in Ahmedabad and Kheda and lowest in Sabarkantha.

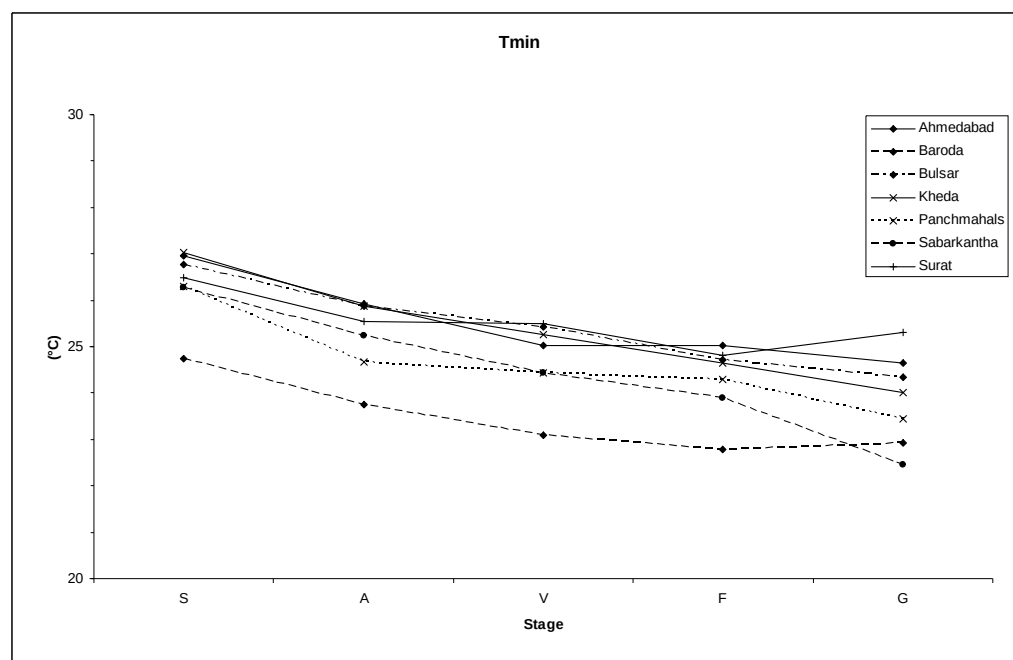


Figure 4.4: Minimum temperature variation during the crop growth period

4.1.5 MORNING RELATIVE HUMIDITY

Table 4.5: Average morning relative humidity during the crop growth period (%)

Stage	Ahmedabad	Baroda	Bulsar	Kheda	Panchmahals	Sabarkantha	Surat
S	76.9	81.9	85.1	80.9	80.4	76.2	80.1
A	84.7	88.2	89.1	88.9	86.8	85.4	84.7
V	87.2	89.9	89.6	91.4	88.6	88.3	85.3
F	86.3	88.0	90.5	91.2	88.8	86.4	83.9
G	81.2	85.3	90.4	87.2	83.8	80.8	82.2
SEM	0.8	0.6	0.4	0.9	0.7	1.0	0.4
CV(%)	5.1	3.6	2.5	4.9	4.2	5.8	2.6
SD	4.2	3.1	2.2	4.3	3.6	4.9	2.1

Crop stagewise average morning relative humidity during the study period (23rd to 42nd meteorological standard week) is presented in Table 4.5 and plotted graphically against different phenophases of rice crop in Figure 4.5. Results illustrated that there was very little variation in morning relative humidity during the crop growth period in all the districts. Highest variation was observed in

Sabarkantha (5.8%) and lowest in Bulsar (2.5%). Range of morning relative humidity for Ahmedabad was from 76.9 to 87.2, Baroda from 81.9 to 89.9, Bulsar from 85.1 to 90.5, Kheda from 80.9 to 91.4, Panchmahals from 80.4 to 88.8, Sabarkantha from 76.2 to 88.3 and for Surat from 80.1 to 85.3 %.

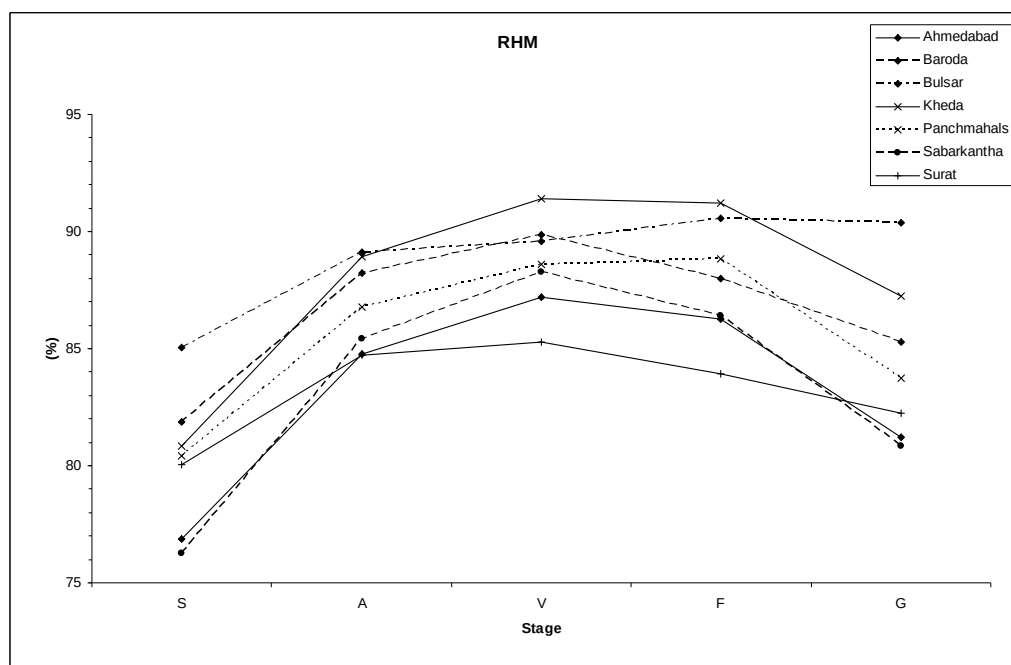


Figure 4.5: Morning relative humidity during the crop growth period

Data further reveal that there was gradual increase in the morning relative humidity from seedling to flowering stage and a gradual decrease thereafter.

4.1.6 AFTERNOON RELATIVE HUMIDITY

Crop stagewise average afternoon relative humidity prevailed rice crop growth period (23rd to 42nd meteorological standard week) is presented in Table 4.6 and plotted graphically in Figure 4.6.

Results illustrated that there was less variation in afternoon relative humidity during the crop growth period in all the districts. Highest variation was observed in Sabarkantha (16.3%) and lowest in Surat (6.3%). Afternoon relative

humidity for Ahmedabad ranged from 45.6 to 66.1, Baroda from 58.4 to 75.8, Bulsar from 67.2 to 81.5, Kheda from 52.1 to 73.4, Panchmahals from 54.1 to 72.0, Sabarkantha from 48.7 to 71.6 and for Surat from 68.3 to 77.8 %.

Table 4.6: Average afternoon relative humidity during the crop growth period (%)

Stage	Ahmedabad	Baroda	Bulsar	Kheda	Panchmahals	Sabarkantha	Surat
S	45.6	58.4	73.1	52.1	54.1	48.7	68.3
A	63.0	72.3	80.9	68.7	68.2	65.0	77.8
V	66.1	75.8	81.5	73.4	72.0	71.6	77.7
F	61.1	68.5	76.9	65.9	67.7	63.9	73.7
G	49.7	59.2	67.2	52.3	55.7	50.9	68.8
Maximum	66.1	75.8	81.5	73.4	72.0	71.6	77.8
Minimum	45.6	58.4	67.2	52.1	54.1	48.7	68.3
SEM	1.8	1.6	1.2	2.0	1.6	2.0	0.9
CV(%)	15.6	11.6	7.9	15.6	12.7	16.3	6.3
SD	8.9	7.8	6.0	9.8	8.1	9.8	4.6

Data further revealed that there was increasing trend in the afternoon relative humidity from seedling to vegetative lag stage and a decreasing trend was observed thereafter.

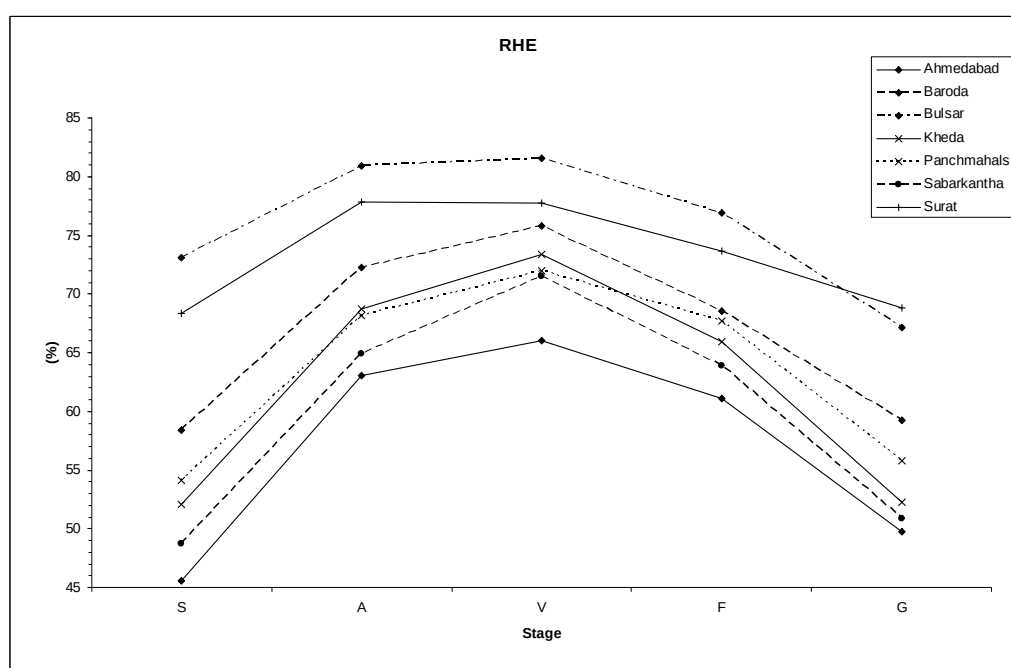


Figure 4.6: Afternoon relative humidity during the crop growth period

4.2 CROP GROWTH SIMULATION MODELLING

A crop simulation model is a computer model used to simulate reality. These models are designed to predict the effect of a future land use scenario on plant growth and yield. Crop simulation models are state of the art technology that allows a user to estimate crop growth and yield as a function of weather conditions and management scenarios. These models are used as the basis for decisions. Various crop simulation models are used nowadays viz. DSSAT, WOFOST, WTGRO, Infocrop, BACROS, CROPGRO, CROPSYS, SUCROS, SWAP, etc.

Two crop growth simulation models viz. DSSAT and WOFOST were calibrated under Gujarat conditions. Efforts were also made to predict rice yield using these models.

4.2.1 DECISION SUPPORT SYSTEM FOR AGROTECHNOLOGY TRANSFER (DSSAT)

The DSSAT has been in use for more than 15 years by researchers in over 100 countries worldwide. DSSAT is a microcomputer software program combining crop soil and weather data bases and programs to manage them, with crop models and application programs, to simulate multi-year outcomes of crop management strategies. As a software package integrating the effects of soil, crop phenotype, weather and management options.

DSSAT also provides for validation of crop model outputs; thus allowing users to compare simulated outcomes with observed results. Crop model

validation is accomplished by inputting the minimum data, running the model, and comparing outputs.

4.2.1.1 MINIMUM DATA SET

The minimum data set (MDS) refers to a minimum set of data required to run the crop models and validate the outputs. Crop validation requires three input data sets:

1. Site weather data for the duration of the growing season,
2. Site soil data, and
3. Management and experimental data for the experiment.

The minimum data set presented in section (3.2.1.1) was utilised to run the crop model and validate the outputs.

4.2.1.2 CALIBRATION OF THE MODEL

Calibration of model was done by adjusting certain model parameters or relationships to make the model work for the desired location. The cultivar characteristics for the rice cv. GR-11 were determined. The calibrated genetic coefficients for GR-11 are given in Table 4.9.

Table 4.7: Calibrated Genetic coefficients for rice cv. GR-11

Parameters	P1	P2R	P5	P2O	G1	G2	G3	G4
Genetic coefficients	570.0	100.0	480.0	11.4	36.0	0.0280	1.00	0.80

4.2.1.3 VALIDATION OF THE MODEL

Adequate validation or assessment of the magnitude of the errors that may result from its use should be performed before using any model. Model validation, in its simplest form is a comparison between simulated and observed values.

The DSSAT model was employed to simulate yield of rice crop for comparison with respective historical yield data with a view to assess the performance of the model in simulating the results. Crop genetic input data, which explain how the life cycle of a cultivar responds to its environment, are not usually available and therefore these were derived interactively. The procedure for determining genetic coefficients involved running the model using a range of values of each coefficient until the desired level of agreement between simulated and observed values was reached. Iterations for the coefficients were stopped when the agreement reached $\pm 10\%$. For the present study the cultivar genetic coefficients for rice cv. GR-11 have been developed. The calibrated genetic coefficients for cv. GR-11 were used as mentioned in Table 4.9.

One of the objectives of this study was to calibrate the genetic coefficients of rice (cv. GR-11) for DSSAT model and also to test other model parameters. The historical yield data formed the basis of the comparison with corresponding results simulated by the model. The results of simulated yields are described below.

4.2.1.3.1 YEAR 2004

The results related to DSSAT model simulation in different districts are presented in Table 4.8 and graphically presented in Figure 4.7. Results revealed that the observed grain yield of rice varied from 758 (Panchmahals) to 2270 kg ha⁻¹ (Kheda) among different districts during 2004, while model simulated grain yield ranged between 642 (Panchmahals) to 2537 kg ha⁻¹ (Ahmedabad) (Figure 4.2.1.3.1.1). The model overestimated the grain yield in Ahmedabad, Bulsar,

Kheda, Sabarkantha and Surat while a totally reverse trend was observed in Baroda and Panchmahals (Figure 4.7) during the year 2004. The differences between model simulated and observed grain yield in all the districts were found negligible with a value of with $R^2 = 95.8\%$. The high coefficient of determination and close scatter of simulated and observed yield around 1:1 regression line (Figure 4.7) indicated close agreement between the observed and simulated Rice yield. The simulated values of grain yield were found in perfect agreement with corresponding observed yield. The results of the simulation performance of the model for grain yield for all the districts was found highly significant with coefficient of determination values of 95.8%.

Table 4.8: Evaluation of DSSAT model with respect to rice grain yield during year 2004 (kg ha^{-1})

S. No.	Parameters	Ahmedabad	Baroda	Bulsar	Kheda	Panchmahal	Sabarkantha	Surat
1	OY	2182	1042	1823	2270	758	1732	1824
2	SDo	562						
3	SY	2537	982	1992	2382	642	1734	1985
4	SDs	701						
5	R^2 (%)	98.3^{**}						
6	Student 't'	0.289^{NS}						
7	PE	9.9						
7	MAE	139.3						
8	MBE	89.0						
9	RMSE	173.3						
10	D	0.98						

where,

OY: Observed yield (kg ha^{-1})

SY: Simulated yield (kg ha^{-1})

SDo: Standard deviation of observed

SDs: Standard deviation of simulated

The test criteria for evaluation of models were also computed. Error per cent of DSSAT simulated grain yields from those corresponding ones observed during the year 2004 was 9.9%. Positive and significant association was observed between simulated and observed grain yield during 2004 with coefficient of determination value of 98.3%. The result of the paired 't' test between simulated and observed grain yield values was found to have been non-significant. The average error as computed by MAE (mean absolute error) was 139.3, while RMSE (Root mean square error) was recorded 173.3. Mean bias error (MBE) described the direction of the error bias. It was also found to be 89.0. The positive value suggested the overestimation of the grain yield by the model. Index of agreement (D) was 0.98. The evaluation of the model on an overall basis revealed that the simulation performance of the model in respect of grain yield was good in year 2004.

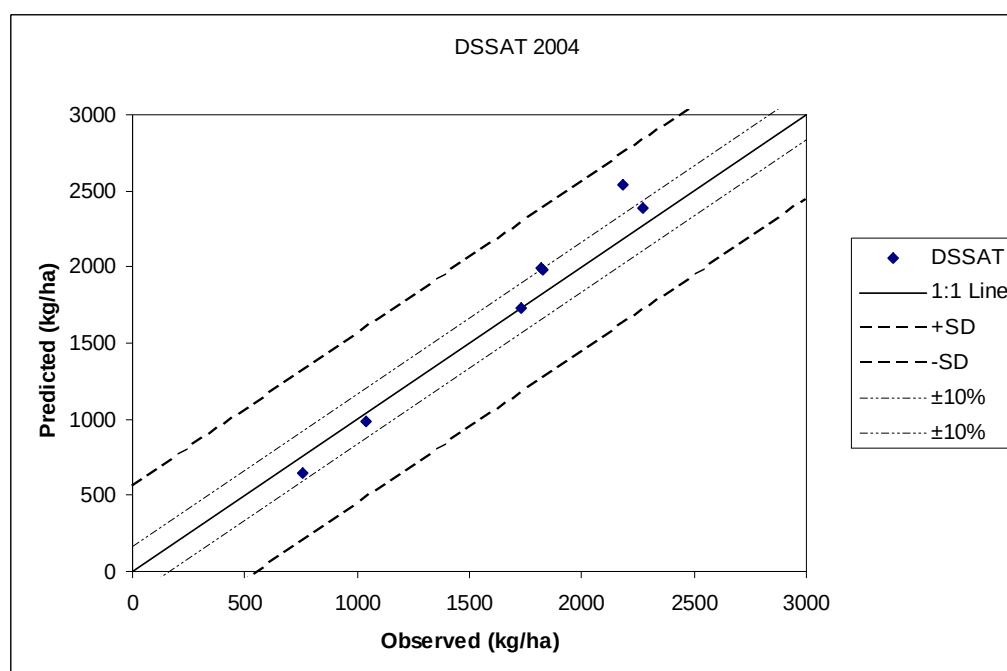


Figure 4.7: Performance of DSSAT model during year 2004

It is difficult to pin point the precise reasons for this deviation as DSSAT is a mechanistic crop growth simulation model capturing the complex effect of climate, genotype and agronomic variable through several functions. Perhaps, such a variation could be intrinsic to the model.

The reasons for underestimation in Baroda was due to the fact that annual rainfall for the year 2004 was 620 mm but most of the rainfall (547 mm) was received before transplanting date used in the model. Though farmers might have gone for earlier sowing and transplanting. Thus, actual yields were higher than the simulated ones.

Similar results had been obtained by Lin (1988), Singh and Padilla (1995), Rao and Subash (1996), Saseendran *et al.*, (1998), Hundal and Kaur (1999), Saseendran *et al.*, (2000), Mall and Aggarwal (2002), Yun (2003), Hundal and Kaur (2004), Kumar and Sharma (2004), Singh *et al.*, (2005) and Sharma and Kumar (2006).

4.2.1.3.2 YEAR 2005

The results of DSSAT simulation modelling in different districts are presented in Table 4.9 and graphically presented in Figure 4.8. Results revealed that the observed rice yield during the year 2005 ranged from 881 (Panchmahals) to 2484 kg ha⁻¹ (Ahmedabad) among different districts, while model simulated rice yield ranged between 920 (Panchmahals) to 2290 kg ha⁻¹ (Ahmedabad). The model overestimated the grain yield in Baroda and Panchmahals while the rice yield was underestimated in Ahmedabad, Bulsar, Kheda, Sabarkantha and Surat. Small differences between model simulated and observed rice grain yield in all

the districts were found with R^2 value of 95.6%. The simulated values of rice yield were found in good agreement with corresponding observed yield. The simulation performance of the model for grain yield for all the districts was found highly significant with coefficient of determination values of 95.6%.

Table 4.9: Evaluation of DSSAT model with respect to rice yield during year 2005 (kg ha^{-1})

S. No.	Parameters	Ahmedabad	Baroda	Bulsar	Kheda	Panchmahal	Sabarkantha	Surat
1	OY	2484	1154	1996	2436	881	2414	1921
2	SDo	645						
3	SY	2290	1241	1950	2283	920	2001	1836
4	SDs	523						
5	R^2 (%)	95.6**						
6	Student 't'	0.213 ^{NS}						
7	PE	10.3						
7	MAE	135.6						
8	MBE	-94.7						
9	RMSE	186.4						
10	D	0.97						

The test criteria for evaluation of models were also computed. Error per cent of DSSAT simulated grain yields from those corresponding ones observed during the year 2005 was 10.3%. Negative and significant association was observed between simulated and observed grain yield during 2005 with coefficient of determination value of 95.6%. The result of the paired 't' test between simulated and observed grain yield values was found to have been non-significant. The average error as computed by MAE was 135.6 with 186.4 RMSE. The MBE was found to be -94.7. The negative sign suggested the underestimation of the grain yield by the model. Index of agreement (D) was 0.97. The evaluation of the model on an overall basis revealed that the simulation performance of the model in respect of grain yield was good in year 2005.

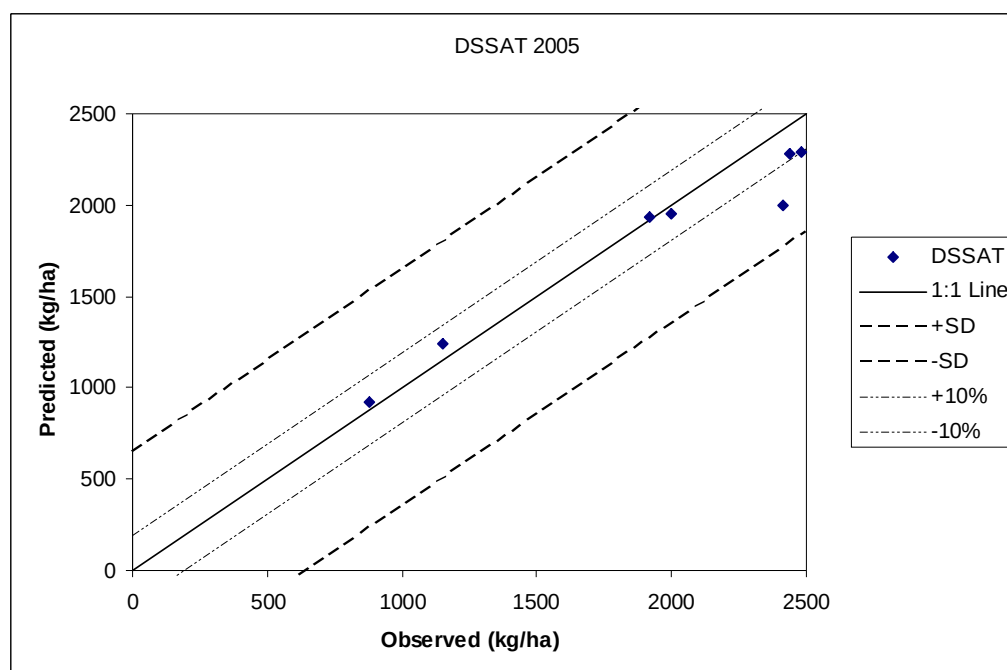


Figure 4.8: Performance of DSSAT model during year 2005

Rao and Subash (1996) during their study at Pilicode simulated rice yield for both kharif and rabi seasons of 1993 and 1994. They reported that simulated and actual yields agreed well in the 1993, while simulated yield was higher than that observed during 1994. Similar results were also reported by Mahmood (1998), Yin and Kropff (1998), Mathauda *et al.*, (2000), Aggarwal and Mall (2002), Tsvetsinskaya *et al.*, (2003) and Patel and Shekh (2006). They pointed that caution was needed in the impact assessment studies made using the average simulated grain yields and mean changes in climatic parameters.

4.2.1.4 SENSITIVITY ANALYSIS OF THE MODEL

A major issue with simulation modeling is the large number of model parameters (calibration values) and input data that are required. The question naturally arises: what happens if we get some of these wrong? The correct

question is: how sensitive is the model to variations in parameters or data? Especially since parameter calibration is largely a black art, sensitivity analysis allows us to see where we should concentrate our calibration and modeling efforts, i.e., where the model is most sensitive. Sensitivity means rate of change in output variable per unit change in input variable or parameter.

Sensitivity study of crop simulation modeling involves exploring the behaviour of the model for different values of parameters.

Tropical countries are more vulnerable to climatic effects in agricultural productivity. Simulation models provide a scientific approach to study the impact of climate change on agricultural production and world food security. Sensitivity test of the crop simulation model is the process by which various input parameters are evaluated with regards to their importance relative to simulation relations. Here, an effort has been made to test the model in terms of mathematical logic and stability to extreme values of weather parameters. The weather parameters selected for this purpose were ambient temperature (± 1 to $\pm 3^{\circ}\text{C}$), solar radiation (± 1 to $\pm 3 \text{ MJm}^{-2} \text{ day}^{-1}$) and concentration of carbon dioxide (100 TO 300 ppm higher concentration to base concentration of 330 ppm). The model simulated rice grain yields under altered weather condition have been compared with corresponding observed yields averaged for the year 2004 and 2005.

4.2.1.4 .1 EFFECTS OF AMBIENT TEMPERATURE

The effects of ambient temperature on simulated grain yield of rice under prevailing conditions and the comparison of this simulated grain yield with base

yield and its per cent change from base yield are presented in Table 4.10, 4.11 and graphically presented in Figure 4.9, 4.10 respectively.

Table 4.10: Effect of elevated ambient temperature (°C) on rice yield

District	yield (kg/ha)				Change (%) over base yield		
	Base	1	2	3	1	2	3
Ahm	2414	2181	2038	1841	-9.6	-15.6	-23.7
Bar	1112	1353	1208	992	21.7	8.6	-10.8
Bul	1971	1981	1889	1885	0.5	-4.2	-4.4
Khe	2333	2197	2094	1943	-5.8	-10.2	-16.7
Pms	781	672	514	458	-14.0	-34.3	-41.4
SK	1868	1784	1601	1398	-4.5	-14.3	-25.2
Srt	1962	1947	1922	1859	-0.7	-2.0	-5.2

Data revealed that there was linear yield decline due to increasing ambient temperature. This indicates that increase in ambient temperature will lead to decreased rice yield in Gujarat.

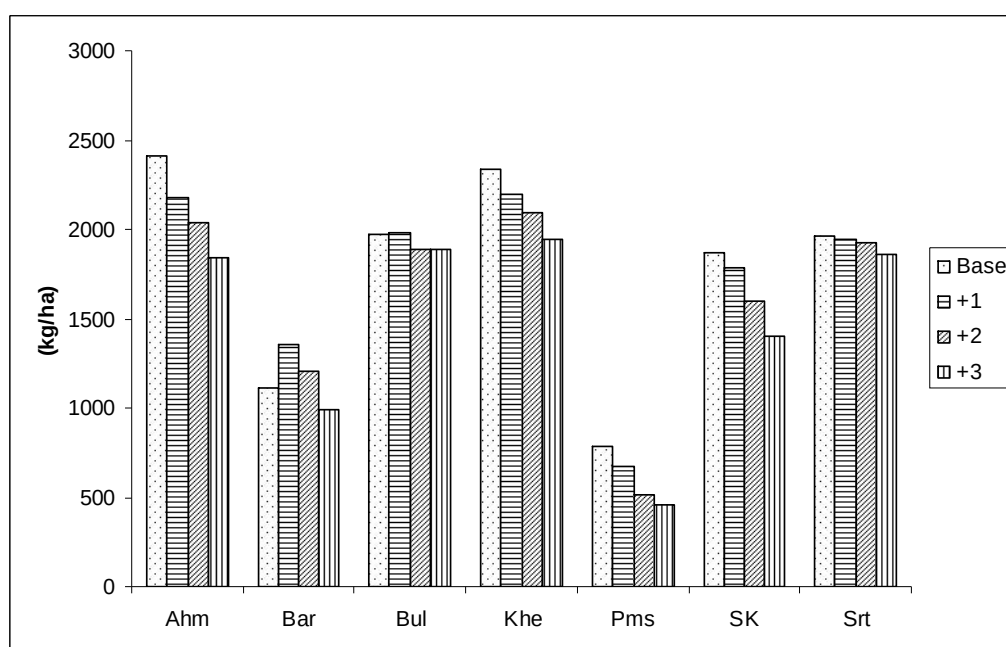


Figure 4.9: Effect of elevated ambient temperature (°C) on rice yield

Data presented in Table 4.11 revealed that linear trend in yield increase was observed due to increasing ambient temperature in all the districts. This indicates that rice yield will increase with decreased ambient temperature in Gujarat.

Table 4.11: Effect of ambient temperature (°C) decrease on rice yield

District	yield (kg/ha)				Change (%) over base yield		
	Base	1	2	3	1	2	3
Ahm	2414	2647	2924	3289	9.7	21.2	36.3
Bar	1112	1193	1388	1643	7.3	24.8	47.8
Bul	1971	2068	2189	2369	4.9	11.1	20.2
Khe	2333	2476	2590	2831	6.2	11.0	21.4
Pms	781	947	1123	1376	21.3	43.8	76.1
SK	1868	2013	2196	2236	7.8	17.6	19.7
Srt	1962	1971	1991	2115	0.5	1.5	7.8

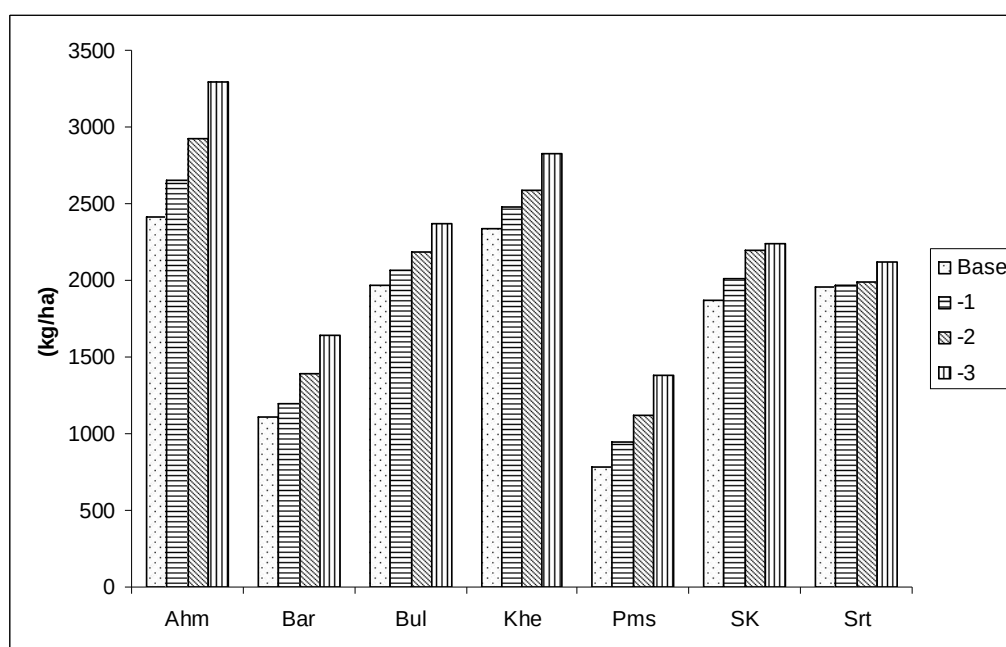


Figure 4.10: Effect of ambient temperature (°C) reduction on rice yield

Sensitivity of DSSAT model simulated grain yield to incremental units of ambient temperature showed a gradual decrease in yield (Table 4.10). The increased ambient temperature decreased the yield by 4 to 41 per cent at 3°C

elevation in mean ambient temperature. The down scaled ambient temperature increased the yield by 7 to 76 per cent at 3°C reduction in mean ambient temperature. Such a behaviour of the model was mainly due to reduction in duration of anthesis and grain filling with rise in ambient temperature and vice versa (Aggarwal and Mall, 2002; Aggarwal *et al.*, 2000; Akula *et al.*, 2005). Saseendran *et al.*, (2000) reported that for every one degree increment there was about 6% decline in rice yield. Hundal and Kaur (2004) and Easterling and Apps (2005) found negative effect of increasing temperature on rice yield. Akula *et al.*, (2005) has reported similar findings for WTGROWS and INFOCROP models. Patel and Shekh (2006) also stated on the basis of sensitivity analysis of CERES-Wheat that elevated maximum temperature decreased wheat yield significantly. Poussin *et al.*, (2003) opined that cold temperatures induced slower development rate and lower aboveground biomass.

4.2.1.4.2. EFFECTS OF SOLAR RADIATION

The results of varying solar radiation and its effects on rice yield as simulated by DSSAT model for elevated and downscaled radiation regimes are presented in in Table 4.12, 4.13 and Figure 4.11, 4.12, respectively.

Table 4.12: Effect of elevated solar radiation ($\text{MJ m}^{-2} \text{d}^{-1}$) on rice yield

District	yield (kg/ha)				Change (%) over base yield		
	Base	1	2	3	1	2	3
Ahm	2414	2626	2809	2967	8.8	16.4	22.9
Bar	1112	1224	1276	1282	10.1	14.8	15.3
Bul	1971	2008	2041	2064	1.9	3.5	4.7
Khe	2333	2392	2454	2526	2.6	5.2	8.3
Pms	781	857	954	983	9.7	22.1	25.9
SK	1868	1960	1989	2064	4.9	6.5	10.5
Srt	1962	1964	1961	1998	0.1	0.0	1.8

It is evident from the data presented in the Table 4.12 that rice yield increased linearly with elevated solar radiation regime. Higher solar radiation resulted in increased photosynthesis leading to increased yield.

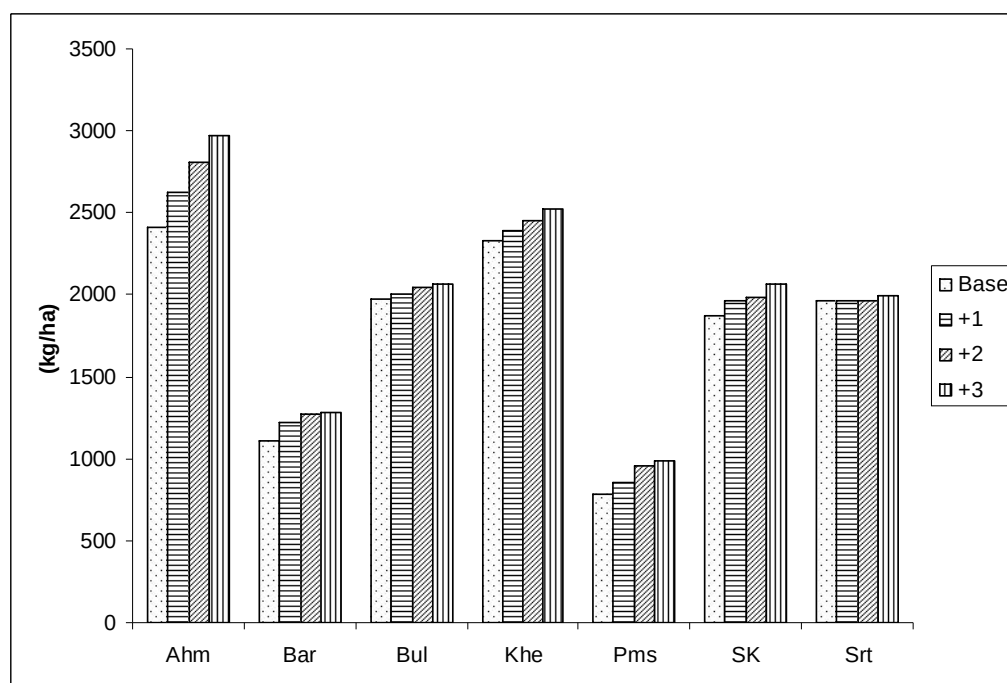


Figure 4.11: Effect of elevated solar radiation ($\text{MJ m}^{-2} \text{d}^{-1}$) on rice yield

The data presented in the Table 4.13 indicated linear decrease in rice yield with lowered solar radiation regime. Lower solar radiation resulted in decreased photosynthesis leading to decreased yield.

Table 4.13: Effect of solar radiation ($\text{MJ m}^{-2} \text{d}^{-1}$) reduction on rice yield

District	yield (kg/ha)				Change (%) over base yield		
	Base	1	2	3	1	2	3
Ahm	2414	2230	2050	1806	-7.6	-15.1	-25.2
Bar	1112	1011	851	637	-9.1	-23.4	-42.7
Bul	1971	1969	1974	1950	-0.1	0.1	-1.1
Khe	2333	2217	2117	2015	-5.0	-9.3	-13.6
Pms	781	720	759	684	-7.9	-2.9	-12.4
SK	1868	1764	1532	1170	-5.5	-18.0	-37.3
Srt	1962	1976	1917	1842	0.7	-2.3	-6.1

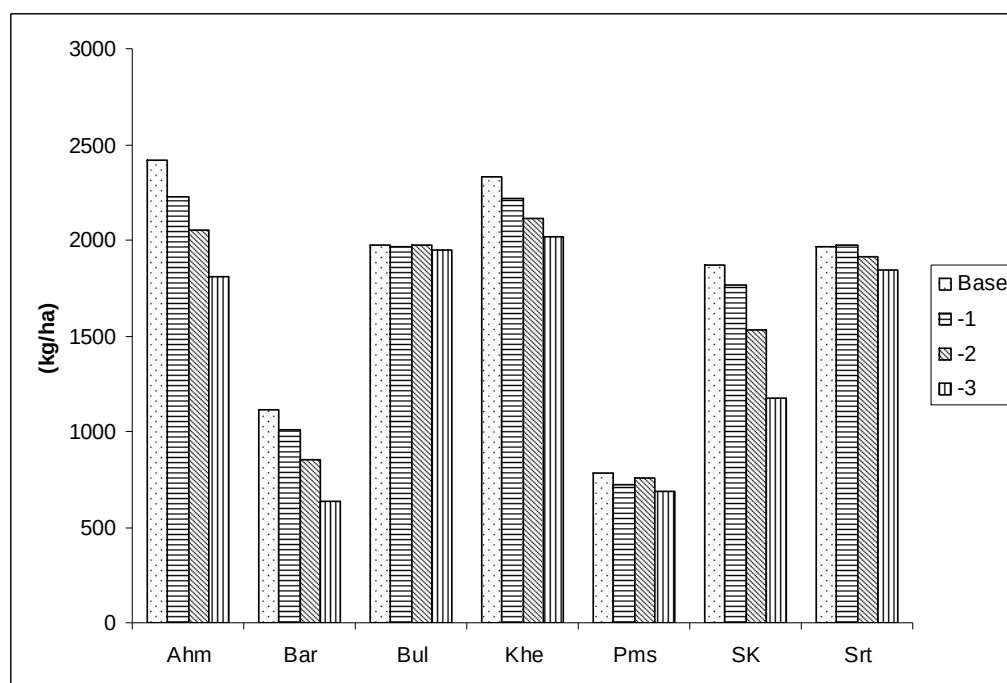


Figure 4.12: Effect of solar radiation ($\text{MJ m}^{-2} \text{d}^{-1}$) reduction on rice yield

Results showed that with increase from 1 to 3 $\text{MJm}^{-2} \text{day}^{-1}$ solar radiation, percentage yield increased from 2 to 26 in comparison with base yield (Table 4.12). Highest yield increment was observed at 3 $\text{MJm}^{-2} \text{day}^{-1}$ in Panchmahal district (25.9%). In case of gradual reduction in solar radiation, gradual decrease in yield in terms of per cent change from base yield was noted as 1 to 42 per cent for reduction in solar radiation by 3 $\text{MJm}^{-2} \text{day}^{-1}$. Kropff *et al.*, (2003) concluded that the yield decline in rice was mainly associated with reduced solar radiation. Akula *et al.*, (2005) using WTGROWS and INFOCROP models for wheat and Patel and Shekh (2006) using CERES-Wheat reported similar effects of alteration in radiation in Wheat.

4.2.1.4.3 EFFECT OF ELEVATED CARBON DIOXIDE

The effect of elevated carbon dioxide (100 to 300 ppm elevation to the base value 330 ppm) on simulated yield of rice have been presented in Table 4.14 and depicted in Figure 4.13.

Table 4.14: Effect of elevated CO₂ concentration (ppm) on rice yield

District	yield (kg/ha)				Change (%) over base yield		
	Base	1	2	3	1	2	3
Ahm	2414	2666	2922	3110	10.5	21.0	28.8
Bar	1112	1295	1321	1335	16.5	18.8	20.1
Bul	1971	2012	2050	2076	2.1	4.0	5.3
Khe	2333	2383	2475	2555	2.2	6.1	9.5
Pms	781	956	1137	1185	22.4	45.5	51.7
SK	1868	1974	2053	2142	5.7	9.9	14.7
Srt	1962	1946	1979	2032	-0.8	0.9	3.6

The data presented in the table indicated linear increase in rice yield with elevated CO₂ concentration. Higher CO₂ concentration resulted in increased photosynthesis leading to higher yield.

Figure 4.13 showed that at 300 ppm elevation in CO₂ concentration over its base value yield increased by 4 to 29 per cent. Patel and Shekh (2006) observed that increased concentration of CO₂ had a significant and positive impact on the grain yield of wheat. Similar results were noted by Matthews et al. (1995) in case of rice. This showed that the model used in this study had the potential for assessing the impacts of climate change on rice production. Properly validated crop simulation models could be used with confidence to combine the environmental effects on crop physiological processes and to evaluate the consequences of such influences.

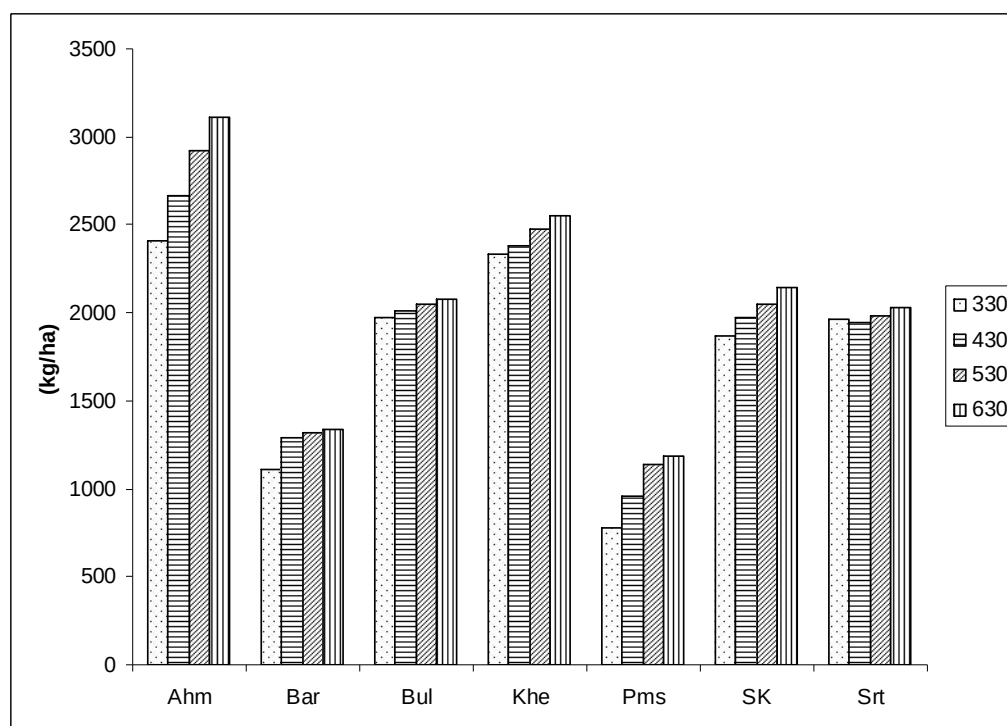


Figure 4.13: Effect of elevated CO₂ concentration (ppm) on rice yield

4.2.2 WORLD FOOD STUDY (WOFOST)

WOFOST is a mechanistic model that explains crop growth on the basis of the underlying processes, such as photosynthesis, respiration and how these processes are influenced by environmental conditions. WOFOST is a member of the family of crop growth models developed in Wageningen by the school of C.T. de Wit. Related models are SUCROS, MACROS and ORYZA1. WOFOST was originally developed to assess yield potential of various annual crops in tropical countries. WOFOST has been used to assess the effect of climate change on crop growth. The model is particularly suited to quantify the combined effect of changes in CO₂, temperature, rainfall and solar radiation, on crop development, crop growth and crop water use, as all the relevant processes are simulated separately while taking due account of their interactions.

4.2.2.1 MINIMUM DATA SET

The minimum input data required for WFOST were same as those required by DSSAT and listed section 3.2.2.2. The additional input data set presented in sections (3.2.2.6) was utilised to run the crop model and validate the output.

4.2.2.2 CALIBRATION OF THE MODEL

Calibration of model was done by adjusting certain model parameters or relationships to make the model work for the desired location. The model required fourteen parameters. The details of these calibrated input model parameters are given in Table 4.15.

Table 4.15: Calibrated input model parameters used for WOFOST

Parameter	Value
TSUM1	1753
TSUM2	480
DLO	11.4
TDWI	25.0
SPAN	23.0
TBASE	9.0
CVL	0.754
CVO	0.584
CVR	0.754
CVS	0.754
RML	0.020
RMO	0.030
RMR	0.010
RMS	0.015

4.2.2.3 VALIDATION OF THE MODEL

Adequate validation or assessment of the magnitude of the errors that may result from its use should be performed before using any model. Model validation, in its simplest form is a comparison between simulated and observed values.

The objectives of this study was to calibrate the genetic coefficients of rice (cv. GR-11) for WOFOST model and also to test other model parameters. The experimental results, which formed the basis of the comparison with corresponding results simulated by the model, are described below.

4.2.2.3.1 YEAR 2004

The results of WOFOST model simulation for different districts are presented in Table 4.16 and graphically presented in Figure 4.14. Results revealed that the observed grain yield of rice varied from 758 (Panchmahals) to 2270 kg ha⁻¹ (Kheda) among different districts during 2004, while model simulated grain yield ranged between 617 (Panchmahals) to 2459 kg ha⁻¹ (Kheda). The model overestimated the grain yield in Ahmedabad, Bulsar, Kheda and Sabarkantha while reverse trend was observed in Baroda, Panchmahals and Surat. The simulated grain yield were found in perfect agreement with corresponding observed yield. The simulation performance of the model for grain yield for all the districts was found highly significant with R² values of 95.8%.

Table 4.16: Evaluation of WOFOST model with respect to rice grain yield during year 2004 (kg ha⁻¹)

S. No.	Parameters	Ahmedabad	Baroda	Bulsar	Kheda	Panchmahal	Sabarkantha	Surat
1	OY	2182	1042	1823	2270	758	1732	1824
2	SDo	699						
3	SY	2355	1031	1889	2459	617	1808	1823
4	SDs	669						
5	R ² (%)	99.6**						
6	Student 't'	0.01 ^{NS}						
7	PE	6.83						
7	MAE	93.85						
8	MBE	50.14						
9	RMSE	116.98						
10	D	0.99						

The test criteria for evaluation of models were also computed. Error per cent of WOFOST simulated grain yields from those corresponding ones observed during the year 2004 was 6.83%. Positive and significant association was observed between simulated and observed grain yield during 2004 with coefficient of determination value of 99.6%. The result of the paired 't' test between simulated and observed grain yield values was found to have been non-significant. The average error as computed by MAE was 93.85, while RMSE was recorded 116.98. Mean bias error was found to be 50.14. The positive value indicated the overestimation of the grain yield by the model. Index of agreement was found 0.99. The evaluation of the model on an overall basis revealed that the simulation performance of the model in respect of grain yield was excellent in year 2004.

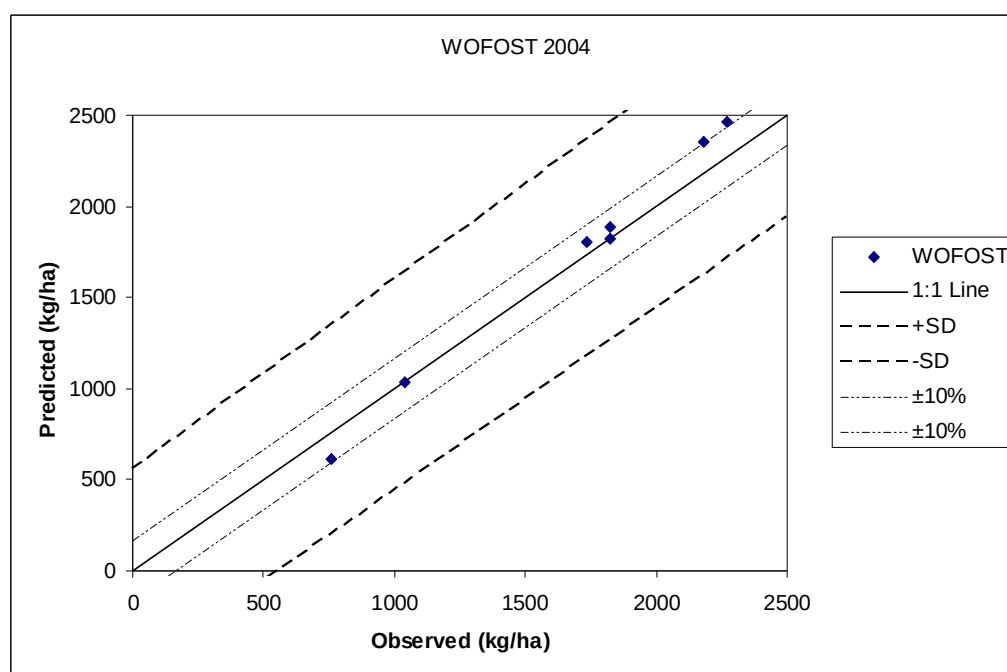


Figure 4.14: Performance of WOFOST model during year 2004

It is difficult to pin point the precise reasons for this deviation as WOFOST is a mechanistic crop growth simulation model representing the complex effect of climate, genotype and agronomic variable through several functions.

The results are in good agreement with the findings of Sadasivam *et al.*, (1989), Herrera *et al.*, (1990), Ramasamy (2000), Mall and Aggarwal (2002), Kropff *et al.*, (2003), Abou *et al.*, (2004) and Das *et al.*, (2007).

4.2.2.3.2 YEAR 2005

The results of WOFOST model simulation during year 2005 for different districts presented in Table 4.17 and graphically presented in Figure 4.15 revealed that the observed grain yield of rice during the year 2005 varied from 881 (Panchmahals) to 2484 kg ha⁻¹ (Ahmedabad) among different districts, while model simulated grain yield fluctuated from 922 (Panchmahals) to 2432 kg ha⁻¹ (Kheda). The model overestimated the grain yield in Baroda and Panchmahals while it underestimated rice yield in Ahmedabad, Bular, Kheda, Sabarkantha and Surat. Model simulated values of grain yield were found in perfect agreement with corresponding observed yield. The results of the simulation performance of the model for grain yield for all the districts was found highly significant with R² values of 97.1%.

The test criteria for evaluation of model indicated that the error per cent of WOFOST simulated grain yields from those corresponding ones observed during the year 2005 was 7.34%. Negative and significant association was observed between simulated and observed grain yield during 2005 with coefficient of determination value of 97.1%. The result of the paired 't' test between simulated

and observed grain yield values was found to have been non-significant. The average error as computed by MAE was 91.14, while RMSE was recorded 134.60. Mean bias error was found to be – 66.57. The negative sign indicated the underestimation of the grain yield by the model. Index of agreement was found 0.99. The evaluation of the model on an overall basis revealed that the simulation performance of the model in respect of grain yield was excellent in year 2005.

Table 4.17: Evaluation of WOFOST model with respect to rice grain yield during year 2005 (kg ha⁻¹)

S. No.	Parameters	Ahmedabad	Baroda	Bulsar	Kheda	Panchmahal	Sabarkantha	Surat
1	OY	2484	1154	1996	2436	881	2414	1921
2	SDo							645
3	SY	2386	1199	1862	2432	922	2105	1914
4	SDs	574						
5	R ² (%)	97.1**						
6	Student 't'	0.40 ^{NS}						
7	PE	7.34						
7	MAE	91.14						
8	MBE	-66.57						
9	RMSE	134.60						
10	D	0.99						

Similar results were reported by Jansen (1990), Matthews *et al.*, (1995), Casanova *et al.*, (2000) and Aggarwal and Mall (2002).

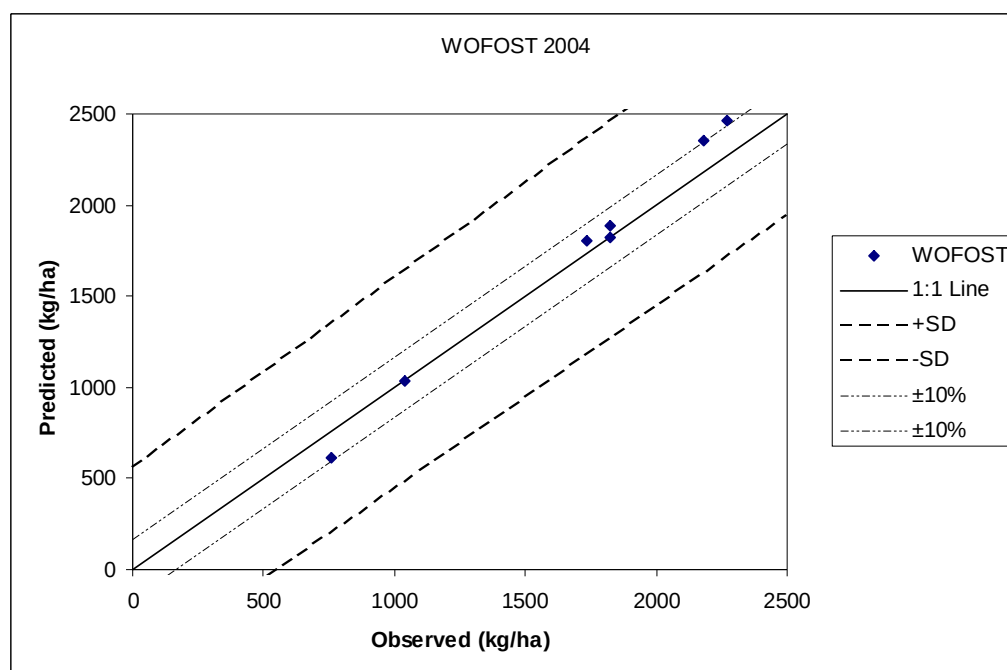


Figure 4.15: Performance of WOFOST model during year 2004

4.3 AGROMETEOROLOGICAL MODELLING

Various agrometeorologically based models are generally crop-weather relationship models which may be defined as a simplified representation of the complex relationship between weather or climate and crop performance using established mathematical and/or statistical techniques. Generally, multiple and stepwise regression techniques are employed using more than one variable. Apart from meteorological variables, other variables such as soil characteristics, biometric observation, growth indices, derived meteorological parameters and a technological trend have been correlated with crop yields. Numerous studies were carried out to use crop-weather relationships for the development and applications of crop-weather models suitable for monitoring and predicting crop yields.

Preharvest yield prediction can help in taking policy decisions with greater confidence in the food procurement and distribution, price policies, export-import policies and for exercising several administrative measures for storage and marketing of agricultural commodities. Such forecast mainly depends on crop weather relationship. To estimate the effect of weather variables on production of rice in Gujarat, yield data were collected for assessing joint influence of weather variables employing different statistical approaches. The approaches employed were.

1. Weekwise approach using original weather variables
2. Crop stagewise approach using original weather variables
3. Periodwise approach using original weather variables
4. Week number as weight using generated weather variables
5. Correlation coefficient as weight using generated weather variables.

The weather variables viz. bright sunshine hours, rainfall, maximum and minimum temperature, and morning and afternoon relative humidity related to 12, 14, 16, 18 and 20 weeks crop period were considered in the models of 1st, 4th and 5th approaches to explore the possibility of yield prediction before 8, 6, 4, 2 and 0 weeks of harvest, respectively. In case of crop stagewise approach weather variables were considered upto 1st, 2nd, 3rd, 4th and 5th stages i.e. seedling, active tillering, vegetative lag, flowering, grain development and maturity stages respectively, to provide forecasts before 16, 13, 9, 5 and 2 weeks of harvest, respectively. In periodwise approach weather variables were considered upto 1st, 2nd, 3rd, 4th and 5th periods i.e. June, July, August, September and October

respectively, to provide predictions before 4, 3, 2, 1 and 0 months of harvest, respectively. In case of each of the model the variables included were determined based on stepwise regression procedure utilizing historical weather data. The model was selected on the basis of coefficient of determination and earliness of forecasting.

The results for different approaches are presented and discussed in the subsequent sections.

4.3.1 WEEKWISE APPROACH USING ORIGINAL WEATHER VARIABLES

In this approach, original weekwise weather variables were utilized for fitting the regression equations. The fitted equations, their coefficients of multiple determinations for five different models corresponding to 12, 14, 16, 18 and 20 weeks crop periods are presented in Tables 4.18, 4.19, 4.20, 4.21, 4.22, 4.23 and 4.24 for different districts.

4.3.1.1 Ahmedabad District

The results relating to different weeks are presented in Table 4.18. The results related to 12 and 14 weeks crop period were the same. The set of explanatory variables observed to enter in the equations consisted of weekly weather variables viz., X_{605} and X_{609} . These variables explained 68.4% variation in yield of rice. The results indicated that the partial regression coefficients for afternoon relative humidity of 27th week (X_{605}) and 31st week (X_{609}) were positive and significant.

The results of 16 week crop period revealed that the set of explanatory variables entered in the equation consisted of weekly weather variables viz., X_{114} ,

X_{201} , X_{404} , X_{405} , X_{407} , X_{415} , X_{511} , X_{515} , X_{605} and X_{609} . These variables explained 99.8% variation in yield of rice crop. The partial regression coefficients for minimum temperature of 27th week (X_{405}) and 37th week (X_{415}), morning relative humidity of 37th week (X_{515}) and afternoon relative humidity of 27th week (X_{605}) and 31st week (X_{609}) were positive and significant, whereas partial regression coefficients for bright sunshine hours of 36th week (X_{114}), rainfall of 23rd week (X_{201}), minimum temperature of 26th week (X_{404}) and 29th week (X_{407}) and morning relative humidity of 33rd week (X_{511}) were negative and significant.

Table 4.18: Partial regression coefficients of rice yield on different original weather variables in weekwise approach in Ahmedabad district N = 17

Variables in the equation	Weeks				
	12	14	16	18	20
Constant A_0	-1606.895**	-1606.895**	-1190.093*	-24526.124**	-17104.953**
X_{605}	23.698**	23.698**	34.175**	19.163**	19.288**
X_{609}	22.202**	22.202**	30.282**	13.998**	25.298**
X_{201}	-	-	-7.329**	-	-
X_{404}	-	-	-206.459**	-	-
X_{405}	-	-	304.295**	-	-
X_{407}	-	-	-411.569**	-	-
X_{511}	-	-	-24.203**	-	-30.446**
X_{114}	-	-	-64.859**	-	-
X_{415}	-	-	306.035**	38.361**	-
X_{515}	-	-	18.940**	-	-
X_{202}	-	-	-	-6.263**	-
X_{505}	-	-	-	2.750*	-
X_{510}	-	-	-	154.789**	79.139**
X_{411}	-	-	-	-179.094**	-
X_{417}	-	-	-	178.146**	-
X_{517}	-	-	-	85.350**	62.919**
X_{218}	-	-	-	-2.794**	-
X_{318}	-	-	-	58.603**	115.242**
X_{214}	-	-	-	-	1.180**
X_{618}	-	-	-	-	6.413**
X_{120}	-	-	-	-	106.926**
X_{420}	-	-	-	-	29.313*
Adjusted R^2 (%)	68.4	68.4	99.8	99.9	99.8

*, ** Significant at 5% and 1% level of significance, respectively

The set of explanatory variables entered in the equation relating to 18 week crop period were weekly weather variables viz., X_{202} , X_{218} , X_{318} , X_{417} , X_{411} , X_{415} , X_{505} , X_{510} , X_{517} , X_{605} and X_{609} . About 99.9% variation in yield of the rice crop was explained by these variables. Results further indicated that the partial regression coefficients for maximum temperature of 40th week (X_{318}), minimum temperature of 37th week (X_{415}) and 39th week (X_{417}), morning relative humidity of 27th week (X_{505}), 32nd week (X_{510}) and 39th week (X_{517}) and afternoon relative humidity of 27th week (X_{605}) and 31st week (X_{609}) were found positive and significant, whereas partial regression coefficients for rainfall of 24th week (X_{202}) and 40th week (X_{218}) and minimum temperature of 33rd week (X_{411}) were found negative and significant.

The set of weekly weather variables that entered in the equation relating to 20 week crop period were X_{120} , X_{214} , X_{318} , X_{420} , X_{510} , X_{511} , X_{517} , X_{605} , X_{609} and X_{618} and explained about 99.8% variation in yield of the rice crop. Positive and significant partial regression coefficients were observed for bright sunshine hours of 42nd week (X_{120}), rainfall of 36th week (X_{214}), maximum temperature of 40th week (X_{318}), minimum temperature of 42nd week (X_{420}), morning relative humidity of 32nd week (X_{510}) and 39th week (X_{517}) and afternoon relative humidity of 27th week (X_{605}), 31st week (X_{609}), 40th week (X_{618}), whereas negative and significant partial regression coefficients were observed for morning relative humidity of 33rd week (X_{511}).

Among the equations fitted under this approach, in model of 12 and 14 weeks crop period, R^2 was about 68.4%. In case of 16, 18 and 20 weeks models,

R^2 was very high (more than 99%). Thus, 16 week model could be considered as an earliest yield prediction model based on high R^2 value under this approach.

4.3.1.2 Baroda District

The results related to weekwise approach are presented in Table 4.19. Results of 12 week crop period revealed that the weekly weather variables viz., X_{106} , X_{110} , X_{111} , X_{202} , X_{509} and X_{511} entered in the model. These variables explained about 99.4% variation in rice yield. The results indicated that the partial regression coefficients for bright sunshine hours of 28th week (X_{106}) and 33rd week (X_{111}) and morning relative humidity of 31st week (X_{509}) and 33rd week (X_{511}) were positive and significant whereas the partial regression coefficients for bright sunshine hours of 32nd week (X_{110}) and rainfall of 24th week (X_{202}) were negative and significant.

Table 4.19: Partial regression coefficients of rice yield on different original weather variables in weekwise approach in Baroda district N = 12

Variables in the equation	Weeks				
	12	14	16	18	20
Constant A_0	-5052.940**	-6210.565**	-6210.565**	-4330.445**	-6130.228**
X_{202}	-0.332*	-	-	-	-
X_{106}	19.055*	-	-	31.168**	-
X_{509}	37.453**	44.235**	44.235**	38.013**	40.311**
X_{110}	-42.512**	-	-	-	-
X_{111}	178.411**	-	-	-	-
X_{511}	24.461**	-	-	-	-
X_{102}	-	77.562**	77.562**	70.066**	65.380**
X_{514}	-	30.395*	30.395*	25.543**	33.678**
X_{303}	-	-	-	-28.150**	-
X_{218}	-	-	-	16.970**	-
X_{510}	-	-	-	-	-8.857*
X_{610}	-	-	-	-	14.412**
X_{311}	-	-	-	-	48.420**
X_{320}	-	-	-	-	-51.180**
Adjusted R^2 (%)	99.4	87.1	87.1	99.6	99.6

*, ** Significant at 5% and 1% level of significance, respectively

The set of explanatory variables entered in the equations of 14 and 16 weeks crop period were the same and consisted of weekly weather variables viz., X_{102} , X_{509} and X_{514} . These variables explained about 87.1% of variation in yield of the rice crop. The partial regression coefficients for bright sunshine hours of 24th week (X_{102}) and morning relative humidity of 31st week (X_{509}) and 36th week (X_{514}) were found positive and significant.

Weekly weather variables viz., X_{102} , X_{106} , X_{218} , X_{303} , X_{509} and X_{514} entered in the equation relating to 18 week crop period and explained about 99.6% variation in yield of the rice crop. Partial regression coefficients for bright sunshine hours of 24th week (X_{102}) and 28th week (X_{106}), rainfall of 40th week (X_{218}) and morning relative humidity of 31st week (X_{509}) and 36th week (X_{514}) were positive and significant, whereas partial regression coefficient for maximum temperature of 25th week (X_{303}) was negative and significant.

Weekly weather variables that entered in the equation related to 20 week crop period were X_{102} , X_{311} , X_{320} , X_{509} , X_{510} , X_{514} and X_{610} and explained about 99.6% variation in yield of the rice crop. Results revealed that the partial regression coefficients for bright sunshine hours of 24th week (X_{102}), maximum temperature of 33rd week (X_{311}), morning relative humidity of 31st week (X_{509}) and 36th week (X_{514}) and afternoon relative humidity of 32nd week (X_{610}) were positive and significant, whereas partial regression coefficient for maximum temperature of 42nd week (X_{320}) and morning relative humidity of 32nd week (X_{510}) were negative and significant.

Coefficient of determination was very high for the equations related to all the crop periods. It was 99.4% for 12 week, 87.1% for 14 and 16 weeks and 99.6% in 18 and 20 weeks models. Looking to the R^2 value and earliness of forecast, 12 week model was considered as a yield prediction model under this approach.

4.3.1.3 Bulsar District

The results related to different crop periods are presented in Table 4.20. Only 49.1% variation in yield of the rice crop was explained by weekly weather variables X_{101} , X_{106} , X_{211} and X_{605} in 12 week crop period. Results indicated that the partial regression coefficients for bright sunshine hours of 23rd week (X_{101}) and rainfall of 33rd week (X_{211}) were positive and significant, whereas partial regression coefficients for bright sunshine hours of 28th week (X_{106}) and afternoon relative humidity of 27th week (X_{605}) were negative and significant.

The variables entered in 14 and 16 weeks crop period were the same. The set of explanatory variables entered in the equations consisted of weekly weather variables viz., X_{106} , X_{107} , X_{114} , X_{207} , X_{211} and X_{614} . These variables explained 78.1% variation in yield of the rice crop. The partial regression coefficients for bright sunshine hours of 29th week (X_{107}) and rainfall of 29th week (X_{207}) and 33rd week (X_{211}) were positive and significant, whereas partial regression coefficients for bright sunshine hours of 28th week (X_{106}) and 36th week (X_{114}) and afternoon relative humidity of 36th week (X_{614}) were found negative and significant.

Table 4.20: Partial regression coefficients of rice yield on different original weather variables in weekwise approach in Bulsar district N = 26

Variables in the equation	Weeks				
	12	14	16	18	20
Constant A_0	3926.284**	5128.229**	5128.229**	5788.423**	6276.784**
X_{101}	70.082*	-	-	-	-
X_{605}	-22.368**	-	-	-	-
X_{106}	-202.831**	-135.696**	-135.696**	-86.852**	-70.601**
X_{211}	1.657**	2.344**	2.344**	3.730**	2.428**
X_{107}	-	69.929**	69.929**	106.213**	-
X_{207}	-	1.794**	1.794**	2.468**	-
X_{114}	-	-154.646**	-154.646**	-106.465**	-
X_{614}	-	-32.018**	-32.018**	-41.871**	-
X_{103}	-	-	-	-23.633**	-
X_{203}	-	-	-	-0.152**	-
X_{305}	-	-	-	-69.951**	-
X_{405}	-	-	-	59.487**	-
X_{308}	-	-	-	103.573**	-
X_{109}	-	-	-	-33.494**	22.381**
X_{111}	-	-	-	25.878**	-
X_{212}	-	-	-	-0.844**	-
X_{313}	-	-	-	-170.012**	-
X_{413}	-	-	-	-70.315**	-
X_{216}	-	-	-	0.604**	-
X_{517}	-	-	-	41.795**	-
X_{314}	-	-	-	-	93.612**
X_{117}	-	-	-	-	-139.812**
X_{617}	-	-	-	-	-24.502**
X_{318}	-	-	-	-	12.450**
X_{618}	-	-	-	-	-16.249**
X_{219}	-	-	-	-	1.369*
X_{320}	-	-	-	-	-115.819**
Adjusted R^2 (%)	49.1	78.1	78.1	99.8	96.0

*, ** Significant at 5% and 1% level of significance, respectively

The results relating to 18 week crop period revealed that the set of explanatory variables entered in the equation were weekly weather variables viz., X_{103} , X_{106} , X_{107} , X_{109} , X_{111} , X_{114} , X_{203} , X_{207} , X_{211} , X_{212} , X_{216} , X_{305} , X_{308} , X_{313} , X_{405} , X_{413} , X_{517} and X_{614} . About 99.8% variation in rice yield was explained by these variables. Results indicated that the partial regression coefficients for bright

sunshine hours of 29th week (X_{107}) and 33rd week (X_{111}), rainfall of 29th week (X_{207}), 33rd week (X_{211}) and 38th week (X_{216}), maximum temperature of 30th week (X_{308}), minimum temperature of 27th week (X_{405}) and morning relative humidity of 39th week (X_{517}) were found positive and significant, whereas partial regression coefficients for bright sunshine hours of 25th week (X_{103}), 28th week (X_{106}), 31st week (X_{109}) and 36th week (X_{114}), rainfall of 25th week (X_{203}) and 34th week (X_{212}), maximum temperature of 27th week (X_{305}) and 35th week (X_{313}), minimum temperature of 35th week (X_{413}) and afternoon relative humidity of 36th week (X_{614}) were found negative and significant.

The set of weekly weather variables found to enter in the equation relating to 20 week crop period were X_{106} , X_{109} , X_{117} , X_{211} , X_{219} , X_{314} , X_{318} , X_{320} , X_{617} and X_{618} and explained about 96.0% variation in yield of the rice crop. Positive and significant partial regression coefficients were observed bright sunshine hours of 31st week (X_{109}), rainfall of 33rd week (X_{211}) and 41st week (X_{219}), maximum temperature of 36th week (X_{314}) and 40th week (X_{318}), whereas for bright sunshine hours of 28th week (X_{106}) and 39th week (X_{117}), maximum temperature of 42nd week (X_{320}) and afternoon relative humidity of 39th week (X_{617}) and 40th week (X_{618}) negative and significant partial regression coefficients were observed.

The fitted equations under this approach revealed that R^2 was low (49.1%) in 12 week model. While for 14 and 16 weeks crop period model it was high (78.1%). It was very high in 18 week (99.8%) and 20 week (96.0%) models. Thus, 18 week model could be considered as a yield prediction model based on very high R^2 value and earliness of forecasting under this approach.

4.3.1.4 Kheda District

The results for Kheda district related to different crop periods are presented in Table 4.21. Results related to 12 and 14 weeks crop period were the same and only 21.4% variation in yield of the rice crop was explained by a single weekly weather variable X_{609} , which corresponds to afternoon relative humidity of 31st week (X_{609}) and its regression coefficient was found positive and significant.

The results of 16 week crop period revealed that only one weekly weather variable viz., X_{616} entered in the equation and explained about 38.5% variation in rice yield. The partial regression coefficients for afternoon relative humidity of 38th week (X_{616}) was found positive and significant.

Table 4.21: Partial regression coefficients of rice yield on different original weather variables in weekwise approach in Kheda district N =26

Variables in the equation	Weeks				
	12	14	16	18	20
Constant A_0	359.135	359.135	512.897	9466.191**	8682.131**
X_{609}	17.952**	17.952**	-	-	-
X_{616}	-	-	20.180**	-	-
X_{316}	-	-	-	-78.358**	-59.172**
X_{318}	-	-	-	-143.733**	-152.216**
X_{410}	-	-	-	-	317.718**
X_{610}	-	-	-	-	12.873**
X_{412}	-	-	-	-	-202.966**
X_{119}	-	-	-	-	-79.210**
X_{519}	-	-	-	-	-32.924**
Adjusted R^2 (%)	21.4	21.4	38.5	59.5	90.7

*, ** Significant at 5% and 1% level of significance, respectively

Results related to 18 week crop period revealed that the set of explanatory variables entered in the equation were weekly weather variables viz., X_{316} and X_{318} . About 59.5% variation in rice yield was explained by these variables. Results revealed that the partial regression coefficients for maximum temperature

of 38th week (X_{316}) and 40th week (X_{318}) were negative and significant, which indicated adverse effect of maximum temperature.

The set of weekly weather variables entered in the equation related to 20 week crop period were X_{119} , X_{316} , X_{318} , X_{410} , X_{412} , X_{519} and X_{610} which accounted about 90.7% variation in yield of the rice crop. Partial regression coefficients were observed positive and significant for minimum temperature of 32nd week (X_{410}) and afternoon relative humidity of 32nd week (X_{610}), whereas negative and significant partial regression coefficients were observed for bright sunshine hours of 41st week (X_{119}), maximum temperature of 38th week (X_{316}) and 40th week (X_{318}), minimum temperature of 34th week (X_{412}) and morning relative humidity of 41st week (X_{519}).

The fitted equations under this approach revealed that R^2 was very low (21.4%) for 12 and 14 weeks model and low (38.5%) in 16 week model. In 18 week model R^2 was high (59.5%). It was very high in 20 week (90.7%) model. Thus, 20 week model could be considered as a yield prediction model based on very high R^2 value under this approach.

4.3.1.5 Panchmahal District

The results related to different crop periods for Panchmahal district are presented in Table 4.22. Results related to 12 week crop period revealed that the set of explanatory variables entered in the equation were weekly weather variables viz., X_{102} , X_{208} , X_{302} , X_{402} , X_{410} , X_{507} and X_{602} . These variables explained about 96.0% variation in rice yield. The partial regression coefficients for rainfall of 30th week (X_{208}) and maximum temperature of 24th week (X_{302}) were found

positive and significant and partial regression coefficients for bright sunshine hours of 24th week (X_{102}), minimum temperature of 24th week (X_{402}) and 32nd week (X_{410}), morning relative humidity of 29th week (X_{507}) and afternoon relative humidity of 24th week (X_{602}) were found negative and significant.

Table 4.22: Partial regression coefficients of rice yield on different original weather variables in weekwise approach in Panchmahal district N = 17

Variables in the equation	Weeks				
	12	14	16	18	20
Constant A_0	8881.231**	-127.091**	-8088.625**	-5766.101**	-4112.559**
X_{102}	-105.445**	-76.370**	-	-	-
X_{302}	105.017**	113.806**	-	-	-
X_{402}	-164.139**	-134.122**	-	-58.820**	-56.440**
X_{602}	-8.904**	-	-	-	-4.301**
X_{507}	-54.412**	-45.599**	-	-	-
X_{208}	2.778**	1.937**	-	-	-
X_{410}	-80.157*	-	-	-	-
X_{513}	-	34.253**	-	-	-
X_{314}	-	45.155**	-	-	-
X_{401}	-	-	33.932*	-	-
X_{607}	-	-	-11.421**	-5.651*	-13.034**
X_{111}	-	-	75.985**	-	-
X_{213}	-	-	5.408**	5.078**	4.948**
X_{514}	-	-	35.552**	-	-
X_{416}	-	-	185.056**	-	-
X_{616}	-	-	10.059**	15.901**	13.565**
X_{104}	-	-	-	-17.795*	-
X_{310}	-	-	-	164.080**	130.210**
X_{610}	-	-	-	26.505**	19.916**
X_{215}	-	-	-	-1.141**	-1.241**
X_{518}	-	-	-	4.960*	9.987**
X_{219}	-	-	-	-	-2.134**
X_{419}	-	-	-	-	10.883**
Adjusted R^2 (%)	96.0	97.6	98.3	98.2	99.9

*, ** Significant at 5% and 1% level of significance, respectively

The results of 14 week crop period revealed that weekly weather variables viz., X_{102} , X_{208} , X_{302} , X_{314} , X_{402} , X_{507} and X_{513} entered in the equation and explained about 97.6% variation in rice yield. Partial regression coefficients for rainfall of

30th week (X_{208}), maximum temperature of 24th week (X_{302}) and 36th week (X_{314}) and morning relative humidity of 35th week (X_{513}) were positive and significant, whereas partial regression coefficients related to bright sunshine hours of 24th week (X_{102}), minimum temperature of 24th week (X_{402}) and morning relative humidity of 29th week (X_{507}) were found negative and significant.

Results of 16 week crop period explained about 98.3% variation in rice yield and consisted of weekly weather variables viz., X_{111} , X_{213} , X_{401} , X_{416} , X_{514} , X_{607} and X_{616} in the equation. Results further showed that the partial regression coefficients for bright sunshine hours of 33rd week (X_{111}), rainfall of 35th week (X_{213}), minimum temperature of 23rd week (X_{401}) and 38th week (X_{416}), morning relative humidity of 36th week (X_{514}) and afternoon relative humidity of 38th week (X_{616}) were positive and significant and partial regression coefficient related to afternoon relative humidity of 29th week (X_{607}) was negative and significant.

The set of explanatory variables observed to enter in the equation related to 18 week crop period were weekly weather variables viz., X_{104} , X_{213} , X_{215} , X_{310} , X_{402} , X_{518} , X_{607} , X_{610} and X_{616} . About 98.2% variation in rice yield was explained by these variables. Results revealed that the partial regression coefficients for rainfall of 35th week (X_{213}), maximum temperature of 32nd week (X_{310}), morning relative humidity of 40th week (X_{518}) and afternoon relative humidity of 32nd week (X_{610}) and 38th week (X_{616}) were positive and significant, whereas the partial regression coefficients for bright sunshine hours of 26th week (X_{104}), rainfall of 37th week (X_{215}), minimum temperature of 24th week (X_{402}) and afternoon relative humidity of 29th week (X_{607}) were found negative and significant.

Weekly weather variables observed to enter in the equation related to 20 week crop period were X_{213} , X_{215} , X_{219} , X_{310} , X_{402} , X_{419} , X_{518} , X_{602} , X_{607} , X_{610} and X_{616} . About 99.9% variation in yield of the rice crop was explained by them. Partial regression coefficients were observed positive and significant for rainfall of 35th week (X_{213}), maximum temperature of 32nd week (X_{310}), minimum temperature of 41st week (X_{419}), morning relative humidity of 40th week (X_{518}) and afternoon relative humidity of 32nd week (X_{610}) and 38th week (X_{616}), whereas negative and significant partial regression coefficients were observed for rainfall of 37th week (X_{215}) and 41st week (X_{219}), minimum temperature of 24th week (X_{402}) and afternoon relative humidity of 24th week (X_{602}) and 29th week (X_{607}).

In general the R^2 was very high for different equations fitted under this approach. It was 96.0% in 12 week, 97.6% in 14 week, 98.3% in 16 week, 98.2% in 18 week and 99.9% in 20 week model. Considering earliness of forecasting, 12 week model could be considered as a yield prediction model under this approach.

4.3.1.6 Sabarkantha District

The results for Sabarkantha district are presented in Table 4.23. The set of explanatory variables entered in the equation related to 12 week crop period were weekly weather variables viz., X_{111} , X_{501} and X_{604} . These variables explained about 83.4% variation in yield of rice. The partial regression coefficients for morning relative humidity of 23rd week (X_{501}) and afternoon relative humidity of 26th week (X_{604}) were positive and significant, whereas the partial regression coefficient for bright sunshine hours of 33rd week (X_{111}) was found negative and significant.

The results of 14 week crop period revealed that the weekly weather variables viz., X_{311} , X_{313} , X_{501} , X_{503} , X_{505} , X_{508} , X_{604} and X_{610} entered in the equation and explained about 99.8% variation in rice yield. Partial regression coefficients for maximum temperature of 35th week (X_{313}), morning relative humidity of 23rd week (X_{501}), 25th week (X_{503}) and 27th week (X_{505}) and afternoon relative humidity of 26th week (X_{604}) were positive and significant, whereas negative and significant partial regression coefficients were found related to maximum temperature of 33rd week (X_{311}), morning relative humidity of 30th week (X_{508}) and afternoon relative humidity of 32nd week (X_{610}).

Table 4.23: Partial regression coefficients of rice yield on different original weather variables in weekwise approach in Sabarkantha district N = 14

Variables in the equation	Weeks				
	12	14	16	18	20
Constant A_0	-919.392	-1075.724**	-1238.549**	-1238.549**	-1795.962**
X_{501}	29.187**	37.252**	36.308**	36.308**	41.403**
X_{604}	10.524*	8.986**	9.707**	9.707**	16.691**
X_{111}	-55.923*	-	-	-	-
X_{503}	-	2.678*	-	-	-
X_{505}	-	28.553**	21.483**	21.483**	-
X_{508}	-	-34.239**	-27.122**	-27.122**	-
X_{610}	-	-6.400**	-	-	-
X_{311}	-	-59.887**	-42.255**	-42.255**	-
X_{313}	-	68.835**	58.591**	58.591**	-
X_{315}	-	-	12.428**	12.428**	-
X_{316}	-	-	-21.143**	-21.143**	-
X_{301}	-	-	-	-	66.336**
X_{213}	-	-	-	-	-0.877**
X_{218}	-	-	-	-	-1.149*
X_{319}	-	-	-	-	-22.219**
X_{320}	-	-	-	-	-65.978**
Adjusted R^2 (%)	83.4	99.8	99.9	99.9	99.8

*, ** Significant at 5% and 1% level of significance, respectively

Results of 16 and 18 weeks crop period were the same and explained about 99.9% variation in rice yield. Explanatory variables entered in the equation

consisted of weekly weather variables viz., X_{311} , X_{313} , X_{315} , X_{316} , X_{501} , X_{505} , X_{508} and X_{604} . Results showed that the partial regression coefficients for maximum temperature of 35th week (X_{313}) and 37th week (X_{315}), morning relative humidity of 23rd week (X_{501}) and 27th week (X_{505}) and afternoon relative humidity of 26th week (X_{604}) were positive and significant and partial regression coefficient related to maximum temperature of 33rd week (X_{311}) and 38th week (X_{316}) and morning relative humidity of 30th week (X_{508}) were negative and significant.

The set of explanatory variables related to 20 week crop period entered in the equation were weekly weather variables viz., X_{213} , X_{218} , X_{301} , X_{319} , X_{320} , X_{501} and X_{604} . These variables explained about 99.8% variation in rice yield. Results revealed that positive and significant partial regression coefficients were observed for maximum temperature of 23rd week (X_{301}), morning relative humidity of 23rd week (X_{501}) and afternoon relative humidity of 26th week (X_{604}), whereas negative and significant partial regression coefficients were observed for rainfall of 35th week (X_{213}) and 40th week (X_{218}) and maximum temperature of 41st week (X_{319}) and 42nd week (X_{320}).

The R^2 was very high for all the equations fitted under this approach. The R^2 was 83.4% in 12 week, 99.8% in 14 and 20 weeks and 99.9% in 16 and 18 weeks model. Considering very high R^2 value and earliness of forecasting, 14 week model could be considered as a yield prediction model under this approach.

4.3.1.7 Surat District

The results related to different crop period in Surat district are presented in Table 4.24. Results of 12, 14 and 16 weeks crop period were the same. The set of

explanatory variables entered in the equation were weekly weather variables viz., X_{207} and X_{401} . These variables explained about 50.5% variation in rice yield. The partial regression coefficients were positive and significant for both rainfall of 29th week (X_{207}) and minimum temperature of 23rd week (X_{401}).

Table 4.24: Partial regression coefficients of rice yield on different original weather variables in weekwise approach in Surat district N = 18

Variables in the equation	Weeks				
	12	14	16	18	20
Constant A_0	-287.585	-287.585	-287.585	2498.608*	2851.463**
X_{401}	80.032**	80.032**	80.032**	78.203**	72.400**
X_{207}	0.478*	0.478*	0.478*	-	-
X_{318}	-	-	-	-63.466**	-
X_{618}	-	-	-	-8.707*	-
X_{208}	-	-	-	-	-0.06408**
X_{211}	-	-	-	-	-1.380**
X_{218}	-	-	-	-	-2.751**
X_{219}	-	-	-	-	-1.656**
X_{304}	-	-	-	-	57.631**
X_{305}	-	-	-	-	-17.237**
X_{320}	-	-	-	-	-89.509**
X_{416}	-	-	-	-	-18.608**
X_{509}	-	-	-	-	-2.833**
X_{620}	-	-	-	-	-6.243**
Adjusted R^2 (%)	50.5	50.5	50.5	65.7	99.9

*, ** Significant at 5% and 1% level of significance, respectively

The results of 18 week crop period reveal the weekly weather variables entered in the equation were X_{318} , X_{401} and X_{618} . These variables explained about 65.7% variation in rice yield. Positive and significant partial regression coefficients was observed for minimum temperature of 23rd week (X_{401}), whereas negative and significant partial regression coefficients were observed for maximum temperature of 40th week (X_{318}) and afternoon relative humidity of 40th week (X_{618}).

More than 99% variation in rice yield was explained by the set of explanatory variables entered in the equation related to 20 week crop period. The entered variables consisted of X_{208} , X_{211} , X_{218} , X_{219} , X_{304} , X_{305} , X_{320} , X_{401} , X_{416} , X_{509} and X_{620} . Results revealed that partial regression coefficients were observed positive and significant for maximum temperature of 26th week (X_{304}) and minimum temperature of 23rd week (X_{401}). The partial regression coefficients for rainfall of 30th week (X_{208}), 33rd week (X_{211}), 40th week (X_{218}) and 41st week (X_{219}), maximum temperature of 27th week (X_{305}) and 42nd week (X_{320}), minimum temperature of 38th week (X_{416}), morning relative humidity of 31st week (X_{509}) and afternoon relative humidity of 42nd week (X_{620}) were observed negative and significant.

The R^2 was high (50.5%) in 12, 14 and 16 weeks. It was also high (65.7%) in 18 week and was very high (99.9%) in 20 week model. Thus, 20 week model could be considered as a yield prediction model under this approach considering very high R^2 value.

4.3.2 CROP STAGewise APPROACH USING ORIGINAL WEATHER VARIABLES

Original crop stagewise weather variables were utilized in this approach for fitting the regression equations to get an idea about the influence of weather variables prevailed during different crop stages on rice yield. The fitted equations and their coefficients of multiple determinations for five different models corresponding to 1, 2, 3, 4 and 5 stages are presented in Tables 4.25, 4.26, 4.27, 4.28, 4.29, 4.30 and 4.31.

4.3.2.1 Ahmedabad District

The results relating to different crop stages are presented in Table 4.25. None of the variable entered in the equation related to 1 stage crop period. Results related to 2, 3 and 4 crop stages were same in which only one weather variable X_{62} i.e. for afternoon relative humidity during active tillering stage entered as explanatory variable in the equation and explained 38.9% variation in yield of rice. The results indicated that the partial regression coefficient for afternoon relative humidity during active tillering (A) stage (X_{62}) was positive and significant.

Table 4.25: Partial regression coefficients of rice yield on different original weather variables in stagewise approach in Ahmedabad district N = 17

Variables in the equation	Stages				
	1	2	3	4	5
Constant A_0	-	-1497.973	-1497.973	-1497.973	7045.845**
X_{62}	-	45.931**	45.931**	45.931**	87.764**
X_{12}	-	-	-	-	-53.710**
X_{52}	-	-	-	-	-71.563**
X_{13}	-	-	-	-	-146.960**
X_{43}	-	-	-	-	107.612**
X_{53}	-	-	-	-	19.346**
X_{14}	-	-	-	-	33.078**
X_{15}	-	-	-	-	162.938**
X_{35}	-	-	-	-	-262.527**
X_{45}	-	-	-	-	-44.731**
Adjusted R^2 (%)	-	38.9	38.9	38.9	99.8

*, ** Significant at 5% and 1% level of significance, respectively

The results pertaining to 5 stage crop period revealed that the set of explanatory variables entered in the equation consisted of weather variables viz., X_{12} , X_{13} , X_{14} , X_{15} , X_{35} , X_{43} , X_{45} , X_{52} , X_{53} and X_{62} . These variables explained 99.8% variation in yield of the rice crop. The partial regression coefficients for bright sunshine hours of flowering (F) stage (X_{14}) and grain development (G) stage

(X_{15}), minimum temperature of vegetative lag (V) stage (X_{43}), morning relative humidity of vegetative lag (V) stage (X_{53}) and afternoon relative humidity of active tillering (A) stage (X_{62}) were positive and significant, whereas partial regression coefficients for bright sunshine hours of active tillering (A) stage (X_{12}) and vegetative lag (V) stage (X_{13}), maximum temperature of grain development (G) stage (X_{35}), minimum temperature of grain development (G) stage (X_{45}) and morning relative humidity of active tillering (A) stage (X_{52}) were observed to be negative and significant.

Among the fitted equations under this approach, R^2 was low (38.9%) in case of 2, 3 and 4 stage models and R^2 was very high (99.8%) in 5 stage model. Thus, 5 stage model could be considered as a yield prediction model based on very high R^2 value under this approach.

4.3.2.2 Baroda District

The results presented in Table 4.26 showed that the stage 1 and 2 models were same and only one weather variable entered as explanatory variable in the equations viz., X_{11} which explained 45.9% variation in yield of rice. The partial regression coefficient for bright sunshine hours during seedling (S) stage (X_{11}) was found positive and significant.

Similar results were obtained for 3 and 4 stage models. Results revealed that the set of explanatory variables entered in the equation consisted of weather variables viz., X_{11} , X_{53} and X_{62} . These variables explained 84.7% variation in yield of the rice crop. All the partial regression coefficients for bright sunshine hours of seedling (S) stage (X_{11}), morning relative humidity of vegetative lag (V)

stage (X_{53}) and afternoon relative humidity of active tillering (A) stage (X_{62}) were positive and significant.

Table 4.26: Partial regression coefficients of rice yield on different original weather variables in stagewise approach in Baroda district N = 12

Variables in the equation	Stages				
	1	2	3	4	5
Constant A_0	242.970	242.970	-5825.801**	-5825.801**	-4787.921**
X_{11}	134.400**	134.400**	138.633**	138.633**	153.550**
X_{62}	-	-	13.693*	13.693*	-
X_{53}	-	-	56.253**	56.253**	51.621**
X_{22}	-	-	-	-	0.864**
X_{25}	-	-	-	-	1.188**
Adjusted R^2 (%)	45.9	45.9	84.7	84.7	96.4

*, ** Significant at 5% and 1% level of significance, respectively

Results related to 5 stage crop period revealed that weather variables viz., X_{11} , X_{22} , X_{25} and X_{53} entered in the equation as the set of explanatory variables and these variables explained about 96.4% variation in yield of the rice crop. Positive and significant partial regression coefficients were observed for bright sunshine hours of seedling (S) stage (X_{11}), rainfall of active tillering (A) stage (X_{22}) and grain development (G) stage (X_{25}) and morning relative humidity of vegetative lag (V) stage (X_{53}).

Low R^2 (45.9%) was observed in case of 1 and 2 stage models. R^2 was high (84.7%) in 3 and 4 stage model and very high in 5 stage model (96.4%). Thus, based on very high R^2 value, 5 stage model could be considered as a yield prediction model under this approach.

4.3.2.3 Bulsar District

The results of Bulsar district presented in Table 4.27 indicated that none of the weather variables could enter in 1, 2, 3 and 4 stage models. Only one weather variable entered as explanatory variable in the equation related to 5 stage crop

period viz., X_{15} which explained 15.4% variation in yield of rice. The partial regression coefficient for bright sunshine hours during grain development (G) stage (X_{15}) was found negative and significant.

Table 4.27: Partial regression coefficients of rice yield on different original weather variables in stagewise approach in Bulsar district N = 26

Variables in the equation	Stages				
	1	2	3	4	5
Constant A_0	-	-	-	-	2736.439**
X_{15}	-	-	-	-	-110.949*
Adjusted R^2 (%)	-	-	-	-	15.4

*, ** Significant at 5% and 1% level of significance, respectively

Very low R^2 (15.4%) was observed in case of 5 stage model. Thus no model could be considered as a yield prediction model under this approach.

4.3.2.4 Kheda District

Results related to Kheda district are presented in Table 4.28. Results related to 1, 2, 3 and 4 stage crop period were same and only one weather variable entered as explanatory variable in the equations viz., X_{21} which explained 22.4% variation in yield of rice. The partial regression coefficient for rainfall during seedling (S) stage (X_{21}) was positive and significant.

Table 4.28: Partial regression coefficients of rice yield on different original weather variables in stagewise approach in Kheda district N = 26

Variables in the equation	Stages				
	1	2	3	4	5
Constant A_0	1542.994**	1542.994**	1542.994**	1542.994**	8175.231**
X_{21}	1.101**	1.101**	1.101**	1.101**	-
X_{35}	-	-	-	-	-187.475**
Adjusted R^2 (%)	22.4	22.4	22.4	22.4	56.6

*, ** Significant at 5% and 1% level of significance, respectively

Only one weather variable viz. entered in the equation related to 5 stage crop period and explained about 56.6% variation in rice yield. The partial

regression coefficient for maximum temperature during grain development (G) stage (X_{35}) was negative and significant.

Very low R^2 (22.4%) was observed in 1, 2, 3 and 4 stage models. R^2 was moderate (56.6%) in 5 stage model but was not sufficiently reliable. Thus no model could be considered as a yield prediction model under this approach.

4.3.2.5 Panchmahal District

The results presented in Table 4.29 show that all the weather variables were removed in 1, 2 and 3 stage models being not fulfilling the criteria of selection. Results showed that the weather variables observed to enter as explanatory variable in the equation related to 4 stage crop period viz., X_{41} and X_{64} explained 43.3% variation in yield of rice. The partial regression coefficient for afternoon relative humidity during flowering (F) stage (X_{64}) was positive and significant whereas, negative and significant partial regression coefficient was observed for minimum temperature during seedling (S) stage (X_{41}).

Table 4.29: Partial regression coefficients of rice yield on different original weather variables in stagewise approach in Panchmahal district N = 17

Variables in the equation	Stages				
	1	2	3	4	5
Constant A_0	-	-	-	2343.826	5375.232**
X_{64}	-	-	-	30.408**	-
X_{41}	-	-	-	-141.915*	-
X_{35}	-	-	-	-	-139.395**
Adjusted R^2 (%)	-	-	-	43.3	49.7

*, ** Significant at 5% and 1% level of significance, respectively

Results of 5 stage crop period reveal that only one weather variable entered as explanatory variable in the equation viz., X_{35} and explained about 49.7% variation in yield of the rice crop. Partial regression coefficient for maximum

temperature during grain development (G) stage (X_{35}) was observed negative and significant.

R^2 was low in case of 4 stage (43.3%) and 5 stage (49.7%) models. Thus no model could be considered as a yield prediction model under this approach.

4.3.2.6 Sabarkantha District

The results pertaining to different stages of crop are presented in Table 4.30. Results showed that only one weather variable viz., X_{51} was observed to enter as explanatory variable in the equation and explained 26.0% variation in yield of rice. The partial regression coefficient for morning relative humidity during seedling (S) stage (X_{51}) was found positive and significant.

Results of 2 stage crop model showed that explanatory variables entered in the equation consisted of the weather variables viz., X_{42} and X_{51} which explained about 48.0% variation in rice yield. Positive and significant partial regression coefficients were observed for minimum temperature during active tillering (A) stage (X_{42}) and morning relative humidity during seedling (S) stage (X_{51}).

Similar results were obtained for 3 and 4 stage models. Results reveal that only one weather variable viz., X_{13} was observed to enter as explanatory variable in the equation and explained 55.1% variation in yield of rice. The partial regression coefficient for bright sunshine hours of vegetative lag (V) stage (X_{13}) was negative and significant.

The results of 5 stage crop period reveal that weather variables viz., X_{13} and X_{15} entered in the equation as the set of explanatory variables and these variables explained about 77.3% variation in yield of the rice crop. Partial regression

coefficients for bright sunshine hours of vegetative lag (V) stage (X_{13}) and grain development (G) stage (X_{15}) were found negative and significant.

Table 4.30: Partial regression coefficients of rice yield on different original weather variables in stagewise approach in Sabarkantha district N = 14

Variables in the equation	Stages				
	1	2	3	4	5
Constant A_0	-2529.178	-9923.533*	2015.895**	2015.895**	3281.562**
X_{51}	54.231*	81.021**	-	-	-
X_{42}	-	211.877*	-	-	-
X_{13}	-	-	-179.204**	-179.204**	-157.360**
X_{15}	-	-	-	-	-178.646**
Adjusted R^2 (%)	26.0	48.0	55.1	55.1	77.3

*, ** Significant at 5% and 1% level of significance, respectively

Very low (26.0%) and low R^2 (48.0%) was observed in case of 1 and 2 stage models. R^2 was moderate (55.1%) in 3 and 4 stage models and high (77.3%) in 5 stage model. Thus based on high R^2 value, 4 stage model was could be considered as a yield prediction model under this approach.

4.3.2.7 Surat District

Results of Surat district are presented in Table 4.31. Similar results were obtained for all the crop stages viz., 1, 2, 3, 4 and 5 and only one weather variable viz., X_{61} entered as explanatory variable in the equations which explained 33.0% variation in yield of rice. The partial regression coefficient for afternoon relative humidity during seedling (S) stage (X_{61}) was positive and significant.

Table 4.31: Partial regression coefficients of rice yield on different original weather variables in stagewise approach in Surat district N = 18

Variables in the equation	Stages				
	1	2	3	4	5
Constant A_0	3365.796**	3365.796**	3365.796**	3365.796**	3365.796**
X_{21}	-20.511**	-20.511**	-20.511**	-20.511**	-20.511**
Adjusted R^2 (%)	33.0	33.0	33.0	33.0	33.0

*, ** Significant at 5% and 1% level of significance, respectively

Low R^2 (33.0%) was observed in 1, 2, 3, 4 and 5 stage models. Thus no model could be considered as a yield prediction model under this approach.

4.3.3 PERIODWISE APPROACH USING ORIGINAL WEATHER VARIABLES

Meteorological periodwise original weather variables were used in this approach and five models related to 1, 2, 3, 4 and 5 periods were fitted. The fitted equations and their coefficients of multiple determinations for five different models corresponding to 1, 2, 3, 4 and 5 periods are presented in Tables 4.32, 4.33, 4.34, 4.35, 4.36, 4.37 and 4.38.

4.3.3.1 Ahmedabad District

The results presented in Table 4.32 reveal that all the variables were removed in 1 period crop duration. Results of 2 period crop duration showed that only one weather variable viz., X_{62} entered in the model as an explanatory variable. This variable explained around 41.7% variation in yield of rice. The results indicated that the partial regression coefficient for afternoon relative humidity of second (July) period (X_{62}) was found positive and significant.

Table 4.32: Partial regression coefficients of rice yield on different original weather variables in periodwise approach in Ahmedabad district N = 17

Variables in the equation	Periods				
	1	2	3	4	5
Constant A_0	-	-1024.821	-8999.056**	-5432.990**	-5432.990**
X_{62}	-	38.818**	43.542**	37.427**	37.427**
X_{22}	-	-	2.021*	-	-
X_{13}	-	-	-273.020**	-	-
X_{23}	-	-	3.018**	-	-
X_{33}	-	-	237.505**	-	-
X_{44}	-	-	-	63.229*	63.229*
X_{64}	-	-	-	50.521**	50.521**
Adjusted R^2 (%)	-	41.7	83.7	73.0	73.0

*, ** Significant at 5% and 1% level of significance, respectively

The set of explanatory variables observed to enter in the equation related to 3 period crop duration consisted of weather variables viz., X_{13} , X_{22} , X_{23} , X_{33} and X_{62} which explained about 83.7% variation in rice yield. The partial regression coefficients for rainfall of second (July) period (X_{22}) and third (August) period (X_{23}), maximum temperature of third (August) period (X_{33}) and afternoon relative humidity of second (July) period (X_{62}) were found positive and significant whereas, negative and significant partial regression coefficient was observed for bright sunshine hours of third (August) period (X_{13}).

The results related to 4 and 5 period crop duration were the same and the set of explanatory variables entered in the model were X_{44} , X_{62} and X_{64} . These variables explained about 73.0% variation in yield of rice. The results indicated that the partial regression coefficients for minimum temperature of fourth (September) period (X_{44}) and afternoon relative humidity of second (July) period (X_{62}) and fourth (September) period (X_{64}) were found positive and significant.

Among the equations fitted under this approach, in model of 2 period crop duration, R^2 was low (41.7%) and R^2 was high (83.7%) in model of 3 period crop duration. In case of 4 and 5 period crop duration model R^2 was moderate (73.0%). Thus based on high R^2 value, 3 period model could be considered as a yield prediction model under this approach.

4.3.3.2 Baroda District

The results of Baroda district presented in Table 4.33 revealed that similar results were obtained for all the crop periods viz., 1, 2, 3, 4 and 5 and only one weather variable viz., X_{11} entered as explanatory variable in the equations which

explained 50.3% variation in yield of rice. The partial regression coefficient for bright sunshine hours during first (June) period (X_{11}) was positive and significant.

Table 4.33: Partial regression coefficients of rice yield on different original weather variables in periodwise approach in Baroda district N = 12

Variables in the equation	Periods				
	1	2	3	4	5
Constant A_0	132.877	132.877	132.877	132.877	132.877
X_{11}	138.948**	138.948**	138.948**	138.948**	138.948**
Adjusted R^2 (%)	50.3	50.3	50.3	50.3	50.3

*, ** Significant at 5% and 1% level of significance, respectively

Among the equations fitted under this approach for all the crop periods viz., 1, 2, 3, 4 and 5, R^2 was moderate (50.3%) but not sufficiently reliable to be considered as a yield prediction model. Thus none model could be considered as a yield prediction model under this approach.

4.3.3.3 Bulsar District

Results for Bulsar district are presented in Table 4.34. All the weather variables were removed in 1, 2 and 3 period crop models. Results of 4 and 5 crop periods were same and only one weather variable viz., X_{14} entered and explained 21.3% variation in yield of rice. Negative and significant partial regression coefficient was observed for bright sunshine hours during fourth (September) period (X_{14}).

Table 4.34: Partial regression coefficients of rice yield on different original weather variables in periodwise approach in Bulsar district N = 26

Variables in the equation	Periods				
	1	2	3	4	5
Constant A_0	-	-	-	2720.000**	2720.000**
X_{14}	-	-	-	-124.595*	-124.595*
Adjusted R^2 (%)	-	-	-	21.3	21.3

*, ** Significant at 5% and 1% level of significance, respectively

Among the equations fitted under this approach R^2 was very low (21.3%) for 4 and 5 period models. Thus, none model could be considered as a yield prediction model under this approach.

4.3.3.4 Kheda District

Results presented in Table 4.35 for Kheda district revealed that only one weather variable viz., X_{21} entered as an explanatory variable in the equation of 1 period model and explained about 22.4% variation in rice yield. Partial regression coefficient was positive and significant for rainfall during first (June) period (X_{21}).

The variables entered in 2 and 3 period model were the same. The set of explanatory variables entered in the equations consisted of weather variables viz., X_{21} and X_{62} . About 38.6% variation in rice yield was explained by these variables. The partial regression coefficients for rainfall during first (June) period (X_{21}) and afternoon relative humidity during second (July) period (X_{62}) were positive and significant.

Table 4.35: Partial regression coefficients of rice yield on different original weather variables in periodwise approach in Kheda district N = 26

Variables in the equation	Periods				
	1	2	3	4	5
Constant A_0	1542.994**	-194.909	-194.909	-66.827	-66.827
X_{21}	1.101**	1.010**	1.010**	-	-
X_{62}	-	24.784*	24.784*	-	-
X_{64}	-	-	-	29.481**	29.481**
Adjusted R^2 (%)	22.4	38.6	38.6	41.6	41.6

*, ** Significant at 5% and 1% level of significance, respectively

Same results were obtained for 4 and 5 period crop duration and only one weather variable viz., X_{64} entered in the model. About 41.6% variation in yield of

rice was explained by afternoon relative humidity of fourth (September) period (X_{64}) and its regression coefficient was found positive and significant.

The R^2 was very low (22.4%) for 1 period model and low (38.6%) for 2 and 3 period models. It was also low (41.6%) for 4 and 5 period models. Thus, none model could be considered as a yield prediction model under this approach.

4.3.3.5 Panchmahal District

Results related to Panchmahal district are presented in Table 4.36. All the variables were removed in 1, 2 and 3 period models. The set of explanatory variables entered in 4 period model consisted of weather variables viz., X_{41} and X_{64} . These variables explained about 65.2% variation in rice yield. Partial regression coefficient was positive and significant for afternoon relative humidity during fourth (September) period (X_{64}) and it was negative and significant for minimum temperature of first (June) period (X_{41}).

Table 4.36: Partial regression coefficients of rice yield on different original weather variables in periodwise approach in Panchmahal district N = 17

Variables in the equation	Periods				
	1	2	3	4	5
Constant A_0	-	-	-	1923.510	2635.138*
X_{64}	-	-	-	28.177**	-
X_{41}	-	-	-	-114.494*	-
X_{45}	-	-	-	-	-165.023*
X_{65}	-	-	-	-	37.174**
Adjusted R^2 (%)	-	-	-	65.2	67.9

*, ** Significant at 5% and 1% level of significance, respectively

The variables entered in 5 period model consisted of weather variables viz., X_{45} and X_{65} . About 67.9% variation in rice yield was explained by these variables. Positive and significant partial regression coefficient was obtained for afternoon relative humidity during fifth (October) period (X_{65}) whereas, partial regression

coefficient for minimum temperature of fifth (October) period (X_{45}) was negative and significant.

In general the R^2 was moderate (65.2%) for 4 period and (67.9%) for 5 period model but not sufficiently high to be considered as a yield prediction model.

4.3.3.6 Sabarkantha District

The results of Sabarkantha district presented in Table 4.37 reveal that similar results were obtained for 1 and 2 crop periods. Only one weather variable viz., X_{51} entered as explanatory variable in the equations and explained 26.0% variation in yield of rice. The partial regression coefficient for morning relative humidity during first (June) period (X_{51}) was negative and significant.

Results of 3, 4 and 5 periods were the same and only one weather variable viz., X_{13} entered in the equation and explained 41.2% variation in rice yield. Negative and significant partial regression coefficient was observed for bright sunshine hours during third (August) period (X_{13}).

Table 4.37: Partial regression coefficients of rice yield on different original weather variables in periodwise approach in Sabarkantha district N = 14

Variables in the equation	Periods				
	1 Period	2 Period	3 Period	4 Period	5 Period
Constant A_0	-2529.178	-2529.178	2242.285**	2242.285**	2242.285**
X_{51}	54.231*	54.231*	-	-	-
X_{13}	-	-	-218.235**	-218.235**	-218.235**
Adjusted R^2 (%)	26.0	26.0	41.2	41.2	41.2

* Significant at 5 % and ** Significant at 1 % level of significance

Among the fitted equations R^2 was very low (26.0%) for 1 and 2 period and low (41.2%) for 3, 4 and 5 period models. Thus, none model could be considered as a yield prediction model under this approach.

4.3.3.7 Surat District

Results presented in Table 4.38 revealed that 1, 2, 3 and 4 period model were the same and only one weather variable viz., X_{61} entered as explanatory variable in the equation of the models which explained about 33.0% variation in rice yield. Negative and significant partial regression coefficient was obtained for afternoon relative humidity during first (June) period (X_{61}).

The set of explanatory variables entered in the equation related to 5 period model consisted of weather variables viz., X_{41} , X_{42} and X_{55} . About 65.8% variation in rice yield was explained by these variables. The partial regression coefficient for minimum temperature during first (June) period (X_{41}) was positive and significant whereas, negative and significant partial regression coefficients were observed for minimum temperature during second (July) period (X_{42}) and morning relative humidity during fifth (October) period (X_{55}).

Table 4.38: Partial regression coefficients of rice yield on different original weather variables in periodwise approach in Surat district N = 18

Variables in the equation	Periods				
	1	2	3	4	5
Constant A_0	3365.796**	3365.796**	3365.796**	3365.796**	2897.840**
X_{61}	-20.511**	-20.511**	-20.511**	-20.511**	-
X_{41}	-	-	-	-	133.105**
X_{42}	-	-	-	-	-88.674*
X_{55}	-	-	-	-	-65.004**
Adjusted R^2 (%)	33.0	33.0	33.0	33.0	65.8

*, ** Significant at 5% and 1% level of significance, respectively

The R^2 was low (33.0%) for 1, 2, 3 and 4 period models and moderate (65.8%) for 5 period model. The R^2 of none model was sufficient enough to be considered as a yield prediction model hence, none model was considered as a yield prediction model this approach.

4.3.4 WEEK NUMBER AS WEIGHT APPROACH USING GENERATED WEATHER VARIABLES

In this approach, generated weather variables (week number as weight) were used. The fitted equations and their coefficients of multiple determination of five different models corresponding to 12, 14, 16, 18 and 20 weeks crop periods for different districts are presented in Tables 4.39, 4.40, 4.41, 4.42, 4.43, 4.44 and 4.45.

4.3.4.1 Ahmedabad District

The results of 12 weeks model for Ahmedabad district presented in Table 4.39 indicated that out of 63 generated explanatory variables, only five variables viz., Z_{61} , Z_{52} , Q_{260} , Q_{460} and Q_{352} were entered in the equation. These variables explained about 90.6% variation in the yield of the rice crop. The result indicated that the linear weight of week number to afternoon relative humidity (Z_{61}), second order generated variables Q_{260} (zero weight of week number to cross product of rainfall and afternoon relative humidity) and Q_{352} (quadratic weight of week number to cross product of maximum temperature and morning relative humidity) influenced the yield of rice positively and significantly whereas, the quadratic weight of week number to morning relative humidity (Z_{52}) and zero weight of week number to cross product of minimum temperature and afternoon relative humidity (Q_{460}) influenced the yield of rice negatively and significantly.

The model fitted for 14 weeks crop period reveal that the explanatory variables observed to enter in the equation consisted Z_{60} , Z_{51} , Q_{120} , Q_{260} and Q_{352} . These variables explained 84.7% variation in the yield of the rice crop. The rice

yield was positively and significantly influenced by zero weight of week number to afternoon relative humidity (Z_{60}), zero weight of week number to cross product of rainfall and afternoon relative humidity (Q_{260}) and quadratic weight of week number to cross product of maximum temperature and morning relative humidity (Q_{352}) whereas, negatively and significantly influenced by the first order generated variable Z_{51} (linear weight of week number to morning relative humidity) and second order generated variable Q_{120} (zero weight of week number to cross product of bright sunshine hours and rainfall).

Table 4.39: Partial regression coefficients of rice yield on different generated weather variables in week number as weight approach in Ahmedabad district N = 17

Variables in the equation	Weeks				
	12	14	16	18	20
Constant A_0	6304.225**	3809.301	276.929	-3354.372**	-4076.125**
Z_{61}	3.790**	-	-	-	-
Z_{52}	-0.692**	-	-	-	-
Q_{260}	0.264**	0.520**	0.425**	-	-
Q_{460}	-2.369*	-	-	-	3.965**
Q_{352}	4.361**	3.314**	-	-	-
Z_{60}	-	10.096**	-	-	-
Z_{51}	-	-2.649**	-	-	-
Q_{120}	-	-2.632*	-	-	-
Q_{461}	-	-	-	3.297**	-
Adjusted R^2 (%)	90.6	84.7	51.0	54.3	59.1

*, ** Significant at 5% and 1% level of significance, respectively

The explanatory variable observed to enter in the equation of 16 weeks crop model was Q_{260} . This variable explained 51.0% variation in the yield of the rice crop. The result indicated that the second order generated variable Q_{260} (zero weight of week number to cross product of rainfall and afternoon relative humidity) influenced the yield of rice positively and significantly.

Only one generated weather variable viz., Q_{461} entered in the model of 18 weeks crop period and explained about 54.3% variation in rice yield. The second order generated variable Q_{461} (linear weight of week number to cross product of minimum temperature and afternoon relative humidity) influenced the yield of rice positively and significantly.

Only one generated variable viz., Q_{460} entered in 20 weeks model. The second order generated variable Q_{460} (zero weight of week number to cross product of minimum temperature and afternoon relative humidity) influenced the yield of rice positively and significantly and explained about 59.1% variation in rice yield.

Among the equations fitted under this approach, R^2 was very high (90.6%) in 12 week and high (84.7%) in 14 week models. It was moderate (51.0%, 54.3% and 59.1%) in 16, 18 and 20 weeks models respectively. Thus considering very high R^2 value and earliness of forecast, 12 week model could be considered as a yield prediction model under this approach.

4.3.4.2 Baroda District

Results of Baroda district are presented in Table 4.40. Results indicated that the generated weather variables viz., Z_{52} and Q_{140} entered in the equation and explained about 78.7% variation in the yield of the rice crop. The quadratic weight of week number to morning relative humidity (Z_{52}) and zero weight of week number to cross product of bright sunshine hours and minimum temperature (Q_{140}) influenced the yield of rice positively and significantly.

Model of 14 weeks crop period reveal that the explanatory variables viz., Q_{140} , Q_{260} , Q_{350} and Q_{251} entered in the equation. These variables explained 87.7% variation in the yield of the rice crop. The rice yield was positively and significantly influenced by second order generated variables Q_{140} (zero weight of week number to cross product of bright sunshine hours and minimum temperature), Q_{260} (zero weight of week number to cross product of rainfall and afternoon relative humidity) and Q_{350} (zero weight of week number to cross product of maximum temperature and morning relative humidity) whereas, the second order generated variable Q_{251} (linear weight of week number to cross product of rainfall and morning relative humidity) negatively and significantly influenced the rice yield.

Table 4.40: Partial regression coefficients of rice yield on different generated weather variables in week number as weight approach in Baroda district N = 12

Variables in the equation	Weeks				
	12	14	16	18	20
Constant A_0	-6019.919**	-4855.154**	342.468*	-151.637	354.748*
Z_{52}	0.138**	-	-	-	-
Q_{140}	8.815**	17.624**	-	-	-
Q_{260}	-	0.307**	-	-	-
Q_{350}	-	1.307**	-	-	-
Q_{251}	-	-0.176*	-	-	-
Q_{232}	-	-	0.345**	-	0.576**
Q_{160}	-	-	-	2.415*	-
Q_{242}	-	-	-	0.525**	-
Adjusted R^2 (%)	78.7	87.7	63.9	73.4	61.6

*, ** Significant at 5% and 1% level of significance, respectively

Only one generated variable viz., Q_{232} entered in the equation of 16 weeks crop model and explained about 63.9% variation in the yield of the rice crop. The second order generated variable Q_{232} (quadratic weight of week number to cross

product of rainfall and maximum temperature) influenced the yield of rice positively and significantly.

The generated weather variables viz., Q_{160} and Q_{242} entered in 18 weeks model. These variables explained about 73.4% variation in rice yield. The second order generated variables Q_{160} (zero weight of week number to cross product of bright sunshine hours and afternoon relative humidity) and Q_{242} (quadratic weight of week number to cross product of rainfall and minimum temperature) positively and significantly influenced the rice yield.

The second order generated variable viz., Q_{232} (quadratic weight of week number to cross product of rainfall and maximum temperature) entered in 20 weeks model and influenced the yield of rice positively and significantly. This variable explained about 61.6% variation in rice yield.

The R^2 was high (78.7%) in 12 week and (87.7%) in 14 week models. It was moderate (63.9%) in 16 weeks, (73.4%) in 18 weeks and (61.6%) in 20 weeks models. Thus, considering high R^2 value and earliness of forecast, 14 week model could be considered as a yield prediction model under this approach.

4.3.4.3 Bulsar District

The results of Bulsar district are presented in Table 4.41. Results of 12 weeks model indicated that only one variable viz., Z_{62} (quadratic weight of week number to afternoon relative humidity) entered in the equation and influenced the yield of rice positively and significantly. This variable explained about 15.3% variation in the yield of the rice crop.

All the 63 generated variables were removed in 14 weeks model. Only one variable viz., Z_{62} (quadratic weight of week number to afternoon relative humidity) entered in the equation related to 16 weeks crop period. About 21.5% variation in the yield of the rice crop was explained by this variable. The rice yield was positively and significantly influenced by first order generated variable Z_{62} (quadratic weight of week number to afternoon relative humidity).

Same variable viz., Z_{62} entered in 18 weeks model and explained about 28.1% variation in rice yield. First order generated variable Z_{62} (quadratic weight of week number to afternoon relative humidity) positively and significantly influenced rice yield.

Table 4.41: Partial regression coefficients of rice yield on different generated weather variables in week number as weight approach in Bulsar district N = 26

Variables in the equation	Weeks				
	12	14	16	18	20
Constant A_0	-573.912	-	-680.967	-509.158	-543.602
Z_{62}	0.06928*	-	0.03117*	0.02137**	-
Z_{61}	-	-	-	-	0.215**
Adjusted R^2 (%)	15.3	-	21.5	28.1	24.1

*, ** Significant at 5% and 1% level of significance, respectively

The explanatory variable observed to enter in the equation of 20 weeks crop model was Z_{61} . This variable explained 24.1% variation in the yield of the rice crop. The result indicated that the first order generated variable Z_{61} (linear weight of week number to afternoon relative humidity) influenced the yield of rice positively and significantly.

In general R^2 was very low (<30%) in all the equations fitted under this approach. Thus, none of the model could be considered as a yield prediction model under this approach.

4.3.4.4 Kheda District

Results related to Kheda district presented in Table 4.42 indicated that the second order generated weather variable viz., Q_{260} entered in the equation of 12 weeks period and explained about 36.4% variation in the yield of the rice crop. Zero weight of week number to cross product of rainfall and afternoon relative humidity (Q_{260}) influenced the yield of rice positively and significantly.

Model of 14 weeks crop period revealed that only one first order generated variable viz., Z_{20} entered in the equation and explained about 33.8% variation in the yield of the rice crop. The first order generated variable Z_{20} (zero weight of week number to rainfall) positively and significantly influenced rice yield.

Table 4.42: Partial regression coefficients of rice yield on different generated weather variables in week number as weight approach in Kheda district
N = 26

Variables in the equation	Weeks				
	12	14	16	18	20
Constant A_0	1130.597**	1065.230**	1182.596**	-442.133	-1190.358
Q_{260}	0.137**	-	0.141**	-	-
Z_{20}	-	0.939**	-	-	-
Q_{562}	-	-	-	0.387**	-
Z_{61}	-	-	-	-	0.250**
Adjusted R^2 (%)	36.4	33.8	33.8	38.1	37.4

*, ** Significant at 5% and 1% level of significance, respectively

Only one second order generated variable viz., Q_{260} (zero weight of week number to cross product of rainfall and afternoon relative humidity) entered in the equation of 16 weeks crop duration. This variable explained about 33.8% variation in the yield of the rice crop and influenced the yield of rice positively and significantly.

The generated weather variable viz., Q_{562} entered in 18 weeks model and explained about 38.1% variation in rice yield. The second order generated

variable Q_{562} (quadratic weight of week number to cross product of morning and afternoon relative humidity) positively and significantly influenced the rice yield.

The equation related to 20 weeks model consisted of first order generated variable viz., Z_{61} (linear weight of week number to afternoon relative humidity). This variable explained about 37.4% variation and positively and significantly influenced the rice yield.

The R^2 was low in general (<50%) for all the weeks. Thus, none model could be considered as a yield prediction model under this approach.

4.3.4.5 Panchmahal District

Results presented in Table 4.43 for Panchmahal district indicated that only one generated weather variable viz., Z_{20} entered in the equation and explained about 20.6% variation in the yield of the rice crop. Zero weight of week number to rainfall (Z_{20}) influenced the yield of rice positively and significantly.

Second order generated variable Q_{240} (zero weight of week number to cross product of rainfall and minimum temperature) entered in model of 14 weeks crop period. This variable explained about 21.6% variation in the yield of the rice crop and positively and significantly influenced the rice yield.

Only one generated variable viz., Q_{362} entered in the equation of 16 weeks crop model and explained about 53.6% variation in rice crop yield. The second order generated variable Q_{362} (quadratic weight of week number to cross product of maximum temperature and afternoon relative humidity) influenced the yield of rice positively and significantly.

The second order generated weather variable viz., Q_{562} entered in the equation related to 18 weeks model. This variable explained about 57.8% variation in rice crop yield. The influence of second order generated variable Q_{562} (quadratic weight of week number to cross product of morning and afternoon relative humidity) was positive and significant on the rice crop yield.

Table 4.43: Partial regression coefficients of rice yield on different generated weather variables in week number as weight approach in Panchmahal district N = 17

Variables in the equation	Weeks				
	12	14	16	18	20
Constant A_0	94.346	192.772	-3110.273**	-1606.536**	-2354.100**
Z_{20}	0.953*	-	-	-	-
Q_{240}	-	0.351*	-	-	-
Q_{362}	-	-	1.787**	-	1.627**
Q_{562}	-	-	-	0.413**	-
Adjusted R^2 (%)	20.6	21.6	53.6	57.8	56.8

*, ** Significant at 5% and 1% level of significance, respectively

Only one generated variable viz., Q_{362} (quadratic weight of week number to product of maximum temperature and afternoon relative humidity) entered in the equation related to 20 weeks model and influenced the yield of rice positively and significantly. This variable explained about 56.8% variation in rice yield.

The R^2 was very low (20.6%) in 12 weeks and (21.6%) in 14 weeks models. It was moderate (53.6%) in 16 weeks, (57.8%) in 18 weeks and (56.8%) in 20 weeks models. Reliability of all the models was sceptical. Thus, **no** model could be considered as a yield prediction model under this approach.

4.3.4.6 Sabarkantha District

Results for Sabarkantha district are presented in Table 4.44. Results indicated that only one second order generated weather variable viz., Q_{132} (quadratic weight of week number to cross product of bright sunshine hours and

maximum temperature) entered in the equation related to 12 week crop model and explained about 65.9% variation in rice crop yield. This variable influenced the yield of rice negatively and significantly.

The generated variable observed to enter in equation of 14 weeks crop period was Q_{161} (linear weight of week number to cross product of bright sunshine hours and afternoon relative humidity). This variable negatively and significantly influenced the rice yield and explained about 50.4% variation in the yield of the rice crop.

Table 4.44: Partial regression coefficients of rice yield on different generated weather variables in week number as weight approach in Sabarkantha district N = 14

Variables in the equation	Weeks				
	12	14	16	18	20
Constant A_0	2239.454**	2266.397**	2741.690**	3232.794**	3891.956**
Q_{132}	-7.727**	-	-	-	-
Q_{161}	-	-4.306**	-	-	-
Q_{162}	-	-	-5.375**	-	-
Q_{131}	-	-	-	-10.123**	-
Z_{11}					-2.400**
Adjusted R^2 (%)	65.9	50.4	62.9	62.9	66.2

*, ** Significant at 5% and 1% level of significance, respectively

The second order generated variable viz., Q_{162} (quadratic weight of week number to cross product of bright sunshine hours and afternoon relative humidity) entered in the equation of 16 weeks crop model and explained about 62.9% variation in rice crop yield. This variable negatively and significantly influenced the yield of rice crop.

The generated weather variable entered in the equation related to 18 weeks model was Q_{131} (linear weight of week number to cross product of bright sunshine hours and maximum temperature). This variable explained about 62.9% variation

in rice crop yield. The influence of this variable on the rice crop yield was negative and significant.

Only one generated variable viz., Z_{11} (linear weight of week number to bright sunshine hours) entered in the equation related to 20 weeks model and influenced the yield of rice negatively and significantly. This variable explained about 66.2% variation in rice yield.

In general the R^2 was moderate in all the models. It was (65.9%) in 12 weeks, (50.4%) in 14 weeks, (62.9%) in 16 and 18 weeks and (66.2%) in 20 weeks models. Reliability of all the models was not upto the mark. Thus, **no** model could be considered as a reliable yield prediction model under this approach.

4.3.4.7 Surat District

Results for Surat district presented in Table 4.45 showed that all the generated weather variables were removed in 12, 14 and 16 weeks crop period. Results indicated that the set of weather variables observed to enter in the equation related to 18 week crop period consisted of generated weather variables viz., Z_{60} , Z_{32} and Q_{350} and explained about 57.3% variation in rice crop yield. The variable Q_{350} (zero weight of week number to product of maximum temperature and morning relative humidity) positively and significantly influenced the rice yield whereas, first order generated variable Z_{60} (zero weight of week number to afternoon relative humidity) and Z_{32} (quadratic weight of week number to maximum temperature) negatively and significantly influenced the rice yield.

Table 4.45: Partial regression coefficients of rice yield on different generated weather variables in week number as weight approach in Surat district N = 18

Variables in the equation	Weeks				
	12	14	16	18	20
Constant A_0	-	-	-	7433.146**	3970.714**
Z_{60}	-	-	-	-0.125**	-
Z_{32}	-	-	-	-2.074**	-
Q_{350}	-	-	-	1.544*	-
Q_{352}	-	-	-	-	-0.766*
Adjusted R^2 (%)	-	-	-	57.3	29.7

*, ** Significant at 5% and 1% level of significance, respectively

The generated weather variable entered in the equation related to 20 weeks model was Q_{352} (quadratic weight of week number to cross product of maximum temperature and morning relative humidity). This variable explained about 29.7% variation in rice crop yield. Negative and significant influence of this variable was observed on the rice crop yield.

R^2 was moderate in (57.3%) in 18 weeks model and it was very low (29.7%) in 20 weeks model. Reliability of none of the models was upto the mark. Thus, no model could be considered as a yield prediction model under this approach.

4.3.5 CORRELATION COEFFICIENT AS WEIGHT APPROACH USING GENERATED WEATHER VARIABLES

In this approach, 63 generated weather variables (correlation coefficient as weight) were utilized. The fitted equations and coefficients of multiple determination of five different models corresponding to 12, 14, 16, 18 and 20 weeks crop periods are presented in Tables 4.46, 4.47, 4.48, 4.49, 4.50, 4.51 and 4.52 for different districts.

4.3.5.1 Ahmedabad District

The results of Ahmedabad district for different five models using correlation coefficient as weight are presented in Table 4.46. Total 63 generated variables were used to fit the equations for different periods.

Results related to 12 weeks crop period generated variable indicated that out of 63 generated explanatory variables, the variables that entered in the equation were Z'_{11} , Z'_{62} and Q'_{131} . The variation explained by these explanatory variables was about 78.1%. The results revealed that the first order generated variable Z'_{62} (quadratic weight of correlation coefficient to afternoon relative humidity) and second order generated variable Q'_{131} (quadratic weight of correlation coefficients to cross product of bright sunshine hours and maximum temperature) influenced the yield of rice positively and significantly, whereas first order generated variable Z'_{11} (linear weight of correlation coefficients to bright sunshine hours) influenced the yield of rice negatively and significantly.

Table 4.46: Partial regression coefficients of rice yield on different generated weather variables in correlation coefficient as weight approach in Ahmedabad district N = 17

Variables in the equation	Weeks				
	12	14	16	18	20
Constant A_0	-2468.539**	-1763.163**	-7620.251*	-9226.419*	-2071.286**
Z'_{11}	-181.174**	-	-43.242*	-	-30.243*
Z'_{62}	59.099**	40.355**	64.868**	89.397**	63.720**
Q'_{131}	5.524*	-	-	-	-
Q'_{260}	-	0.279**	-	-	-
Z'_{42}	-	-	215.306*	-	-
Q'_{340}	-	-	-	6.370*	-
Adjusted R^2 (%)	78.1	73.3	79.2	74.2	74.8

*, ** Significant at 5% and 1% level of significance, respectively

In fitted model of 14 weeks crop period, the explanatory variables observed to enter in the equation consisted Z'_{62} and Q'_{260} . These variables explained about 73.3% variation in the yield of the rice crop. The generated variables Z'_{62} (quadratic weight of correlation coefficients to afternoon relative humidity) and Q'_{260} (quadratic weight of correlation coefficients to cross product of rainfall and afternoon relative humidity) positively and significantly influenced the rice yield.

The model of 16 weeks crop period revealed that the explanatory variables entered in the equation were Z'_{11} , Z'_{42} and Z'_{62} and these variables explained about 79.2% variation in the yield of the rice crop. The first order generated variables Z'_{42} (quadratic weight of correlation coefficient to minimum temperature) and Z'_{62} (quadratic weight of correlation coefficient to afternoon relative humidity) influenced the yield of rice positively and significantly, whereas first order generated variable Z'_{11} (linear weight of correlation coefficients to bright sunshine hours) influenced the yield of rice negatively and significantly.

The explanatory variables entered in the equation related to 18 weeks model consisted Z'_{62} (quadratic weight of correlation coefficient to afternoon relative humidity) and Q'_{340} (zero weight of correlation coefficients to cross product of maximum and minimum temperature). About 74.2% variation in rice yield was explained by these variables and their influence was positive and significant.

The variables Z'_{11} and Z'_{62} entered in 20 weeks model and explained about 74.8% variation in the yield of rice. Results revealed that the first order generated variable Z'_{62} (quadratic weight of correlation coefficient to afternoon relative humidity) positively and significantly influenced the yield of rice whereas, first

order generated variable Z'_{11} (linear weight of correlation coefficients to bright sunshine hours) influenced the yield of rice negatively and significantly.

The R^2 was moderate in all the equations fitted under this approach, in case of 12 weeks crop period, R^2 was (78.1%) and it was (73.3%) in 14 weeks, (79.2%) in 16 weeks, (74.2%) in 18 weeks and (74.8%) in 20 weeks period crop model. None models' R^2 value was reliable enough to be considered as a yield prediction model under this approach.

4.3.5.2 Baroda District

The results of Baroda district are presented in Table 4.47. Results related to 12 weeks crop period indicated that out of 63 generated explanatory variables only one variable Z'_{21} (linear weight of correlation coefficient to rainfall) entered in the equation and explained about 71.1% variation in rice yield. This variable positively and significantly influenced the rice crop yield.

Only one generated weather variable viz., Z'_{21} entered in the equation of 14 weeks model. About 74.1% variation in the yield of the rice crop was explained by this variable. The first order generated variable Z'_{21} (linear weight of correlation coefficient to rainfall) positively and significantly influenced the yield of rice.

The model of 16 weeks crop periods revealed that Z'_{21} and Q'_{121} entered the equation as explanatory variables, and explained 95.0% variation in the yield of the rice crop. The first order generated variable Z'_{21} (linear weight of correlation coefficient to rainfall) and second order generated weather variable Q'_{121} (linear

weight of correlation coefficients to cross product of bright sunshine hours and rainfall) influenced the yield of rice positively and significantly.

Table 4.47: Partial regression coefficients of rice yield on different generated weather variables in correlation coefficient as weight approach in Baroda district N = 12

Variables in the equation	Weeks				
	12	14	16	18	20
Constant A_0	882.215**	785.883**	566.011**	555.491**	-805.916
Z'_{21}	1.748**	3.809**	4.763**	5.684**	5.963**
Q'_{121}	-	-	1.062**	1.232**	-
Z'_{41}	-	-	-	-	0.401*
Q'_{350}	-	-	-	-	14.195**
Adjusted R^2 (%)	71.1	74.1	95.0	94.0	96.2

*, ** Significant at 5% and 1% level of significance, respectively

Similar variables entered in the equation related to 18 weeks model. About 94.0% variation in rice yield was explained by these variables. Influence of both the generated weather variables was positive and significant.

The variables that entered in the equation related to 20 weeks model were Z'_{21} , Z'_{41} and Q'_{350} . These variables explained about 96.2% variation in the yield of rice. Results revealed that the positive and significant influence of all the generated variables viz., Z'_{21} (linear weight of correlation coefficient to rainfall), Z'_{41} (linear weight of correlation coefficient to minimum temperature) and Q'_{350} (zero weight of correlation coefficients to cross product of maximum temperature and morning relative humidity) were observed on the yield of rice.

Moderate R^2 (71.1%) in 12 weeks and (74.1%) in 14 weeks was observed. The R^2 was very high (>90%) in 16 weeks, 18 weeks and 20 weeks period crop model. Thus, based on very high R^2 value and earliness of forecast 16 weeks model could be considered as a yield prediction model under this approach.

4.3.5.3 Bulsar District

The results presented in Table 4.48 for Bulsar district related to 12 weeks crop period indicated that only one generated variable Q'_{361} entered in the equation. This variable explained about 32.5% variation in yield of rice. The rice crop yield was positively and significantly influenced by the variable Q'_{361} (linear weight of correlation coefficient to cross product of maximum temperature and afternoon relative humidity).

Only one first order generated weather variable viz., Z'_{11} entered the equation of 14 weeks model and explained about 38.6% variation in the yield of the rice crop. The first order generated variable Z'_{11} (linear weight of correlation coefficient to bright sunshine hours) negatively and significantly influenced the yield of rice.

Table 4.48: Partial regression coefficients of rice yield on different generated weather variables in correlation coefficient as weight approach in Bulsar district N = 26

Variables in the equation	Weeks				
	12	14	16	18	20
Constant A_0	571.024	2554.280**	2329.940**	2930.010**	2181.959**
Q'_{361}	0.516**	-	-	-	-
Z'_{11}	-	-129.784**	-99.384*	-	-132.250**
Z'_{21}	-	-	1.357*	2.609**	1.304*
Z'_{31}	-	-	-	-40.008*	-32.686
Q'_{141}	-	-	-	-	1.644*
Q'_{341}	-	-	-	-	1.353**
Adjusted R^2 (%)	32.5	38.6	46.5	50.0	71.4

*, ** Significant at 5% and 1% level of significance, respectively

The variables observed to enter in the equation related to 16 weeks model were Z'_{11} and Z'_{21} and explained about 46.5% variation in the yield of the rice crop. The first order generated variable Z'_{21} (linear weight of correlation coefficient to rainfall) influenced the yield of rice positively and significantly

whereas, linear weight of correlation coefficient to bright sunshine hours (Z'_{11}) negatively and significantly influenced the yield of rice.

The variables entered in the equation related to 18 weeks model consisted of weather variables Z'_{21} and Z'_{31} . These variables explained about 50.0% variation in rice yield. The influence of first order generated variable Z'_{21} (linear weight of correlation coefficient to rainfall) on rice yield was positive and significant whereas, the influence of first order generated variable Z'_{31} (linear weight of correlation coefficient to maximum temperature) was found negative and significant.

The generated weather variables Z'_{11} , Z'_{21} , Z'_{31} , Q'_{141} and Q'_{341} entered in the equation related to 20 weeks model and explained about 71.4% variation in the yield of rice. Positive and significant influence was observed for the weather variables viz., Z'_{21} (linear weight of correlation coefficient to rainfall), Q'_{141} (linear weight of correlation coefficients to products of bright sunshine hours and maximum temperature) and Q'_{341} (linear weight of correlation coefficients to cross products of maximum and minimum temperature) whereas, negative and significant influence of weather variables viz., Z'_{11} (linear weight of correlation coefficient to bright sunshine hours) and Z'_{31} (linear weight of correlation coefficient to maximum temperature) was observed on the yield of rice.

The observed R^2 was low (32.5%) in 12 weeks, (38.6%) in 14 weeks and (46.5%) in 16 weeks model whereas it was moderate (50.0%) in 18 weeks and (71.4%) in 20 weeks period crop model. Thus, no model could be considered as a yield prediction model under this approach.

4.3.5.4 Kheda District

The results of Kheda district are presented in Table 4.49. Results related to 12 weeks crop period indicated that only one generated variable Z'_{22} entered in the equation and explained about 48.1% variation in yield of rice. The rice crop yield was positively and significantly influenced by the variable Z'_{22} (quadratic weight of correlation coefficient to rainfall).

Similar variable viz., Z'_{22} (quadratic weight of correlation coefficient to rainfall) entered the equation of 14 weeks model and explained about 48.4% variation in the yield of the rice crop. This variable positively and significantly influenced the yield of rice.

Results related to 16 weeks model revealed that the variables observed to enter in the equation were Z'_{10} and Z'_{11} . These variables explained about 62.7% variation in the yield of the rice crop. The first order generated variable Z'_{10} (zero weight of correlation coefficient to bright sunshine hours) influenced the yield of rice positively and significantly whereas, linear weight of correlation coefficient to bright sunshine hours (Z'_{11}) negatively and significantly influenced the yield of rice.

Table 4.49: Partial regression coefficients of rice yield on different generated weather variables in correlation coefficient as weight approach in Kheda district N = 26

Variables in the equation	Weeks				
	12	14	16	18	20
Constant A_0	1082.943**	1070.618**	1813.066**	2782.819**	3084.855**
Z'_{22}	12.047**	12.442**	-	-	-
Z'_{10}	-	-	186.169*	-	-
Z'_{11}	-	-	-213.017**	-	-
Q'_{151}	-	-	-	-2.010**	-2.401**
Adjusted R^2 (%)	48.1	48.4	62.7	59.7	61.2

*, ** Significant at 5% and 1% level of significance, respectively

Only one generated weather variable viz., Q'_{151} (linear weight of correlation coefficients to cross products of bright sunshine hours and morning relative humidity) entered in the equation related to 18 weeks model and explained about 59.7% variation in rice yield. The influence of this variable on rice yield was found negative and significant.

Similar variable entered in the equation related to 20 weeks model and explained about 61.2% variation in the yield of rice. Positive and significant influence of this weather variable was observed on the yield of rice.

The R^2 was low (48.1%) in 12 weeks and (48.4%) in 14 weeks model. It was moderate (62.7%) in 16 weeks, (59.7%) in 18 weeks and (61.2%) in 20 weeks period crop model. The R^2 of none of the model was reliable enough to be considered as a yield prediction model under this approach.

4.3.5.5 Panchmahal District

The results of Panchmahal district presented in Table 4.50 related to 12 weeks crop period revealed that the generated weather variables Z'_{11} and Z'_{42} entered in the equation. These variables explained about 51.3% variation in yield of rice. The variables Z'_{11} (linear weight of correlation coefficient to bright sunshine hours) and Z'_{42} (quadratic weight of correlation coefficient to minimum temperature) negatively and significantly influenced the yield of rice.

Only one generated weather variable viz., Z'_{11} (linear weight of correlation coefficient to bright sunshine hours) entered in 14 weeks model and explained about 43.4% variation in rice yield. The influence of this variable on rice yield was found positive and significant.

Table 4.50: Partial regression coefficients of rice yield on different generated weather variables in correlation coefficient as weight approach in Panchmahal district N = 17

Variables in the equation	Weeks				
	12	14	16	18	20
Constant A_0	3767.453*	445.532**	-3622.789**	-6587.709**	-4002.461**
Z'_{11}	-5.059**	33.523**	-	-	-
Z'_{42}	-119.322*	-	-	-	-
Z'_{21}	-	-	2.279*	-	-
Z'_{61}	-	-	50.182**	-	51.453**
Q'_{351}	-	-	-29.338**	-	-
Q'_{352}	-	-	30.584**	-	-
Q'_{562}	-	-	-0.475**	-	-
Z'_{52}	-	-	-	85.537**	-
Z'_{51}	-	-	-	-	45.471*
Q'_{462}	-	-	-	-	-1.538*
Adjusted R^2 (%)	51.3	43.4	90.1	62.2	79.4

*, ** Significant at 5% and 1% level of significance, respectively

The set of generated weather variables observed to enter in the equation related to 16 weeks model were Z'_{21} , Z'_{61} , Q'_{351} , Q'_{352} and Q'_{562} . These variables explained about 90.1% variation in the yield of the rice crop. The weather variables Z'_{21} (linear weight of correlation coefficient to rainfall), Z'_{61} (linear weight of correlation coefficient to afternoon relative humidity) and Q'_{352} (quadratic weight of correlation coefficients to product of maximum temperature and morning relative humidity) influenced the yield of rice positively and significantly whereas, Q'_{351} (linear weight of correlation coefficients to cross products of maximum temperature and morning relative humidity) and Q'_{562} (quadratic weight of correlation coefficients to product of morning and afternoon relative humidity) negatively and significantly influenced the yield of rice.

Only one generated weather variable viz., Z'_{52} entered in the equation related to 18 weeks model and explained about 62.2% variation in rice yield. The

influence of first order generated variable Z'_{52} (quadratic weight of correlation coefficients to morning relative humidity) was found positive and significant on rice yield.

The variables entered in the equation related to 20 weeks model were Z'_{51} , Z'_{61} and Q'_{462} . These variables explained about 79.4% variation in the rice yield. Positive and significant influence of the weather variables Z'_{51} (linear weight of correlation coefficients to morning relative humidity) and Z'_{61} (linear weight of correlation coefficients to afternoon relative humidity) was observed on the yield of rice whereas, Q'_{462} (quadratic weight of correlation coefficients to cross products of minimum temperature and afternoon relative humidity) negatively and significantly influenced the yield of rice

The R^2 was low (43.4%) in 14 weeks and moderate (51.3%) in 12 weeks, (62.2%) in 18 weeks and (79.4%) in 20 weeks model. It was very high (90.1%) in 16 weeks period crop model. Thus, based on very high R^2 value and earliness of forecasting 16 weeks model could be considered as a yield prediction model under this approach.

4.3.5.6 Sabarkantha District

The results of five different models using generated weather variables for Sabarkantha district are presented in Table 4.51. Results revealed that only one weather variable viz., Z'_{61} (linear weight of correlation coefficient to afternoon relative humidity) entered in the equation related to 12 weeks crop period and explained about 72.5% variation in yield of rice. This variable positively and significantly influenced the rice yield.

Similar variable entered in 14 weeks model and explained about 68.7% variation in rice yield. The influence of this variable on rice yield was found positive and significant.

Table 4.51: Partial regression coefficients of rice yield on different generated weather variables in correlation coefficient as weight approach in Sabarkantha district N = 14

Variables in the equation	Weeks				
	12	14	16	18	20
Constant A_0	1236.734**	1982.505**	-1375.681	374.800	2282.542**
Z'_{61}	14.406**	0.884**	5.863**	7.370**	6.502**
Z'_{40}	-	-	-574.830**	-	-
Z'_{42}	-	-	653.970**	116.002*	-
Q'_{151}	-	-	1.990**	-	-
Q'_{351}	-	-	0.554*	-	-
Q'_{162}	-	-	-5.786**	-4.303**	-2.953*
Adjusted R^2 (%)	72.5	68.7	98.0	90.5	83.5

*, ** Significant at 5% and 1% level of significance, respectively

The set of generated weather variables observed to enter in the equation related to 16 weeks model were Z'_{40} , Z'_{61} , Z'_{42} , Q'_{151} , Q'_{351} and Q'_{162} and explained about 98.0% variation in the yield of the rice crop. The weather variables Z'_{61} (linear weight of correlation coefficient to afternoon relative humidity), Z'_{42} (quadratic weight of correlation coefficient to minimum temperature), Q'_{151} (linear weight of correlation coefficients to cross products of bright sunshine hours and morning relative humidity) and Q'_{351} (linear weight of correlation coefficients to cross products of maximum temperature and morning relative humidity) influenced the yield of rice positively and significantly whereas, Z'_{40} (zero weight of correlation coefficient to minimum temperature) and Q'_{162} (quadratic weight of correlation coefficients to cross products of bright sunshine hours and afternoon relative humidity) negatively and significantly influenced the yield of rice.

The generated weather variables viz., Z'_{61} , Z'_{42} and Q'_{162} entered in the equation related to 18 weeks model and explained about 90.5% variation in rice yield. The influence of first order generated variables Z'_{61} (linear weight of correlation coefficient to afternoon relative humidity) and Z'_{42} (quadratic weight of correlation coefficient to minimum temperature) was found positive and significant on rice yield whereas, influence of the second order generated variable Q'_{162} (quadratic weight of correlation coefficients to cross products of bright sunshine hours and afternoon relative humidity) was negative and significant on the rice yield.

The variables entered in the equation related to 20 weeks model were Z'_{61} and Q'_{162} . These variables explained about 83.5% variation in the rice yield. Positive and significant influence of the weather variable Z'_{61} (linear weight of correlation coefficient to afternoon relative humidity) was observed on the yield of rice whereas, Q'_{162} (quadratic weight of correlation coefficients to cross products of bright sunshine hours and afternoon relative humidity) negatively and significantly influenced the yield of rice.

The R^2 was moderate (72.5%) in 12 weeks and (68.7%) in 14 weeks crop period model. It was very high (98.0%) in 16 weeks and (90.5%) in 18 weeks model. The R^2 was observed high (83.5%) in 20 weeks period crop model. Thus, based on very high R^2 value and earliness of forecasting, 16 weeks model could be considered as a yield prediction model under this approach.

4.3.5.7 Surat District

The results for Surat district are presented in Table 4.52. Results related to 12 weeks crop period revealed that the weather variables viz., Z'_{11} , Z'_{61} and Q'_{240} entered in the equation and explained about 67.8% variation in rice yield. The variable Z'_{11} (linear weight of correlation coefficients to bright sunshine hours) positively and significantly influenced the rice yield whereas, the variables Z'_{61} (linear weight of correlation coefficients to afternoon relative humidity) and Q'_{240} (zero weight of correlation coefficients to cross products of rainfall and minimum temperature) negatively and significantly influenced the yield of rice.

The variables Z'_{11} and Z'_{51} entered in 14 weeks model. These variables explained about 64.6% variation in rice yield. The influence of the variables Z'_{11} (linear weight of correlation coefficients to bright sunshine hours) and Z'_{51} (linear weight of correlation coefficients to morning relative humidity) on rice yield was negative and significant.

Table 4.52: Partial regression coefficients of rice yield on different generated weather variables in correlation coefficient as weight approach in Surat district N = 18

Variables in the equation	Weeks				
	12	14	16	18	20
Constant A_0	3025.041**	4546.387**	3166.203**	4574.748**	5647.675**
Z'_{11}	5.695**	-16.832**	-	-	-
Z'_{61}	-16.002**	-	-31.574**	-17.003**	-
Q'_{240}	-0.08776*	-	-	-	-
Z'_{51}	-	-32.106**	-	-	-
Q'_{560}	-	-	0.167*	-	-
Z'_{31}	-	-	-	-45.999**	-94.477**
Z'_{32}	-	-	-	-	-146.363*
Q'_{352}	-	-	-	-	2.387**
Q'_{562}	-	-	-	-	-0.361**
Adjusted R^2 (%)	67.8	64.6	60.9	63.4	88.4

*, ** Significant at 5% and 1% level of significance, respectively

The set of generated weather variables Z'_{61} and Q'_{560} entered in the equation related to 16 weeks model and explained about 60.9% variation in the yield of rice crop. The weather variable Q'_{560} (zero weight of correlation coefficients to cross products of morning and afternoon relative humidity) influenced the yield of rice positively and significantly whereas, Z'_{61} (linear weight of correlation coefficient to afternoon relative humidity) influenced the yield of rice negatively and significantly.

The first order generated weather variables viz., Z'_{31} (linear weight of correlation coefficient to maximum temperature) and Z'_{61} (linear weight of correlation coefficient to afternoon relative humidity) entered in the equation related to 18 weeks model. These variables explained about 63.4% variation in rice yield and negatively and significantly influenced the yield of rice.

The variables entered in the equation related to 20 weeks model were Z'_{31} , Z'_{32} , Q'_{352} and Q'_{562} . About 88.4% variation in the rice yield was explained by these variables. The influence of the weather variable Q'_{352} (quadratic weight of correlation coefficients to cross products of maximum temperature and morning relative humidity) was observed positive and significant on rice yield whereas, the weather variables Z'_{31} (linear weight of correlation coefficient to maximum temperature) and Z'_{32} (quadratic weight of correlation coefficient to maximum temperature) negatively and significantly influenced the yield of rice.

The R^2 was moderate (67.8%) in 12 weeks, (64.6%) in 14 weeks, (60.9%) in 16 weeks and (63.4%) in 18 weeks crop period model. It was observed high

(88.4%) in 20 weeks period crop model. Thus, based on high R^2 value 20 weeks model could be considered as a yield prediction model under this approach.

4.3.6 GENERAL DISCUSSION

The examination of the results in the previous sections (4.3.1, 4.3.2, 4.3.3, 4.3.4 and 4.3.5) of this chapter brings out the following points.

4.3.6.1 The effects of weather variables (X_{ij})

In order to investigate the effects of weekwise, crop stagewise and periodwise weather variables on the rice yields, the variables which appeared in the equations and had significant partial regression coefficients were considered to have influence on the rice productivity. The overall look on the results showed favourable as well as detrimental effects of weather variables on rice yields.

Generated variables did not show any improvement in the yield forecasting of rice yield in comparison to weekwise, stagewise and periodwise approaches. Hence, they were not discussed.

4.3.6.1.1 Ahmedabad District

4.3.6.1.1.1 The bright sunshine hours

The effect of bright sunshine hours was beneficial during 20th week (X_{120}) corresponding to maturity (M) stage and detrimental during 14th week (X_{114}), which corresponded to flowering (F) crop stage. Ramdoss & Subramaniam (1980), Shanker & Gupta (1981), Takami & Kumashiro (1982), Chatterjee and Mandal (1988), Dua & Garrity (1988), Chakravarty (1990), Reddy & Reddy (1992), Yang & Yang (1994), Pamplona (1996), Gupta *et al.*, (2000), Kokate *et al.*, (2000), Sarangi *et al.*, (2001), Sarmah & Handique (2001), Kropff *et al.*,

(2003), Nigam & Mishra (2003), Pathak *et al.*, (2003) and Khan (2005) also reported similar effect of sunshine hours on rice yield.

The effect of bright sunshine hours was found favourable during 4th (X₁₄) and 5th stage (X₁₅) corresponding to flowering (F) and grain development (G) stages whereas, increasing bright sunshine hours were found unfavourable during 2nd (X₁₂) and 3rd (X₁₃) stages which corresponded to active tillering (A) and vegetative lag (V) crop stages. Barany (1971), Ghosh *et al.*, (1973), IRRI (1975), Munakata (1976), Yashida & Parao (1976), Jain *et al.*, (1980), McMennamy (1980), Aggrawal *et al.*, (1986), Viswambharan *et al.*, (1989), Kawakata & Yajima (1995), Haloi & Dey (2000), Yu *et al.*, (2001), Kandinan *et al.*, (2002), Mandal & Ghosh (2003), Rao (2003), Gaouna *et al.*, (2004) and Khan and Bhagat (2005) found similar effect of bright sunshine hours on the rice yield.

Increasing bright sunshine hours were detrimental during 3rd (X₁₃) period (August) which corresponded to vegetative lag (V) crop stage. Similar results are reported by Jain *et al.*, (1980) and Aggrawal *et al.*, (1986).

4.3.6.1.1.2 The rainfall

The effect of rainfall was found beneficial during 14th (X₂₁₄) week i.e. flowering (F) crop stage and detrimental during 1st (X₂₀₁) and 2nd week (X₂₀₂) corresponding to seedling (S) stage and 18th (X₂₁₈) week which corresponded to grain development (G) crop stage. Similar results were reported by Das (1971), Van (1974), Huda *et al.*, (1975), Lomas (1985), Viswambharan *et al.*, (1989), Reddy & Reddy (1992), Rao (2003) and Shah (2006).

The effect of rainfall was beneficial during 2nd (X₂₂) i.e. July and 3rd (X₂₃) period i.e. August corresponding to active tillering (A) and vegetative lag (V) crop stages. Das (1971), Huda *et al.*, (1975), Jansen (1990) and Murai *et al.*, (1991) found similar effects of rainfall on rice yield. Singh *et al.* (1996) also found that rainfall was favourable for the rice yield upto the initial maturity phase. Thus, the present findings are in agreement with these works. The effect of rainfall could not be observed in flowering and grain development stages which might be due to supplementary irrigation provided through well and canals which were not considered in the prediction models.

4.3.6.1.1.3 The maximum temperature

In the present investigation, the effect of increasing maximum temperature was beneficial during 18th week (X₃₁₈), which corresponded to grain development (G) stage. Jain *et al.*, (1980), Aggrawal *et al.*, (1986), Lin (1988), Jansen (1990), Mahmood (1997) and Haloi & Dey (2000) also reported similar results of maximum temperature on rice yield.

The effect of higher maximum temperature was beneficial during 5th (X₃₅) stage which corresponded to the grain development (G) stage in crop stagewise approach. The results are in good agreement with the findings of Jain *et al.*, (1980), Aggrawal *et al.*, (1986), Lin (1988), Jansen (1990), Mahmood (1997) and Haloi & Dey (2000).

Rising maximum temperature was beneficial during August i.e. 3rd (X₃₃) period which corresponds to the vegetative lag (V) stage in periodwise approach. Aggrawal *et al.*, (1986) and Mahmood (1997) also reported similar effects of

increasing maximum temperature on rice yield. No significant effect of maximum temperature was observed in seedling (S) and active tillering (A) crop stages which might be due to the standing water is maintained in rice fields by rainfall or irrigation which utilised the excess heat energy for evaporation of water from the field.

4.3.6.1.1.4 The minimum temperature

The effect of rising minimum temperature was beneficial during 5th (X₄₀₅), 15th (X₄₁₅), 17th (X₄₁₇) and 20th (X₄₂₀) weeks which corresponded to active tillering (A), flowering (F), grain development (G) and maturity (M) crop stages respectively. The detrimental effect of rising minimum temperature was observed during 4th (X₄₀₄), 7th (X₄₀₇) and 11th (X₄₁₁) weeks which corresponded to seedling (S), active tillering (A) and vegetative lag (V) crop stages respectively. Munakata (1976), Murai *et al.*, (1991), Dingkuhn *et al.*, (1995), Yin *et al.*, (1996b) and Kandinan *et al.*, (2002) have reported similar effects of minimum temperature on the yield of rice.

The beneficial effect of increasing minimum temperature was observed during 3rd (X₄₃) stage i.e. vegetative lag (V) crop stage and negative effect of minimum temperature was observed during 5th (X₄₅) stage which corresponded to the grain development (G) crop stage. The results are similar to the findings of Huda *et al.*, (1975) and Lin (1988).

Minimum temperature was conducive for rice plant growth during September i.e. 4th (X₄₄) period corresponding to flowering (F) crop stage. Findings reported by Huda *et al.*, (1975), Yashida & Parao (1976), Chaudhary &

Sodhi (1979), Jacob & Pearson (1994), Dingkuhn *et al.*, (1995), Yin *et al.*, (1996a), Kandinan *et al.*, (2002) and Yajima (2005) are in agreement with the present findings. They reported that lower minimum temperature during flowering (F) stage resulted in increased sterility of pollen in rice.

4.3.6.1.1.5 The morning relative humidity

Beneficial effect of morning relative humidity in general was observed in weekwise approach. Higher morning relative humidity in 5th (X₅₀₅), 10th (X₅₁₀), 15th (X₅₁₅) and 17th (X₅₁₇) weeks corresponding to active tillering (A), vegetative lag (V), flowering (F) and grain development (G) crop stages respectively had beneficial effect on the rice yield. Negative effect was observed in 10th (X₅₁₀) week i.e. vegetative lag (V) crop stage. Aggrawal *et al.*, (1986) during their study at Raipur found beneficial effect of morning relative humidity on rice yield during all the crop stages except seedling stage. Jain *et al.*, (1980), Haloi & Dey (2000) and Sarmah & Handique (2001) also reported similar findings.

Beneficial effect of morning relative humidity was observed in 3rd (X₅₃) stage which corresponded to the vegetative lag (V) crop stage, whereas detrimental effect was observed in 2nd (X₅₂) stage which corresponded to the active tillering (A) crop stage. Results of Aggrawal *et al.*, (1986) and Shi (1990) were in agreement with the current findings.

4.3.6.1.1.6 The afternoon relative humidity

Increasing afternoon relative humidity had positive influence on rice yield in general throughout the crop growth period. The beneficial effect of the afternoon relative humidity was reflected during 5th (X₅₀₅), 9th (X₅₀₉) and 18th (X₅₁₈) weeks

in weekwise approach, which corresponded to active tillering (A), vegetative lag (V) and grain development (G) stages respectively. Similar beneficial effects were observed in 2nd (X₆₂) stage in stagewise approach which corresponded to the active tillering (A) stage. The beneficial effect of the afternoon relative humidity was also observed during 2nd (X₆₂) and 4th (X₆₄) period in periodwise approach, which corresponded to the active tillering (A) and flowering (F) crop stages respectively. The results are similar to the findings of Jain *et al.*, (1980), Aggrawal *et al.*, (1986) and Haloi & Dey (2000).

4.3.6.1.2 Baroda District

4.3.6.1.2.1 The bright sunshine hours

The effect of bright sunshine hours was found beneficial during 1st (X₁₀₁), 6th (X₁₀₆) and 11th (X₁₁₁) weeks which corresponded to seedling (S), active tillering (A) and vegetative lag (V) crop stages respectively. Negative effect of bright sunshine hours was observed during 10th (X₁₁₀) week corresponding to the vegetative lag (V) crop stage. The results are in good agreement with the findings of Barany (1971), Munakata (1976), Jain *et al.*, (1980), Aggrawal *et al.*, (1986), Viswambharan *et al.*, (1989), Summerfield *et al.*, (1992), Kawakata & Yajima (1995), Yin & Kropff (1996), Haloi & Dey (2000), Yu *et al.*, (2001), Mandal & Ghosh (2003) and Gaouna *et al.*, (2004).

Higher bright sunshine hours had positive influence on rice yield during 4th (X₁₄) and 5th (X₁₅) stages corresponding to flowering (F) and grain development (G) crop stages respectively. The bright sunshine hours had negative influence on rice yield during 2nd (X₁₂) and 3rd (X₁₃) stages corresponding to active tillering

(A) and vegetative lag (V) crop stages respectively. Barany (1971), Ghosh *et al.*, (1973), IRRI (1975), Munakata (1976), Yashida & Parao (1976), Jain *et al.*, (1980), McMennamy (1980), Aggrawal *et al.*, (1986), Viswambharan *et al.*, (1989), Kawakata & Yajima (1995), Haloi & Dey (2000), Yu *et al.*, (2001), Kandinan *et al.*, (2002), Mandal & Ghosh (2003), Rao (2003), Gaouna *et al.*, (2004) and Khan & Bhagat (2005) also reported similar effects of increasing bright sunshine hours on rice yield.

The effect of bright sunshine hours was found unfavourable during August i.e. 3rd period (X₁₃) which corresponded to vegetative lag (V) crop stage. The results are in good agreement with the findings of Jain *et al.*, (1980) and Aggrawal *et al.*, (1986).

4.3.6.1.2.2 The rainfall

The effect of rainfall was beneficial during 18th (X₂₁₈) week which corresponded to grain development (G) crop stage. Higher rainfall had detrimental effect on rice yield during 1st (X₂₀₁) week i.e. seedling (S) stage. Similar results were reported by Ghosh *et al.*, (1973), Huda *et al.*, (1975), IRRI(1977), Aggrawal *et al.*, (1986), Reddy & Reddy (1992) and Shah (2006).

Rainfall during July i.e. 2nd (X₂₂) and August 3rd (X₂₃) period had beneficial effect on rice yield which corresponded to active tillering (A) and vegetative lag (V) crop stages respectively. The present findings are in agreement with the works of Das (1971), Huda *et al.*, (1975), Jansen (1990) and Murai *et al.*, (1991).

4.3.6.1.2.3 The maximum temperature

Rising maximum temperature was beneficial during 12th week (X₃₁₂) which corresponded to flowering (F) stage and detrimental during 2nd (X₃₀₂) and 20th (X₃₂₀) week which corresponded to seedling (S) and maturity (M) crop stages respectively. Similar results were reported by Ghosh *et al.*, (1973), Yashida & Parao (1976), Jain *et al.*, (1980), Aggrawal *et al.*, (1986), Reddy & Reddy (1992), Yin *et al.*, (1996a), Mahmood (1997), Haloi & Dey (2000), Shimono *et al.*, (2004) and Sreenivas *et al.*, (2005).

4.3.6.1.2.4 The minimum temperature

Significant effect of minimum temperature could not be established in any of the crop growth stages in weekwise, stagewise and periodwise approaches.

4.3.6.1.2.5 The morning relative humidity

The beneficial effect of morning relative humidity was observed in 9th (X₅₀₉) and 11th (X₅₁₁) weeks corresponding to vegetative lag (V) stage and 14th (X₅₁₄) weeks which corresponded to flowering (F) stage of crop growth. Negative influence of morning relative humidity was observed in 10th (X₅₁₀) week i.e. vegetative lag (V) stage. Similar results were obtained by Aggrawal *et al.*, (1986).

Positive effect of increasing morning relative humidity was reflected in 3rd (X₅₃) stage which corresponded to vegetative lag (V) crop stage. The results are in good agreement with the findings of Aggrawal *et al.*, (1986).

4.3.6.1.2.6 The afternoon relative humidity

Increasing afternoon relative humidity had beneficial effects on rice yield in 10th (X₆₁₀) week corresponding to vegetative lag (V) crop stage. Jain *et al.*,

(1980), Aggrawal *et al.*, (1986) and Haloi & Dey (2000) also reported similar effects of afternoon relative humidity on the yield of rice.

Afternoon relative humidity had beneficial effects on rice yield during 2nd (X₆₂) stage in stagewise approach which corresponded to the active tillering (A) stage. The results are in good agreement with the findings of Jain *et al.*, (1980), Aggrawal *et al.*, (1986) and Haloi & Dey (2000).

4.3.6.1.3 Bulsar District

4.3.6.1.3.1 The bright sunshine hours

Higher bright sunshine hours had positive effect on the yield of rice during 1st (X₁₀₁), 7th (X₁₀₇) and 11th (X₁₁₁) weeks corresponding to seedling (S), active tillering (A) and vegetative lag (V) crop stages respectively in weekwise approach. The effect of bright sunshine hours was found detrimental during 3rd (X₁₀₃), 6th (X₁₀₆), 9th (X₁₀₉), 14th (X₁₁₄) and 17th (X₁₁₇) weeks which corresponded to seedling (S), active tillering (A), vegetative lag (V), flowering (F) and grain development (G) crop stages respectively. Results on similar line were reported by Barany (1971), Munakata (1976), Jain *et al.*, (1980), Aggrawal *et al.*, (1986), Viswambharan *et al.*, (1989), Summerfield *et al.*, (1992), Kawakata & Yajima (1995), Yin & Kropff (1996), Rai and Chandrahas (1997), Haloi & Dey (2000), Yu *et al.*, (2001), Mandal & Ghosh (2003) and Gaouna *et al.*, (2004).

Detrimental effect of bright sunshine hours was observed in 5th (X₁₅) stage i.e. grain development (G) stage in stagewise approach. Kokate *et al.*, (2000) also reported similar negative effect of increasing bright sunshine hours on rice yield in general.

The effect of bright sunshine hours was found detrimental during 4th (X₁₄) period i.e. September which corresponded to flowering (F) crop stage in periodwise approach. Findings of Kokate *et al.*, (2000) showed similar detrimental effect of bright sunshine hours on rice yield.

4.3.6.1.3.2 The rainfall

The effect of increasing rainfall was beneficial to rice yield during 7th (X₂₀₇), 11th (X₂₁₁), 16th (X₂₁₆) and 19th (X₂₁₉) weeks which corresponded to active tillering (A), vegetative lag (V), grain development (G) and maturity (M) crop stages respectively. The effect of rainfall was detrimental during 3rd (X₂₀₃) and 12th week (X₂₁₂) which corresponded to seedling (S) and flowering (F) crop stages respectively. Similar results were reported by Das (1971), Ghosh *et al.*, (1973), Huda *et al.*, (1975), IRRI(1977), Aggrawal *et al.*, (1986), Jansen(1990), Murai *et al.*, (1991) and Shah (2006).

4.6.1.3.3 The maximum temperature

The effect of maximum temperature was beneficial during 8th (X₃₀₈), 14th (X₃₁₄) and 18th (X₃₁₈) weeks which corresponded to vegetative lag (V), flowering (F) and grain development (G) crop stages respectively. Maximum temperature had detrimental effect during 5th (X₃₀₅), 13th (X₃₁₃) and 20th (X₃₂₀) weeks which corresponded to active tillering (A), flowering (F) and maturity (M) crop stages respectively. The results are similar to the findings of Jain *et al.*, (1980), Shanker & Gupta (1981), Aggrawal *et al.*, (1986), Lin (1988), Jansen(1990), Mathews *et al.*, (1995), Mahmood (1997), Samui *et al.*, (1999), Haloi & Dey (2000), Kokate *et al.*, (2000), Mathuda *et al.*, (2000), Saseendran *et al.*, (2000), Poussin *et al.*,

(2003), Easterling & Apps (2005), Khan (2005), Khan & Bhagat, (2005) and Motha & Baier (2005).

The effect of maximum temperature could not be observed during seedling stage which might be due to continuous standing water in the field which might have smothered the effect of high temperature.

4.6.1.3.4 The minimum temperature

Rising minimum temperature showed positive effect on rice yield during 7th (X₄₀₇) week which corresponded to active tillering (A) stage. Negative influence of higher minimum temperature was observed in 13th (X₄₁₃) week corresponding to flowering (F) crop stage. The results are in good agreement with the findings of Huda *et al.*, (1975), Yashida & Parao (1976), Chaudhary & Sodhi (1979), Jacob & Pearson (1994), Dingkuhn *et al.*, (1995), Yin *et al.*, (1996a), Kandinan *et al.*, (2002) and Yajima (2005).

4.3.6.1.3.5 The morning relative humidity

The effect of morning relative humidity was observed beneficial in 17th week (X₅₁₇) in weekwise approach which corresponded to grain development (G) stage of crop growth. Agrawal *et al.* (1986) also reported beneficial effects for above average relative humidity throughout the growth phase of the crop in general.

4.3.6.1.3.6 The afternoon relative humidity

Negative effect of the afternoon relative humidity on rice yield was observed in general in weekwise approach in Bulsar district. The detrimental effect of afternoon relative humidity on rice yield was observed during 5th (X₆₀₅)

and 14th (X₆₁₄) weeks corresponding to active tillering (A) and flowering (F) crop stages respectively and 17th (X₆₁₇) and 18th (X₆₁₈) weeks which corresponded to grain development (G) crop stage. Results are in good agreement with the findings of Jain *et al.*, (1980), Aggrawal *et al.*, (1986) and Haloi & Dey (2000).

4.3.6.1.4 Kheda District

4.3.6.1.4.1 The bright sunshine hours

The detrimental effect of bright sunshine hours to rice yield was found during 19th week (X₁₁₉) which corresponded to maturity (S) crop stage. Jain *et al.*, (1980) also reported similar negative effects of increasing bright sunshine hours on the yield of rice.

4.3.6.1.4.2 The rainfall

Rainfall had beneficial effect on rice yield during 1st stage (X₂₁) which corresponded to seedling (S) crop stage in stagewise approach. Das (1971), Prabhakaran (1985), Aggrawal *et al.*, (1986), Rao (2003) and Shah (2006) reported similar effect of rainfall during seedling stage on rice yield.

In periodwise approach positive influence of increasing rainfall was observed on rice yield during June i.e. 1st period (X₂₁) which corresponded to seedling (S) crop stage. Similar results were reported by Das (1971), Prabhakaran (1985), Aggrawal *et al.*, (1986), Rao (2003) and Shah (2006).

4.3.6.1.4.3 The maximum temperature

Rising maximum temperature had detrimental effect on the yield of rice during 16th (X₃₁₆) and 18th week (X₃₁₈) which corresponded to flowering (F) crop stage in weekwise approach. Results obtained by Huda *et al.*, (1975), Chaudhary

& Sodhi (1979), Singh & Padilla (1995) are in good agreement with the present findings.

The effect of maximum temperature was detrimental during 5th (X₃₅) stage which corresponded to the grain development (G) stage in crop stagewise approach. Mandal & Ghosh (2003) reported similar detrimental effect of maximum temperature during grain development stage on rice yield.

4.3.6.1.4.4 The minimum temperature

The beneficial effect of minimum temperature was found during 10th week (X₄₁₀), which corresponded to vegetative lag (V) crop stage. The effect of minimum temperature was detrimental during 12th (X₄₁₂) week corresponding to the flowering (F) stage in weekwise approach. Similar results were reported by Huda *et al.*, (1975), Yashida & Parao (1976), Chaudhary & Sodhi (1979), Jacob & Pearson (1994), Dingkuhn *et al.*, (1995), Yin *et al.*, (1996a), Kandinan *et al.*, (2002) and Yajima (2005).

No effect was observed during seedling, active tillering and grain development stages as frequent irrigation by canal and well might have mitigated detrimental effect of minimum temperature on rice growth and yield.

4.3.6.1.4.5 The morning relative humidity

Higher morning relative humidity had significant negative effect on rice yield in 19th (X₅₁₉) week corresponding to maturity (M) crop stage in weekwise approach. Huda *et al.*, (1975) and Nigam & Mishra (2003) also reported similar detrimental effect of increasing morning relative humidity on the yield of rice.

4.3.6.1.4.6 The afternoon relative humidity

The effect of increasing afternoon relative humidity was found beneficial in general. The positive effect of increasing afternoon relative humidity was found during 9th (X₆₀₉) and 10th week (X₆₁₀) which corresponded to vegetative lag (V) stage and 16th (X₆₁₆) week corresponding to grain development (G) stage. The results are in good agreement with the findings of Jain *et al.*, (1980), Aggrawal *et al.*, (1986) and Haloi & Dey (2000).

The beneficial effect of the afternoon relative humidity on rice yield was observed during 2nd (X₆₂) period i.e. July which corresponded to active tillering (A) stage and 4th period (X₆₄) i.e. September, which corresponded to the flowering (F) crop stage. Jain *et al.*, (1980), Aggrawal *et al.*, (1986) Haloi & Dey (2000) reported similar beneficial effects of afternoon relative humidity on the rice yield.

4.3.6.1.5 Panchmahal District

4.3.6.1.5.1 The bright sunshine hours

The effect of bright sunshine hours was found beneficial during 11th week (X₁₁₁), which corresponded to vegetative lag (V) crop stage. The detrimental effect of increasing bright sunshine hours on rice yield were observed in 2nd (X₁₀₂) and 4th (X₁₀₄) weeks which corresponded to seedling (S) crop stage in weekwise approach. Results reported by Barany (1971), Jain *et al.*, (1980), Kawakata & Yajima (1995) and Gaouna *et al.*, (2004) were in good agreement with the current findings.

4.3.6.1.5.2 The rainfall

The effect of rainfall was beneficial during 8th (X₂₀₈) and 13th (X₂₁₃) weeks which corresponded to vegetative lag (V) and flowering (F) crop stages respectively. The effect was detrimental during 15th week (X₂₁₅) and 19th week (X₂₁₉) which corresponded to seedling (S) and maturity (M) crop stages respectively in weekwise approach. Das (1971), Huda *et al.*, (1975), Lomas (1985), Reddy & Reddy (1992) and Shah (2006) also reported similar results.

4.3.6.1.5.3 The maximum temperature

The effect of increasing maximum temperature was beneficial during 2nd (X₃₀₂), 10th (X₃₁₀) and 14th (X₃₁₄) weeks which corresponded to seedling (S), vegetative lag (V) and flowering (F) crop stages respectively in weekwise approach. Similar results were obtained by Ghosh *et al.*, (1973), Huda *et al.*, (1975), Munakata (1976), Yashida & Parao (1976), Aggrawal *et al.*, (1986), Reddy & Reddy (1992), Collinson *et al.*, (1995), Yin *et al.*, (1996a), Mahmood (1997), Shimono *et al.*, (2004) and Sreenivas *et al.*, (2005).

The effect of maximum temperature was detrimental during 5th (X₃₅) stage which corresponded to the grain development (G) stage in crop stagewise approach. Mandal & Ghosh (2003) reported similar detrimental effect of maximum temperature on rice yield.

4.3.6.1.5.4 The minimum temperature

Minimum temperature had beneficial effect on rice yield during 1st (X₄₀₁), 16th (X₄₁₆) and 19th (X₄₁₉) weeks corresponding to seedling (S), grain development (G) and maturity (M) crop stages respectively. Detrimental effect of

increasing minimum temperature was observed during 2nd (X₄₀₂) and 10th (X₄₁₀) weeks which corresponded to seedling (S) and vegetative lag (V) crop stages respectively. Huda *et al.*, (1975) and Kandinan *et al.*, (2002) also reported similar effects of increasing minimum temperature on rice yield.

Increasing minimum temperature had harmful effect on rice yield during 1st (X₄₁) i.e. seedling (S) stage. The results are in good agreement with the findings of Dingkuhn *et al.*, (1995) and Yin *et al.*, (1996b).

4.3.6.1.5.5 The morning relative humidity

The effect of the rising morning relative humidity was found beneficial during 12th (X₅₁₂) and 14th week (X₅₁₄) i.e. flowering (F) stage and 18th week (X₅₁₈) corresponding to grain development (G) stage. The effect was found detrimental during 7th week (X₅₀₇) which corresponded to active tillering (A) stage in weekwise approach. Aggrawal *et al.*, (1986) and Shi (1990) reported similar results.

4.3.6.1.5.6 The afternoon relative humidity

The increasing afternoon relative humidity had beneficial effect on rice yield during 10th (X₆₁₀) and 16th (X₆₁₆) week which corresponded to vegetative lag (V) and grain development (G) stages respectively. The effect was found detrimental during 2nd (X₆₀₂) and 7th week (X₆₀₇) which corresponded to seedling (S) and active tillering (A) crop stages in weekwise approach. Similar results were reported by Jain *et al.*, (1980), Aggrawal *et al.*, (1986) and Haloi & Dey (2000).

The beneficial effect of the afternoon relative humidity was observed during 4th stage (X₆₄) i.e. flowering (F) stage in stagewise approach. Sarmah & Handique

(2001) reported general beneficial effect of increasing afternoon relative humidity on rice yield.

Similar beneficial effect of the afternoon relative humidity was observed during 4th period (X₆₄) i.e. September which corresponded to flowering (F) stage in periodwise approach. Similar beneficial effect of increasing afternoon relative humidity on rice yield in general were reported by Sarmah & Handique (2001).

4.3.6.1.6 Sabarkantha District

4.3.6.1.6.1 The bright sunshine hours

Increasing bright sunshine hours during 11th (X₁₁₁) week corresponding to vegetative lag (V) crop stage had negative effect on the yield of rice. Jain *et al.*, (1980) and Aggrawal *et al.*, (1986) also reported similar effects of bright sunshine hours on rice yield.

The detrimental effect of bright sunshine hours was observed during 3rd (X₁₃) and 5th stage (X₁₅) which corresponded to vegetative lag (V) and grain development (G) crop stages respectively. Similar effects of bright sunshine hours on rice yield were reported by Jain *et al.*, (1980), Aggrawal *et al.*, (1986) and Kokate *et al.*, (2000).

The effect of rising bright sunshine hours was detrimental during 3rd period (X₁₃) which corresponded to vegetative lag (V) crop stage. The findings are in good agreement with the results of Jain *et al.*, (1980) and Aggrawal *et al.*, (1986).

4.3.6.1.6.2 The rainfall

The effect of rainfall was detrimental during 13th (X₂₁₃) and 18th week (X₂₁₈) which corresponded to flowering (F) and grain development (G) crop stages

respectively in weekwise approach. Similar effects of increasing rainfall on rice yield were reported by Van (1974), Prabhakaran (1985), Aggrawal *et al.*, (1986), Viswambharan *et al.*, (1989) and Rao (2003).

4.3.6.1.6.3 The maximum temperature

Maximum temperature was beneficial during 1st week (X₃₀₁) which corresponded to seedling (S) crop stage and 13th (X₃₁₃) and 15th week (X₃₁₅) which corresponded to flowering (F) crop stage. The effect of increasing maximum temperature was detrimental during 11th (X₃₁₁) and 16th week (X₃₁₆) which corresponded to active vegetative lag (V) and grain development (G) crop stage respectively and 19th (X₃₁₉) and 20th week (X₃₂₀) which corresponded to maturity (M) crop stage. Similar results were reported by Ghosh *et al.*, (1973), Huda *et al.*, (1975), Munakata (1976), Yashida & Parao (1976), Jain *et al.*, (1980), Aggrawal *et al.*, (1986), Reddy & Reddy (1992), Collinson *et al.*, (1995), Yin *et al.*, (1996a), Mahmood (1997), Haloi & Dey (2000), Mandal & Ghosh (2003), Shimono *et al.*, (2004) and Sreenivas *et al.*, (2005).

4.3.6.1.6.4 The minimum temperature

The beneficial effect of increased minimum temperature was observed during 2nd (X₄₂) stage i.e. active tillering (A) stage in stagewise approach. Samui *et al.*, (1999) and Gupta *et al.*, (2000) reported similar effect of minimum temperature on rice yield.

4.3.6.1.6.5 The morning relative humidity

Higher morning relative humidity was found beneficial during 1st (X₅₀₁) and 3rd (X₅₀₃) week which corresponded to seedling (S) stage and 5th week (X₅₀₅)

which corresponded to active tillering (A) stage. The effect was found detrimental during 6th week (X₅₀₆) which corresponded to active tillering (A) stage in weekwise approach. Aggrawal *et al.*, (1986) and Shi (1990) obtained similar effects of morning relative humidity on rice yield.

Beneficial effect of the morning relative humidity on rice yield was observed during 1st (X₅₁) stage corresponding to seedling (S) crop stage in stagewise approach. Jain *et al.*, (1980), Haloi & Dey (2000) and Sarmah & Handique (2001) reported similar effect of morning relative humidity in general on rice yield.

The beneficial effect of morning relative humidity was observed in 1st (X₅₁) period i.e. June, which corresponded to the seedling (S) stage in periodwise approach. Similar results were obtained by Jain *et al.*, (1980), Haloi & Dey (2000) and Sarmah & Handique (2001).

4.3.6.1.6.6 The afternoon relative humidity

The effect of the rising afternoon relative humidity was found beneficial to the yield of rice during 1st week (X₅₀₁) i.e. seedling (S) stage and detrimental during 10th week (X₆₁₀) which corresponded to vegetative lag (V) stage. Jain *et al.*, (1980) and Haloi & Dey (2000) reported similar effects of afternoon relative humidity on rice yield.

4.3.6.1.7 Surat District

4.3.6.1.7.1 The bright sunshine hours

No effect of bright sunshine hours was observed in weekwise, stagewise and periodwise approaches.

4.6.1.7.2 The rainfall

Positive effect of rainfall was observed during 7th week (X₂₀₇) corresponding to active tillering (A) crop stage and negative effect was observed during 8th (X₂₀₈) and 11th (X₂₁₁) weeks corresponding to vegetative lag (V) stage and 18th (X₂₁₈) and 19th (X₂₁₉) weeks corresponding to grain development (G) and maturity (M) crop stages respectively. Results reported by Van (1974), Aggrawal *et al.*, (1986), Viswambharan *et al.*, (1989), Jansen (1990), Murai *et al.*, (1991), Reddy & Reddy (1992) and Rao (2003) were similar to the present findings.

4.3.6.1.7.3 The maximum temperature

Increasing maximum temperature during seedling (S) stage i.e. 1st (X₃₀₁) was conducive to rice yield. The effect of maximum temperature was detrimental during 2nd (X₃₀₂), 18th (X₃₀₇) and 20th (X₃₂₀) weeks which corresponded to seedling (S), grain development (G) and maturity (M) crop stage respectively. Similar results were reported by Huda *et al.*, (1975), Munakata (1976), Jain *et al.*, (1980), Aggrawal *et al.*, (1986), Collinson *et al.*, (1995), Yin *et al.*, (1996b), Mahmood (1997), Haloi & Dey (2000) and Mandal & Ghosh (2003).

The effect of rising maximum temperature was detrimental during October i.e. 5th (X₃₅) period which corresponded to the grain development (G) stage in periodwise approach. Mandal & Ghosh (2003) also reported similar detrimental effects of maximum temperature on rice yield.

4.3.6.1.7.4 The minimum temperature

Minimum temperature had beneficial effect on rice yield during 1st week (X₄₀₁) which corresponded to seedling (S) stage whereas detrimental effect was

observed during 16th week (X_{416}) which corresponded to grain development (G) crop stage. Huda *et al.*, (1975) and Lin (1988) reported similar effects of minimum temperature on rice yield.

The harmful effect of minimum temperature was observed during 2nd (X_{42}) period which corresponded to the active tillering (A) stage. Similar results were reported by Munakata (1976), Murai *et al.*, (1991), Dingkuhn *et al.*, (1995), Yin *et al.*, (1996b) and Kandinan *et al.*, (2002).

4.3.6.1.7.5 The morning relative humidity

Increasing morning relative humidity had detrimental effect on rice yield during 9th week (X_{509}) which corresponded to vegetative lag (V) crop stage. Results on similar effects of morning relative humidity on the yield of rice were reported by Huda *et al.*, (1975) and Nigam & Mishra (2003).

4.3.6.1.7.6 The afternoon relative humidity

High afternoon relative humidity had detrimental effects on rice yield in general. The effect of the afternoon relative humidity was found detrimental during 18th (X_{618}) and 20th week (X_{620}) which corresponded to grain development (G) and maturity (M) crop stages respectively. Similar results were reported by Jain *et al.*, (1980), Aggrawal *et al.*, (1986) and Haloi & Dey (2000).

The detrimental effect of afternoon relative humidity on rice yield was found during 1st stage (X_{61}) which corresponded to seedling (S) stage in stagewise approach. Aggrawal *et al.*, (1986) also reported similar results.

The effect of the afternoon relative humidity was found detrimental during 1st period (X_{61}) which corresponded to seedling (S) stage in periodwise approach. The results are in good agreement with the findings of Aggrawal *et al.*, (1986).

4.3.7 Evaluation of models for yield prediction

For assessing joint influence of weather variables and suggesting suitable model for prediction of rice yield, five different approaches were employed. For the selection of the prediction model from different approaches, the fitted regression equations which accounted more than 75 per cent of the total variation in rice yield and predicted yield early was proposed as the prediction model.

For better understanding the subscripts of crop week numbers were replaced by corresponding meteorological standard weeks (eg. bright sunshine hours of 1st week, X_{101} could be replaced by the bright sunshine hours of 23rd meteorological standard week; X_{1W23}) as the independent variables in the proposed model.

Out of the five approaches, three approaches using original observed weather variables (1) weekwise, (2) stagewise and (3) periodwise average weather variables and two approaches using generated weather variables (1) week number as weight and (2) correlation coefficient as weight were used for fitting of the models. Approaches using shorter interval i.e. weekly weather variables either original or generated were found superior to the approaches using longer period averaged weather variables i.e. stagewise and periodwise approaches.

4.3.7.1 Ahmedabad District

All the five approaches were used for fitting of the models i.e. weekwise, stagewise, periodwise, week number as weight and correlation coefficient as

weight, all were identified as acceptable models. Models fitted with weekwise approach, 16 week model, 5 stage model fitted with stagewise approach, 3 period model fitted with periodwise approach, 12 week model fitted with week number as weight approach, and 12 week model in correlation coefficient as weight approach, were finally identified, which explained $> 75\%$ variation in productivity. The earliest prediction (8 weeks before harvest) was made with 3 period model fitted with periodwise approach and 12 week model fitted with week number as weight and correlation coefficient as weight approaches, but the reliability was higher in case of 12 week model fitted with week number as weight approach. So out of these five models, the 12 week model fitted with week number as weight approach which provided earlier rice yield prediction (8 weeks before harvest) and explained higher variation in rice yield (90.6%) is preferred. Thus, the recommended rice yield prediction model for Ahmedabad district is

$$Y = 6304.22 + 3.80 RHE^1 - 0.69 RHM^2 + 0.26 (RF \cdot RHE)^0 - 2.37 (MINT \cdot RHE)^0 + 4.36 (MAXT \cdot RHM)^2 \quad (\text{Adjusted } R^2 = 90.6\%)$$

or

$$Y = 6304.22 + 3.80 Z_{61} - 0.69 Z_{52} + 0.26 Q_{260} - 2.37 Q_{460} + 4.36 Q_{352} \quad (\text{Adjusted } R^2 = 90.6\%)$$

4.3.7.2 Baroda District

Out of the five approaches used for fitting the models, model fitted with periodwise approach could not be identified as acceptable model. Models fitted with weekwise approach, 12 week model, 5 stage model fitted with stagewise approach, 14 week model fitted with week number as weight approach, and 16

week model in correlation coefficient as weight approach, were finally identified, which explained > 75% variation in productivity. The earliest prediction (8 weeks before harvest) was made with 12 week model fitted with weekwise approach. So out of these four models, the 12 week model fitted with weekwise approach which provided earlier prediction of rice yield (8 weeks before harvest) and explained higher variation in rice yield (99.4%) is preferred. Thus, the recommended rice yield prediction model for Baroda district is

$$Y = -5050.94 - 0.33 RF_2 + 19.06 BSS_6 + 37.45 RHM_9 - 42.51 BSS_{10} + 178.41 BSS_{11} + 24.46 RHM_{11} \quad (\text{Adjusted } R^2 = 99.4\%)$$

or

$$Y = -5050.94 - 0.33 X_{2W_{24}} + 19.06 X_{1W_{28}} + 37.45 X_{5W_{31}} - 42.51 X_{1W_{32}} + 178.41 X_{1W_{33}} + 24.46 X_{5W_{33}} \quad (\text{Adjusted } R^2 = 99.4\%)$$

4.3.7.3 Bulsar District

Four out of the five approaches, which were used for fitting the models, models fitted with stagewise, periodwise, week number as weight and correlation coefficient as weight approaches could not be identified as acceptable models. Only one, 18 week model fitted with weekwise approach which provided earlier rice yield prediction (2 weeks before harvest) and explained higher variation in rice yield (99.8%) is preferred. Thus, the recommended rice yield prediction model for Bulsar district is

$$Y = 5788.42 - 23.63 BSS_3 - 0.15 RF_3 - 69.95 MAXT_5 + 59.49 MINT_5 - 86.85 BSS_6 + 106.21 BSS_7 + 2.47 RF_7 + 103.57 MAXT_8 - 33.49 BSS_9 + 25.88$$

$$BSS_{11} + 3.73 RF_{11} - 0.84 RF_{12} - 170.01 MAXT_{13} - 70.32 MINT_{13} - 106.46$$

$$BSS_{14} - 41.87 RHE_{14} + 0.60 RF_{16} + 41.80 RHM_{17} \text{ (Adjusted } R^2 = 99.8\%)$$

or

$$Y = 5788.42 - 23.63 X_{1W25} - 0.15 X_{2W25} - 69.95 X_{3W27} + 59.49 X_{4W27} - 86.85$$

$$X_{1W28} + 106.21 X_{1W29} + 2.47 X_{2W29} + 103.57 X_{3W30} - 33.49 X_{1W31} + 25.88$$

$$X_{1W33} + 3.73 X_{2W33} - 0.84 X_{2W34} - 170.01 X_{3W35} - 70.32 X_{4W35} - 106.46$$

$$X_{1W36} - 41.87 X_{6W36} + 0.60 X_{2W38} + 41.80 X_{5W39} \text{ (Adjusted } R^2 = 99.8\%)$$

4.3.7.4 Kheda District

Out of the five approaches, which were used for fitting the models, models fitted with stagewise, periodwise, week number as weight and correlation coefficient as weight approaches could not be identified as acceptable models. Only one, 20 week model fitted with weekwise approach which provided rice yield prediction (0 weeks before harvest) and explained higher variation in rice yield (90.7%) is preferred. Thus, the recommended rice yield prediction model for Kheda district is

$$Y = 8682.13 + 317.72 MINT_{10} + 12.87 RHE_{10} - 202.97 MINT_{12} - 59.17$$

$$MAXT_{18} - 79.21 BSS_{19} - 32.92 RHM_{19} \text{ (Adjusted } R^2 = 99.8\%)$$

or

$$Y = 8682.13 + 317.72 X_{4W32} + 12.87 X_{6W32} - 202.97 X_{4W34} - 59.17 X_{3W40} -$$

$$79.21 X_{1W41} - 32.92 X_{5W41} \text{ (Adjusted } R^2 = 99.8\%)$$

4.3.7.5 Panchmahal District

Three out of five approaches which were used for fitting of the models, model fitted with stagewise, periodwise, week number as weight approaches

could not be identified as acceptable models. Models fitted with weekwise approach, 12 week model and 16 week model in correlation coefficient as weight approach were finally identified, which explained > 75% variation in productivity. So out of the two models, the 12 week model fitted with weekwise approach which provided earlier prediction of the rice yield (8 weeks before harvest) and explained higher variation in rice yield (96.0%) is preferred. Thus, the recommended rice yield prediction model for Panchmahal district is

$$Y = 8881.23 - 105.44 \text{ BSS}_2 + 105.02 \text{ MAXT}_2 - 164.14 \text{ MINT}_2 - 8.90 \text{ RHE}_2 - 54.41 \text{ RHM}_7 + 2.78 \text{ RF}_8 - 80.16 \text{ MINT}_{10} \quad (\text{Adjusted } R^2 = 96.0\%)$$

or

$$Y = 8881.23 - 105.44 X_{1W_{24}} + 105.02 X_{3W_{24}} - 164.14 X_{4W_{24}} - 8.90 X_{6W_{24}} - 54.41 X_{5W_{29}} + 2.78 X_{2W_{30}} - 80.16 X_{4W_{32}} \quad (\text{Adjusted } R^2 = 96.0\%)$$

4.3.7.6 Sabarkantha District

Out of the five approaches, models fitted with stagewise, periodwise and week number as weight approaches could not be identified as acceptable models. The 14 week model fitted with weekwise approach and 16 week model in correlation coefficient as weight approach were finally identified which explained > 75% variation in productivity but earlier yield prediction was observed in 14 week model fitted with weekwise approach. So out of these two models, the model (14 week) which provided earlier prediction (6 weeks before harvest) and explained higher (99.8%) variation in rice yield is preferred. Thus, the recommended rice yield prediction model for Sabarkantha district is

$$Y = -1075.72 + 37.25 \text{ RHM}_1 + 2.68 \text{ RHM}_3 + 8.99 \text{ RHE}_4 + 28.55 \text{ RHM}_5 - 34.24 \\ \text{RHM}_6 - 6.40 \text{ RHE}_{10} - 59.89 \text{ MAXT}_{11} + 68.84 \text{ MAXT}_{13} \\ (\text{Adjusted } R^2 = 99.8\%)$$

or

$$Y = -1075.72 + 37.25 X_{5W_{23}} + 2.68 X_{5W_{25}} + 8.99 X_{6W_{26}} + 28.55 X_{5W_{27}} - 34.24 \\ X_{5W_{28}} - 6.40 X_{6W_{32}} - 59.89 X_{3W_{33}} + 68.84 X_{3W_{35}} \\ (\text{Adjusted } R^2 = 99.8\%)$$

4.3.7.7 Surat District

Four out of the five approaches, which were used for fitting the models, models fitted with stagewise, periodwise, week number as weight and correlation coefficient as weight approaches could not be identified as acceptable models. Only one, 20 week model fitted with weekwise approach which provided yield prediction (0 weeks before harvest) and explained higher variation in rice yield (99.9%) is preferred. The recommended rice yield prediction model for Surat district is

$$Y = 2851.46 + 72.40 \text{ MINT}_1 + 57.63 \text{ MAXT}_4 - 17.24 \text{ MAXT}_5 - 0.06 \text{ RF}_8 - 2.83 \\ \text{RHM}_9 - 1.38 \text{ RF}_{11} - 18.61 \text{ MINT}_{16} - 2.75 \text{ RF}_{18} - 1.66 \text{ RF}_{19} - 89.51 \\ \text{MAXT}_{20} - 6.24 \text{ RHE}_{20} \quad (\text{Adjusted } R^2 = 99.8\%)$$

or

$$Y = 2851.46 + 72.40 X_{4W_{23}} + 57.63 X_{3W_{26}} - 17.24 X_{3W_{27}} - 0.06 X_{2W_{30}} - 2.83 \\ X_{5W_{31}} - 1.38 X_{2W_{33}} - 18.61 X_{4W_{38}} - 2.75 X_{2W_{40}} - 1.66 X_{2W_{41}} - 89.51 X_{3W_{42}} \\ - 6.24 X_{6W_{42}} \quad (\text{Adjusted } R^2 = 99.8\%)$$

4.4 Testing of models for yield prediction

The selected Agrometeorological models were compared with crop growth simulation models DSSAT and. The results are presented below in Tables 4.53, 4.54, 4.55, 4.56, 4.57, 4.58 and 4.59 and Figures 4.16, 4.17, 4.18, 4.19, 4.20 and 4.21.

The developed Agrometeorological models were equally efficient to the crop growth simulation models viz. DSSAT and WOFOST in all the districts except in Baroda district where the performance of WOFOST and DSSAT respectively was found superior to the developed model.

4.4.1 Ahmedabad district

The observed yield during year 2004 was 2182 kg/ha which was predicted 2537, 2355 and 2380 kg/ha by DSSAT, WOFOST and Agrometeorological model. The percent deviations were 16.3, 7.9 and 9.1 from the observed value. The performance of WOFOST and Agrometeorological model was satisfactory in 2004 but WOFOST was found superior.

Table 4.53: Simulated forecasts by different models in Ahmedabad district.

Year	Observed Yield (kg/ha)	Modelled yield		
		DSSAT	WOFOST	Agrometeorological Model
2004	2182	2537(16.3)	2355(07.9)	2380(09.1)
2005	2484	2290(-07.8)	2386(-03.9)	2295(-07.6)

Figures in parenthesis are per cent deviation from observed yield.

During the year 2005 the observed yield was 2484 kg/ha and predicted yield was 2290, 2386 and 2295 kg/ha by DSSAT, WOFOST and Agrometeorological model respectively. The respective percent deviations were 7.8, 3.9 and 7.6 from the observed value. Negative deviations indicated underestimation by the model.

All the models underestimated the rice yield of Ahmedabad during 2005. The performance of all the models was satisfactory in 2005 but WOFOST was superior to the rest of the two models.

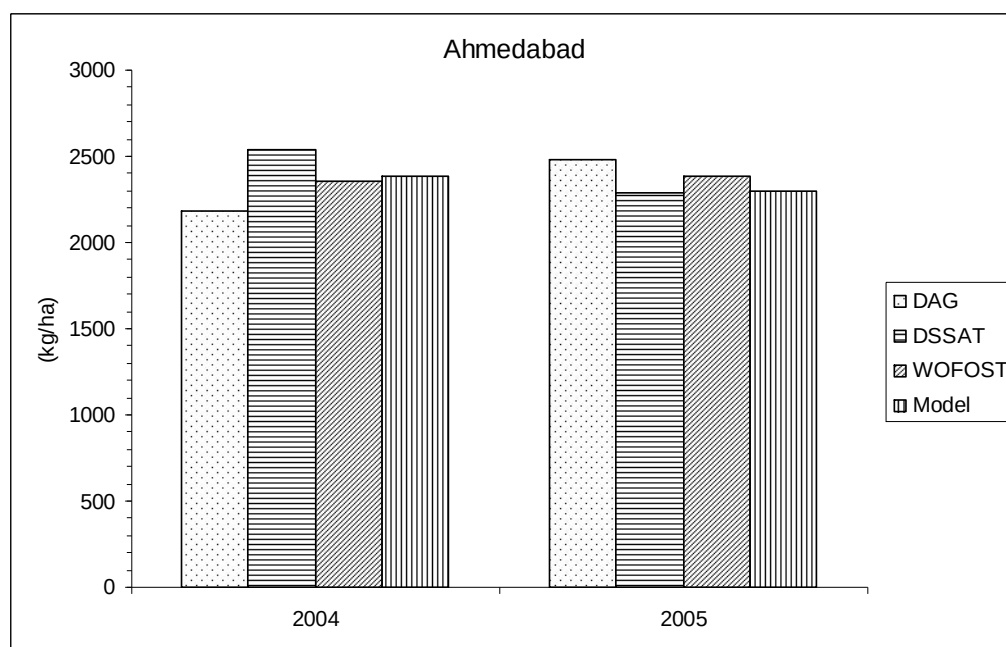


Figure 4.16: Comparison of simulated forecasts by different models in Ahmedabad district with observed rice yield

4.4.2 Baroda district

During the year 2004 observed yield was 1042 kg/ha, whereas the predicted yield by DSSAT, WOFOST and Agrometeorological model was 982, 1001 and 1101 kg/ha respectively. The percent deviations were 7.5, 3.9 and 5.7 from the observed value. Negative deviation indicated underestimation by the model. DSSAT and WOFOST underestimated the rice yield of Baroda during 2004. The performance of all the models was satisfactory in 2004 but WOFOST was superior to rest of the two.

Table 4.54: Simulated forecasts by different models in Baroda district.

Year	Observed Yield (kg/ha)	Modelled yield		
		DSSAT	WOFOST	Agrometeorological Model
2004	1042	982(-05.7)	1001(-03.9)	1101(05.7)
2005	1154	1241(07.5)	1209(04.8)	1464(26.8)

Figures in parenthesis are per cent deviation from observed yield.

During the year 2005 the observed yield was 1154 kg/ha and predicted yield was 1241, 1209 and 1464 kg/ha by DSSAT, WOFOST and Agrometeorological model respectively. The respective percent deviations were 7.5, 4.8 and 26.8 from the observed value. The performance of Agrometeorological model was not upto the mark but the performance of DSSAT and WOFOST was found satisfactory in 2005 and WOFOST was found superior.

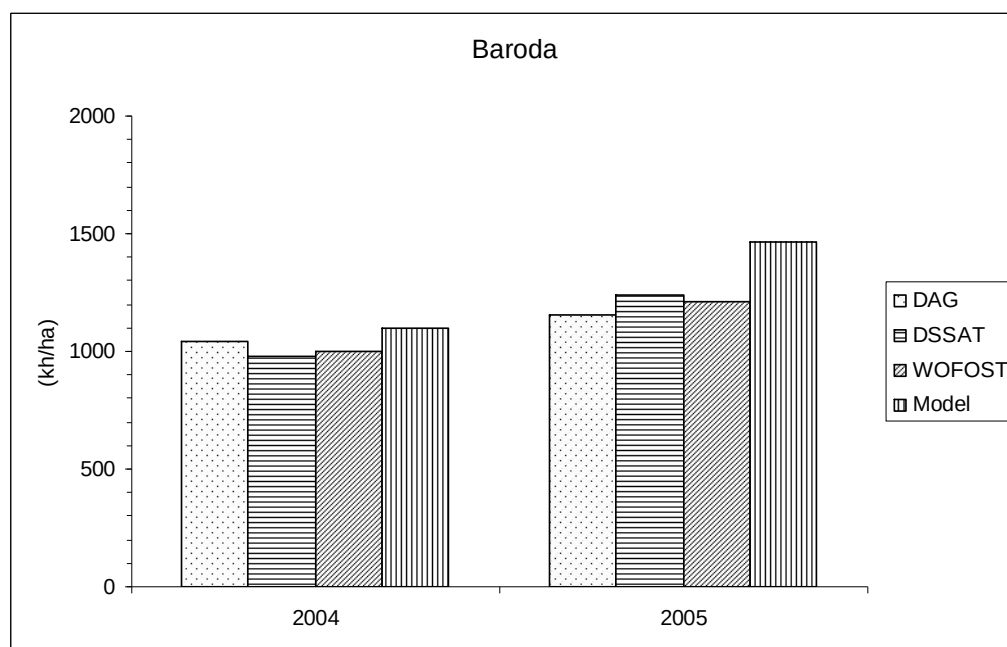


Figure 4.17: Comparison of simulated forecasts by different models in Baroda district with observed rice yield

4.4.3 Bulsar district

Table 4.55: Simulated forecasts by different models in Bulsar district.

Year	Observed Yield (kg/ha)	Modelled yield		
		DSSAT	WOFOST	Agrometeorological Model
2004	1823	1992(09.3)	1889(03.6)	1824(00.1)
2005	1996	1950(-02.3)	1862(-06.7)	1993(-00.2)

Figures in parenthesis are per cent deviation from observed yield.

During the year 2004 the predicted yield by DSSAT, WOFOST and Agrometeorological model was 1992, 1889 and 1824 kg/ha respectively, whereas observed yield of the district was 1823 kg/ha. The percent deviations were 7.0, 3.6 and 0.1 from the observed value. The performance of all the models was satisfactory in 2004 but Agrometeorological model was found superior to the rest of the two.

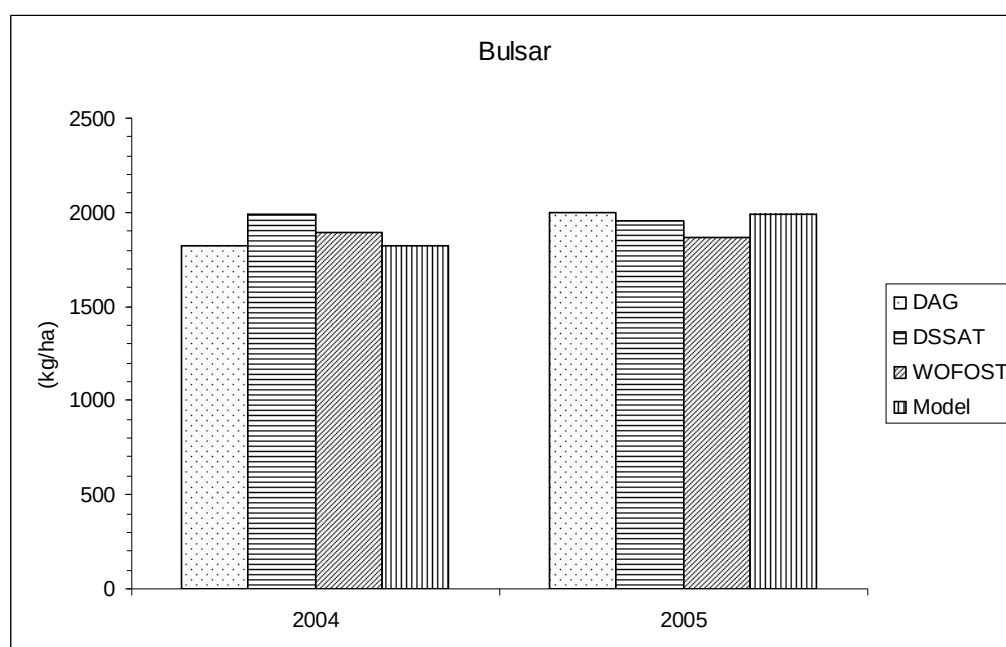


Figure 4.18: Comparison of simulated forecasts by different models in Bulsar district with observed rice yield

Observed yield during the year 2005 was 1996 kg/ha and predicted yield was 1950, 1862 and 1993 kg/ha by DSSAT, WOFOST and Agrometeorological model respectively. The respective percent deviations were 2.3, 6.7 and 0.2 from the observed value. Negative deviation indicated underestimation by the model. All the models underestimated the rice yield of Bulsar district during 2005. The performance of all the models was satisfactory in 2005 but Agrometeorological model was found superior to the rest of the two.

4.4.4 Kheda district

The predicted yield by DSSAT, WOFOST and Agrometeorological model during the year 2004 was 2382, 2459 and 2242 kg/ha respectively, whereas observed yield of the district was 2270 kg/ha. The percent deviations were 4.9, 8.3 and 1.2 from the observed value. Negative deviation indicated underestimation by the model. The Agrometeorological model underestimated the rice yield of Kheda during 2004. The performance of all the models was satisfactory in 2004 but Agrometeorological model was found superior to the rest of the two.

Table 4.56: Simulated forecasts by different models in Kheda district.

Year	Observed Yield (kg/ha)	Modelled yield		
		DSSAT	WOFOST	Agrometeorological Model
2004	2270	2382(04.9)	2459(08.3)	2242(-01.2)
2005	2436	2283(-06.3)	2432(-00.2)	2404(-01.3)

Figures in parenthesis are per cent deviation from observed yield.

Observed yield during the year 2005 was 2436 kg/ha against the predicted yield of 2283, 2432 and 2404 kg/ha by DSSAT, WOFOST and Agrometeorological model respectively. The respective percent deviations were

6.3, 0.2 and 1.3 from the observed value. Negative deviation indicated underestimation by the model. All the models underestimated the rice yield of Kheda during the year 2005. The performance of all the models was satisfactory in 2005 but WOFOST was found superior to the rest of the two.

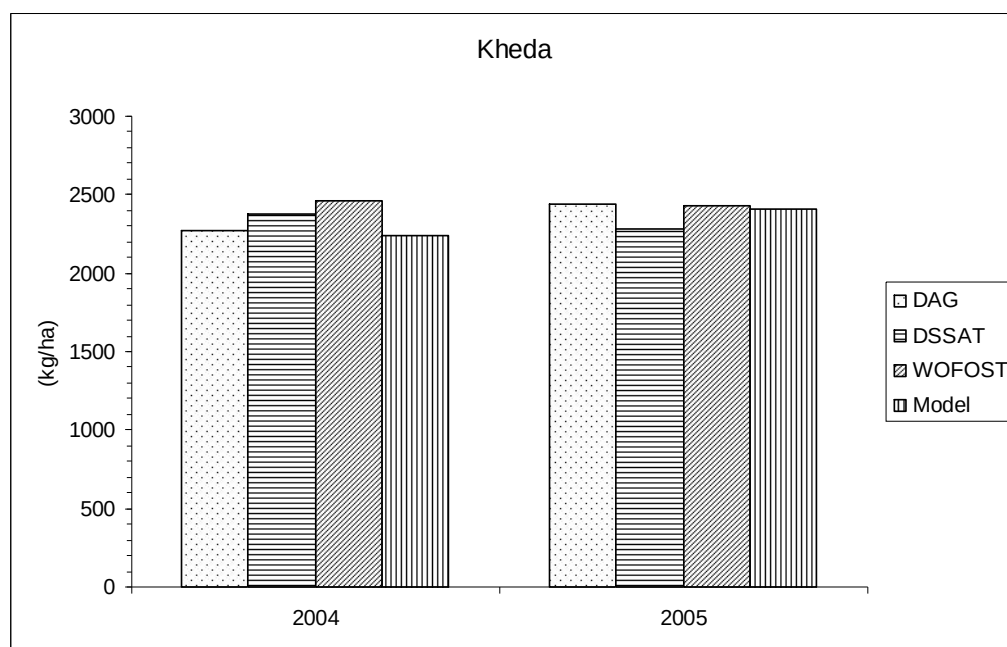


Figure 4.19: Comparison of simulated forecasts by different models in Kheda district with observed rice yield

4.4.5 Panchmahal district

The observed yield of the Panchmahal district during the year 2004 was 758 kg/ha and the predicted yield by DSSAT, WOFOST and Agrometeorological model was 642, 617 and 721 kg/ha respectively. The percent deviations were 15.3, 18.6 and 4.9 from the observed value. Negative deviation indicated underestimation by the model. All the models underestimated the rice yield of Panchmahal district during 2004. The performance of DSSAT and WOFOST was not satisfactory but the performance of Agrometeorological model was satisfactory and was found superior to the rest of the two in 2004.

Table 4.57: Simulated forecasts by different models in Panchmahal district.

Year	Observed Yield (kg/ha)	Modelled yield		
		DSSAT	WOFOST	Agrometeorological Model
2004	758	642(-15.3)	617(-18.6)	721(-04.9)
2005	881	920(04.4)	922(04.6)	874(-00.8)

Figures in parenthesis are per cent deviation from observed yield.

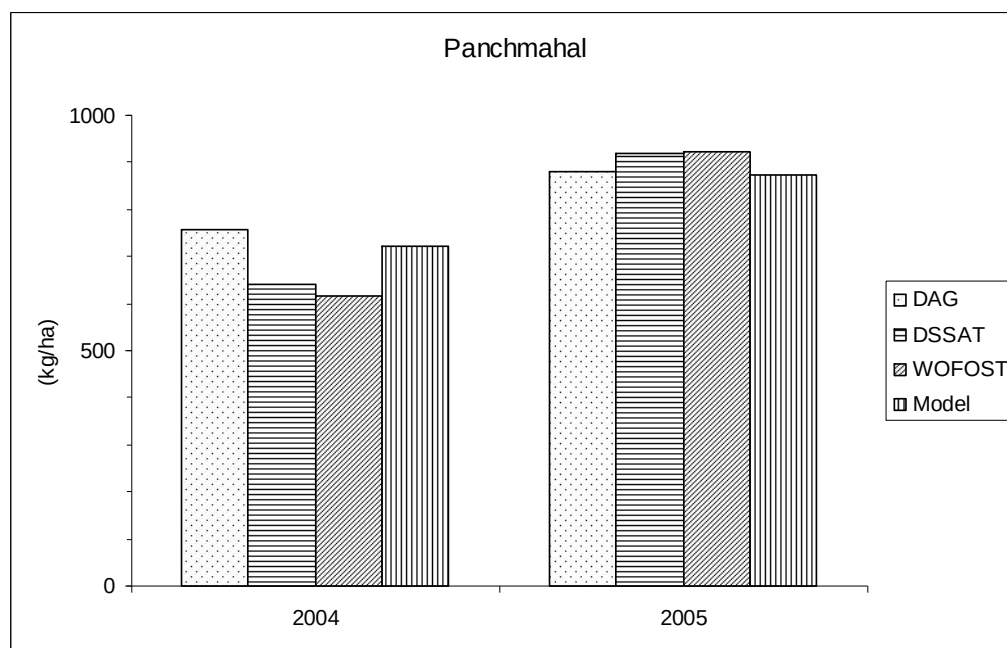


Figure 4.20: Comparison of simulated forecasts by different models in Panchmahal district with observed rice yield

The observed yield during the year 2005 was 881 kg/ha, whereas the predicted yield was 920, 922 and 874 kg/ha by DSSAT, WOFOST and Agrometeorological model respectively. The respective percent deviations were 4.4, 4.6 and 0.8 from the observed value. Negative deviation indicated underestimation by the model. Agrometeorological model underestimated the rice yield of Panchmahal district during 2005. The performance of all the models was satisfactory in 2005 but Agrometeorological model was found superior to the rest of the two.

4.4.6 Sabarkantha district

The observed yield was 1732 kg/ha during the year 2004 and the predicted yield by DSSAT, WOFOST and Agrometeorological model was 1734, 1808 and 1729 kg/ha respectively. The percent deviations were 0.1, 4.4 and 0.2 from the observed value. Negative deviation indicated underestimation by the model. Agrometeorological model underestimated the rice yield of Sabarkantha district during 2004. The performance of all the models was satisfactory. DSSAT was found superior in 2004.

Table 4.58: Simulated forecasts by different models in Sabarkantha district.

Year	Observed Yield (kg/ha)	Modelled yield		
		DSSAT	WOFOST	Agrometeorological Model
2004	1732	1734(00.1)	1808(04.4)	1729(-00.2)
2005	2414	2001(-17.1)	2105(-12.8)	2424(00.4)

Figures in parenthesis are per cent deviation from observed yield.

The observed yield during the year 2005 was 2414 kg/ha, whereas the predicted yield was 2001, 2105 and 2424 kg/ha by DSSAT, WOFOST and Agrometeorological model respectively. The respective percent deviations were 17.1, 12.8 and 0.4 from the observed value. Negative deviation indicated underestimation by the model. DSSAT and WOFOST underestimated the rice yield of Sabarkantha during 2005. The performance of DSSAT and WOFOST was not satisfactory. The performance of Agrometeorological model was satisfactory in 2005 and it was found superior.

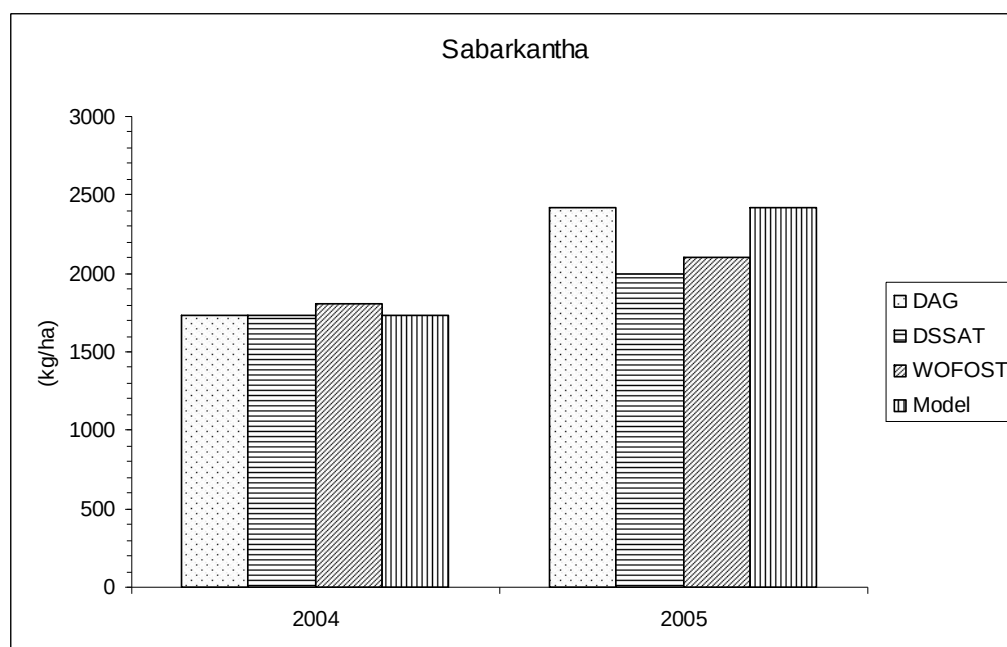


Figure 4.21: Comparison of simulated forecasts by different models in Sabarkantha district with observed rice yield

4.4.7 Surat district

The observed yield during the year 2004 was 1824 kg/ha and the predicted yield by DSSAT, WOFOST and Agrometeorological model was 1985, 1823 and 1826 kg/ha respectively. The deviations were 8.8, 0.1 and 0.1 percent from the observed value. Negative deviation indicated underestimation by the model. WOFOST underestimated the rice yield of Surat during 2004. The performance of all the models was satisfactory and WOFOST was found superior.

Table 4.59: Simulated forecasts by different models in Surat district.

Year	Observed Yield (kg/ha)	Modelled yield		
		DSSAT	WOFOST	Agrometeorological Model
2004	1824	1985(08.8)	1823(-00.1)	1826(00.1)
2005	1921	1938(00.9)	1914(-00.4)	1923(00.1)

Figures in parenthesis are per cent deviation from observed yield.

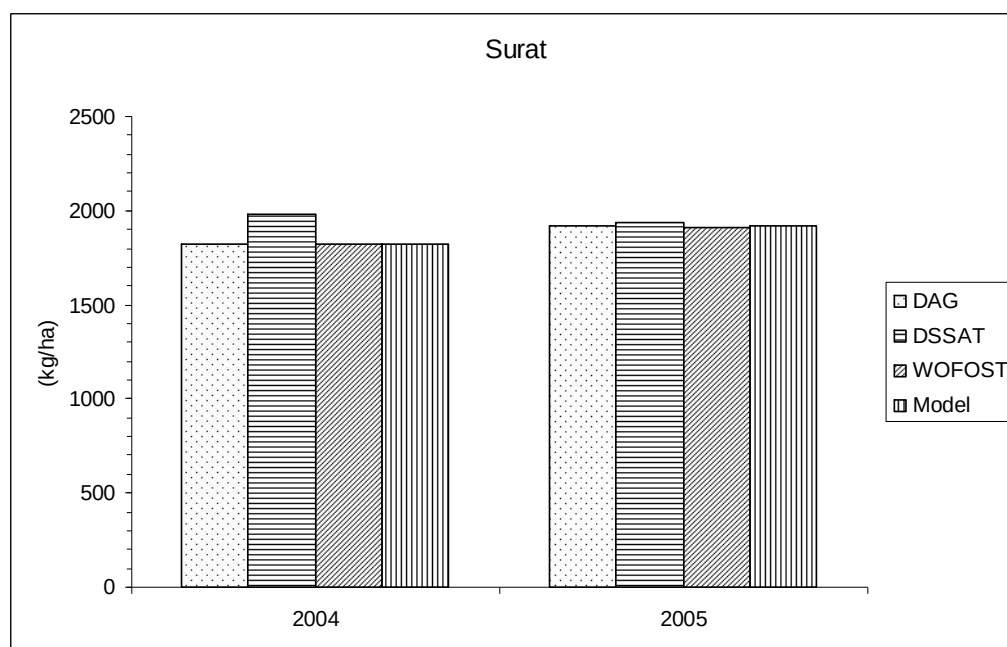


Figure 4.22: Comparison of simulated forecasts by different models in Surat district with actual yield data.

The observed yield during the year 2005 was 1921 kg/ha, whereas the predicted yield was 1938, 1914 and 1923 kg/ha by DSSAT, WOFOST and Agrometeorological model respectively. The respective deviations were 0.9, 0.4 and 0.1 percent from the observed value. Negative deviation indicated underestimation by the model. WOFOST underestimated the rice yield of Surat during 2005. The performance of all the models was satisfactory in 2005 and Agrometeorological model was found superior to rest of the two.

5. SUMMARY AND CONCLUSION

This chapter describes brief and precise summary of the procedures and techniques followed, findings achieved and conclusions drawn through the study entitled "Rice yield prediction using Crop Growth Simulation and Agrometeorological models in Gujarat". Two crop growth simulation models were evaluated for testing their worth for forecasting yield. The crop growth simulation models viz. DSSAT and WOFOST were calibrated and validated under Gujarat conditions. The efforts were also made to develop suitable agrometeorological model for predicting the yield of rice by using combined effects of different weather parameters viz. rainfall, bright sunshine hours, maximum and minimum temperature and morning and afternoon relative humidity on rice yield. For the present investigation the major rice growing districts of Gujarat viz., Ahmedabad, Baroda, Bulsar, Kheda, Panchmahal, Sabarkantha and Surat were considered.

The weather condition prevailed during the crop growing season i.e. from 23rd to 42nd meteorological standard weeks were studied. The average of available data was worked out for rainfall, bright sunshine hours, maximum and minimum temperature, and morning and afternoon relative humidity. The different meteorological parameters were averaged over the standard meteorological weeks along with different phenophases of the crop growth.

Meteorological parameters are interlinked with each other. Therefore, it is difficult to separate out the individual effect. An attempt had been made to

identify the effects of important weather parameters on the growth and development of rice crop as well as yield either individually or jointly by statistical technique.

5.1 SUMMARY

The summary of the research findings of the present investigation are briefly outlined in this section.

5.1.1 EFFECT OF WEATHER PARAMETERS ON RICE YIELD

The effect of weather parameters on rice yield of seven districts of Gujarat was studied using available weather parameters and yield of rice crop through statistical technique and graphical presentation.

The average bright sunshine hours were decreasing from seedling to vegetative lag stage and thereafter it showed an increasing trend.

Highest rainfall was observed in Bulsar during active tillering stage and least in Panchmahals during grain development stage.

The maximum temperature decreased drastically from seedling to vegetative lag stage and gradually increased thereafter. Highest maximum temperature during crop growth period was recorded in Ahmedabad and lowest in Bulsar.

Very little variation was observed in stagewise minimum temperature during the crop growth period in all the districts. The minimum temperature decreased gradually during crop growth period. Highest minimum temperature during crop growth period was recorded in Ahmedabad and Kheda and lowest in Sabarkantha.

There was gradual increase in the morning relative humidity from seedling to flowering stage and a gradual decrease thereafter in all the districts.

Data revealed that there was increasing trend in the afternoon relative humidity from seedling to vegetative lag stage and a decreasing trend was observed thereafter.

5.1.2 CALIBRATION OF CROP GROWTH SIMULATION MODELS

The crop growth simulation models (DSSAT and WOFOST) were calibrated using district yield data of the year 2004 and 2005 and weather parameters of the district. Efforts were also made to predict rice yield using these models.

5.1.2.1 DSSAT

Crop genetic input data, which explain how the life cycle of a cultivar responds to its environment, are not usually available and therefore these were derived interactively. The model was run using a range of values of each coefficient until the desired level of agreement between simulated and observed values reached $\pm 10\%$. For the present study the cultivar genetic coefficients for rice cv. GR-11 have been developed. The calibrated genetic coefficients for rice cv. GR-11 are given in Table 5.1.

Table 5.1: Calibrated Genetic coefficients for rice cv. GR-11

Parameters	P1	P2R	P5	P2O	G1	G2	G3	G4
Genetic coefficients	570.0	100.0	480.0	11.4	36.0	0.0280	1.00	0.80

The results related to DSSAT model simulation in different districts revealed that the observed grain yield of rice varied from 758 (Panchmahals) to 2270 kg ha⁻¹ (Kheda) among different districts during 2004, while model simulated grain yield ranged between 964 (Panchmahals) to 2537 kg ha⁻¹

(Ahmedabad). The simulated values of grain yield were found in perfect agreement with corresponding observed yield. The results of the simulation performance of the model for grain yield for all the districts was found highly significant with coefficient of determination values of 98.3%.

The test criteria for evaluation of models were also computed. Error per cent was 12.84%. Positive and significant association was observed between simulated and observed grain yield. The result of the paired 't' test between simulated and observed grain yield values was found to have been non-significant. The average error as computed by MAE was 139.3, while RMSE (Root mean square error) was recorded 173.3. MBE was found to be 89.0. The positive value suggested the overestimation of the grain yield by the model. Index of agreement (D) was 0.98. The evaluation of the model on an overall basis revealed that the simulation performance of the model in respect of grain yield was good in year 2004.

The results of DSSAT simulation modelling in different districts revealed that the observed rice yield during the year 2005 ranged from 881 (Panchmahals) to 2484 kg ha⁻¹ (Ahmedabad) among different districts, while model simulated rice yield ranged between 920 (Panchmahals) to 2290 kg ha⁻¹ (Ahmedabad). The model overestimated the grain yield in Baroda and Panchmahals while the rice yield was underestimated in Ahmedabad, Bulsar, Kheda, Sabarkantha and Surat.

The error per cent of DSSAT simulated grain yields from those corresponding ones observed during the year 2005 was 10.3%. Negative and significant association was observed between simulated and observed grain yield with coefficient of determination value of 95.6%. The result of the paired 't' test

was found to have been non-significant. The average error as computed by MAE was 135.6 with 186.4 RMSE. The MBE was found to be -94.7. The negative sign suggested the underestimation of the grain yield by the model. Index of agreement (D) was 0.97. The simulation performance of the model in respect of grain yield was good in year 2005.

An effort was made to test the model in terms of mathematical logic and stability to extreme values of weather parameters. The weather parameters selected for this purpose were ambient temperature (± 1 to $\pm 3^{\circ}\text{C}$), solar radiation (± 1 to $\pm 3 \text{ MJm}^{-2} \text{ day}^{-1}$) and concentration of carbon dioxide (100 TO 300 ppm higher concentration to base concentration of 330 ppm).

Sensitivity of DSSAT model simulated grain yield to incremental units of ambient temperature showed a gradual decrease in yield. The increased ambient temperature decreased the yield by 4 to 41 per cent at 3°C elevation in mean ambient temperature. This indicated that increase in ambient temperature will lead to decreased rice yield in Gujarat. The down scaled ambient temperature increased the yield by 7 to 76 per cent at 3°C reduction in mean ambient temperature. This indicated that rice yield will increase with decreased ambient temperature in Gujarat.

The results of varying solar radiation and its effects on rice yield as simulated by DSSAT model for elevated and downscaled radiation regimes showed that with increase from 1 to $3 \text{ MJm}^{-2} \text{ day}^{-1}$ solar radiation, percentage yield increased from 2 to 26% in comparison with base yield. Highest yield increment was observed at $3 \text{ MJm}^{-2} \text{ day}^{-1}$ in Panchmahal district (25.9%). In case

of gradual reduction in solar radiation, gradual decrease in yield in terms of per cent change from base yield was noted as 1 to 42 per cent for reduction in solar radiation by $3 \text{ MJm}^{-2} \text{ day}^{-1}$.

The effect of elevated carbon dioxide (100 to 300 ppm elevation to the base value 330 ppm) on simulated yield of rice showed that at 300 ppm elevation in CO_2 concentration over its base value increased rice yield by 4 to 29 per cent. This showed that the model used in this study had the potential for assessing the impacts of climate change on rice production.

5.1.2.2 WOFOST

WOFOST is a mechanistic model that explains crop growth on the basis of the underlying processes, such as photosynthesis, respiration and how these processes are influenced by environmental conditions. Calibration of model was done by adjusting certain model parameters by running the model using a range of values of each coefficient until the desired level of agreement between simulated and observed values reached $\pm 10\%$. The model required fourteen parameters. The details of these calibrated input model parameters are given in Table 5.2.

The results of WOFOST model simulation in year 2004 for different districts revealed that the observed grain yield of rice varied from 758 (Panchmahals) to 2270 kg ha^{-1} (Kheda) among different districts during 2004, while model simulated grain yield ranged between 617 (Panchmahals) to 2459 kg ha^{-1} (Kheda). The model overestimated the grain yield in Ahmedabad, Bulsar, Kheda and Sabarkantha while reverse trend was observed in Baroda,

Panchmahals and Surat. The simulated values of grain yield were found in perfect agreement with corresponding observed yield.

Table 5.2: Calibrated input model parameters used for WOFOST

Parameter	Value
TSUM1	1753
TSUM2	480
DLO	11.4
TDWI	25.0
SPAN	23.0
TBASE	9.0
CVL	0.754
CVO	0.584
CVR	0.754
CVS	0.754
RML	0.020
RMO	0.030
RMR	0.010
RMS	0.015

The test criteria for evaluation of models were also computed. Error per cent of WOFOST simulated grain yields from those corresponding ones observed during the year 2004 was 6.83%. Positive and significant association was observed between simulated and observed grain yield with coefficient of determination value of 99.6%. The result of the paired 't' test between simulated and observed grain yield values was found to have been non-significant. The average error as computed by MAE was 93.85, while RMSE was recorded 116.98. Mean bias error was found to be 50.14. The positive value indicated the

overestimation of the grain yield by the model. Index of agreement was found 0.99. The evaluation of the model on an overall basis revealed that the simulation performance of the model in respect of grain yield was excellent in year 2004.

The results of WOFOST model simulation during year 2005 for different districts revealed that the observed grain yield of rice varied from 881 (Panchmahals) to 2484 kg ha⁻¹ (Ahmedabad) among different districts, while model simulated grain yield fluctuated from 922 (Panchmahals) to 2432 kg ha⁻¹ (Kheda). Model simulated values of grain yield were found in perfect agreement with corresponding observed yield. The error per cent of WOFOST simulated grain yields from those corresponding ones observed during the year 2005 was 7.34%. Negative and significant association was observed between simulated and observed grain yield during 2005 with coefficient of determination value of 97.1%. The result of the paired 't' test between simulated and observed grain yield values was found to have been non-significant. The average error as computed by MAE was 91.14, while RMSE was recorded 134.60. Mean bias error was found to be – 66.57. The negative sign indicated the underestimation of the grain yield by the model. Index of agreement was found 0.99. The evaluation of the model on an overall basis revealed that the simulation performance of the model in respect of grain yield was excellent in year 2005.

5.1.3 AGROMETEOROLOGICAL MODEL

The historical rice yield data of different districts and weather parameters were used through statistical technique by five different approaches to predict the rice yield. For the selection of the prediction model from different approaches, the

fitted regression equations which accounted more than 75 per cent of the total variation in rice yield and predicted yield early was proposed as the prediction model. The five approaches were

1. Weekwise approach using original weather variables
2. Crop stagewise approach using original weather variables
3. Periodwise approach using original weather variables
4. Week number as weight using generated weather variables
5. Correlation coefficient as weight using generated weather variables.

The weather variables viz. bright sunshine hours, rainfall, maximum and minimum temperature, and morning and afternoon relative humidity related to 12, 14, 16, 18 and 20 weeks crop period were considered in the models of 1st, 4th and 5th approaches to explore the possibility of yield prediction before 8, 6, 4, 2 and 0 weeks of harvest, respectively. In case of crop stagewise approach weather variables were considered upto 1st, 2nd, 3rd, 4th and 5th stages i.e. seedling, active tillering, vegetative lag, flowering, grain development and maturity stages respectively, to provide forecasts before 16, 13, 9, 5 and 2 weeks of harvest, respectively. In periodwise approach weather variables were considered upto 1st, 2nd, 3rd, 4th and 5th periods i.e. June, July, August, September and October respectively, to provide predictions before 4, 3, 2, 1 and 0 months of harvest, respectively. In case of each of the model the variables included were determined based on stepwise regression procedure utilizing historical weather data. The model was selected on the basis of coefficient of determination and earliness of forecasting.

To investigate the effects of weekwise, crop stagewise and periodwise weather variables on the rice yields, the variables which appeared in the equations and had significant partial regression coefficients were considered to have influence on the rice productivity. The overall look on the results showed favourable as well as detrimental effects of weather variables on rice yields.

Generated variables did not show any improvement in the yield forecasting of rice yield in comparison to weekwise, stagewise and periodwise approaches.

Out of the five approaches, three approaches using original observed weather variables (1) weekwise, (2) stagewise and (3) periodwise average weather variables and two approaches using generated weather variables (1) week number as weight and (2) correlation coefficient as weight were used for fitting of the models. Approaches using shorter interval i.e. weekly weather variables either original or generated were found superior to the approaches using longer period averaged weather variables i.e. stagewise and periodwise approaches.

In Ahmedabad, models fitted with weekwise approach, 16 week model, 5 stage model fitted with stagewise approach, 3 period model fitted with periodwise approach, 12 week model fitted with week number as weight approach, and 12 week model in correlation coefficient as weight approach, were finally identified, which explained > 75% variation in productivity. The 12 week model fitted with week number as weight approach which provided earlier rice yield prediction (8 weeks before harvest) and explained higher variation in rice yield (90.6%) is recommended as rice yield prediction model for Ahmedabad district

$$Y = 6304.22 + 3.80 \text{ RHE}^1 - 0.69 \text{ RHM}^2 + 0.26 (\text{RF} \cdot \text{RHE})^0 - 2.37 (\text{MINT} \cdot \text{RHE})^0 + 4.36 (\text{MAXT} \cdot \text{RHM})^2 \quad (\text{Adjusted } R^2 = 90.6\%)$$

or

$$Y = 6304.22 + 3.80 Z_{61} - 0.69 Z_{52} + 0.26 Q_{260} - 2.37 Q_{460} + 4.36 Q_{352} \quad (\text{Adjusted } R^2 = 90.6\%)$$

Models fitted with weekwise approach, 12 week model, 5 stage model fitted with stagewise approach, 14 week model fitted with week number as weight approach, and 16 week model in correlation coefficient as weight approach, were finally identified, which explained > 75% variation in productivity in Baroda district. The 12 week model fitted with weekwise approach which provided earlier prediction of rice yield (8 weeks before harvest) and explained higher variation in rice yield (99.4%) is recommended as rice yield prediction model for Baroda district

$$Y = -5050.94 - 0.33 \text{ RF}_2 + 19.06 \text{ BSS}_6 + 37.45 \text{ RHM}_9 - 42.51 \text{ BSS}_{10} + 178.41 \text{ BSS}_{11} + 24.46 \text{ RHM}_{11} \quad (\text{Adjusted } R^2 = 99.4\%)$$

or

$$Y = -5050.94 - 0.33 X_{2W_{24}} + 19.06 X_{1W_{28}} + 37.45 X_{5W_{31}} - 42.51 X_{1W_{32}} + 178.41 X_{1W_{33}} + 24.46 X_{5W_{33}} \quad (\text{Adjusted } R^2 = 99.4\%)$$

Four out of the five approaches, which were used for fitting the models, models fitted with stagewise, periodwise, week number as weight and correlation coefficient as weight approaches could not be identified as acceptable models in Bulsar district. The 18 week model fitted with weekwise approach which provided earlier rice yield prediction (2 weeks before harvest) and explained

higher variation in rice yield (99.8%) is preferred. Thus, the recommended rice yield prediction model for Bulsar district is

$$Y = 5788.42 - 23.63 \text{ BSS}_3 - 0.15 \text{ RF}_3 - 69.95 \text{ MAXT}_5 + 59.49 \text{ MINT}_5 - 86.85 \text{ BSS}_6 + 106.21 \text{ BSS}_7 + 2.47 \text{ RF}_7 + 103.57 \text{ MAXT}_8 - 33.49 \text{ BSS}_9 + 25.88 \text{ BSS}_{11} + 3.73 \text{ RF}_{11} - 0.84 \text{ RF}_{12} - 170.01 \text{ MAXT}_{13} - 70.32 \text{ MINT}_{13} - 106.46 \text{ BSS}_{14} - 41.87 \text{ RHE}_{14} + 0.60 \text{ RF}_{16} + 41.80 \text{ RHM}_{17} \text{ (Adjusted } R^2 = 99.8\%)$$

or

$$Y = 5788.42 - 23.63 X_{1W_{25}} - 0.15 X_{2W_{25}} - 69.95 X_{3W_{27}} + 59.49 X_{4W_{27}} - 86.85 X_{1W_{28}} + 106.21 X_{1W_{29}} + 2.47 X_{2W_{29}} + 103.57 X_{3W_{30}} - 33.49 X_{1W_{31}} + 25.88 X_{1W_{33}} + 3.73 X_{2W_{33}} - 0.84 X_{2W_{34}} - 170.01 X_{3W_{35}} - 70.32 X_{4W_{35}} - 106.46 X_{1W_{36}} - 41.87 X_{6W_{36}} + 0.60 X_{2W_{38}} + 41.80 X_{5W_{39}} \text{ (Adjusted } R^2 = 99.8\%)$$

The models fitted with stagewise, periodwise, week number as weight and correlation coefficient as weight approaches could not be identified as acceptable models in Kheda district. The 20 week model fitted with weekwise approach which provided rice yield prediction (0 weeks before harvest) and explained higher variation in rice yield (90.7%) is recommended as rice yield prediction model for Kheda district

$$Y = 8682.13 + 317.72 \text{ MINT}_{10} + 12.87 \text{ RHE}_{10} - 202.97 \text{ MINT}_{12} - 59.17 \text{ MAXT}_{18} - 79.21 \text{ BSS}_{19} - 32.92 \text{ RHM}_{19} \text{ (Adjusted } R^2 = 99.8\%)$$

or

$$Y = 8682.13 + 317.72 X_{4W_{32}} + 12.87 X_{6W_{32}} - 202.97 X_{4W_{34}} - 59.17 X_{3W_{40}} - 79.21 X_{1W_{41}} - 32.92 X_{5W_{41}} \text{ (Adjusted } R^2 = 99.8\%)$$

In Panchmahal district the models fitted with weekwise approach, 12 week model and 16 week model in correlation coefficient as weight approach were finally identified, which explained > 75% variation in productivity. The 12 week model fitted with weekwise approach which provided earlier prediction of the rice yield (8 weeks before harvest) and explained higher variation in rice yield (96.0%) is recommended as rice yield prediction model for Panchmahal district

$$Y = 8881.23 - 105.44 \text{ BSS}_2 + 105.02 \text{ MAXT}_2 - 164.14 \text{ MINT}_2 - 8.90 \text{ RHE}_2 - 54.41 \text{ RHM}_7 + 2.78 \text{ RF}_8 - 80.16 \text{ MINT}_{10} \quad (\text{Adjusted } R^2 = 96.0\%)$$

or

$$Y = 8881.23 - 105.44 X_{1W_{24}} + 105.02 X_{3W_{24}} - 164.14 X_{4W_{24}} - 8.90 X_{6W_{24}} - 54.41 X_{5W_{29}} + 2.78 X_{2W_{30}} - 80.16 X_{4W_{32}} \quad (\text{Adjusted } R^2 = 96.0\%)$$

For Sabarkantha district the 14 week model fitted with weekwise approach and 16 week model in correlation coefficient as weight approach were finally identified which explained > 75% variation in productivity but earlier yield prediction was observed in 14 week model fitted with weekwise approach. The model (14 week) which provided earlier prediction (6 weeks before harvest) and explained higher (99.8%) variation in rice yield is preferred. Thus, the recommended rice yield prediction model for Sabarkantha district is

$$Y = -1075.72 + 37.25 \text{ RHM}_1 + 2.68 \text{ RHM}_3 + 8.99 \text{ RHE}_4 + 28.55 \text{ RHM}_5 - 34.24 \text{ RHM}_6 - 6.40 \text{ RHE}_{10} - 59.89 \text{ MAXT}_{11} + 68.84 \text{ MAXT}_{13} \\ (\text{Adjusted } R^2 = 99.8\%)$$

or

$$Y = -1075.72 + 37.25 X_5w_{23} + 2.68 X_5w_{25} + 8.99 X_6w_{26} + 28.55 X_5w_{27} - 34.24 X_5w_{28} - 6.40 X_6w_{32} - 59.89 X_3w_{33} + 68.84 X_3w_{35}$$

(Adjusted $R^2 = 99.8\%$)

Four out of the five approaches, which were used for fitting the models, models fitted with stagewise, periodwise, week number as weight and correlation coefficient as weight approaches could not be identified as acceptable models in Surat district. The 20 week model fitted with weekwise approach which provided yield prediction 0 weeks before harvest and explained higher variation in rice yield (99.9%) is recommended as rice yield prediction model for Surat district

$$Y = 2851.46 + 72.40 MINT_1 + 57.63 MAXT_4 - 17.24 MAXT_5 - 0.06 RF_8 - 2.83 RHM_9 - 1.38 RF_{11} - 18.61 MINT_{16} - 2.75 RF_{18} - 1.66 RF_{19} - 89.51 MAXT_{20} - 6.24 RHE_{20}$$

(Adjusted $R^2 = 99.8\%$)

or

$$Y = 2851.46 + 72.40 X_4w_{23} + 57.63 X_3w_{26} - 17.24 X_3w_{27} - 0.06 X_2w_{30} - 2.83 X_5w_{31} - 1.38 X_2w_{33} - 18.61 X_4w_{38} - 2.75 X_2w_{40} - 1.66 X_2w_{41} - 89.51 X_3w_{42} - 6.24 X_6w_{42}$$

(Adjusted $R^2 = 99.8\%$)

The developed agrometeorological models were equally efficient to the crop growth simulation models viz. DSSAT and WOFOST in all the districts except in Baroda district where the performance of WOFOST and DSSAT respectively was found superior to the developed model.

In Ahmedabad district the performance of WOFOST and Agrometeorological model was satisfactory in 2004 but WOFOST was found

superior. The performance of all the models was satisfactory in 2005 but WOFOST was superior to the rest of the two models.

The performance of all the models was satisfactory in 2004 but WOFOST was superior to rest of the two in Baroda district. The performance of Agrometeorological model was not upto the mark but the performance of DSSAT and WOFOST was found satisfactory in 2005 and WOFOST was found superior.

The performance of all the models in Bulsar district was satisfactory in 2004 and 2005 but Agrometeorological model was found superior to the rest of the two.

In Kheda district performance of all the models was satisfactory in 2004 but Agrometeorological model was found superior to the rest of the two. The performance of all the models was satisfactory in 2005 but WOFOST was found superior to the rest of the two.

The performance of DSSAT and WOFOST was not satisfactory in Panchmahal but the performance of Agrometeorological model was satisfactory and was found superior to the rest of the two in 2004. The performance of all the models was satisfactory in 2005 but Agrometeorological model was found superior to the rest of the two.

The performance of all the models was satisfactory in Sabarkantha district but DSSAT was found superior in 2004. The performance of DSSAT and WOFOST was not satisfactory in 2005. The performance of Agrometeorological model was satisfactory and it was found superior in 2005.

The performance of all the models was satisfactory in 2004 and WOFOST was found superior in Surat district. The performance of all the models was

satisfactory in 2005 and Agrometeorological model was found superior to rest of the two.

5.2 CONCLUSION

The findings of the present investigation can be broadly concluded as follows

1. The simulation performance of the DSSAT model for grain yield for all the districts was found highly significant with coefficient of determination values of 98.3% and 95.6% in year 2004 and 2005 respectively.
2. The increased ambient temperature decreased the yield by 4 to 41 per cent at 3°C elevation in mean ambient temperature and the down scaled ambient temperature increased the yield by 7 to 76 per cent at 3°C reduction in mean ambient temperature.
3. With increase from 1 to 3 MJm⁻² day⁻¹ solar radiation, percentage yield increased from 2 to 26 in comparison with base yield and gradual decrease in yield in terms of per cent change from base yield was noted as 1 to 42 per cent for reduction in solar radiation by 3 MJm⁻² day⁻¹.
4. The effect of elevated carbon dioxide showed that at 300 ppm elevation in CO₂ concentration over its base value increased rice yield by 4 to 29 per cent.
5. Positive and significant association was observed between simulated and observed grain yield by WOFOST with coefficient of determination value of 99.6% in year 2004 and 97.1% in 2005.
6. Generated variables did not show any improvement in the yield forecasting of rice yield in comparison to weekwise, stagewise and periodwise approaches.

7. Approaches using shorter interval i.e. weekly weather variables either original or generated were found superior to the approaches using longer period averaged weather variables i.e. stagewise and periodwise approaches.

8. In Ahmedabad 12 week model fitted with week number as weight approach which provided earlier rice yield prediction (8 weeks before harvest) and explained higher variation in rice yield (90.6%) is recommended as rice yield prediction model

$$Y = 6304.22 + 3.80 RHE^1 - 0.69 RHM^2 + 0.26 (RF \cdot RHE)^0 - 2.37 (MINT \cdot RHE)^0 + 4.36 (MAXT \cdot RHM)^2 \quad (\text{Adjusted } R^2 = 90.6\%)$$

or

$$Y = 6304.22 + 3.80 Z_{61} - 0.69 Z_{52} + 0.26 Q_{260} - 2.37 Q_{460} + 4.36 Q_{352} \quad (\text{Adjusted } R^2 = 90.6\%)$$

9. The 12 week model fitted with weekwise approach which provided earlier prediction of rice yield (8 weeks before harvest) and explained higher variation in rice yield (99.4%) is recommended as rice yield prediction model for Baroda district

$$Y = -5050.94 - 0.33 RF_2 + 19.06 BSS_6 + 37.45 RHM_9 - 42.51 BSS_{10} + 178.41 BSS_{11} + 24.46 RHM_{11} \quad (\text{Adjusted } R^2 = 99.4\%)$$

or

$$Y = -5050.94 - 0.33 X_{2W_{24}} + 19.06 X_{1W_{28}} + 37.45 X_{5W_{31}} - 42.51 X_{1W_{32}} + 178.41 X_{1W_{33}} + 24.46 X_{5W_{33}} \quad (\text{Adjusted } R^2 = 99.4\%)$$

10. The 18 week model fitted with weekwise approach which provided earlier rice yield prediction (2 weeks before harvest) and explained higher variation in

rice yield (99.8%) is recommended as rice yield prediction model for Bulsar district

$$Y = 5788.42 - 23.63 \text{ BSS}_3 - 0.15 \text{ RF}_3 - 69.95 \text{ MAXT}_5 + 59.49 \text{ MINT}_5 - 86.85 \text{ BSS}_6 + 106.21 \text{ BSS}_7 + 2.47 \text{ RF}_7 + 103.57 \text{ MAXT}_8 - 33.49 \text{ BSS}_9 + 25.88 \text{ BSS}_{11} + 3.73 \text{ RF}_{11} - 0.84 \text{ RF}_{12} - 170.01 \text{ MAXT}_{13} - 70.32 \text{ MINT}_{13} - 106.46 \text{ BSS}_{14} - 41.87 \text{ RHE}_{14} + 0.60 \text{ RF}_{16} + 41.80 \text{ RHM}_{17} \text{ (Adjusted } R^2 = 99.8\%)$$

or

$$Y = 5788.42 - 23.63 X_{1W25} - 0.15 X_{2W25} - 69.95 X_{3W27} + 59.49 X_{4W27} - 86.85 X_{1W28} + 106.21 X_{1W29} + 2.47 X_{2W29} + 103.57 X_{3W30} - 33.49 X_{1W31} + 25.88 X_{1W33} + 3.73 X_{2W33} - 0.84 X_{2W34} - 170.01 X_{3W35} - 70.32 X_{4W35} - 106.46 X_{1W36} - 41.87 X_{6W36} + 0.60 X_{2W38} + 41.80 X_{5W39} \text{ (Adjusted } R^2 = 99.8\%)$$

11. The 20 week model fitted with weekwise approach which provided rice yield prediction (0 weeks before harvest) and explained higher variation in rice yield (90.7%) is recommended as rice yield prediction model for Kheda district

$$Y = 8682.13 + 317.72 \text{ MINT}_{10} + 12.87 \text{ RHE}_{10} - 202.97 \text{ MINT}_{12} - 59.17 \text{ MAXT}_{18} - 79.21 \text{ BSS}_{19} - 32.92 \text{ RHM}_{19} \text{ (Adjusted } R^2 = 99.8\%)$$

or

$$Y = 8682.13 + 317.72 X_{4W32} + 12.87 X_{6W32} - 202.97 X_{4W34} - 59.17 X_{3W40} - 79.21 X_{1W41} - 32.92 X_{5W41} \text{ (Adjusted } R^2 = 99.8\%)$$

12. The 12 week model fitted with weekwise approach which provided earlier prediction of the rice yield (8 weeks before harvest) and explained higher

variation in rice yield (96.0%) is recommended as rice yield prediction model for Panchmahal district

$$Y = 8881.23 - 105.44 \text{ BSS}_2 + 105.02 \text{ MAXT}_2 - 164.14 \text{ MINT}_2 - 8.90 \text{ RHE}_2 - 54.41 \text{ RHM}_7 + 2.78 \text{ RF}_8 - 80.16 \text{ MINT}_{10} \quad (\text{Adjusted } R^2 = 96.0\%)$$

or

$$Y = 8881.23 - 105.44 X_{1W_{24}} + 105.02 X_{3W_{24}} - 164.14 X_{4W_{24}} - 8.90 X_{6W_{24}} - 54.41 X_{5W_{29}} + 2.78 X_{2W_{30}} - 80.16 X_{4W_{32}} \quad (\text{Adjusted } R^2 = 96.0\%)$$

13. The 14 week model which provided earlier prediction (6 weeks before harvest) and explained higher (99.8%) variation in rice yield is recommended as rice yield prediction model for Sabarkantha district

$$Y = -1075.72 + 37.25 \text{ RHM}_1 + 2.68 \text{ RHM}_3 + 8.99 \text{ RHE}_4 + 28.55 \text{ RHM}_5 - 34.24 \text{ RHM}_6 - 6.40 \text{ RHE}_{10} - 59.89 \text{ MAXT}_{11} + 68.84 \text{ MAXT}_{13} \quad (\text{Adjusted } R^2 = 99.8\%)$$

or

$$Y = -1075.72 + 37.25 X_{5W_{23}} + 2.68 X_{5W_{25}} + 8.99 X_{6W_{26}} + 28.55 X_{5W_{27}} - 34.24 X_{5W_{28}} - 6.40 X_{6W_{32}} - 59.89 X_{3W_{33}} + 68.84 X_{3W_{35}} \quad (\text{Adjusted } R^2 = 99.8\%)$$

14. The 20 week model fitted with weekwise approach which provided yield prediction 0 weeks before harvest and explained higher variation in rice yield (99.9%) is recommended as rice yield prediction model for Surat district

$$Y = 2851.46 + 72.40 \text{ MINT}_1 + 57.63 \text{ MAXT}_4 - 17.24 \text{ MAXT}_5 - 0.06 \text{ RF}_8 - 2.83 \text{ RHM}_9 - 1.38 \text{ RF}_{11} - 18.61 \text{ MINT}_{16} - 2.75 \text{ RF}_{18} - 1.66 \text{ RF}_{19} - 89.51 \text{ MAXT}_{20} - 6.24 \text{ RHE}_{20} \quad (\text{Adjusted } R^2 = 99.8\%)$$

or

$$Y = 2851.46 + 72.40 X_{4W_{23}} + 57.63 X_{3W_{26}} - 17.24 X_{3W_{27}} - 0.06 X_{2W_{30}} - 2.83 X_{5W_{31}} - 1.38 X_{2W_{33}} - 18.61 X_{4W_{38}} - 2.75 X_{2W_{40}} - 1.66 X_{2W_{41}} - 89.51 X_{3W_{42}} - 6.24 X_{6W_{42}} \quad (\text{Adjusted } R^2 = 99.8\%)$$

15. The developed agrometeorological models were equally comparable to the crop growth simulation models viz. DSSAT and WOFOST in all the districts except in Baroda district where the performance of WOFOST and DSSAT respectively was found superior to the developed model.
16. The average performance of all the models was adept in yield prediction for all the districts with percent deviation of ± 0.9 to $\pm 9.9\%$ for DSSAT, ± 0.2 to ± 6.1 for WOFOST and ± 0.1 to $\pm 16.8\%$ for agrometeorological model.
17. The developed agrometeorological models efficiently predicted the rice yield upto 8 weeks i.e. two months before harvest of the crop with very high accuracy ($>90\%$).

5.3 SUGGESTIONS FOR FUTURE STUDY

Crop-weather yield relationship should be studied by integration of spatial and temporal data by Remote Sensing (RS) clubbing with Geographic Information System (GIS) and crop simulation models.

The crop growth simulation models required to be calibrated at original code level for Indian farming conditions.

Detailed phenological/ physiological experimental studies required to develop mechanistic model using understanding of basic physiological growth/ development processes.

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